Numerical and Experimental Investigation on the Function of Siphons for Tipping-Bucket Rain Gauges

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ABSTRACT

Siphons can effectively reduce the influence of rainfall intensity on the mechanical bias of tipping-bucket rain gauges (TBRs). To identify the function of siphons for TBRs, this study investigated three types of siphons: a Texas Electronics (TE) siphon, a RIMCO (RIM) siphon, and a Sutron siphon, with both computational fluid dynamics (CFD) simulations and laboratory experiments. To provide better structural designs, further simulations were conducted to adjust two parameters of the siphons: d , the distance from the cap to the outer part, and w , the distance from the main part to the cap part. The simulation results reveal that the most significant advantage of a siphon over a rain gauge collector is to provide stable outflow for the tipping bucket. The stable outflow rates were around 1.5 g s^{-1} (TE) and 1.55 g s^{-1} (RIM), while the Sutron siphon increased from 1.75 to 2.45 g s^{-1} . The ratio of stable outflow time to a complete siphon event was 69% (TE), 81% (Sutron), and 83% (RIM). In experiments with rainfall intensity higher than 1 mm min^{-1} , the RIM and TE siphons showed oscillations in the outflow during consecutive siphon events, whereas the Sutron siphon was relatively stable. Further simulations showed that the recommended d and w for the TE siphon are 2.5 and 1.1 mm, respectively, while the recommendations for the RIM siphon are $d = 2.5 \text{ mm}$ and $w = 0.9 \text{ mm}$. The manufacturer's specifications for d and w are best for the Sutron siphon. These results help to understand the functionality of siphons for TBRs, and benefit the structural design of common siphons.

1. Introduction

Tipping-bucket rain gauges (TBRs) are widely used in hydrology and meteorology to measure rainfall because they are simple, durable, inexpensive, and easy to install in urban and remote areas (Humphrey et al. 1997; Fankhauser 1998; Shedekar et al. 2016). However, TBR measurements are underestimated due to wetting, evaporation, and wind turbulence at the gauge orifice (Colli et al. 2016a,b; Baghapour et al. 2017). TBRs also underestimate rainfall volume and intensity because of rainwater that is missed as the bucket flips (Molini et al. 2005). A nonlinear relationship usually exists between rainfall intensity and raw volume measurements from the tipping bucket.

To reduce the influence of rainfall intensity on the mechanical bias of TBRs, three main approaches have been adopted. First, the dynamic calibration method is often

adopted to determine the relationship between the rainfall intensity and the raw measurement of the TBR, and then a calibration relationship is used to correct the raw measurement (Calder and Kidd 1978; Niemczynowicz 1986; La Barbera et al. 2002; Liao et al. 2020).

The second approach is often adopted in meteorological stations in China. This approach involves using a double-tipping-bucket rain gauge (model SL3-1, manufactured by Shanghai Meteorological Instrument Factory, Co., Ltd.) to minimize the influence of rainfall intensity on mechanical bias (Yue-yue et al. 2014; Stagnaro et al. 2016). The SL3-1 TBR has two tipping buckets: an upper tipping bucket turns over and injects rainwater into a converging funnel between the upper and lower tipping buckets; and the lower tipping bucket receives the water emanating from the converging funnel and measures the rainfall. The upper tipping bucket and the converging funnel collectively function to stabilize natural rainfall such that uniform

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rainfall intensity flows into the lower tipping bucket (Yin and Ling-jun 2012; Chan et al. 2015). As such, the TBR can be calibrated with a single rainfall intensity. This approach has been shown to be effective in operational observations and experiments (Yue-yue et al. 2014; Rui-feng et al. 2016).

The last and perhaps most attractive approach involves equipping a siphon to the receiver of a TBR. It is increasingly prevalent to equip a siphon between the rain gauge collecting funnel and the tipping bucket of a TBR. Thus, rainwater accumulates in the siphon and triggers a siphon emptying event. Then, rainwater is injected into the tipping bucket at the almost same “speed,” independent of the rainfall intensity. Siphons have the same function as double tipping buckets, insofar as they stabilize natural rainfall to ensure relatively uniform intensity of flow into the tipping bucket (Maksimović et al. 1991; Simić and Maksimović 1994; Vuerich et al. 2009). Siphons thus facilitate TBR measurements, especially with uncorrected TBRs. A siphon event is mainly driven by gravity, hydrostatic pressure, and molecular cohesion (Boatwright et al. 2011; Hughes and Gurung 2014), and therefore, its outflow is more stable than that of an ordinary rain gauge collecting funnel. Consequently, siphons are an effective approach to reducing the influence of rainfall intensity on the mechanical bias of TBRs. Indeed, siphons are increasingly used in experiments to correct rainfall data (Maksimović et al. 1991) and for field comparisons of rainfall intensity gauges (Vuerich et al. 2009; Lanza et al. 2010).

However, the function of siphons in TBRs has not been investigated comprehensively with simulations and experiments. Thus, we investigated three common types of siphons with both computational fluid dynamics (CFD) simulations and laboratory experiments. The numerical and laboratory results of this study can improve our knowledge of siphons and help to select appropriate siphons for TBRs. Simulations were also carried out to optimize the parameters of siphons in an effort to improve their structural design.

2. Methodology

a. Simulation setup

The structure of a siphon consists of three parts: the cap part, the main part, and the outer part (Fig. 1). The cap part screws onto the main part, while the main part screws onto the outer part. A siphon channel is formed by these three parts, and it can be shown as a computational domain (see Fig. 1). The function of the outer part is to provide a zone for accumulating rainwater to trigger a siphon emptying event. The functions of the cap and main parts are combined with the outer part to form a siphon channel.

In this study, three types of siphons were investigated: a Texas Electronics (TE) siphon, a Sutron siphon, and a RIMCO RIM7499 (RIM) siphon. The collectors for the TBRs with these three siphons were 200, 205, and 203 mm in diameter, respectively. Geometric 3D models were built based on the actual size of the TBRs through geometric 3D software. The chamfers of the TE siphon (Fig. 1a) were also built with a geometric 3D model. Although these three siphons are similar in structure, there are four key differences in terms of size and materials: the distance from the cap part to the outer part; the length of the outflow nozzle (the Sutron siphon has the longest outflow nozzle); the diameter of the cap part; and the material of the siphons (the TE and RIM siphons are made of brass and the Sutron siphon is made of stainless steel). The geometrical characteristics and materials of these three siphons are listed in Table 1.

The geometric 3D models can be discretized into a series of control volumes for CFD simulations with structured and unstructured mesh methods. In general, the former method provides fewer nodes and elements than the latter. However, an unstructured mesh method was used in this study because the complexity of the siphons causes difficulties with a structured mesh method. To guarantee reliable numerical results, the mesh was refined by a subdivision method to improve the mesh quality. The mesh quality was checked by using the skewness and aspect ratio to ensure that the mesh was adequate for CFD simulations. The statistics and mesh quality of the different meshes are shown in Table 2.

The volume-of-fluid (VOF) model and the Reynolds average Navier–Stokes (RANS) realizable k – ϵ model were used in this study for the numerical calculations. The VOF model can reveal the air and water two-phased flow as it changes during a siphon emptying event. The RANS realizable k – ϵ model is a two-equation turbulence model for Navier–Stokes equations in CFD simulations. The momentum equation of the VOF, also used by Aydin et al. (2015), is as follows (ANSYS 2005):

$$\frac{\partial}{\partial t}(\rho u_j) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial P_s}{\partial x_j} + \frac{\partial}{\partial x_j}\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \rho g_j + F_j, \quad (1)$$

where $\mathbf{u}$ is the velocity vector, P_s is pressure, μ is the dynamic viscosity of fluid, and F is body force. In the VOF model, the fraction of each phase in the calculation domain is controlled by Eq. (2):

$$\frac{1}{\rho_q} \left[\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla \cdot (\alpha_q \rho_q \mathbf{v}_q) \right] = S_{\alpha q} + \sum_{p=1}^n (\dot{m}_{pq} - \dot{m}_{qp}), \quad (2)$$

FIG. 1. Geometric 3D models and meshes of three different siphons: (a) TE siphon, (b) Sutron siphon, and (c) RIM siphon. The cap part, main part, and outer part combine to form a siphon channel, shown as a computational domain in CFD simulations.

where α_q is the fluid's volume fraction in a cell of phase q . If the cell is empty, α_q is zero, and if the cell is full, α_q is 1.0. The cell has an interface between two fluid phases for $0 < \alpha_q < 1$ (ANSYS 2005). Further, $S_{\alpha q}$ is a source term and zero by default, $\dot{m}_{qp}$ is the mass transfer from

phase q to phase p , and $\dot{m}_{pq}$ is the mass transfer from phase p to phase q (Aydin et al. 2015).

Furthermore, water surface tension and wall adhesion were considered in the simulations. For the coefficient of surface tension in the VOF model, 0.0735 N m^{-1} at 15°C

TABLE 1. Geometrical characteristics and materials of the three siphons.

	TE (mm)	Sutor (mm)	RIM (mm)
Diameter of outflow nozzle	3	3	2.8
Length of outflow nozzle	18.5	38.5	31.7
Distance from the cap part to outer part	1.2	1	2
Shapes of cap part	Hexagonal prism	Cylinder	Cylinder
Diameter of cap part	12	12.7	12.7
Outer part	Uniform diameter	Variable diameter	Variable diameter
Diameters of outer part	24	26.4, 23.2	23, 28.2
Materials of siphon	Brass	Stainless steel	Brass
Diameters of rain gauge collecting funnel	200	205	203

TABLE 2. Mesh statistics and mesh quality of three different siphons. Nodes and elements are the statistics of the mesh information. The maximum skewness and maximum aspect ratio are two parameters for checking the mesh quality.

Type	Mesh statistics		Max skewness	Max aspect ratio
	Nodes (million)	Elements (million)		
TE	0.39	0.26	0.75	8.33
Sutron	0.31	0.21	0.72	8.2
RIM	0.26	0.18	0.73	9.5

was set. The contact angle of the brass and stainless-steel siphon materials was 79.75° and 56.3° , respectively (Fig. 2). The roughness of the brass and stainless steel was 0.3 and $0.45\ \mu\text{m}$, respectively. These parameters were measured in the laboratory of the Materials and Structures Department, Nanjing Hydraulic Research Institute, China.

RANS-based methods provide economical computations of turbulent flows, and previous simulation studies of the effect of wind on rainfall measurements were performed with a RANS-based $k-\varepsilon$ turbulence model (Nešpor and Sevruck 1999; Nešpor et al. 2000; Constantinescu et al. 2007). Furthermore, the Reynolds stress-equation model, standard $k-\varepsilon$, and realizable $k-\varepsilon$ turbulence models provide better results for channel siphons (Aydin and Emiroglu 2013). Therefore, the RANS realizable $k-\varepsilon$ model was selected for this study.

To improve the structural design of siphons, further simulations were carried out to optimize two parameters: d , the distance between the cap part and the outer part (Fig. 3a); and w , the distance from the main part to the cap part (Fig. 3b). The reason for optimizing these two parameters pertains to the differences in the geometric 3D models (Table 1) among the three siphons. These two parameters were changed in simulations to reveal a better understanding of their function and to improve their structural design.

b. Experimental setup

A TBR calibration system (Fig. 4a) was constructed to reveal the characteristics of the three siphons and to compare their differences. In this system, a peristaltic pump was used to simulate different rainfall intensity, and an electric balance with accuracy of $0.01\ \text{g}$ was

FIG. 2. Measurements of the contact angles of brass and stainless-steel siphon materials: (a) contact angle of brass (TE and RIM siphons) and (b) contact angle of stainless steel (Sutron siphon).

FIG. 3. Diagram of two parameters to improve siphon design: (a) d , the distance from the cap part to the outer part, and (b) w , the distance from the main part to the cap part.

used to determine the outflow water mass of the siphons. A MATLAB program was run (Fig. 4a) to control the peristaltic pump and electric balance. During calibration experiments, this program automatically provided the output data of the balance and calculated the average relative error of the tipping buckets after calibration.

The distance between the siphon and the electric balance was kept the same in each treatment to ensure the same conditions for the different siphons, and to maintain the position of the water injected into the rain gauge collecting funnel (Fig. 4b). In the experiments, an interesting phenomenon occurred: the outflow water mass during the first siphon emptying event differed from that of subsequent siphon emptying events. To explore the differences between the first and subsequent siphon emptying events, a transparent siphon structure was constructed to determine the change in water level during the siphon emptying events. The benefit of using a transparent siphon structure is that water mixed with orange pigment can be clearly recorded by a camera during the emptying events (Fig. 12). The dimensions of

this transparent custom-made siphon were similar to that of the RIM siphon.

3. Results and discussion

a. Simulation results

The first siphon emptying event was simulated, and the result is shown in Fig. 5, where red represents water and blue represents air. At $t = 0$ s, the initial water volume was the same as it was with the experiments for the first trigger of the siphon event. For the TE siphon, water filled the siphon channel and began to outflow around 0.20 s. At 2.05 s, the emptying event completed, and residual water emerged in the siphon. As shown in Fig. 5, the entire emptying event can be divided into seven stages (“O” represents the initial state and “A” through “F” are time steps) according to the outlet mass flow rate (Fig. 7). The most significant feature of the siphon emptying event is that the siphon channel is filled with water to provide a stable flow rate for the tipping bucket. Additionally, at the end of this event (at 2.05 s), most residual water remained in the bottom of the outer

FIG. 4. TBR calibration system in experiments: (a) components of the TBR calibration system and (b) schematic diagram of this system.

FIG. 5. Volume fraction of water in the first siphon emptying event simulation, where red denotes water and blue denotes air: (a) TE siphon, (b) Sutron siphon, and (c) RIM siphon. The letters “O” (the initial state) and “A” through “F” divide the emptying event into seven stages.

part, while some residual water remained in the outflow nozzle (Fig. 5).

The total pressure distribution inside the siphon had different characteristics at different stages (Fig. 6, taking the RIM siphon as an example). The total pressure consists of static pressure and dynamic pressure (the reference pressure is atmospheric pressure). At $t = 0.22$ s, the pressure distribution was unstable, yet it became relatively stable from stages “B” to “D.” At this relatively stable duration, high pressure distributed at the lower region of the outflow nozzle, and there was negative pressure in the upper region. This pressure distribution guaranteed that the water discharged from the outflow nozzle and remained at a stable outflow rate.

At $t = 2.36$ s, corresponding the highest outflow rate of point “E” in Fig. 7, the highest pressure (246 Pa) was distributed in the lower region of the outflow nozzle. At $t = 2.42$ s, the total pressure approached the atmospheric pressure after the emptying event ended.

The outlet mass flow rate of the first siphon emptying event for these three siphons is shown in Fig. 7. The results show that the mass flow rate changed dramatically at the beginning and end of the emptying event, but in the middle (i.e., from stages “B” to “C”), the mass flow rate was relatively stable. This differs from an ordinary collecting funnel outflow, which is affected by raw rainfall intensity. In this stable outflow stage, the outflow rate was 1.5 and 1.55 g s^{-1} for the TE and RIM

FIG. 6. Distribution of total pressure during the siphon emptying event simulation of the RIM siphon. The total pressure consists of static pressure and dynamic pressure (the reference pressure is atmospheric pressure).

siphon, respectively. These outflow rates are respectively equivalent to 2.86 and 2.82 mm min^{-1} rainfall intensity for the tipping bucket. A stable outflow with a siphon leads to a constant measuring error due to water loss as the tipping bucket rotates (Molini et al. 2005). Thus, TBRs with siphons can be easily calibrated based on constant rainfall intensity. The Sutron siphon showed a slightly increasing trend, from 1.75 to 2.45 g s^{-1} , equivalent to 3.24 to 4.54 mm min^{-1} rainfall intensity for the tipping bucket. Here, T_2 was used to represent the relative stable outflow time from point “B” to “C.” As shown in Fig. 7, T_2 for the TE and Sutron siphons is 1.29 and 1.48 s , respectively. From “C” to “D,” the RIM siphon provided an extra 0.28 s of relatively stable outflow state, whereas the outflow rate of the TE and Sutron siphons decreased sharply. Overall, the total relatively stable outflow time T_2 for the TE, Sutron, and RIM siphons was 1.29 , 1.48 and 1.83 s , respectively. Here, the ratio of T_2 to the complete siphon emptying duration (inferred as R_t) was used to reflect the function of a siphon. A higher R_t indicates that the siphon can provide longer stable outflow for the tipping bucket during siphon events. And the R_t for the Sutron (81%) and RIM (83%) siphons was higher than that of the TE siphon (69%).

Rainwater loss during the movement of the tipping bucket leads to underestimations of precipitation at higher rainfall intensities (Marsalek 1981; Vasvári 2005), and this error is typically remedied by dynamic calibrations and corrections of the raw measurements using a calibration curve (Niemczynowicz 1986). Fortunately, if a TBR is equipped with a proper siphon, during the stable siphon emptying stage, the siphon can deliver water to the bucket at a constant flow rate under the condition of varying rainfall intensity. Therefore, the multiple-rainfall-intensity calibration for TBR can be

simplified to a single-rainfall-intensity calibration. A proper siphon can stabilize the outflow rate during T_2 , and the tipping bucket can be regulated to compensate for the loss of water so that measurement errors with TBRs are limited to an acceptable range (e.g., $\pm 2\%$).

The mass flow rate curves changed dramatically at points “C,” “D,” and “E” during the emptying event (Fig. 7). This can be explained by analyzing the force condition of the water at different locations in the siphon channel. Taking the TE siphon as an example, at $t = 1.61 \text{ s}$ in Fig. 8 (corresponding to point “C” in Fig. 7), the water surface tension changed dramatically, because the channel size changed from a formerly wide space to a narrow one. In Fig. 8a, f_1 and f_2 are used to analyze the force condition. Here, f_1 is viscous force, and f_2 is the resultant force of surface tension and wall friction force.

FIG. 7. Outlet mass flow rate of the three siphons in the first siphon emptying event. Points “O” and “A” through “F” correspond to their states in Fig. 5 and divide the event into seven stages.

FIG. 8. Analysis of the forces condition of water at different locations of the TE siphon channel, corresponding to three extremum points (“C,” “D,” and “E” in Fig. 7): (a) $t = 1.61$ s, (b) $t = 1.76$ s, and (c) $t = 1.85$ s. The force f_1 is viscous force; f_2 represents the resultant force of surface tension and wall friction force; f_3 is the resultant force of surface tension and wall friction force; f_4 represents viscous force; f_5 is the resultant force of viscous force and gravity; and f_6 represents the resultant force of surface tension and wall friction force.

They were relatively equal before 1.61 s during the stable outflow stage. However, after point “C” in Fig. 7, f_2 surpassed f_1 , giving rise to a decrease in outflow rate. At point “D” in Fig. 7 ($t = 1.76$ s), the water surface encountered the narrowest space in a complete siphon event, and force f_3 (the resultant force of surface tension and wall friction force) was greater than f_4 (viscous force), resulting in the lowest mass flow rate in the entire emptying event. For point “E,” corresponding to $t = 1.85$ s in Fig. 5, f_5 (the resultant force of viscous force and gravity) became greater than f_6 (the resultant force of surface tension and wall friction force), which generated the highest mass flow rate in the siphon event.

It is interesting that the RIM siphon did not have the extremum point “D” (Fig. 7). The reason for this phenomenon may be the distance between the cap part and the outer part (i.e., d , as shown in Fig. 3a). The d of the RIM siphon is the widest among the three siphons (1.2 mm for the TE siphon, 1 mm for the Sutron siphon, and 2 mm for the RIM siphon). Further simulations were performed by changing this parameter (d) to explore its functions. The simulation results show that the parameter d can affect the extremum point “D” in the siphon emptying event (Fig. 9). When d is 1 mm (originally $d = 1.2$ mm for the TE siphon), the extremum point “D” in the outflow-rate curve was obvious during each siphon emptying event, while the extremum point “D” disappeared at $d = 2.5$ mm. Furthermore, the change in d also affected the duration time T_2 and the value of R_α (the proportion of T_2 to a complete siphon emptying duration). With the disappearance of the extremum point “D,” T_2 (from point “B” to “D”) became

longer, increasing by 0.3 s for the TE siphon (Fig. 9a) and by 0.1 s for the RIM siphon (Fig. 9c). By contrast, the T_2 of the Sutron siphon decreased by 0.13 s. Although there are slight increases in unstable duration for the TE (increase by 0.05 s) and RIM (increase by 0.04 s) siphons at $d = 2.5$ mm, the total duration of a siphon event also increases with a higher degree than the increase in unstable duration. Consequently, R_t is a preferred metric for siphons to determine optimal d . The R_t increased from 69% to 78.7% (TE siphon) and from 83% to 83.7% (RIM siphon) at $d = 2.5$ mm. Thus, a d of 2.5 mm is recommended for the TE and RIM siphons, and a d of 1 mm (the original size) is better for the Sutron siphon.

The parameter w denotes the distance from the main part to the cap part (Fig. 3b). For the TE siphon, when w was changed to 0.9 mm, T_2 was the longest (1.47 s), but there were obvious fluctuations at the end of the siphon event. The value of R_t was highest (79.1%) at $w = 1.1$ mm, which may be a preferred choice for the TE siphon (Fig. 10a). For the Sutron siphon, the time T_2 and the R_t were almost the same despite an increase in w , but there were more fluctuations at the beginning of the siphon event (Fig. 10b). For the RIM siphon, T_2 was the longest (1.86 s) at $w = 0.9$ mm. As w increased, the value of R_t was highest (86%) at $w = 0.9$ mm (Fig. 10c). Thus, a w of 1.1 mm is preferable for the TE siphons, whereas a w of 0.9 mm is better for the Sutron and RIM siphons.

b. Experimental results

The residual water mass of the different siphons (inferred as M_r) was measured in the laboratory experiments to verify the accuracy of the simulated results

FIG. 9. Outlet mass flow rates of different siphons as the parameter d , the distance from the cap to the outer part, changes from 1 to 2.5 mm: (a) TE siphon, (b) Sutron siphon, and (c) RIM siphon.

(Table 3). As can be seen in Table 3, the simulated M_r was a bit less than that of the experiments for the RIM siphon, whereas the simulated M_r was higher than the measured values for the TE and Sutron siphons.

FIG. 10. Outlet mass flow rates of different siphons as the parameter w , the distance from the main part to the cap part, changes from 0.9 to 1.5 mm: (a) TE siphon, (b) Sutron siphon, and (c) RIM siphon.

Nonetheless, the simulations had a high coincidence and can provide useful details regarding siphon events.

The outflow water mass (inferred as M_o) in consecutive siphon emptying events of different siphons was measured at different rainfall intensities (Fig. 11). The

TABLE 3. Residual water in three different siphons according to simulated and laboratory results ($n = 6$) of the first siphon emptying process.

Siphon type	TE	Sutron	RIM
Simulated value (g)	0.712	0.569	0.572
Laboratory mean (g)	0.623	0.512	0.622
Laboratory standard deviation (g)	0.019	0.029	0.033

M_o of the three siphons was relatively stable at low rainfall intensity, especially at intensities of 0.1 and 0.4 mm min^{-1} . The Sutron siphon displayed the most stable curves of M_o among these three siphons. The M_o of the Sutron siphon was stable at around 10 g with a rainfall intensity under 1 mm min^{-1} . For rainfall intensity above 1 mm min^{-1} , the RIM and TE siphons showed oscillations in the outflow during consecutive siphon events, whereas the outflow was relatively stable with the Sutron siphon (Fig. 11b). According to the results of the CFD simulations, R_t was 81% for the Sutron siphon, ranking second among the three siphons. In addition, the WMO field intercomparison experiments (Vuerich et al. 2009; Lanza et al. 2010) showed a large dispersion and a residual bias in the RIM siphon rain gauge measurements obtained at a resolution of 1 min. Therefore, the Sutron siphon may be the preferred choice for TBRs.

The most interesting phenomenon is that the value of M_o during the first siphon emptying event differed from that during subsequent siphon emptying events. After the first siphon emptying event was triggered, the M_o of subsequent events increased and was relatively stable at a low rainfall intensity. Although TBRs measurements are seldom associated with the first siphon process, this phenomenon is interesting and worthy of further exploration.

To explore the difference between the first and subsequent siphon emptying events, a custom-made transparent siphon and orange pigment were used to record consecutive emptying events at rainfall intensity of 0.4 mm min^{-1} (Fig. 12). The change of the water level inside the siphon was thus conspicuous.

The probable reason for this phenomenon is the residual water at the end of the outflow nozzle. The first activation of the siphon event began at 10 s and ended at 12 s (Fig. 12). The second siphon event began at 32 s, but it was clear that the water level inside the siphon was higher than it was during the first trigger of the siphon. The second siphon event completed at 35 s and lasted longer than the first emptying event. The third and subsequent siphon events were almost the same as the second event. The reason for this may be that residual water in the outflow tube has water surface tension force

FIG. 11. Outflow mass of each emptying event of different siphons in consecutive siphon events under varying rain intensity in laboratory experiments: (a) TE siphon, (b) Sutron siphon, and (c) RIM siphon.

that generates air in the outflow tube that is compressed during the second and subsequent siphon events. When the force caused by a difference in air pressure between the internal compressed air pressure

FIG. 12. Change in water level during the first and second siphon emptying events displayed in orange pigment water at a rainfall intensity of 0.4 mm min^{-1} . The first siphon is triggered at $t = 10 \text{ s}$, and residual water is formed after the first siphon event at $t = 12 \text{ s}$. The second siphon emptying event is triggered at $t = 32 \text{ s}$ and finishes at 35 s .

and external atmospheric pressure is greater than the water surface tension force, the residual water is discharged, triggering the second and subsequent siphon events.

During the experiments, another interesting phenomenon was found: the siphon event was no longer effective over a certain threshold of rainfall intensity (Fig. 11). The streamflow became continuous (Fig. 13), and water did not accumulate in the siphon. Continuous flow formed at the side of the rain gauge collector and continued until the peristaltic pump stopped. The continuous outflow rate was the same as the simulated

rainfall intensity of the peristaltic pump. This implies that TBRs equipped with a siphon also require dynamic calibration when the rainfall intensity exceeds a threshold. The TE siphon was ineffective when the intensity exceeded 2 mm min^{-1} , and the RIM siphon was ineffective when the intensity exceeded 3 mm min^{-1} . The curves in Fig. 11 show more fluctuation with an increase in rainfall intensity, especially at 2 mm min^{-1} for the TE siphon (Fig. 11a), 4 mm min^{-1} for the Sutron siphon (Fig. 11b), and 3 mm min^{-1} for the RIM siphon (Fig. 11c). These fluctuations may be associated with the geometrical

FIG. 13. Siphons become ineffective over a certain threshold of rainfall intensity. (a) Water cannot accumulate in the siphon and (b) the outflow of the siphon becomes continuous.

dimension of w of each siphon. The Sutron siphon showed obvious fluctuations (Fig. 11b) at 4 mm min^{-1} rainfall intensity, and it had the shortest w (0.9 mm) among the three siphons. The TE siphon oscillated at 2 mm min^{-1} rainfall intensity and had the longest w (1.5 mm) among the three siphons. This demonstrates that there is an inversely proportional relationship between the flow rate at which instability arises and the w of the siphon. Our analysis may indicate that a w of 0.9 mm is preferable. However, the CFD simulation results for the TE siphon (Fig. 10a) showed that a w of 0.9 mm can prolong the proportion of instable outflow during a siphon emptying event. Further experiments are needed to explore this phenomenon.

4. Conclusions

The simulation results reveal that the significant advantage of a siphon over a rain gauge collecting funnel is that the siphon can provide a stable outflow rate for the tipping bucket to reduce the influence of rainfall intensity on the mechanical bias of TBRs. The outflow rate during the stable outflow stage was 1.5 g s^{-1} for the TE siphon and 1.55 g s^{-1} for the RIM siphon (equivalent to 2.86 and 2.82 mm min^{-1} of rainfall intensity, respectively). The Sutron siphon showed an increasing trend, from 1.75 to 2.45 g s^{-1} (equivalent to 3.24 to 4.54 mm min^{-1} of rainfall intensity). The stable siphon outflow times T_2 for the TE, Sutron, and RIM siphons were 1.29, 1.48, and 1.83 s, respectively. The ratios of T_2 to the complete siphon duration R_t for the TE, Sutron, and RIM siphons were 69%, 81%, and 83%, respectively.

Two parameters (d , the distance between the cap part and the outer part, and w , the distance between the main part and the cap part) were tested in simulations to improve the structural design of siphons. An adjusted d of 2.5 mm is recommended for the TE and RIM siphons. This adjustment provides a higher R_t during the emptying event for the TE (78.7%) and RIM (83.7%) siphons. The original d of 1 mm is better for the Sutron siphon. An adjusted w of 1.1 mm is a better choice for the TE siphons, and a w of 0.9 mm is a better choice for the RIM siphon. These adjustments increase the R_t during the emptying event for the TE (79.1%) and RIM (86%) siphon. The original size of w is recommended for the Sutron siphon.

Laboratory experiments revealed that the Sutron siphon has the most stable curve of siphon outflow mass in consecutive siphon events among the three siphons. For rainfall intensity above 1 mm min^{-1} , the RIM and TE siphons showed oscillating outflow in consecutive siphon events, whereas the outflow was relatively stable with the Sutron siphon. According to the CFD simulations, the R_t (81%) for the Sutron siphon ranked

second among these three siphons. Together, these results suggest that the Sutron siphon is the preferred choice for TBRs.

Our laboratory experiments showed that the outflow water mass of the first siphon emptying event was less than that of subsequent events under different rain intensities. In addition, residual water in the outflow nozzle was observed by using a custom-made transparent siphon. This residual water caused a higher water-head to trigger subsequent siphon emptying events.

The first siphon emptying event was simulated in this study, but subsequent events were not simulated because the outflow rate fluctuated dramatically at the end of the first siphon event. Indeed, the flow state is complicated and involves viscous force, wall friction, gravity, and water surface tension. CFD simulations are relatively ideal computations, and thus it remains difficult to simulate the real state of subsequent siphon events. Nonetheless, the CFD simulations and laboratory experiments in this study can be adopted to identify the function of siphons for TBRs and provide a better structural design.

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REFERENCES

- ANSYS, 2005: FLUENT version 6.2 user's guide. ANSYS Rep., 1864 pp., ftp://115.88.84.229/disk1/Program_install_files/fluvent/fluvent6.3/doc/fluvent6.2/help/pdf/ug/flu62ug.pdf.
- Aydin, M. C., and M. E. Emiroglu, 2013: Determination of capacity of labyrinth side weir by CFD. *Flow Meas. Instrum.*, **29**, 1–8, <https://doi.org/10.1016/j.flowmeasinst.2012.09.008>.
- , M. Öztürk, and A. Yücel, 2015: Experimental and numerical investigation of self-priming siphon side weir on a straight open channel. *Flow Meas. Instrum.*, **45**, 140–150, <https://doi.org/10.1016/j.flowmeasinst.2015.06.014>.
- Baghapour, B., C. Wei, and P. E. Sullivan, 2017: Numerical simulation of wind-induced turbulence over precipitation gauges. *Atmos. Res.*, **189**, 82–98, <https://doi.org/10.1016/j.atmosres.2017.01.016>.
- Boatwright, A. L., S. Puttick, and P. Licence, 2011: Can a siphon work in vacuo? *J. Chem. Educ.*, **88**, 1547–1550, <https://doi.org/10.1021/ed2001818>.
- Calder, I. R., and C. H. R. Kidd, 1978: A note on the dynamic calibration of tipping-bucket gauges. *J. Hydrol.*, **39**, 383–386, [https://doi.org/10.1016/0022-1694\(78\)90013-6](https://doi.org/10.1016/0022-1694(78)90013-6).
- Chan, Y. W., C. L. Yu, and K. H. Tam, 2015: Inter-comparison of raingauges on rainfall amount and intensity measurements

- in a tropical environment. *J. Geod. Geomatics Eng.*, **3**, 12–25, <https://doi.org/10.17265/2332-8223/2015.04.002>.
- Colli, M., L. G. Lanza, R. Rasmussen, and J. M. Thériault, 2016a: The collection efficiency of shielded and unshielded precipitation gauges. Part I: CFD airflow modeling. *J. Hydrometeorol.*, **17**, 231–243, <https://doi.org/10.1175/JHM-D-15-0010.1>.
- , —, —, and —, 2016b: The collection efficiency of shielded and unshielded precipitation gauges. Part II: Modeling particle trajectories. *J. Hydrometeorol.*, **17**, 245–255, <https://doi.org/10.1175/JHM-D-15-0011.1>.
- Constantinescu, G. S., W. F. Krajewski, C. E. Ozdemir, and T. Tokyay, 2007: Simulation of airflow around rain gauges: Comparison of LES with RANS models. *Adv. Water Resour.*, **30**, 43–58, <https://doi.org/10.1016/j.advwatres.2006.02.011>.
- Fankhauser, R., 1998: Influence of systematic errors from tipping bucket rain gauges on recorded rainfall data. *Water Sci. Technol.*, **37** (11), 121–129, <https://doi.org/10.2166/wst.1998.0450>.
- Hughes, S., and S. Gurung, 2014: Exploring the boundary between a siphon and barometer in a hypobaric chamber. *Sci. Rep.*, **4**, 4741, <https://doi.org/10.1038/srep04741>.
- Humphrey, M. D., J. D. Istok, J. Y. Lee, J. A. Hevesi, and A. L. Flint, 1997: A new method for automated dynamic calibration of tipping-bucket rain gauges. *J. Atmos. Oceanic Technol.*, **14**, 1513–1519, [https://doi.org/10.1175/1520-0426\(1997\)014<1513:ANMFAD>2.0.CO;2](https://doi.org/10.1175/1520-0426(1997)014<1513:ANMFAD>2.0.CO;2).
- La Barbera, P., L. G. Lanza, and L. Stagi, 2002: Tipping bucket mechanical errors and their influence on rainfall statistics and extremes. *Water Sci. Technol.*, **45** (2), 1–9, <https://doi.org/10.2166/wst.2002.0020>.
- Lanza, L. G., E. Vuerich, and I. Gnecco, 2010: Analysis of highly accurate rain intensity measurements from a field test site. *Adv. Geosci.*, **25**, 37–44, <https://doi.org/10.5194/adgeo-25-37-2010>.
- Liao, M., J. Liu, A. Liao, Z. Cai, Y. Huang, P. Zhuo, and X. Li, 2020: Investigation of tipping-bucket rain gauges using digital photographic technology. *J. Atmos. Oceanic Technol.*, **37**, 327–339, <https://doi.org/10.1175/JTECH-D-19-0064.1>.
- Maksimović, Č., L. Bužek, and J. Petrović, 1991: Corrections of rainfall data obtained by tipping bucket rain gauge. *Atmos. Res.*, **27**, 45–53, [https://doi.org/10.1016/0169-8095\(91\)90005-H](https://doi.org/10.1016/0169-8095(91)90005-H).
- Marsalek, J., 1981: Calibration of the tipping-bucket raingage. *J. Hydrol.*, **53**, 343–354, [https://doi.org/10.1016/0022-1694\(81\)90010-X](https://doi.org/10.1016/0022-1694(81)90010-X).
- Molini, A., L. G. Lanza, and P. La Barbera, 2005: The impact of tipping-bucket rain gauge measurement errors on design rainfall for urban-scale applications. *Hydrol. Processes*, **19**, 1073–1088, <https://doi.org/10.1002/hyp.5646>.
- Nešpor, V., and B. Sevruck, 1999: Estimation of wind-induced error of rainfall gauge measurements using a numerical simulation. *J. Atmos. Oceanic Technol.*, **16**, 450–464, [https://doi.org/10.1175/1520-0426\(1999\)016<0450:EOWIEO>2.0.CO;2](https://doi.org/10.1175/1520-0426(1999)016<0450:EOWIEO>2.0.CO;2).
- , W. F. Krajewski, and A. Kruger, 2000: Wind-induced error of raindrop size distribution measurement using a two-dimensional video disdrometer. *J. Atmos. Oceanic Technol.*, **17**, 1483–1492, [https://doi.org/10.1175/1520-0426\(2000\)017<1483:WIEORS>2.0.CO;2](https://doi.org/10.1175/1520-0426(2000)017<1483:WIEORS>2.0.CO;2).
- Niemczynowicz, J., 1986: The dynamic calibration of tipping-bucket raingauges. *Nord. Hydrol.*, **17**, 203–214, <https://doi.org/10.2166/nh.1986.0013>.
- Rui-feng, L., C. Su-ting, and Z. Jin, 2016: Analysis of measurement errors of double tipping rain gauges (in Chinese). *Qixiang Keji*, **44**, 576–580.
- Shedekar, V. S., K. W. King, N. R. Fausey, A. B. O. Soboyejo, R. D. Harmel, and L. C. Brown, 2016: Assessment of measurement errors and dynamic calibration methods for three different tipping bucket rain gauges. *Atmos. Res.*, **178–179**, 445–458, <https://doi.org/10.1016/j.atmosres.2016.04.016>.
- Simić, M., and Č. Maksimović, 1994: Effect of the siphon control on the dynamic characteristics of a tipping bucket rain gauge. *Hydrol. Sci. J.*, **39**, 35–46, <https://doi.org/10.1080/02626669409492718>.
- Stagnaro, M., M. Colli, L. G. Lanza, and P. W. Chan, 2016: Performance of post-processing algorithms for rainfall intensity using measurements from tipping-bucket rain gauges. *Atmos. Meas. Tech.*, **9**, 5699–5706, <https://doi.org/10.5194/amt-9-5699-2016>.
- Vasvári, V., 2005: Calibration of tipping bucket rain gauges in the Graz urban research area. *Atmos. Res.*, **77**, 18–28, <https://doi.org/10.1016/j.atmosres.2004.12.012>.
- Vuerich, E., C. Monesi, L. G. Lanza, L. Stagi, and E. Lanzinger, 2009: WMO field intercomparison of rainfall intensity gauges. WMO IOM Rep. 99, 290 pp., https://www.wmo.int/pages/prog/www/IMOP/publications/IOM-99_FI-RI.pdf.
- Yin, Y., and Y. Ling-jun, 2012: Failure analysis and troubleshooting of SL3-1 double tipping bucket rain sensors (in Chinese). *Qixiang Keji*, **40**, 319–320.
- Yue-yue, M. A., Z. Hong-he, and Y. Zhen-guo, 2014: Failure analysis of premature corrosion on a new type of ring in SL3-1 double tipping bucket rain sensor. *J. Fudan Univ. Nat. Sci.*, **53**, 557–566.