CFD Modeling of Storm Sewer Geysers in Partially Filled Dropshafts

Sumit R. Zanje, S.M.ASCE[1]; Pratik Mahyawansi[2]; Arturo S. Leon, Ph.D., P.E., D.WRE[3]; and Cheng-Xian Lin, Ph.D.[4]

[1]Dept. of Civil and Environmental Engineering, Florida International Univ., Miami, FL (corresponding author). Email: szanj001@fiu.edu
[2]Dept. of Civil and Environmental Engineering and Dept. of Mechanical and Materials Engineering, Florida International Univ., Miami, FL. Email: pmahy002@fiu.edu
[3]Dept. of Civil and Environmental Engineering and Dept. of Mechanical and Materials Engineering, Florida International Univ., Miami, FL. Email: arleon@fiu.edu
[4]Dept. of Mechanical and Materials Engineering, Florida International Univ., Miami, FL. Email: lincx@fiu.edu

ABSTRACT

Geysers in storm sewer systems occur due to the uncontrolled release of trapped air through dropshafts. This study presents an unsteady three-dimensional (3D) computational fluid dynamics (CFD) model to simulate the two-phase flow dynamics of geysers starting with partially filled dropshafts. The CompressibleInterFoam (CIF) solver of OpenFOAM is used in the geyser simulations due to its suitability for modeling two compressible and immiscible fluids. The successive mixing of air and water entering the dropshaft causes a reduction in the density of the air-water mixture. Also, the non-uniform and chaotic mix of air and water in the dropshaft may lead to small bursts in the dropshaft that may cause depressurization in the dropshaft. This, in turn, could lead to rapid changes in the velocity of mostly the air and in a lesser degree of the water in the horizontal pipe. The increase in the relative velocities of air and water inside the horizontal pipe causes the transition from stratified to wavy and ultimately to slug flow. This results in successive eruptions as a result of the blowout of slugs through the dropshaft. Besides providing insights into the geyser processes, the present study provides criteria for performing a computationally efficient numerical simulation of geysers.

Keywords: air-water flow, combined sewer system, CFD, geyser, OpenFOAM.

INTRODUCTION

Violent sewer geysers are explosive eruptions of air-water mixtures through dropshafts, which often occur during or after heavy precipitation events (e.g., *https://www.youtube.com/watch?v=Jp7zLbBs0Rc*). Combined sewer systems may fill in a non-uniform manner during heavy rain events, resulting in significant air entrapment and highly dynamic conditions. When entrapped air arrives a dropshaft, it may be mixed with water and the mixture may be released violently. The mechanisms leading to geysers are discussed in multiple papers (see, for instance, Leon et al. 2019 and Chegini and Leon 2020). Geysers have been subjected to numerical and experimental studies over the last few decades due to the adverse effects of this phenomenon, such as pedestrian safety, local flooding, and water infrastructure damage (Li and McCorquodale 1999; Huang et al. 2018; Qian et al. 2020).

Vasconcelos and Wright (2005), Lewis (2011), Wright et al. (2011), and Vasconcelos and Wright (2011) studied different air-water interactions and geysering for partially filled dropshafts as a function of the rate of increase of inflows and the ratio between dropshaft and tunnel diameter. Cong et al. (2017) and Muller et al. (2017) performed an extensive set of laboratory experiments to study the role of volume of entrapped air pocket, the ratio between dropshaft and tunnel diameters, and initial pressure head on geyser formation. The authors concluded that geyser eruption occurs most likely when the ratio of dropshaft to tunnel diameter is smaller than 0.62. Vasconcelos and Wright (2003a) and Vasconcelos and Wright (2003b) conducted a series of experiments to understand the mechanism of surge formation during rapid filling and geyser eruption. Huang et al. (2016) demonstrated the influence of vent pipe on the leading edge of the air cavity and concluded that the position of air entrapment is critical, which results in different pressure patterns for the geyser. Leon et al. (2019) experimentally produced violent geysers with eruption heights that may exceed 30 m above the dropshaft top.

Additionally, several efforts have been undertaken to represent the air-water interaction in the sewer system analytically and numerically. Earlier attempts were made to understand the hydrodynamics of a dropshaft-drift under transient conditions using analytical models (1D) such as Hamam and McCorquodale (1982), Guo and Song (1990), and Guo and Song (1991). However, due to the limitations associated with the 1D representation of air-water interaction, several attempts were made to model the sewer geyser phenomenon using 2D and 3D numerical models. Chan et al. (2018) conducted a comprehensive 3D two-phase flow study to investigate the air-pocket dynamics caused by the release of trapped air in tunnel through dropshafts. The study concluded that compressed air with a pressure head of approximately 5 m might lead to explosive eruptions. Cataño-Lopera et al. (2014) conducted 3D full-scale CFD calculations to study the effects of air-water interaction dynamics in a small section of the Chicago tunnel and reservoir plan (TARP) system. Choi et al. (2014) presented a 3D numerical model based on the star-CCM+ (Cd-Adapco 2012). This model uses the experimental data for “spring-like” geysers presented in Vasconcelos and Wright (2011). Recently Chegini and Leon (2020) investigated the impact of air and water compressibility, initial pressure head difference on geyser formation using 3D simulations and validated with experimental results published by Leon et al. (2019). Overall, very few detailed numerical studies of violent geysers under partially filled dropshaft conditions have been conducted, and this study aims to fill this gap.

The current study utilizes OpenFOAM (CFD Direct 2018) to numerically investigate geyser eruptions under partially filled dropshaft conditions. The paper is organized as follows; first, the numerical domain and simulation parameters are described. Then, numerical investigations are presented and discussed. Emphasis is given to describing the processes leading to geyser eruptions. Finally, concluding remarks are made.

COMPUTATIONAL SETUP

Figure 1 shows the computational setup and Table 1 presents the geometrical parameters of the setup. The numerical domain consists of a horizontal pipe, a vertical pipe, a tank with air at constant pressure, and a cylinder at the top of the vertical pipe for simulating the eruption after the ejected air-water mixture has exited the dropshaft. The upstream and downstream end of the horizontal pipe is maintained at a constant pressure to create an initial constant flow in the horizontal pipe. The air tank is located upstream of the vertical pipe. A 3D mesh of the setup geometry was generated using *snappyHexMesh* (CFD Direct 2018), an OpenFOAM meshing utility. A snapshot of the generated mesh is presented in Figure 2, with enlarged views at the junction of the horizontal pipe and dropshaft. A mesh in the form of a cylinder is attached at the top of the vertical shaft to represent the atmospheric region and measure geyser height. According to the mesh convergence study in Chegini and Leon (2020), the maximum cell size to accurately simulate geysers is 0.02 cm, which results in 2,088,410 cells for our domain. Five boundary conditions are considered: wall for the pipe and air tank faces, atmospheric pressure for the cylinder top, pressure inlet (p_1) for upstream pipe end, pressure outlet (p_2) for the downstream pipe end, and pressure (p_t) for the air tank. For the walls, the no-slip boundary

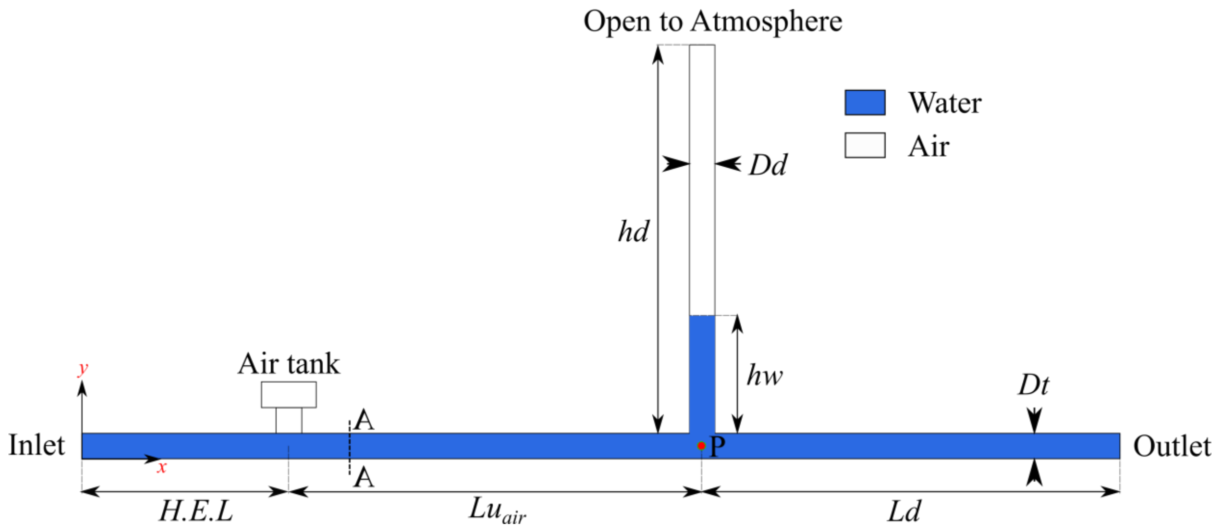

Figure 1: Schematic of the geyser computational setup

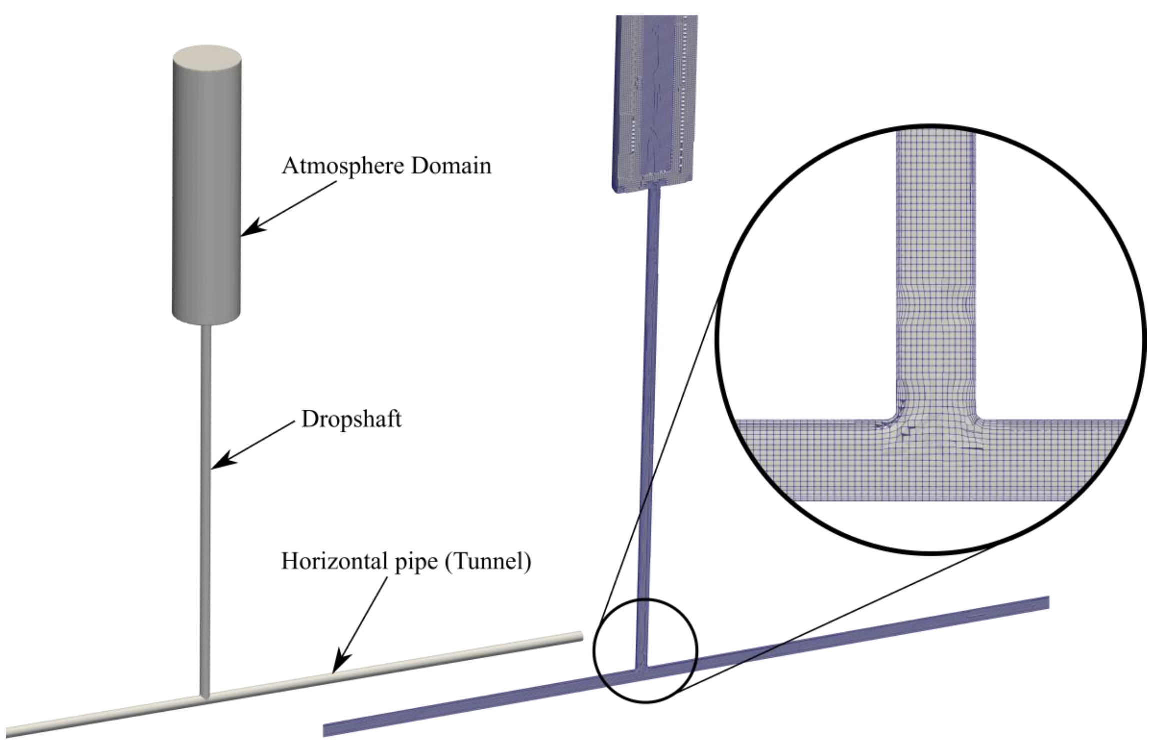

Figure 2: 3D mesh using *snappyHexMesh*

condition is applied for the velocity field, *U*, and zero gradients for pressure, *p*, and temperature, *T*. The initial water level in the dropshaft is 1.2 m. The value of p_t was set equal to the pressure at the bottom of the dropshaft. The *compressibleInterFoam* (CIF) solver is selected based on the physics involved in geysers. The CIF can model two compressible and non-isothermal immiscible flows using the volume-of-fluid (VOF) technique. The realizable k-ε model is selected for its suitability for simulating violent geysers (Chegini and Leon 2018). The initial temperature of the water and air in the system is at 20.0 ºC. The atmospheric pressure is set to 102,032 Pa. With the continuous supply of air and water in this setup, it is possible to achieve continuous eruptions. Considering the computational limitations, the simulation is terminated after the first eruption.

Table 1: Parameters of the computational setup

Parameters	Value
Diameter of horizontal pipe, *Dt*	0.152 m
Diameter of vertical pipe, *Dd*	0.152 m
Height of the dropshaft, *hd*	6 m
Initial water level, *hw*	1.2 m
Pipe length, Lu_{air}[1]	10 m
Pipe length, *H.E.L*[2]	30 m
Downstream pipe length, *Ld*	10 m
Point 'P' coordinate	(40,0,0) m
Section A-A coordinate[3]	(31,0,0) m

RESULTS AND DISCUSSION

This section briefly describes the mechanisms preceding and during geyser eruptions for the setup discussed previously. It is noted that the dropshaft is partially filled with water in the current setup. This setup is different from the experimental work in Leon et al. (2019) where the dropshaft was initially full of water. The mechanisms leading to geyser eruptions for the current setup are discussed below:

(1) A large air pocket is transported in the horizontal pipe towards the dropshaft without producing significant fluctuations, as shown in Figures 3a and 3b. This can be corroborated with Figures 6 and 7 for a time smaller than about t=12.20 s, when the air pocket front arrives point 'P' (Figure 1). It is noted that before about 12.20 s, the air pocket in the horizontal pipe advances very slowly because there is no significant initial pressure gradient. Thus, before about 12.20 s, the flow regime in the horizontal pipe is stratified.

(2) As shown in Figure 4a, the large air pocket enters the dropshaft and rises in the form of a Taylor-like bubble due to buoyancy. Like a classical Taylor bubble, the free surface of the water in the dropshaft is lifted upward with the ascending air pocket until it breaks the

[1]Horizontal pipe length from the air tank to dropshaft
[2]Horizontal pipe length from pipe inlet to air tank
[3]Section in horizontal pipe

surface. This can be observed in Figure 4b. The initial air pocket is followed by a trailing mixture of air and water that enters the dropshaft like a churning flow from the horizontal pipe. As shown in Figure 5, a sudden pressure drop is recorded in the vertical pipe with the rise of the air pocket. Then, pressure rises again as the water enters the dropshaft at approximately t=13.5 s. This sudden drop in hydrostatic pressure in vertical pipe creates a significant pressure gradient between vertical and horizontal pipe, accelerating the air and water in the horizontal pipe. This can be seen in Figure 6 and Figure 7 at approximately t=11.3 to 13.0 s. The rapid increase in water and air velocity causes the transition from stratified to wavy and ultimately to slug flow (Figure 3c). It is worth mentioning that air velocity is leading the water velocity by about 2.05 s. There is a flow discontinuity and the continuous supply of air from the horizontal to the dropshaft is blocked once the slugs form in the horizontal pipe. This can be corroborated with Figures 6 and 7 at approximately t=13.6 s, which shows a decreasing air and water velocity trend in the horizontal pipe. Due to the lack of sufficient air supply to the dropshaft, the water inside the dropshaft falls back.

(3) After t=16.5 s, air pockets again start advancing towards the dropshaft, and then mixing with water in the dropshaft (Figure 3d and Figure 4c). As air mixes in the water, it forms a forth-like mixture with a density lesser than water (Figure 4d-e). During this process, multiple cycles of rising and falling in the velocity of air and water were observed (Figure 6 and Figure 7 from t=20 s to t=30.5 s). Each cycle may result in the reduction of the density of the air-water mixture inside the dropshaft. It is noted that before an eruption, the air-water mixture is lifted to a higher level in the next cycle. As shown in Figure 8, the volume of water inside the dropshaft decreases from t=22.6 s to t=37.5 s. An eruption is evidenced by a sudden depressurization of pressure point P (Figure 5 at approximately t=36.85 s). New slugs can form in the horizontal pipe and be violently propelled during this process. This process continues till the system has enough air and water supply.

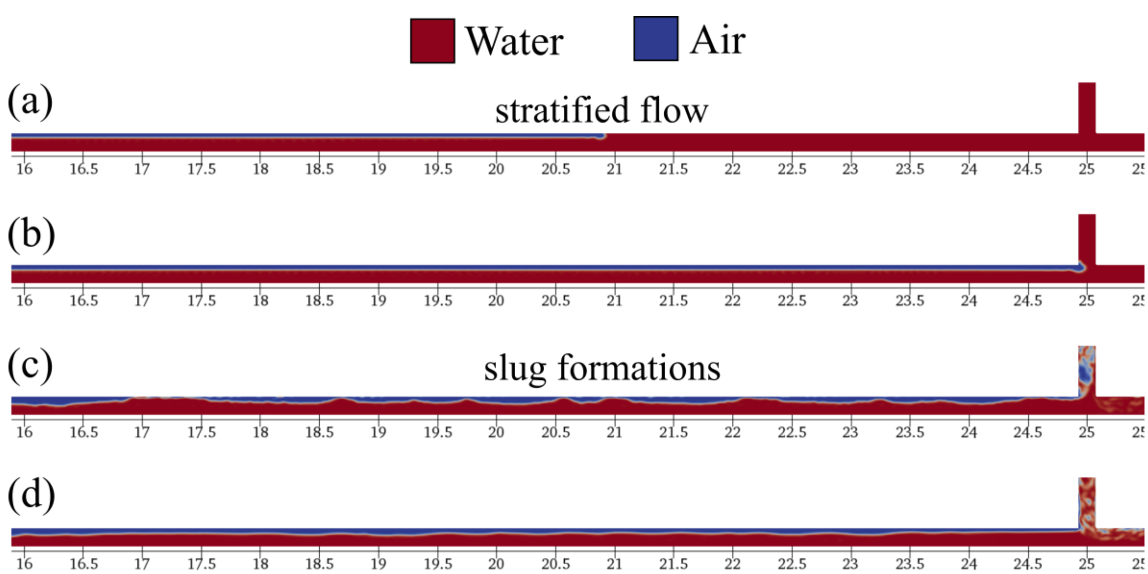

Figure 3: Snapshots of air-water phase fraction in the horizontal pipe at (a) 6.0 s, (b) 12.20 s, (c) 13.08 s, and (d) 16.50 s.

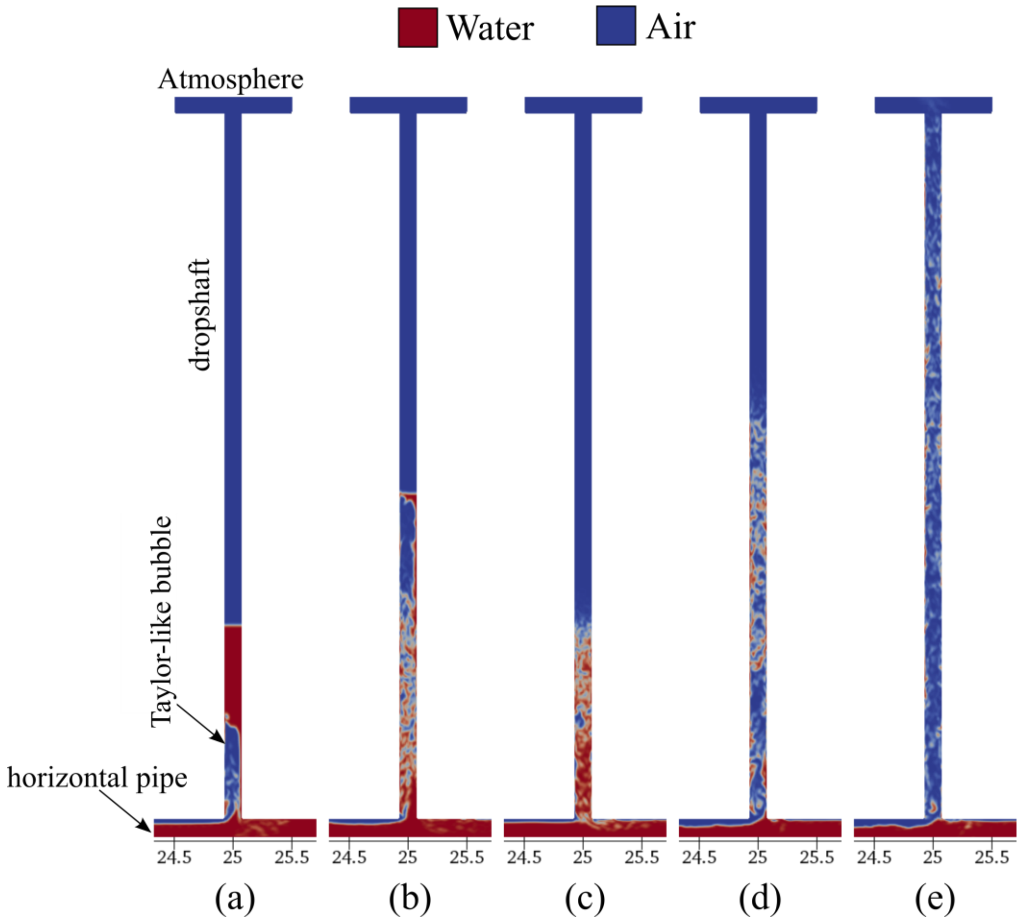

Figure 4: Snapshots of air-water phase fraction in the vertical pipe at (a) 13.0 s, (b) 14.10 s, (c) 16.75 s, (d) 26.50 s, and (e) 35.0 s

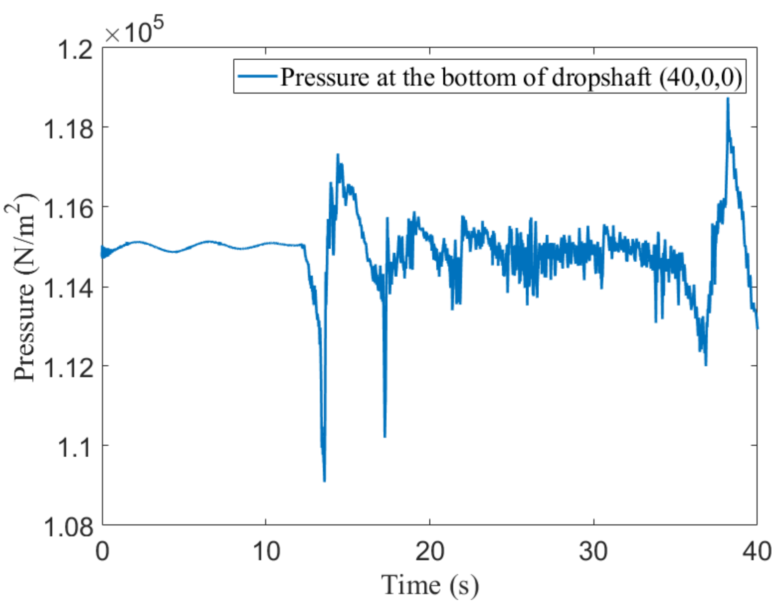

Figure 5. Pressure fluctuations at point 'P' in Figure 1 (40,0,0) m

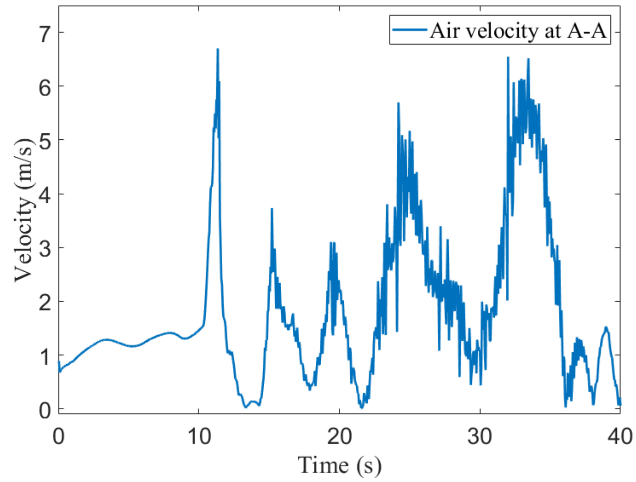

Figure 6. The velocity of air in the horizontal pipe at section A-A

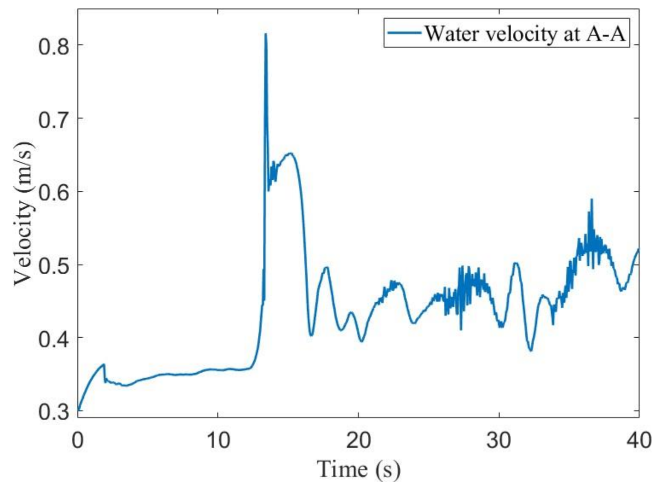

Figure 7. Water velocity in the horizontal pipe at section A-A

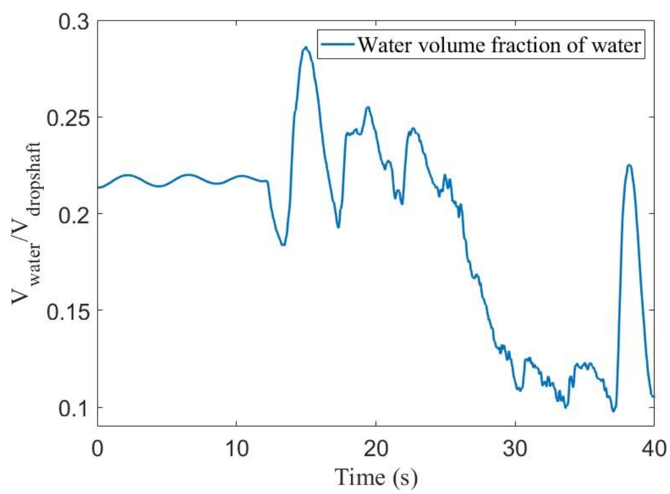

Figure 8. Variation of the water volume inside the dropshaft

CONCLUSION

This work presents the results of a numerical study on geysers in sewer systems, starting with a partially filled dropshaft. The characteristics of geyser eruptions were analyzed using pressure and velocity time traces in the horizontal and vertical pipes obtained numerically. It is found that with enough air supply (trapped air), a mixture of air-water with decreasing density is formed in the dropshaft resulting in the rising of this mixture. Furthermore, this non-uniform, chaotic mixture of air and water may lead to small initial bursts in the dropshaft that creates a significant pressure gradient between the horizontal pipe and dropshaft, which may cause rapid acceleration of the air in the horizontal pipe and in lesser degree of the water. This acceleration increases the relative velocity between the air and water, which causes the transition from stratified to slug flow. The occurrence of a geyser eruption is manifested through a sudden pressure drop in the dropshaft. Ongoing detailed CFD simulations and experimental tests will enhance this investigation. As part of a subsequent study, these findings will be used to explore retrofitting strategies to minimize geysers in storm sewers.

ACKNOWLEDGMENTS

The author gratefully acknowledges the financial support of the National Science Foundation (NSF) under Grant number 1928850. The views expressed are solely those of the authors. NSF does not endorse any products or commercial services mentioned.

REFERENCES

Cataño-Lopera, Y. A., Tokyay, T. E., Martin, J. E., Schmidt, A. R., Lanyon, R., Fitzpatrick, K., Scalise, C. F., and García, M. H. (2014). "Modeling of a Transient Event in the Tunnel and Reservoir Plan System in Chicago, Illinois." *Journal of Hydraulic Engineering*, 140(9),05014005.

Cd-Adapco. (2012). *Star-CCM+ 7*. CD-adapco, Melville, NY.

CFD Direct. (2018). *OpenFOAM 6.0*. The OpenFOAM Foundation Ltd., London.

Chan, S. N., Cong, J., and Lee, J. H. W. (2018). "3D Numerical Modeling of Geyser Formation by Release of Entrapped Air from Horizontal Pipe into Vertical Shaft." *Journal of Hydraulic Engineering*, 144(3),04017071.

Chegini, T., and Leon, A. (2018). "Comparison of Various Turbulence Models for Violent Geysers in Vertical Pipes." In *World Environmental and Water Resources Congress 2018*, pages 99–108. American Society of Civil Engineers.

Chegini, T., and Leon, A. S. (2020). "Numerical investigation of field-scale geysers in a vertical shaft." *Journal of Hydraulic Research*, 58(3),503–515.

Choi, Y. J., Leon, A. S., and Apte, S. V. (2014). "Three-Dimensional Numerical Modeling of Air-Water Geyser Flows." In *World Environmental and Water Resources Congress 2014*, pages 1535–1548.

Cong, J., Chan, S. N., and Lee, J. H. W. (2017). "Geyser Formation by Release of Entrapped Air from Horizontal Pipe into Vertical Shaft." *Journal of Hydraulic Engineering*, 143(9),04017039.

Elayeb, I. S. (2017). *An Experimental Study on Violent Geysers in Vertical Shafts*. (Master's thesis, Oregon State University, Corvallis, USA). Retrieved from https://ir.library.oregonstate.edu/concern/graduate thesis or dissertations/fn1071742.

Guo, Q., and Song, C. C. S. (1990). “Surging in Urban Storm Drainage Systems.” *Journal of Hydraulic Engineering*, 116(12),1523–1537.
Guo, Q., and Song, C. C. S. (1991). “Dropshaft Hydrodynamics under Transient Conditions.” *Journal of Hydraulic Engineering*, 117(8),1042–1055.
Hamam, M. A., and McCorquodale, J. A. (1982). “Transient conditions in the transition from gravity to surcharged sewer flow.” *Canadian Journal of Civil Engineering*, 9(2),189–196.
Huang, B., Wang, W., Wu, S., and Zhu, D. Z. (2016). “Experimental Study of Cavity Outflow and Geysering in Circular Pipes.” In *World Environmental and Water Resources Congress 2016*, pages 265–274.
Huang, B., Wu, S., Zhu, D. Z., and Wang, F. (2018). “Mitigating peak pressure of storm geysering by orifice plates installed at the top of vent pipes.” *Water Science and Technology*, 78(7),1587–1596.
Leon, A., and Zanje, S. (2019). “Experiments and Numerical Modeling of Field-scale geysers in Stormsewer Systems.” In *38th IAHR World Congress, September 2019*, Panama City, Panama.
Leon, A. S., Elayeb, I. S., and Tang, Y. (2019). “An experimental study on violent geysers in vertical pipes.” *Journal of Hydraulic Research*, 57(3),283–294.
Lewis, J. W. (2011). *A physical investigation of air/water interactions leading to geyser events in rapid filling pipelines*. (Doctoral dissertation, University of Michigan).
Li, J., and McCorquodale, A. (1999). “Modeling Mixed Flow in Storm Sewers.” *Journal of Hydraulic Engineering*, 125(11),1170–1180.
Muller, K. Z., Wang, J., and Vasconcelos, J. G. (2017). “Water Displacement in Shafts and Geysering Created by Uncontrolled Air Pocket Releases.” *Journal of Hydraulic Engineering*, 143(10),04017043.
Qian, Y., Zhu, D. Z., Liu, L., Shao, W., Edwini-Bonsu, S., and Zhou, F. (2020). “Numerical and Experimental Study on Mitigation of Storm Geysers in Edmonton, Alberta, Canada.” *Journal of Hydraulic Engineering*, 146(3),04019069.
Vasconcelos, J. G., and Wright, S. J. (2003a). “Laboratory Investigation of Surges Formed During Rapid Filling of Stormwater Storage Tunnels.” In *Proc., 30th IAHR Congress*. International Association for Hydraulic Research.
Vasconcelos, J. G., and Wright, S. J. (2003b). “Surge Associated With Air Expulsion in Near-Horizontal Pipelines.” volume 1: Fora, Parts A, B, C, and D, pages 2897–2905. *Fluids Engineering Division Summer Meeting*.
Vasconcelos, J. G., and Wright, S. J. (2005). “Experimental Investigation of Surges in a Stormwater Storage Tunnel.” *Journal of Hydraulic Engineering*, 131(10),853–861.
Vasconcelos, J. G., and Wright, S. J. (2011). “Geysering Generated by Large Air Pockets Released through Water-Filled Ventilation Shafts.” *Journal of Hydraulic Engineering*, 137(5),543–555.
Wright, S. J., Lewis, J. W., and Vasconcelos, J. G. (2011). “Geysering in Rapidly Filling Storm-Water Tunnels.” *Journal of Hydraulic Engineering*, 137(1),112–115.
Zhou, L., Liu, D. Y., and Ou, C. Q. (2011). “Simulation of Flow Transients in a Water Filling Pipe Containing Entrapped Air Pocket with VOF Model.” *Engineering Applications of Computational Fluid Mechanics*, 5(1),127–140.