Experimental Study on Edmonton's Storm Geyser Formation Mechanism and Mitigation Measures

By

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Water Resources Engineering

Department of Civil and Environmental Engineering

University of Alberta

Abstract

Uncontrolled air movement and release in drainage systems can lead to geyser events, which are defined as the air-water mixture explosively jetting out of manholes. As geysers are always explosive in nature, its occurrence can cause public safety concerns and property damages. Due to the complexity of air-water two-phase flow, the understanding of geyser occurrences is still inadequate, and retrofitting methods are still controversial for field application. This study aims at revealing the mechanism of geyser events and assessing potential geyser mitigation methods that are applicable in the field by conducting laboratory experiments.

To address the geyser occurring in the manhole at the intersection of Gateway Boulevard and 30th Ave., Edmonton, Alberta, a conceptual and simplified scale model of roughly 1:20 was constructed in the T. Blench Hydraulic Lab at the University of Alberta. Eight series of experiments were designed based on the possible combinations of flow conditions in the upstream and downstream pipes. Among them, three series focused on the mechanism of geyser formation, and the other five focused on the potential geyser mitigation methods.

The experiments on the geyser mechanism show that geyser can be triggered by two ways: the rapidly filling flow and the air release from the entrapped air pocket. After a suddenly

further opening of a ball valve, a rapidly filling surge occurs in the upstream pipe and propagates downstream. If the water level in the downstream pipe is high, this rapidly filling flow can fill the chamber quickly and then shoot out of riser to form a single-shoot geyser. When the entire system is pressurized with an entrapped air pocket in the upstream pipe with a stagnant water column in the riser, a suddenly further opening of a valve will induces two phase of geyser events: the first phase is caused by the transient pressure, with one to two geysers, and the second is caused by the air releasing from the air pocket and the geyser event, which could include several independent geysers and last much longer than the first phase.

For the possible geyser mitigation methods, a completely sealed riser top, an orifice plate installed at the riser top, in the middle of riser span and at the riser bottom, a water recirculation chamber (WRC) and an enlarged riser were tested and assessed. A much slow opening of the ball valve was also investigated. The results show that the orifice plate (OP) with a small orifice can greatly decrease the pressure peak in the system and the water amount of water out of the riser, but it will cause most of the air being transported downstream. Also, the water-hammer pressure is observed in cases with an orifice size of 0.2 times of the riser diameter. The water recirculation chamber (WRC) has a minor effect on the pressure in the system and either no geyser is observed or few drops of water come out from the riser. The enlarged riser increases the water amount out of the riser.

Findings of this research could extend the knowledge from two aspects: (1) the details of geyser occurrence, and (2) possible mitigation methods on geyser events.

Acknowledgments

First I would like to express my great appreciation to my supervisor Dr. David Z. Zhu, for all the continuous support of my MSc study and research, and for his motivation and guidance over the past two years. I wish to thank Epcor Utilities INC. and Natural Sciences and Engineering Research Council of Canada (NSERC) for providing funding for this research. I would like to express a special thanks to Perry Fedun, for technical support in the lab. I would like to express special thanks to all the members in our group, especially Jiachun Liu, Yu Qian and Dr. Weiyun Shao, for all your help throughout the research.

My deepest thanks go to my family, my boyfriend and all the friends, who listened and offered help whenever I needed, it’s a pleasure to have all of you with me.

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1. Introduction

1.1 Research Background

As urbanization and land development progresses, pervious surfaces like grassland, forests and wetlands have been changed to impervious surfaces like the concrete ground. Accompanied by increasing extreme precipitation resulted from climate change (Climate Central, 2017), the surface runoff increases, which requires a higher flow capacity of drainage systems. Therefore, with the increasing of the storm runoffs and the same flow capacity of storm sewer system as before, geysers, which are defined as explosive release of water or air-water mixture through vertical shafts connected to a horizontal pipeline, are more likely to happen than before.

During the storm, stormwater enters into the sewer systems rapidly, which could induce a transition from the initial free surface flow in pipe into the pressurized flow, and large air pocket might be entrapped simultaneously. On the other hand, downstream sudden blockage, pump failure or rapid filling of inflow, all are linked with sudden pressure increase within the system. When the pressurized flow moves within the system along with air, it tends to find a way out of the pipe system through the locations of geometry change such as shafts. When air-water mixture reaches the bottom of the shaft, it would move upwards in the shaft due to buoyancy, thus causing geyser event. To date, most of studies on geyser are done by experiments and few experimental study have been used for validation of numerical simulation.

Geyser events have been reported around the world, which may cause human injuries and property damages, and lead to safety concerns. Wright et al. (2011) reported one field observation on geyser occurrence which happened at a manhole in a stormwater tunnel in Minneapolis in July 1997, causing a geyser that is at least 20 m above the land surface. In July 2011, a geyser event occurred in Montreal, Canada, during which a car was lifted up by the strong impact force of the rising water (YouTube, 2011).

Edmonton, Alberta has also been suffering from geyser problem in recent years, one particular geyser location is at the intersection of Gateway Boulevard and 30th Ave., where three geyser events were recorded from 2013 to 2016 since the manhole was built in 2012. In order to understand the mechanism of geyser occurrence in this particular manhole and come up with retrofitting methods to tackle this issue in Edmonton, the experimental study becomes essential.

1.2 Objective of the Study

This thesis aims at understanding the mechanism of geyser occurrence, and the pressure process that corresponds to it. Various series of experiments are designed with a focus on the air-water movement in the upstream pipe, air-water interaction in the chamber and in the riser, and the formation of the geyser. Based on the result analysis of the experimental on the geyser mechanism, three potential mitigation methods have been proposed and tested to investigate the change of the geyser process once the mitigation methods have been applied.

1.3 Scope of the Study and the Structure of the Thesis

This study contains eight series of physical experiments under different boundary conditions to measure the process of pressure in the pipe, which would help to analyze the mechanism of the geyser. The geyser can be caused by the rapid change of flow rate and the air-pocket release. Therefore, two groups of experiments were designed for geyser mechanism. The first group includes two series of experiments, where the inflow rate in the upstream pipe is changed rapidly while the downstream pipe is non-full or full controlled by the downstream overflow weir. The second group includes one series of experiments, where inflow rate in the upstream pipe is changed rapidly while downstream outflow capacity is limited by a partially closed tailgate.

This thesis is divided into six chapters. A brief description of each chapter is summarized below:

- Chapter one introduces the background, the objective and the scope of this study.

- Chapter two reviews literatures on geyser formation and mitigation.
- Chapter three describes the experimental setup and the experimental design.
- Chapter four presents the experimental results on the mechanism of geyser occurrence.
- Chapter five discusses the effectiveness of different mitigation methods on geyser.
- Chapter six contains the conclusions and the suggested topics for future study.

2 Literature Review

2.1 Geyser Formation

An early study by Guo and Song (1991) on the hydrodynamics of a dropshaft-drift tube system under transient conditions found out that water column oscillation and inflow disturbance could cause the water in a dropshaft overshooting the ground surface, resulting in geysers. They also concluded that the geyser was caused by the impact force of rising water in the dropshaft. Their study was the earliest on the formation of geyser by the rapid filling regime, but only the water phase was considered. Zhou et al. (2002 a) did lab experiments to test different air/water behavior in a rapidly filling pipe and observed that the amount of air in the system is the key factor in determine the pressure pattern, but this study only considered the effect of sudden pressure change to the horizontal pipe. Meniconi (2012) did similar experiments to test the water hammer effect pressure, and found that the viscoelasticity of the pipe material and friction can influence the pressure pattern. Zhou et al. (2004) studied pressure transients in horizontal-vertical pipe system experimentally to compare with horizontal pipe system result of Zhou et al. (2002 a), and found the peak pressure variation and magnitude had a small difference, so that amount of air in the system is still the key factor in determining the pressure pattern.

Ramezani et al. (2016) did experiments and found that the cause of air introduced into stormwater distribution system include check towers and pipe bends, pump inlets and plunging jets. Huang et al. (2017) confirmed that geysering may occur during transient process from free surface flow to pressurized flow in ventilated sewer systems. Typically, two mechanisms can cause geyser, which are transient surge or release of air. Both of them are related to air entering into the pipe system. Although geysers can be triggered by different mechanisms, the severity of geyser events is all related to inflow hydrograph and geometric characteristics of deep storage tunnel, as discussed by Vasconcelos et al. (2017). From their study, the following conclusions are made: peak surge is related to junction shaft plan area and time of flow pressurization, but no clear trend is found between entrapped air volume and the inflow or geometry parameters.

Several studies have been done on the entrapment of air pocket in the pipe system. Chanson (1996) studied the air entrainment systemically and found that small bubbles entering the system would gather in highest points to combine and form a large air pocket. Due to density difference, air tends to occupy higher part and water tends to occupy lower part, both in horizontal and vertical pipes. Li and McCorquodale (1999) summarized the previous methods used in analyzing the mixed air-water flow transitioning from free surface flow to pressurized one and concluded that rapid filling of flow in the storage tunnel will form pipe filling bores which can cause the displacement of air, which could further develop into the entrapped air pocket. Abdulmouti (2014) studied two-phase flow systematically and concluded that when gravity was perpendicular to the tube axis, separation of the air and water phase may occur. Vasconcelos and Wright (2006) did physical experiments and found that as the tunnel undergoes a transitioning from a free surface to a pressurized state, air can be trapped to form an air pocket. It was also ascertained that inadequate ventilation and low water flow rate are common reasons for air entrapment.

After the air was entrapped into the system, it may move horizontally within tunnel systems. The mathematical analysis done by Benjamin (1968) provided a basic understanding of hydrodynamic currents and the movement of air cavities within horizontally circular pipe that it would move as gravity current. The velocity of the air pocket is a key factor in determining the severity of geyser process, and it has been studied extensively among researchers. Perron et al. (2006) did physical experiments on how inclination of the plate could impact the final velocity of air bubbles, and found out that the inclination angle and terminal velocity are proportional for a fixed bubble volume. It is also observed that the increment in velocity is different for different bubble sizes. Chosie et al. (2014) did similar experiments on how the air pocket would behave under different pipe slopes, and the motion of entrapped air with ambient velocity is also studied. It is found that ambient flow can affect air pocket propagation, and the main leading edge could be sheared off from the air pocket, but could rejoin the main air pocket after the drag is overcome. Zhou et al. (2002 b) studied how the air volume would influence pressure with tail water, and concluded that larger air pocket has a lower impact on the pressure. Muller (2016) did experiments on the movement of air pocket with/without background flow, and found that background flow only has little influence on air pocket velocity. Apart from air velocity, air pocket volume is also an important factor in determining the geyser severity.

When air/water mixture enters the vertical shaft, the momentum of the rising air might lift water up by some distance. These air pockets always entrain water and can carry them upward to form geyser (Wright et al. 2011). Wright et al. (2011) did air capsule experiments with preserved background pressure and confirmed that under system size and amount of ventilated air, the vertical two-phase flow could lift water up beyond system pressure. Vasconcelos and Wright (2011) did experiments on air-pocket induced geyser, and stated that larger scale experiments are needed in order to assess the effect of turbulent film flows and the possible shear flow instabilities.

When air-water mixture shoots out from the vertical riser, it would be in different forms. Muller et al. (2017) did large-scale field experiments on unrevealing of mechanisms of air release and the displacement of water in vertical shafts and found that a type of mist following the water slug discharge is usually observed when air-water shoot out from the vertical shaft, usually explosive by nature. Morgado et al. (2016) also did experiments on air-water two-phase flow, and concluded that when the air phase interacts with water phase intensely, a chaotic mixture would form and shoot out like a misty flow. Cong et al. (2017) did lab experiments aimed to unravel the mechanism of geyser formation through physical experiments, and found that air/water mixture behave differently under different pressure head and riser diameters, and the way geyser splashed out is different. Without external pressure head, the air pocket would migrate like a slug flow or Taylor bubble; When the pressure head exists in the upstream pipe, riser diameter was large and the air pocket volume was small, the air pocket would accelerate rapidly and jet out. However, all the experiments were conducted without background flow, which is not practical in the real scenario. Another problem with this research is that the scale is too small, with only a 0.05-m-diameter pipe and riser diameter varied from 0.016 m to 0.04 m.

Numerical study on geyser related issues had been done by researchers. Chan et al. (2018) used CFD to simulate geysers, and found that during a geyser event, compression of the air pocket in the riser can lead to rapid acceleration of the overlying water column and its expulsion from the riser. Based on the study of Zhou et al. (2002 b), Li and Zhu (2018) numerically simulated the transient pressure caused by rapid filling flow with an end orifice in a horizontal pipe and effect of air cushioning of an air pocket in a horizontal pipe with different diameter orifice on the pipe end.

Although many studies have done on finding of the mechanism of geyser, most of them were based on an idealized structure rather than a scale model of the prototype. As geysers are sensitive to tunnel geometry, it is essential to investigate the matter base on prototype.

2.2 Geyser Mitigation

To date, there are only a few studies that focused on mitigation method of geyser events, the main methods that have been tested experimentally include: adding a horizontal section to the vertical riser, add a larger diameter section to replace a portion vertical riser and use orifice plates at different locations along the vertical riser.

Wright et al. (2009) proposed two ways of geyser mitigation, the first one was adding a horizontal section to the vertical riser. But this method is hard for construction, because most pipes are installed well below grade. The second method was to replace a portion of the vertical riser with a larger diameter section to the riser so that the vertical riser would have small diameter part near the top of the horizontal pipe and a larger diameter at a short distance above it. This method had been proved to be useful in small water level fluctuations experiments in their study. Figure 2.1 and Figure 2.2 are schematic diagrams of the two methods.

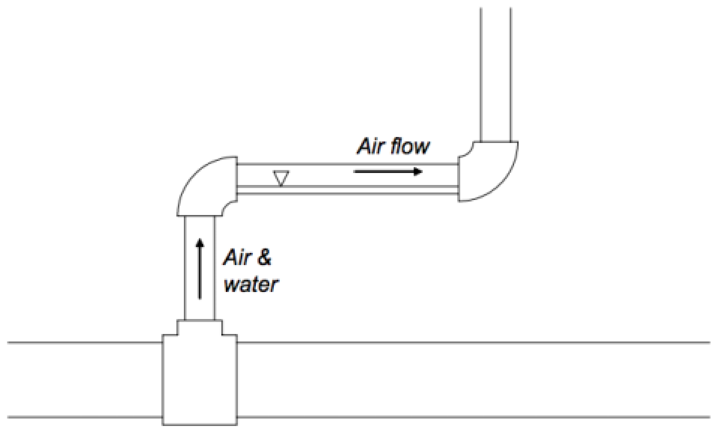


Figure 2.1 Schematic diagram of mitigation of geysers by adding a horizontal section to the vertical riser (Wright et al., 2009)

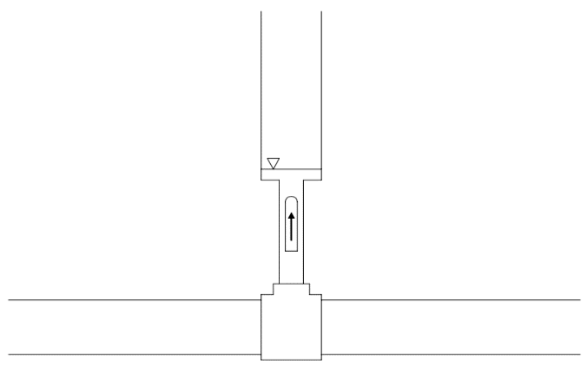


Figure 2.2 Schematic diagram of mitigation of geysers by adding a larger diameter section to the vertical riser (Wright et al., 2009)

Zhou et al. (2002 a) tested the air leakage at the pipe end using different orifice plates, and found that large opening is prone to water hammer effect, while when opening size is small, the pipe system is protected by the air-cushioning effect. Huang (2017) and Huang et al. (2017) studied how an orifice plate on top or bottom of the vertical riser can change the height of geysers. It has been found that installing an orifice plate on the top or bottom can both mitigate the height of the geyser, and significantly reduce the pressure peak during geyser event.

Although geyser mitigation methods were proposed in previous literatures, none of them did detailed analysis on it, so that it is essential to test the effectiveness of mitigation methods explicitly, especially base on the same system for revealing the geyser mechanism.

3. Experimental Setup and Methods

3.1 Experimental Setup

The experimental setup is a scaled model of a portion of stormwater tunnel at the intersection of Gateway Boulevard and 30th Ave., Edmonton. The prototype tunnel includes two manholes: one is an access shaft with a diameter of 1.5 m, and the other is a ventilation shaft with a diameter of 1.2 m. Both shafts were 27 m below grade and were connected to a 5.8m-diameter and 8.0 m-high chamber, which serves as a T-junction connecting the existing southbound tunnel with the new westbound tunnel. The existing storm tunnel is connected to the chamber from the south, with a diameter of 3 m and a slope of 0.08%. The new tunnel is connected to the chamber from the east, with a diameter of 3.5 m and a slope of 0.1%. The invert elevation difference between the existing and the new tunnel is 4 m. Around 5 m downstream of the problematic manhole, the existing southbound tunnel is connected to a temporary bypass drainage pipe with a diameter of 1.2 m.

In the experimental design, the above-mentioned system was scaled and simplified. The cylinder chamber beneath the shaft was simplified to a rectangular chamber. As shown in Figure 3.1, the main experimental part consists of a 0.2 m-diameter acrylic upstream pipe, with a slope of 1%, a 0.3 m×0.3 m×0.45 m cuboid chamber with a 0.057 m-diameter clear acrylic vertical tube connected to the middle of its top, a 0.28 m-diameter clear acrylic downstream pipe, a 0.57 m×0.61 m×0.89 m downstream tank with a flat movable gate attached to its inlet and a circular movable overflow weir at middle of its bottom. The weir has a diameter of 0.3 m and height 0.4 m and can be used to adjust the water depth in the downstream pipe. Water was fed into the upstream pipe from a pressurized tank by the opening of a ball valve. When the water depth in the downstream pipe is controlled by the overflow weir, water can flow through the downstream pipe with full capacity. When it is controlled by the gate, the flow capacity from the downstream pipe to the downstream tank would be reduced.

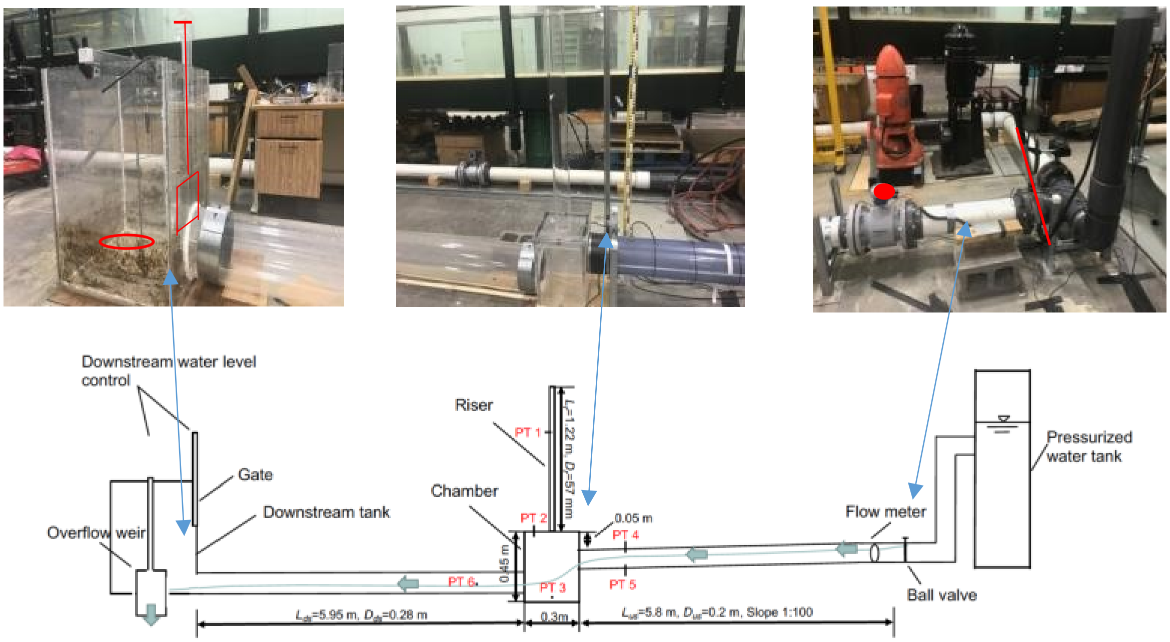


Figure 3.1 Photos and sketch of the experimental setup

3.2 Measurement Apparatus

In order to fully understand the geyser process in the system, pressure along the system was measured and the status of the flow was recorded by video cameras. The measurement apparatus include:

- Pressure measurement: Six piezo-resistive pressure transducers (PT) (OMEGA 2017) with accuracy of 0.2 % were used to measure the pressure variation in the system, as shown Figure 3.1: PT1 was installed on the inner wall of the riser, 0.8 m away from the chamber top， PT2 was placed on the top of the chamber, PT3 was on the chamber wall near the chamber bottom and 0.02 m above chamber bottom, PT4 and PT5 were located on the upstream pipe crown/bottom, 0.3 m away from the chamber, and PT6 was placed on downstream pipe wall, 0.3 m away from the chamber. For most cases, only PT1 to PT4 were used and the pressure at PT6 was measured for specific cases. As the process at PT5 is similar to that of PT4, the pressures at PT5 are not plotted in the following discussions.

- National Instruments NI-BNC 2120 data acquisition board with logging software was used to record pressure data at a frequency of 1000 Hz.
- Video recorder: Four cameras were used in the experiments. Two cameras (Sony DSC-HX300), with the frequency of 60 fps, were used to track the flow in the upstream pipe, which were placed at the front side of the upstream pipe. A GoPro Hero 5, with a frequency of 120 fps, was used to record the air-water mixture movement in the chamber and riser, which was placed in front of the chamber. The fourth camera (Sony HDR-PJ58), with a frequency of 60 fps, was used to film the height of the geyser.
- Length measurement: A long ruler hanging from the ceiling and located near the chamber was used the measure the height of geyser. Scales were attached to the upstream pipe with 0.25 m interval zip tie markers for the analysis of the volume and the velocity of the air pocket.
- Time measurement: Four bulbs were connected with the ball valve through NI-BNC 2120 data acquisition board and installed within the sight of the camera to indicate the time zero and the opening of the valve.
- Inflow rate measurement: A Foxboro (IMT31A) magnetic flow meter was installed near the upstream pipe inlet. Its current output was converted in to voltage output and collected by the NI-BNC 2120 data acquisition board at a frequency of 1000Hz.

3.3 Experimental Program

The purposes of this study is to investigate the mechanism of geyser and to investigate the feasible geyser mitigation measures. Eight series of experiments have been conducted, which are divided into two groups, with three series done to investigate the mechanism of geyser and the other five series conducted to test the mitigation measures. Each experiment was repeated three times for consistency and accuracy.

3.3.1 Series for geyser mechanism

Series A has a total of 12 cases with downstream open channel flow. The fixed parameters in this group include the riser diameter (D_r = 57 mm) and the fixed water depth in the downstream pipe (h_d), which equals to one fourth of the downstream pipe diameter (D_d). The initial inflow rate (Q_0) at the inlet of the upstream pipe is 20, 30, 40 or 50 L/s, which was suddenly increased to the final inflow rate (Q_1) of 80, 100 or 120 L/s. The cases with a combination of Q_0 and Q_1 were numbered in order from A1 to A12 as listed in Table 3.1. The conditions in the chamber/riser and the downstream pipe are shown in Figure 3.2.

Table 3.1 Experimental design for Series A

Test run	D_r (mm)	h_d/D_d	Q_0 (L/s)	Q_1 (L/s)	Initial flow in the upstream pipe
A1	57	1/4	20	80	Free surface flow
A2	57	1/4	20	100	Free surface flow
A3	57	1/4	20	120	Free surface flow
A4	57	1/4	30	80	Free surface flow
A5	57	1/4	30	100	Free surface flow
A6	57	1/4	30	120	Free surface flow
A7	57	1/4	40	80	Pressurized full pipe flow
A8	57	1/4	40	100	Pressurized full pipe flow
A9	57	1/4	40	120	Pressurized full pipe flow
A10	57	1/4	50	80	Pressurized full pipe flow
A11	57	1/4	50	100	Pressurized full pipe flow
A12	57	1/4	50	120	Pressurized full pipe flow

Figure 3.2 Initial flow conditions in the downstream and the chamber/riser for downstream open channel flow (Series A)

Series B has a total of 12 cases with a full pipe flow ($h_d = D_d$) in the downstream pipe and the chamber was partially filled with water. The initial inflow rate was the same as series A, while the final inflow rate was set to be 60, 80 or 100 L/s. The test runs were numbered as B1-B12 in order as shown in Table 3.2. The conditions in the chamber/riser and the downstream pipe are shown in Figure 3.3.

Table 3.2 Experimental design for Series B

Test run	D_r(mm)	h_d/D_d	Q_0 (L/s)	Q_1 (L/s)	Initial flow in the upstream pipe
B1	57	1	20	60	Free surface flow
B2	57	1	20	80	Free surface flow
B3	57	1	20	100	Free surface flow
B4	57	1	30	60	Free surface flow
B5	57	1	30	80	Free surface flow
B6	57	1	30	100	Free surface flow
B7	57	1	40	60	Pressurized full pipe flow
B8	57	1	40	80	Pressurized full pipe flow
B9	57	1	40	100	Pressurized full pipe flow
B10	57	1	50	60	Pressurized full pipe flow
B11	57	1	50	80	Pressurized full pipe flow
B12	57	1	50	100	Pressurized full pipe flow

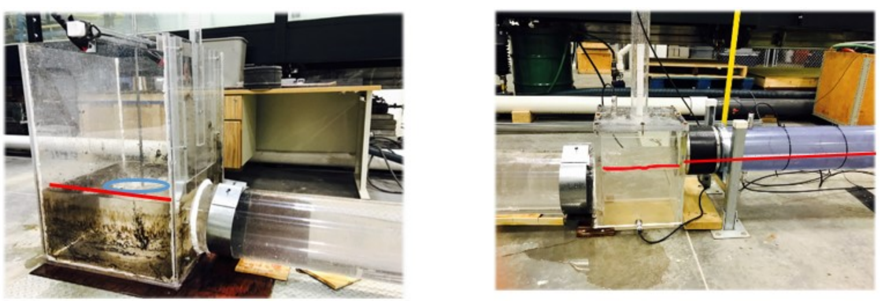


Figure 3.3 Initial conditions in the downstream and chamber/riser for downstream full pipe flow (Series B)

Series C has a total of 12 cases were conducted with downstream full pipe flow, the chamber submerged and the pressurized with an entrapped air pocket in it. The riser diameter was 57 mm for this series. The initial inflow rate was 15, 20, 25 or 30 L/s, and the initial water depth in the vertical riser was 0.1, 0.2 or 0.3 m. The final inflow rate was 40 L/s. These cases are numbered C1 to C12 as shown in Table 3.3. The conditions in the chamber/riser and the downstream pipe are shown in Figure 3.4.

Table 3.3 Experimental design for Series C

Test run	D_r (mm)	h_r (m)	Q_0 (L/s)	Q_1 (L/s)
C1	57	0.1	15	40
C2	57	0.2	15	40
C3	57	0.3	15	40
C4	57	0.1	20	40
C5	57	0.2	20	40
C6	57	0.3	20	40
C7	57	0.1	25	40
C8	57	0.2	25	40
C9	57	0.3	25	40
C10	57	0.1	30	40
C11	57	0.2	30	40
C12	57	0.3	30	40

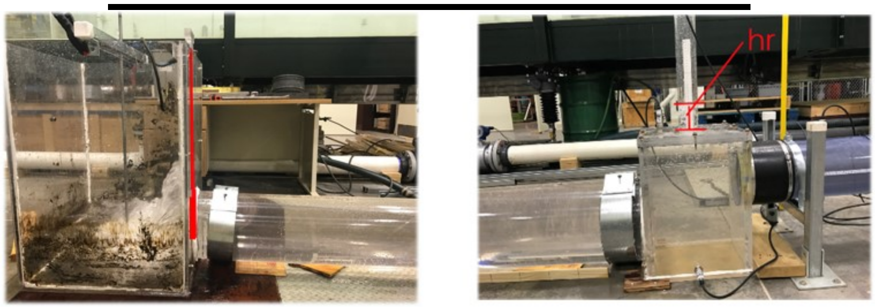


Figure3.4 Initial conditions in the downstream and chamber/riser for downstream full pipe flow with submerged chamber (Series C)

3.3.2 Series for geyser mitigation

In order to address geyser issue, mitigation methods had been applied to selective cases from Series B and Series C. The configuration was based on the experimental setup shown in Figure 3.1.

Series D: with an orifice plate (OP) placed on the top, in the middle or at the bottom of the vertical riser for Case B3. The diameter of the orifice plate (D_{op}) was 6 mm, 12 mm or 30 mm. One additional experiment of fully sealed on top end of the chamber was also tested. The test runs were numbered D1-1 to D1-4, D2-1 to D2-3 and D3-1 to D3-3 as shown in Table 3.4. The configurations of OP at the top, middle and bottom are shown in Figure 3.5.

Table 3.4 Experimental design for adding orifice plate to Case B3

Test run	d_{op} (mm)	Q_0 (L/s)	Q_1 (L/s)	Location of orifice plate
D1-1	0	20	100	top
D1-2	6	20	100	top
D1-3	12	20	100	top
D1-4	30	20	100	top
D2-1	6	20	100	middle
D2-2	12	20	100	middle
D2-3	30	20	100	middle
D3-1	6	20	100	bottom
D3-2	12	20	100	bottom
D3-3	30	20	100	bottom

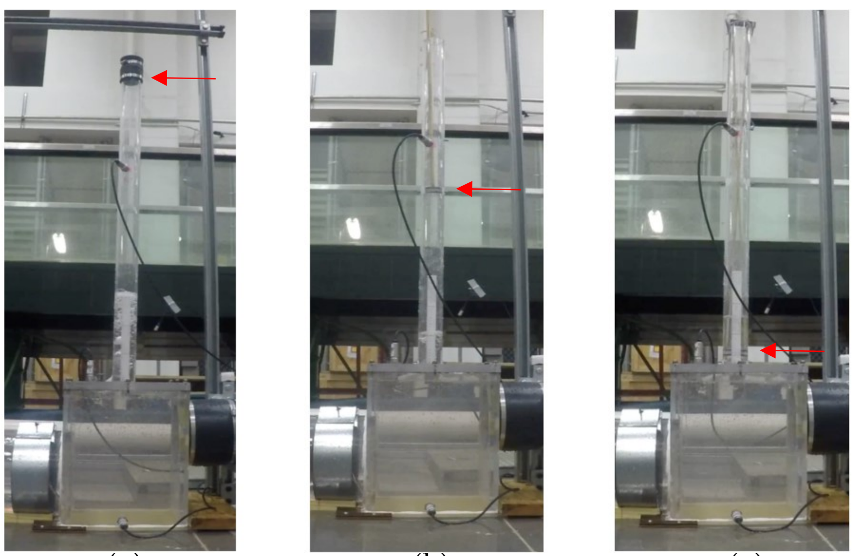

(a) (b) (c)

Figure 3.5 The locations for OP: (a) on the top, (b) in the middle and (c) at the bottom of riser.

Series E with the orifice plate was applied on the top, at the middle or at the bottom of the riser for the cases C4 and C6. The diameter of the orifice plate was 6 mm, 12 mm or 30 mm. The experiments were numbered from E1-1 to E1-8 for the orifice plate applied on the top of the riser, E2-1 to E2-6 for orifice plate applied at the middle of the riser and E3-1 to E3-6 for orifice plate applied at the bottom of the riser as shown in Table 3.5.

Table 3.5 Experimental design for adding orifice plates to Case C4 and C6

Test run	d_{op} (mm)	h_r (m)	Q_0 (L/s)	Q_1 (L/s)	Location of orifice plate
E1-1	0	0.1	20	40	top
E1-2	0	0.3	20	40	top
E1-3	6	0.1	20	40	top
E1-4	6	0.3	20	40	top
E1-5	12	0.1	20	40	top
E1-6	12	0.3	20	40	top
E1-7	30	0.1	20	40	top
E1-8	30	0.3	20	40	top
E2-1	6	0.1	20	40	middle
E2-2	6	0.3	20	40	middle
E2-3	12	0.1	20	40	middle
E2-4	12	0.3	20	40	middle
E2-5	30	0.1	20	40	middle
E2-6	30	0.3	20	40	middle
E3-1	6	0.1	20	40	bottom
E3-2	6	0.3	20	40	bottom
E3-3	12	0.1	20	40	bottom
E3-4	12	0.3	20	40	bottom
E3-5	30	0.1	20	40	bottom
E3-6	30	0.3	20	40	bottom

Series F tested the enlarged riser with a diameter of 100 mm for Cases B1 to B6. The test runs were numbered F1 to F6 as shown in Table 3.6. The configuration of larger diameter riser is shown in Figure 3.6.

Table 3.6 Experimental design for using enlarged riser to cases chosen from Series B

Test run	D_r (mm)	Q_0 (L/s)	Q_1 (L/s)
F1	100	20	60
F2	100	20	80
F3	100	20	100

F4	100	30	60
F5	100	30	80
F6	100	30	100

Figure 3.6 Configuration of 100 mm diameter riser

Series G tested the large diameter riser of 100 mm for Cases C1, C4 to C6, C9 and C12. The test runs were numbered G1 to G6 as shown in Table 3.7.

Table 3.7 Experimental design for using enlarged riser to cases chosen from Series C

Test run	D_r (mm)	h_r (m)	Q_0 (L/s)	Q_1 (L/s)
G1	100	0.1	15	40
G2	100	0.3	25	40
G3	100	0.3	30	40
G4	100	0.1	20	40
G5	100	0.2	20	40
G6	100	0.3	20	40

Series H tested a water recirculation chamber (WRC) for Cases B3 and C6. The WRC was connected to the top end of the riser and its configuration is shown in Figure 3.7. The test runs were numbered H1 and H2 as shown in Table 3.8.

Table 3.8 Adding WRC on top of riser for Case B3 and C6

Test run	WRC	h_r (m)	Q_0 (L/s)	Q_1 (L/s)
H1	Yes	-	20	100
H2	Yes	0.3	20	40

Figure 3.7 Configuration of the WRC

3.4 Experimental Procedure

For all the cases, upon opening of the valve, the inflow rate in the system increased from the initial inflow rate (background inflow rate) to final inflow rate.

The experimental procedures were performed as follow:

- The data collection system was set up and tested before running experiments.

- With the flow running at the desired inflow rate (Q_0), the downstream condition was controlled by either tailgate or overflow weir as needed.

- The ball valve was further manually opened as quickly as possible (about 0.2 s) so that a sudden increase in inflow rate from the initial to the final value (Q_1) was reached. For the test of retrofitting methods, the additional setup of the orifice plate, WRC or larger diameter riser was configured before further opening the valve.

- The experiment process was recorded 10 seconds before further manually opening of the valve.

- All data recording devices were turned off 10 seconds after the system reached its new steady-state.

4. Testing Results for Geyser Mechanism

For all the testing in this thesis, the geyser is defined as air-water mixture splashing out through the riser, and the geyser height (h_g) is indicated by jetting height (h), where the jetting height is measured from the bottom of the riser. If h exceeded the riser height of 1.22 m, then water splashed out from the riser top, and actual geyser happened.

4.1 Downstream Open Channel Flow (Series A)

Twelve cases were tested to in this series. The initial upstream pipe flow condition of free surface flow or pressurized full pipe flow depends on the initial inflow rate. The water depth in the downstream pipe is controlled as one-fourth of the downstream pipe diameter by adjusting the crest height of the overflow weir. For this series, Case A2 was chosen for analysis in detail.

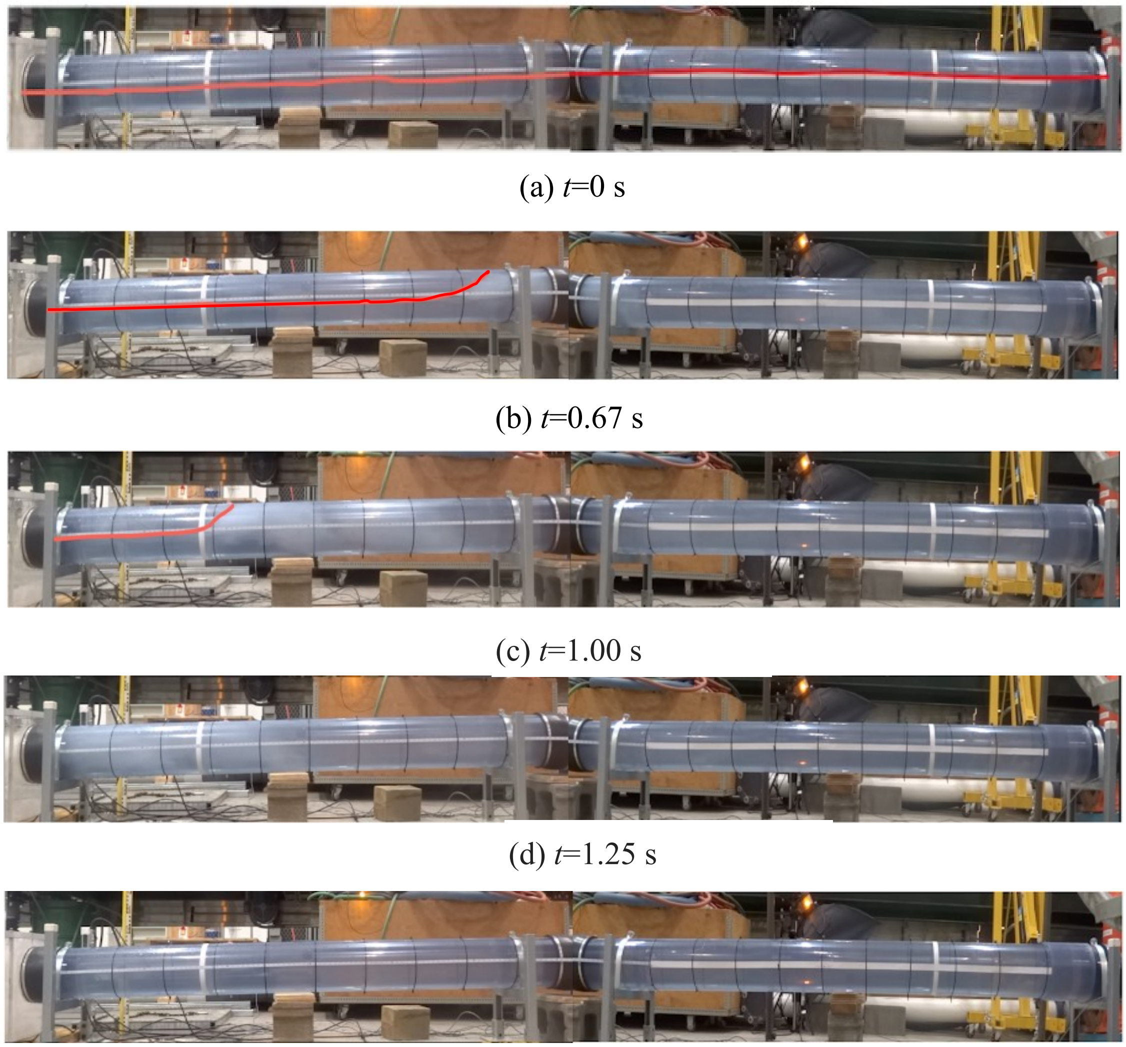
4.1.1 Observation of phenomena

For a smaller initial inflow rate of Q_0=20 or 30 L/s, the initial flow condition in the upstream pipe is open channel flow. Upon quickly fully opening of the valve, the surge front would start to advance towards the chamber and the upstream pipe was quickly filled with water to become pressurized pipe flow. After the surge front reached the chamber, it would stroke the chamber wall which is attached to the downstream pipe, reflected back and mixed with the air which occupied the upper portion of the chamber. As most of the air could directly escape from the downstream pipe, geyser heights were low for this category. A general description of the process is summarized below.

For Case A2, water propagation in the upstream pipe after a sudden flow rate increase is shown in Figure 4.1:

- t = 0 s: the water surface in the upstream pipe is oscillating in a small range, and this is the time when the valve is abruptly opened.

- t=0.67 s: the surge front is moving towards the chamber.
- t=1.00 s: the surge front is approaching the chamber, and the chaotic mixing of air and water is seen behind the surge front.
- t=1.25 s: the surge front reaches the chamber and strikes the chamber wall connected to the downstream pipe.
- t=4.00 s: the inflow with increased inflow rate is continuously fed into the chamber.



(a) t=0 s

(b) t=0.67 s

(c) t=1.00 s

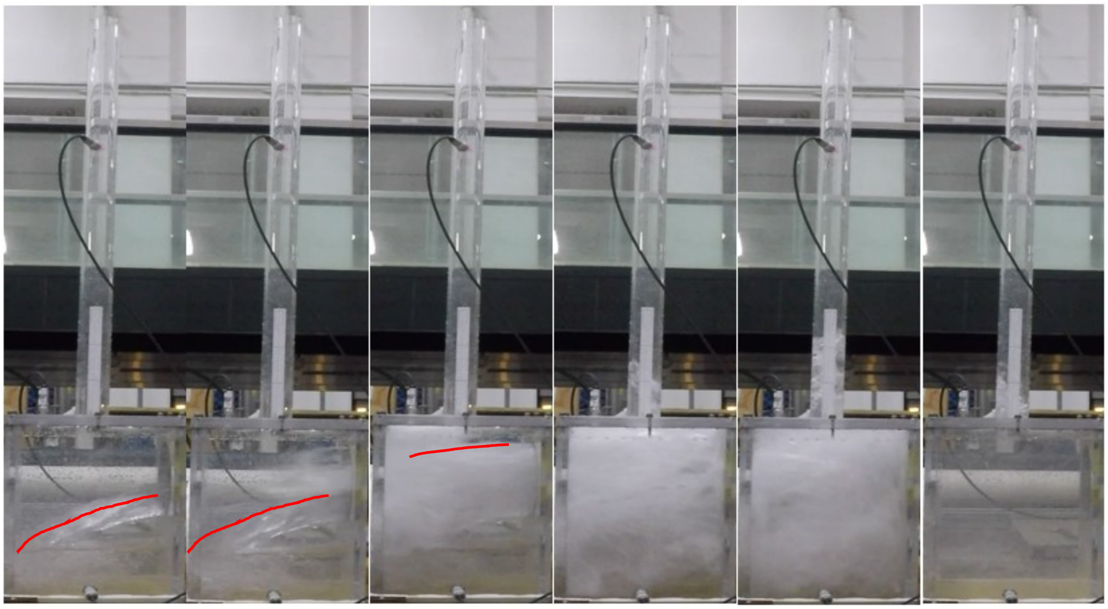
(d) t=1.25 s

(e) t=4.00 s

Figure 4.1 Process of water movement when the inflow rate was changed from 20 to 100 L/s with downstream open channel flow (Case A2)

The corresponding pressure process and the movement of the air-water mixture in the chamber and riser are shown in Figure 4.2. Before fully opening of the valve, the pressures at PT1, PT2 and PT4 are all zero (atmospheric pressure) due to the existence of free surface in the chamber and upstream pipe. The pressure at PT3 indicates the water height in the chamber initially. When the ball valve was quickly opened at t=0 s, water started to advance towards the chamber. At 1.20 s, surge front arrived at the chamber in the form of chaotic air-water mixture, causing the compression of air in the chamber, leading to the increase of pressure at PT4. The pressure at PT3 almost did not change at 1.25 s, which means that air that existed on the upper portion of the chamber had no effect on the water at the lower portion of the chamber. Surge front reached the chamber wall which is connected to the downstream pipe at approximately 1.35 s, and curved back to fill the chamber, which caused a striking behavior and pressure rise at PT2. As the water depth in the downstream tank was low, most of the water and air would directly went out from the system through the downstream pipe, only small portion would strike the chamber wall and reflect back. Water column started to appear in the riser after the chamber was filled with the air-water mixture and became pressurized. Few sharp peaks were recorded at PT2 from around 1.30 s to 6.50 s, before water in downstream pipe accelerated to adapt to the final inflow rate. From the pressure data, it can be seen that pressure reached its final steady state at around 9.00 s, when the oscillation of both positive and negative reading started to narrow down, that was the time when most of the air in the chamber was transported into the downstream tank through the downstream pipe.

(a)



t=0 s t=1.20 s t=1.35 s t=2.03 s t=4.00 s t=9.50 s

(b)

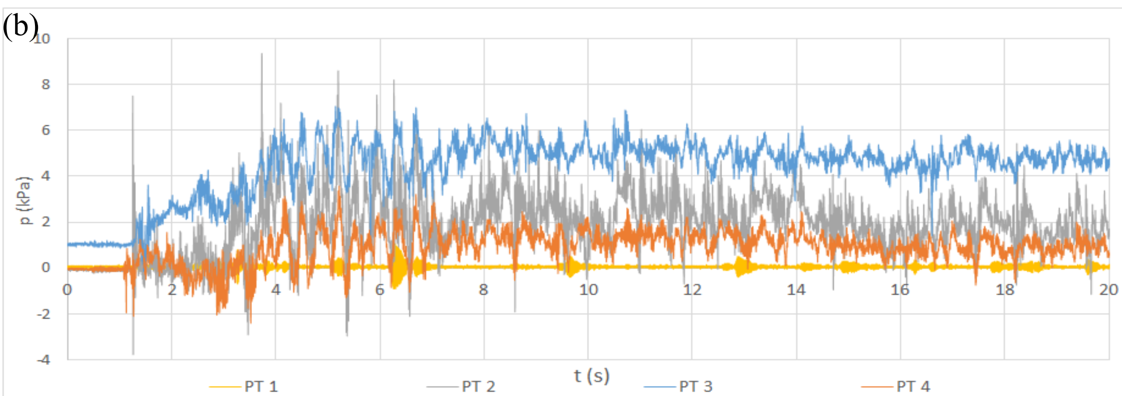


Figure 4.2 Experimental Process of Case A2: (a) air-water movement in the chamber and the riser, and (b) pressure variations.

4.1.2 Summary for Series A

For a small initial inflow rate of 20 or 30 L/s, take Case A2 as an example. Upon opening of the valve, surge front reached the chamber at around 1.25 s, which caused a sudden increase in pressure at PT2-PT4. Intermittent peak pressure occurred several times at PT2, each was related to water hitting the chamber top, and the higher pressure at PT2-PT4 was always associated with higher water depth in the riser. The pressure on the top of the chamber was around 0 kPa (atmospheric pressure) initially, but raised to 7.3 kPa when the chamber became pressurized. Negative pressure was recorded from around 1.00 s to 5.00 s at PT2 and PT4. After 6 seconds, when most of the air has been transported from the chamber to downstream tank, the pressure at PT2 and PT4 stayed positive.

For a larger initial inflow rate of 40 or 50 L/s, water would fill the entire upstream pipe initially. Upon fully opening of the ball valve, the flow occupying the whole section of the upstream pipe was instantly pushed into the chamber. After a short time of intense mixing with air which occupied the upper portion of the chamber, it would directly propagate towards the downstream pipe and flow out of the system through the downstream tank.

The jetting height (h) for this category is low, compared with Series B and C, and all the cases in Series A did not produce actual geyser, as water did not splash out from the riser. The maximum height of water column seen in the riser is 0.53 m. The geyser heights for all cases was shown in Figure 4.3. The ΔQ in the figure is the difference between the final inflow rate and initial inflow rate ($\Delta Q = Q_1 - Q_0$) and h is the maximum geyser height.

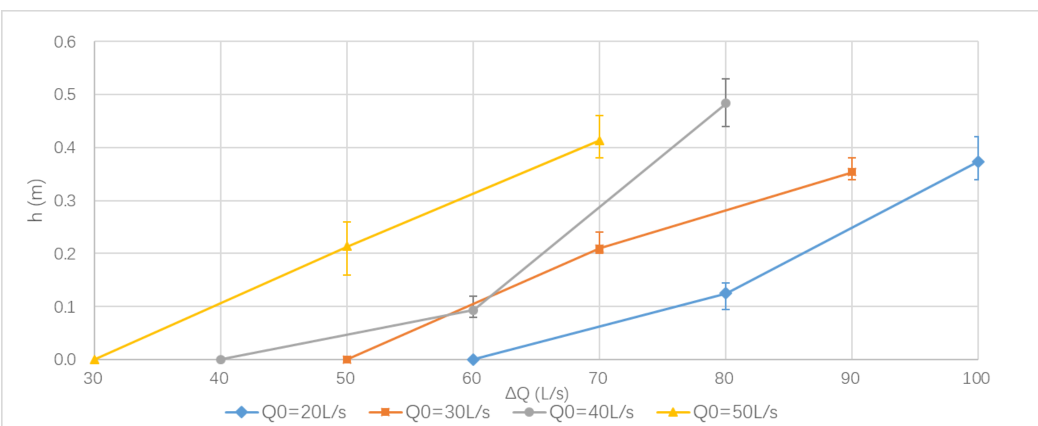


Figure 4.3 Jetting heights of all cases in Series A with downstream open channel flow

4.2 Downstream Full Pipe Flow (Series B)

Twelve cases were tested for this series. For the cases with the initial inflow rate of 20 L/s or 30 L/s, the flow in upstream pipe condition would be open channel flow, and for 40 L/s and 50 L/s cases, the flow in the upstream would be pressurized full pipe flow. The flow in the downstream pipe is controlled to be a full pipe flow by adjusting the crest height of the overflow weir. For this series, Case B3 is chosen for analysis in detail.

4.2.1 Observation of phenomena

As the downstream pipe is full, air in the system has less chance to escape through the downstream pipe when compared with Series A. For open channel flow in the upstream pipe initially, air in the upstream pipe would be pushed into the chamber immediately after fully opening of the valve. Then the water would oscillate in the chamber as no more air existed in the chamber and upstream pipe. For the cases with full pipe flow in the upstream pipe initially, no air existed in the upstream pipe before fully opening of the valve and the corresponding geyser heights are lower than initial free surface flow in the upstream pipe cases due to its smaller increase of the flow rate.

A general description of water movement in the upstream pipe for initial inflow rate of 20 L/s and final inflow rate of 100 L/s (Case B3) is shown in Figure 4.4 and summarized below:

- t=0 s, the water level in the upstream pipe was oscillating in a small range, and this was the time when the valve was suddenly fully opened.
- t=0.67 s, the surge front was approaching the chamber.
- t=1.25 s, the surge front reached the chamber and stroked the chamber wall. The inflow would be continuously fed into the chamber afterwards, like Case A2.

(a) t=0s

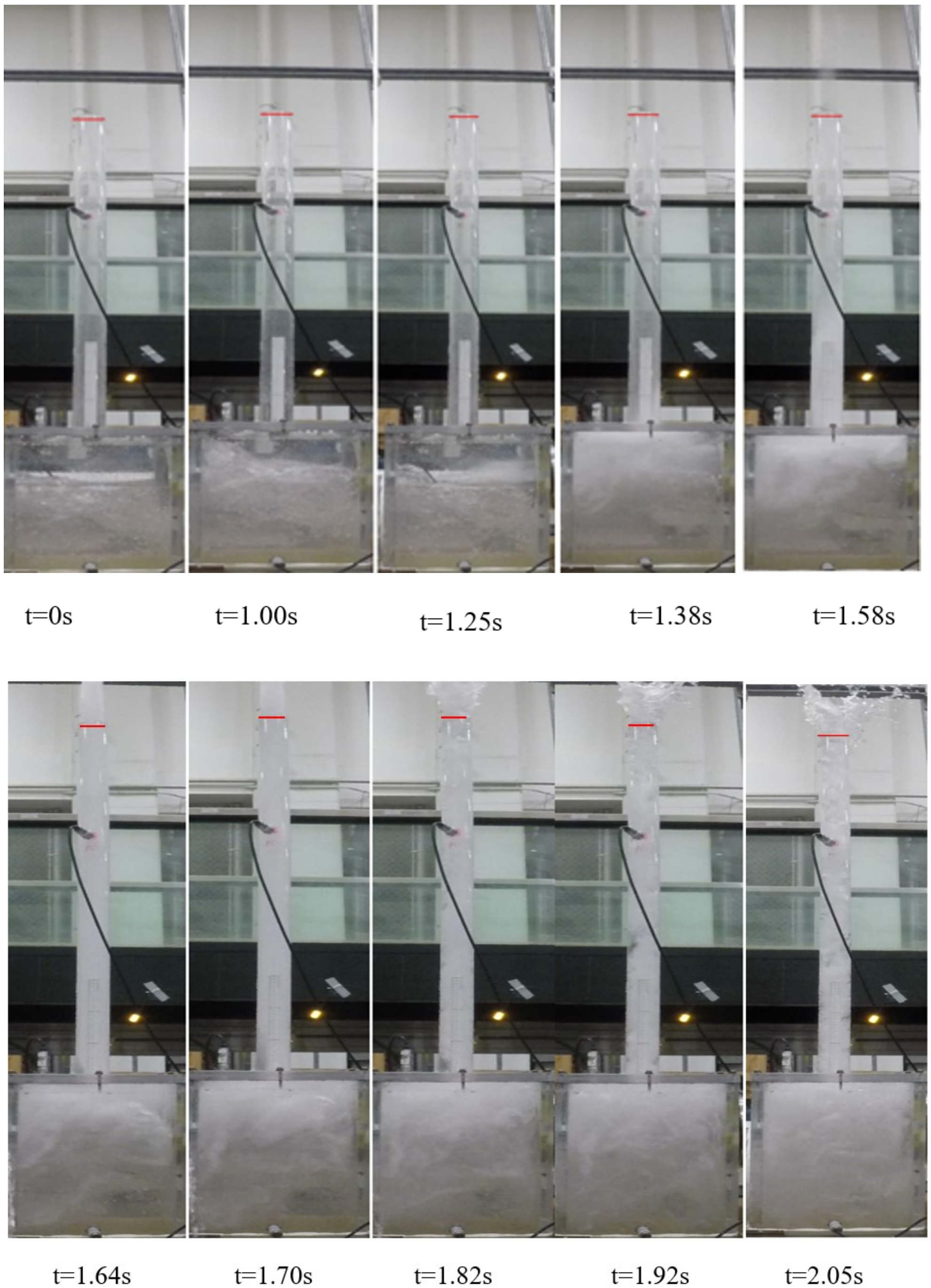
(b) t=0.67 s

(c) t =1.25 s

Figure 4.4 The surge front propagation in the upstream pipe when downstream was full pipe flow and the flow rate is changed from 20 to 100 L/s (Case B3)

The corresponding pressure and the air-water movement in the chamber and riser are shown in Figure 4.5. When the valve was abruptly opened at t=0 s, the pressures at PT2 and PT3 were both around zero (atmospheric pressure), same as Case A2. At t=1.25 s, the surge front reached the chamber, stroke the chamber wall and curved back from 1.25 s to 1.38 s to fill the chamber. At around 1.38 s, the chamber was fully filled, causing pressure rise at PT2-PT4. Water started to jet out of the riser at t=1.58 s, which was around the time when peak pressures at PT2-PT4 were seen with a reading of 47 kPa at PT2. When air-water mixture shootout, the pressure drop was seen at PT1-PT4, which was caused by the air expansion in the chamber. As flow with increased inflow rate was continuously fed into the chamber, two more periodical pressure oscillations were seen. The geyser event ceased at around 2.10 s, when no more water was seen splashing out of the riser. After the geyser event, only small amount of air existed in the chamber within the air-water mixture, so that the pressure in the riser dropped to atmospheric pressure again. From 6.50 s on, after all the air in the chamber was expelled from the system through the downstream pipe, the entire chamber was only filled with water.

(a)



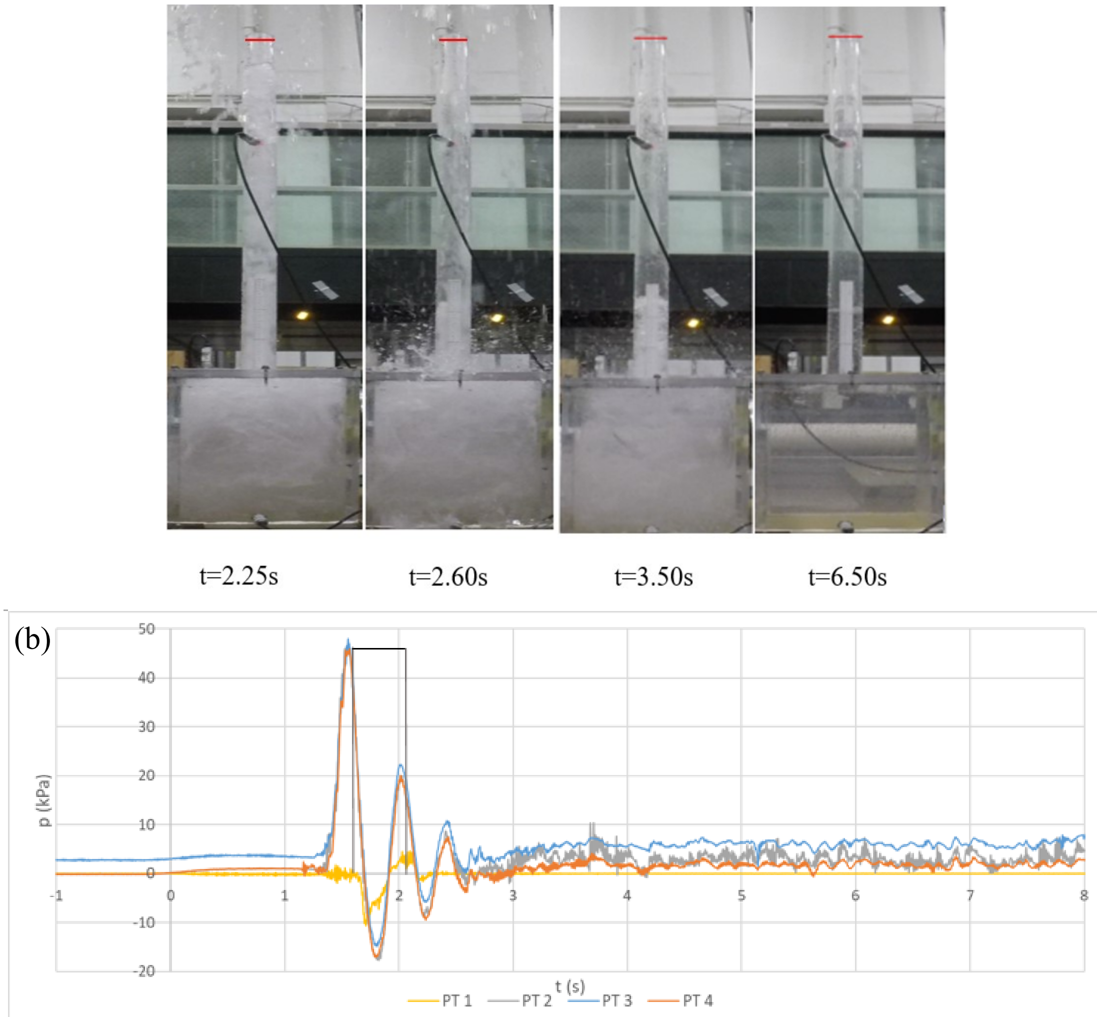


Figure 4.5 Experimental Process of Case B3: (a) air-water movement in the chamber and the riser, and (b) pressure variation.

4.2.2 Summary for Series B

For a small initial inflow rate of 20 or 30 L/s, take Case B3 as an example. As upstream has a free surface initially, a large amount of air was stored along the upper portion of the upstream pipe and the chamber. Upon further opening of the valve, all the air in the upstream pipe was pushed into the chamber rapidly, which was compressed in the chamber, and the pressure increase at PT2-PT4. The air would expand when air-water mixture shoots up, causing the pressure drop at PT2-PT4. After the geyser, oscillation of water surface can be seen in the riser.

For a larger initial inflow rate of 40 or 50 L/s, as the upstream pipe was filled with water initially, and the change in inflow rate is small for those cases, the pressure peak is much lower compared with initial upstream open channel flow cases, as shown in Figure 4.6.

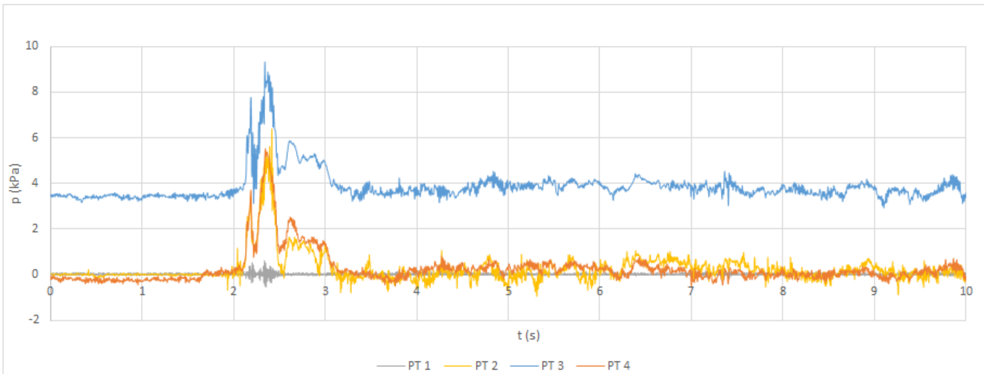


Figure 4. 6 Pressure process of Case B9

The relationship between jetting heights and the changes of inflow rate [ΔQ (= $Q_1 - Q_0$)] is shown in Figure 4.7. The difference in initial and final discharge is the key factor leading to geysers for this series. For the initial inflow rate of 20L/s, the geyser height increased from 1.53 m to 3.18 m and 4.2 m when the final inflow rate is 80 L/s, 100 L/s and 120 L/s respectively. Other initial inflow rates with different final inflow rate showed a similar trend. In summary, geyser would happen when the flow in the upstream pipe is free surface flow at the beginning (Cases B1 to B6), but could also happen when the flow in the upstream pipe is pressurized pipe flow (Cases B7 to B12) initially if the inflow rate change is large.

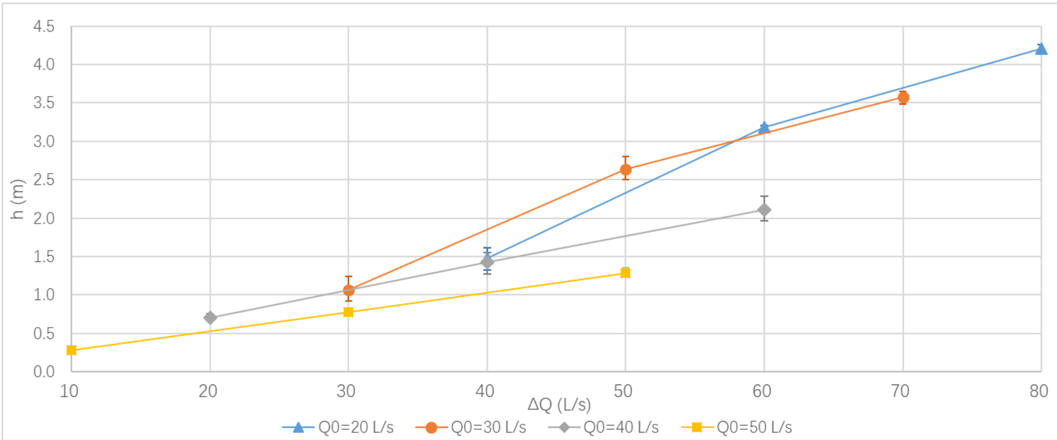


Figure 4.7 Jetting height vs. ΔQ for downstream full pipe flow

The relationship between peak pressures at various locations and maximum geyser heights is summarized in Figure 4.8. As seen from the plot, geyser heights and peak pressures at PT2-PT4 have a positive correlation, and the peak pressures can be postulated for a given geyser height. The peak pressure at PT1 also has a positive correlation with the geyser height, but as it was located at the side wall of the riser, the correlation was not as obvious compared with other pressure measurement locations.

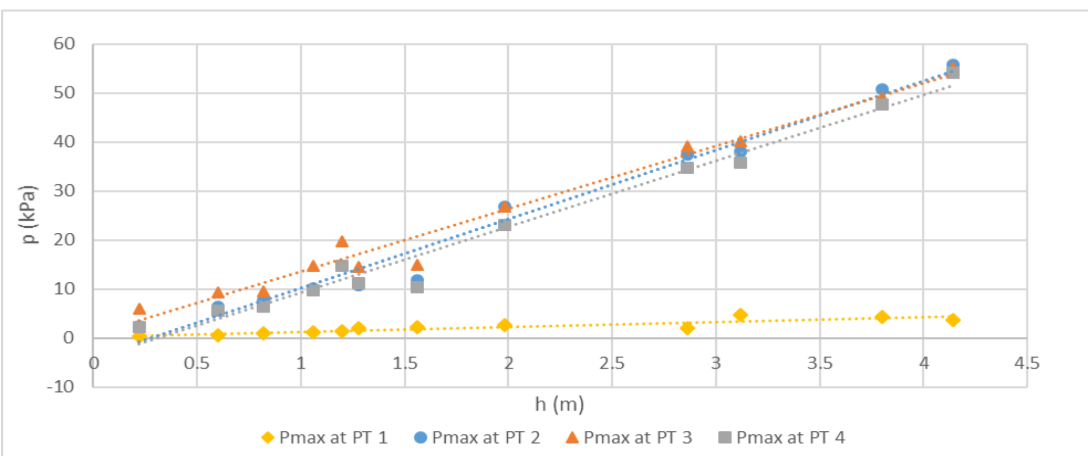


Figure 4.8 Relationship between peak pressures and maximum geyser heights for downstream full pipe flow (Series B).

4.3 Downstream Full Pipe Flow with Submerged Chamber (Series C)

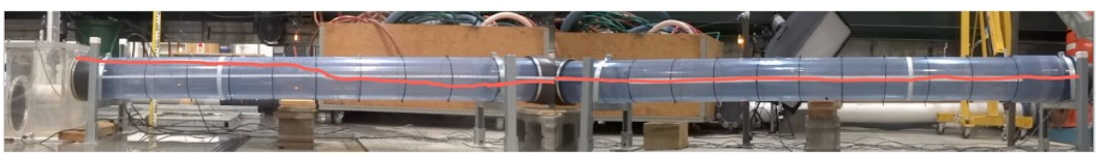
The air pocket in the upstream pipe is entrapped when the tailgate is lowered down to partially block the outflow of the downstream pipe. When the tailgate is lowered down, water stroked on it would form a hydraulic jump that propagates towards the chamber and against the flow direction. When the water filled the downstream pipe and became pressurized, water would fill the chamber and water column was seen in the riser which oscillated up and down in a small range. Afterward, the hydraulic jump would go further toward the upstream and appear in the upstream pipe. As the initial inflow rate was set to a certain value, an air pocket would be entrapped when the balance was reached between the hydraulic jump and the flow. Different initial water depth in the riser can be adjusted by the tailgate.

4.3.1 Observation of phenomena

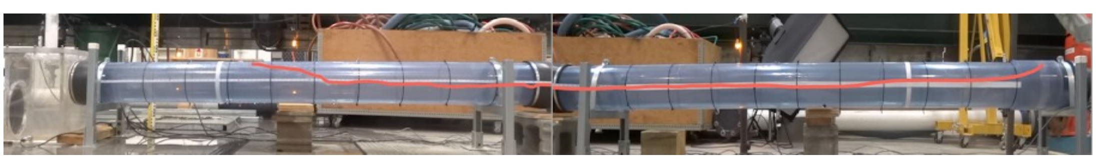
For all the 12 runs, an air pocket was entrapped in the upstream pipe initially. Upon fully opening of the valve, transient pressure could push the thin layer of air which existed on the pipe crown near the chamber into the chamber, and cause the first type of geyser. When the thin layer of air was pushed into the chamber, head of the air pocket was pushed back towards the upstream direction against flow direction, causing the main body of the air pocket became compressed and started to advance towards the chamber. After the head of the air pocket reached the chamber, the main air pocket would release small and discrete air bubbles into the chamber, then they would enter the vertical riser, move upwards along with water, and cause the second type of geyser. Therefore, geysers in this series can be triggered by both the transient pressure and the air releasing from the air pocket.

The process of air pocket movement along upstream pipe (Case C4) is shown in Figure 4.9 and summarized below:

- t=0 s, the head of the air pocket was almost stable and moved slowly backwards towards the upstream before the inflow rate increased. As the head of the air pocket was formed by a hydraulic jump, a thin layer of air can be seen at the upstream pipe crown near the chamber.
- t=0.50 s, the thin layer of water was pushed into the chamber and free surface in the riser started to rise.
- t=1.75 s, air cavity existed in the chamber, the water in the chamber detached from the water in the riser. The tail of air pocket started to advance towards the chamber.
- t=2.67 s, water in the riser and chamber reattached, the tail of air pocket was continuously moving towards the chamber.
- t=3.34 s, the tail of air pocket was moving towards the chamber.
- t=5.25 s, the entire air pocket was moving towards the chamber and the water level in the riser was stable.
- t=8.50 s, the head of the air pocket reached the chamber and the free surface in the riser started to rise again.
- t=10.00 s, the head of the air pocket remained at the connection of upstream pipe and chamber, while the tail of air pocket was still advancing towards the chamber.
- t=20.00 s, the system became stable.

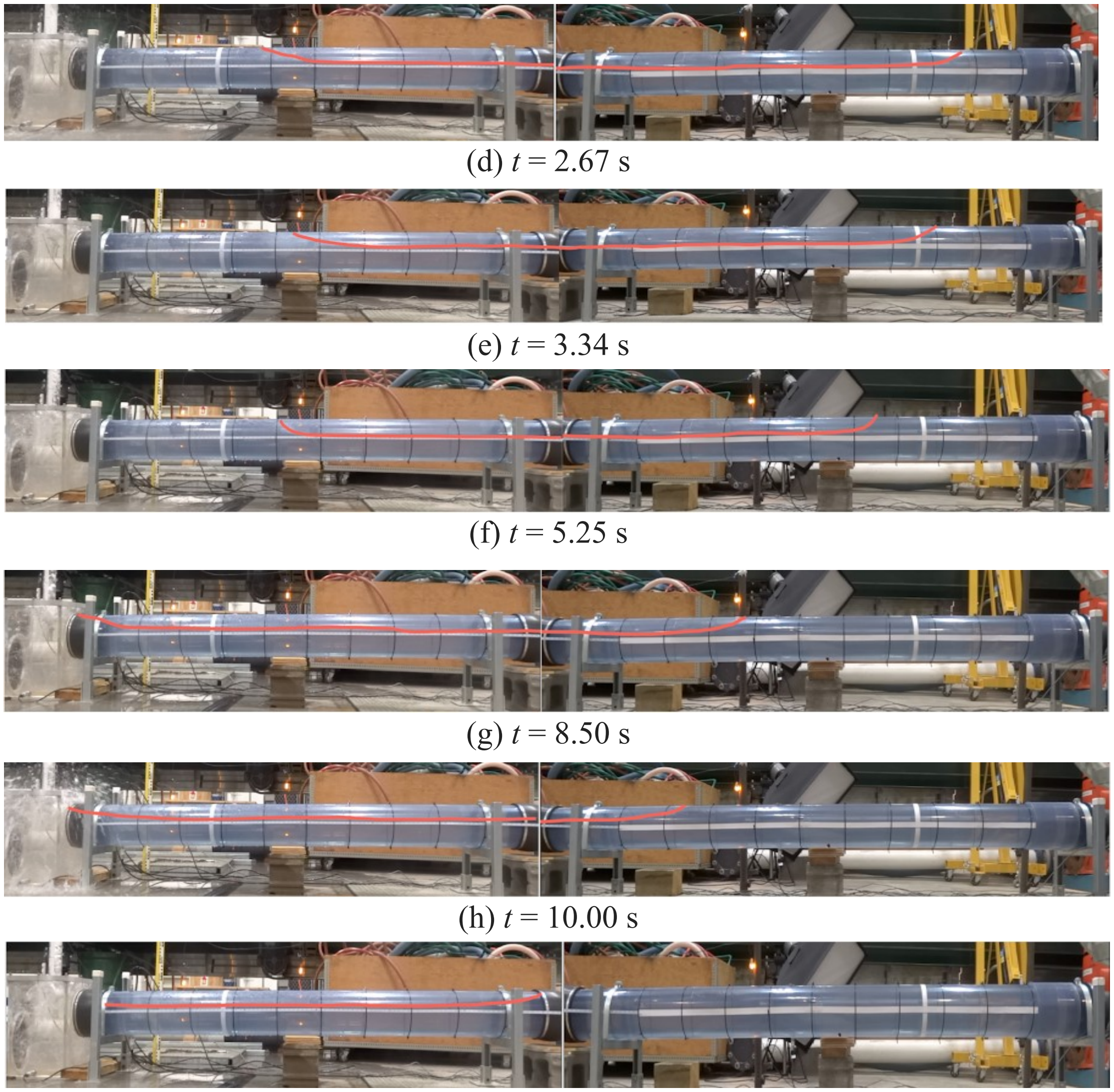


(a) t = 0 s



(b) t = 0.50 s

(c) t = 1.75 s



(d) t = 2.67 s

(e) t = 3.34 s

(f) t = 5.25 s

(g) t = 8.50 s

(h) t = 10.00 s

(i) t = 20.00 s

Figure 4.9 Air pocket propagation in the upstream pipe when Q_0=20 L/s and Q_1=40 L/s, h_r=0.1 m (Case C4)

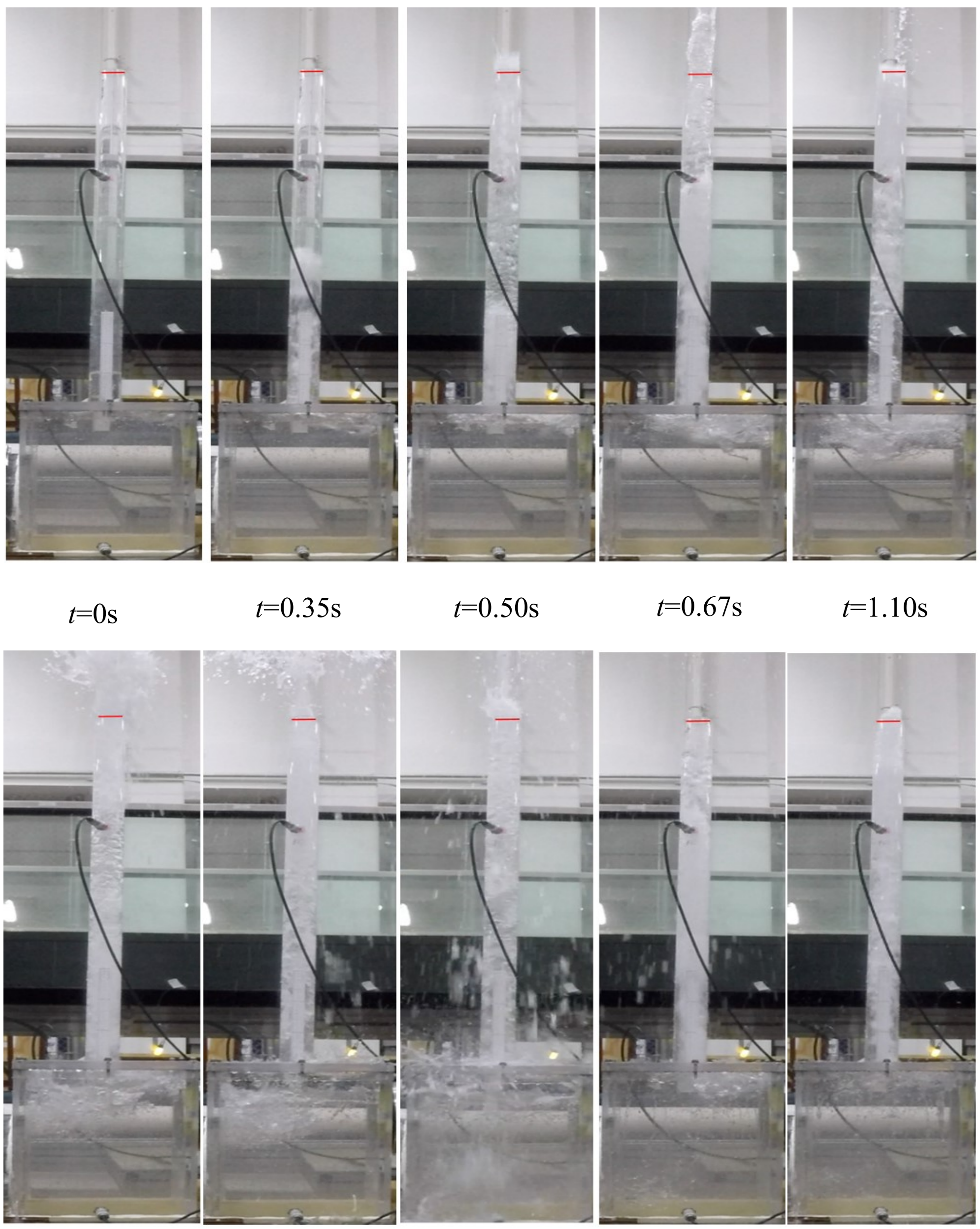
The corresponding process of pressure history and the air/water interaction in the chamber and vertical riser are shown in Figure 4.10. At t=0 s, the water height in the riser is 0.1 m, the water surface in the riser is relatively stable with 0.01 m oscillation up and down. The pressure in the riser at PT1 is zero (atmospheric pressure). The pressure at PT2 is the pressure acting on the chamber top, PT3 is the steady pressure in the chamber and PT4 is the pressure in the air pocket.

After the sudden fully opening of the valve, the pressure wave would propagate towards the chamber. The first splashing of water happened at around 0.50 s, after the thin layer of air was pushed into the chamber and release through the riser, and the surrounding water filled the air space, which caused the first pressure peak in the chamber. The decreasing and increasing of pressure was seen from 0.67 s to 2.67 s, with the decreasing of pressure caused by the air-water mixture out of riser, while the increasing of pressure caused by water from the upstream pipe fed into the chamber to fill the space of air cavity. When air cavity appeared, the junction of the thin layer of air and the head of the air pocket is separated by water plug, which resulted in the entire air pocket separated into two parts and the head of air pocket be pushed back towards the upstream. After the air cavity was filled by water, the impact force of rising water forced the water in the rise to move upwards, which resulted in the second splashing, which happened from 3.34 s to 4.19 s. When head of air pocket that was advancing towards the far upstream encountered the increased rate of flow that was flowing towards the chamber, the head of the air pocket changed its direction. The pressure gradually increased at PT2-PT4 during this time, with a 0.20 s delay of pressure increase was observed at PT1. The pressures at PT2-PT4 were steady from 4.00 s to 8.00 s, which was when the entire air pocket was advancing towards the chamber, while the head of the air pocket had not reached the chamber yet.

As the flow was continuously moving towards the chamber, the head of the air pocket reached the chamber at around 8.69 s. When the head of the air pocket reached the chamber, it was separated into smaller air bubbles due to the existence of the joint of chamber and upstream pipe, and would accumulate on the top of the chamber. The third round of splashing happened from 8.88 s to 9.94 s, after first discrete air bubble was separated from main air pocket entered the chamber then riser bottom and shoot out. The pressure pattern is typical for air pocket release process, with a decrease in pressure at PT2-PT4 indicating that air was gradually released from the riser, followed by an increase in pressure at PT2-PT4 indicating that water in the upstream was fed into the chamber. The pressure increase was an indication of geyser height from 8.88 s to 15.21 s.

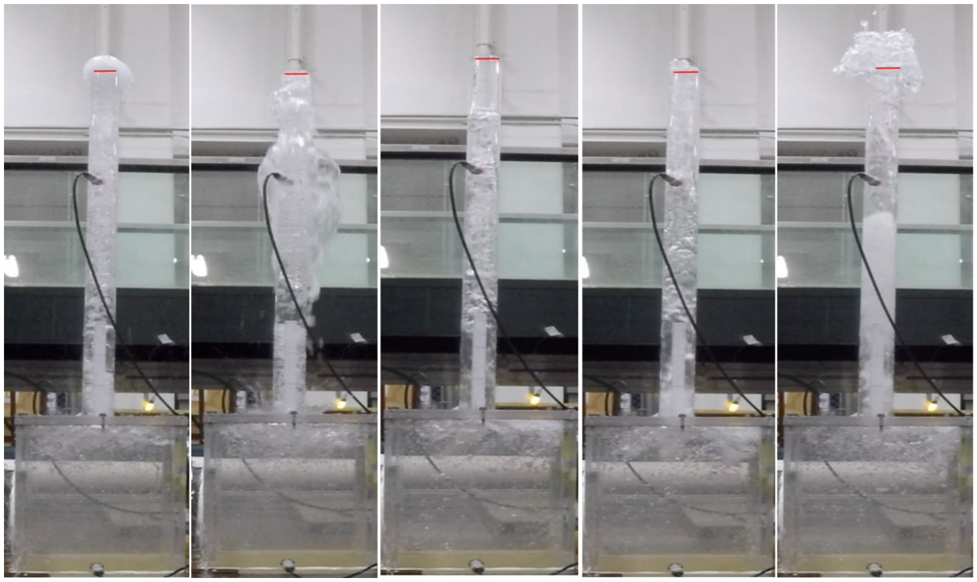
Last round of splashing happened at 17.31 s, just after air pocket became stable and the last air bubble in the main air pocket entered the riser. After the stabilization of air pocket, no more splashing was observed and Taylor bubble was seen rising steadily in the riser. The pressure at PT1 dropped to zero at around 22.65 s, when the free surface in the riser became lower than the location of PT1.

(a)

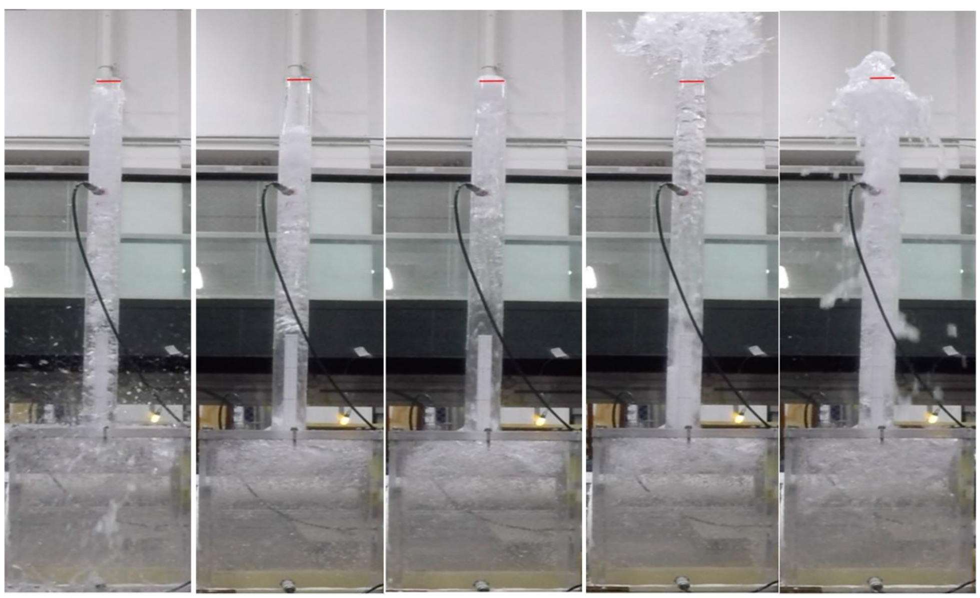


t=0s *t*=0.35s *t*=0.50s *t*=0.67s *t*=1.10s

t=1.30s *t*=1.50s *t*=2.31s *t*=2.83s *t*=3.34s



t=3.63s *t*=4.19s *t*=8.69s *t*=8.88s *t*=9.19s



t=9.94s *t*=10.85s *t*=11.10s *t*=11.46s *t*=12.77s

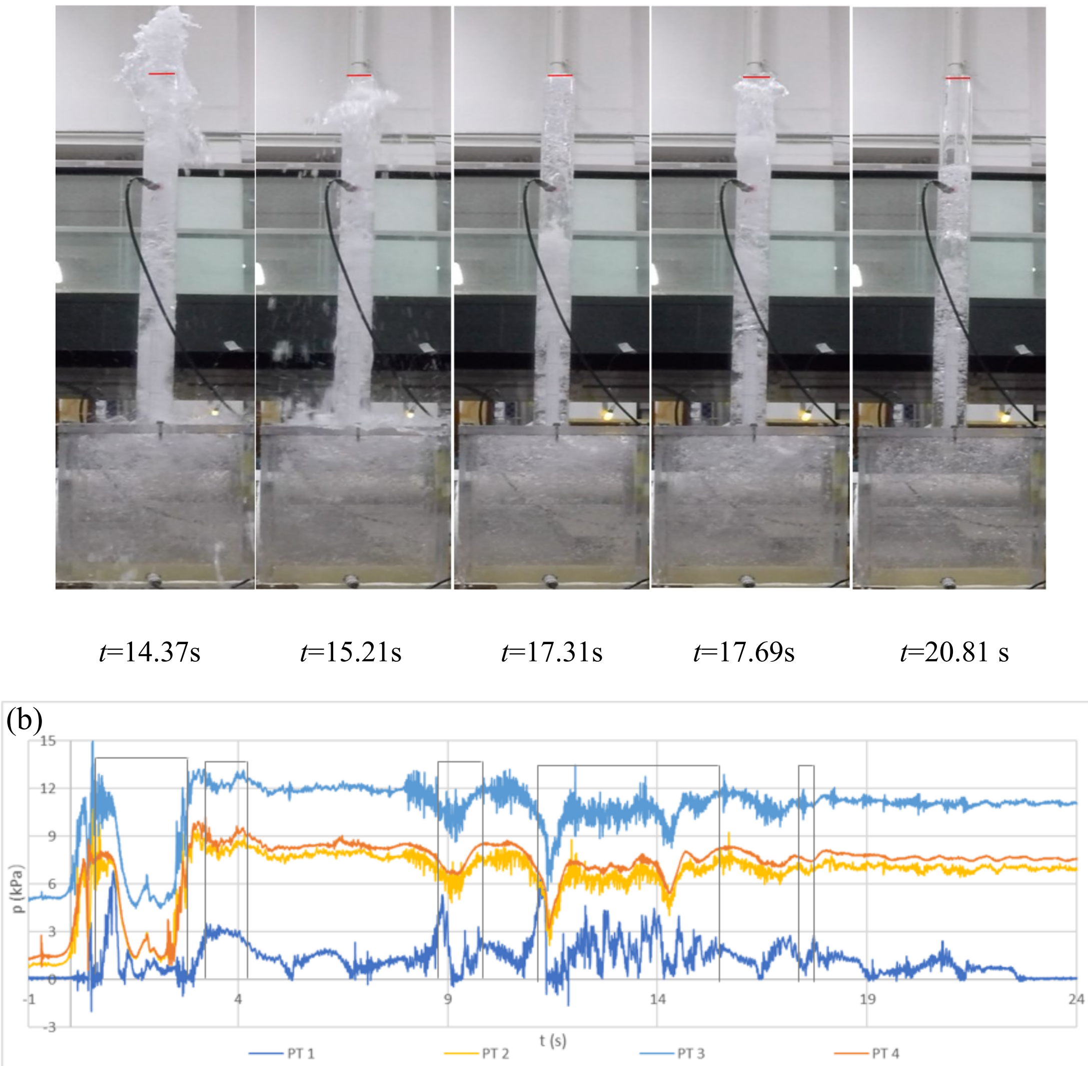
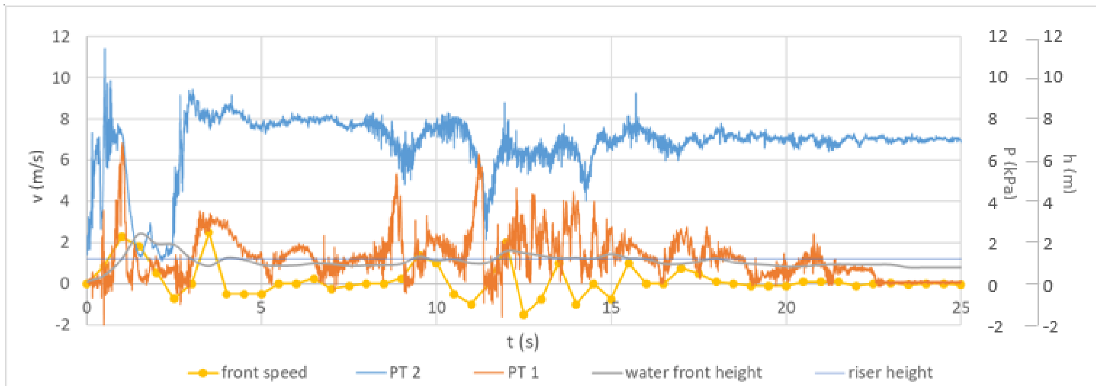
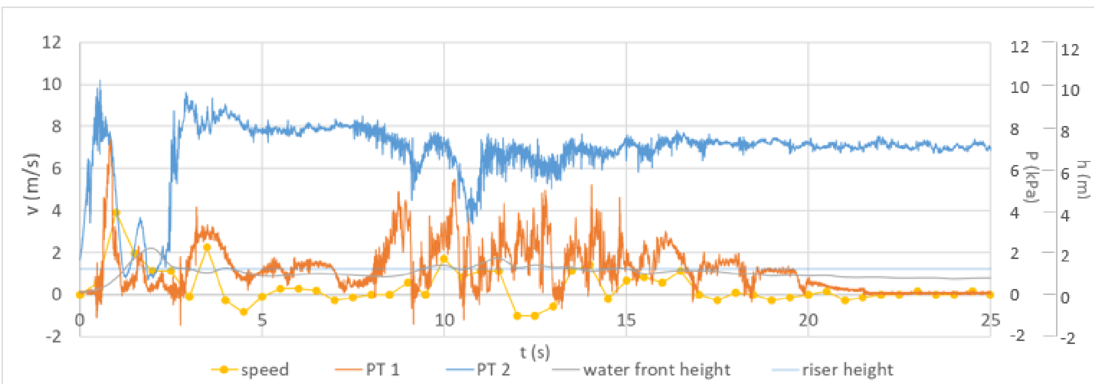


Figure 4.10 Experimental process of Case C4: (a) air-water movement in the chamber and the riser, and (b) pressure variation.

Two runs from Case C4 were used to compare the velocities, heights of the free surface and pressures as shown in Figure 4.11. The speed of the free surface (front speed in the figure) and the water front height were measured twice per second while the pressure data was consistently measured. The straight light blue line is the height of riser, which was used to denote whether the mixture is in the riser or splashed out. It can be seen that the process of the two tests were similar. The time for the front speed was postponed after the pressure has changed. In general, the increase in pressure is the cause for the increase in the front speed.



(a)



(b)

Figure 4.11 The relationship among water front speeds, heights of water surface and pressure process for Case C4.

4.3.2 Summary for Series C

In summary, the air pocket is the leading factor in producing geyser for this series. Although transient pressure wave can always cause the first geyser event, the air release from air pocket is the main process determine the geyser severity and duration. Intermittent geyser events are commonly seen in this series, when the air bubbles are released from the air pocket and enter the riser, finally shoot out.

Figure 4.12 shows the relationship between normalized size of air pocket and initial flow rate in the system. The initial air pocket size was made non-dimensional as $V_{air} / D_u{}^3$ and Q_0* was calculated as $Q_0/\sqrt{gD_u^5}$, where D_u is the diameter of the upstream pipe. From the chart, it can be seen that the size of the initial air pocket mainly depends on the initial inflow rate. The normalized volume of air pocket first increases with the increase of flow rate increment, then decreases. Thus, it can be ascertained that the largest volume of air pocket corresponds to Q_0* around 0.32, of which Q_0 is 18 L/s.

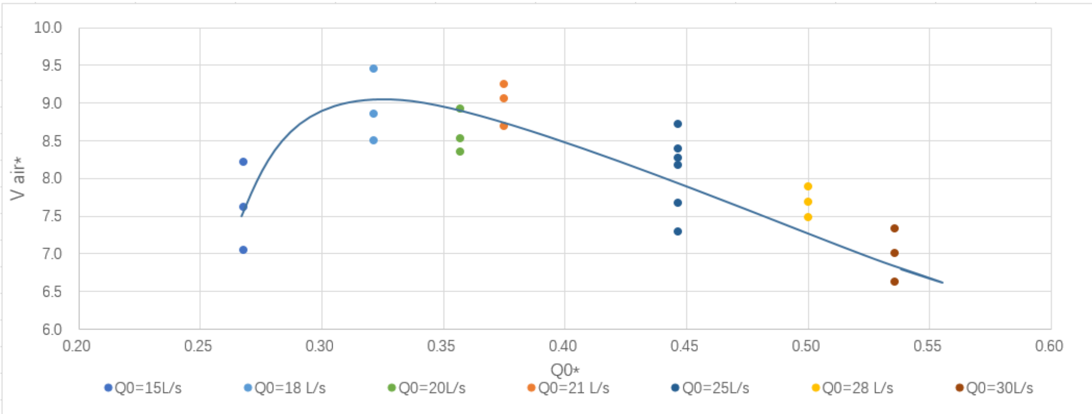


Figure 4.12 Normalized volume of the initial air pocket vs. normalized initial discharge.

The relationship between peak pressures at different locations and the geyser heights is shown in Figure 4.13. It can be seen that the trends are similar for different pressure measurement locations, all peak pressures at PT1-PT4 shows a positive correlation with the maximum geyser height. The fittest trend line for this category is the logarithmic pattern (with biggest R^2 value at different pressure measurement locations), the equations for the geyser height vs. p max at PT1 to PT4 are y=11.416ln(x) -1.6489, y=14.71ln(x) -0.7153, y=15.069ln(x) +3.0986 and y=13.07ln(x) +0.4482 respectively.

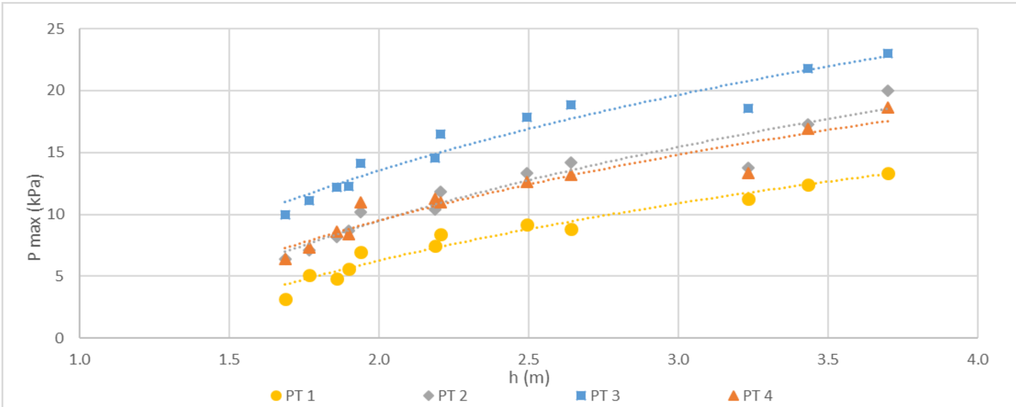


Figure 4.13 Peak pressures at different locations vs. geyser heights for downstream full pipe flow with submerged chamber (Series C)

4.4 Discussion on Geyser Mechanism

For Series A which has a free surface flow in the downstream pipe and a free surface/full pipe flow in the upstream pipe, no visual geyser is seen. As water depth in the downstream pipe is low, the increased flow rate could pass quickly with enough space after the ball valve is opened. If the upstream pipe has a full pipe flow initially, the increase in flow rate is smaller, and would have less impact on the flow in the downstream pipe.

Cases in Series B have a full pressurized pipe flow in the downstream pipe and a partially filled chamber while flow in upstream could either be free surface or full pipe flow depending on the initial inflow rate. For upstream free surface initially, the rapid filling flow would form and moves quickly towards the chamber when the ball valve is fully opened. When surge front reached the chamber, stroke on the chamber wall and curved back, the air brought into the chamber from upstream pipe was compressed, causing pressure rise at PT2-PT4, and when the compressed air tends to move upwards through the riser, geyser could happen. In this series, a single geyser might occur for free surface flow in the upstream pipe initially cases because ΔQ is larger, and only two geysers are observed for pressurized full pipe flow in the upstream pipe initially because ΔQ is smaller.

Cases in Series C has an air pocket entrapped in the upstream initially for all tests. Because tailgate is used to limit the flow capacity in the system, the system would be pressurized throughout the experiment. Two kinds of geyser can always happen for this series, the first is transient pressure wave pushing the thin layer of air on the pipe crown into chamber and riser, and the second is the air releasing from the air pocket. As air pocket is formed by the hydraulic jump, a thin layer of air can be seen between the head of air pocket and chamber. When the thin layer of air encounters the transient pressure change, it would be pushed into the chamber. Due to buoyancy, the thin layer of air tends to occupy the upper portion of the chamber, along with water and then it would enter into the riser and shoot out of the riser. Air cavity usually happens after the releasing of the thin layer of air, which is caused by the pressure in the chamber not enough to lift mixture in the riser to go up and shoot out through the riser. During this process, the head of the air pocket was pushed back towards the valve. When the head of the air pocket encountered the flow with increased inflow rate that is moving towards the chamber, the head of the air pocket would change its moving direction as the moving flow with increased inflow rate has more momentum. When the entire air pocket started to move towards the chamber, the second form of geyser may occur, which is caused by air releasing from the air pocket. As a vertical corner existed at the connection of the upstream pipe and the chamber, the air bubbles from the main air pocket would be released into chamber one by one and it would occupy the top of the chamber, then it would move upwards in the riser and intermittent geyser events would happen.

In summary, in terms of geyser severity, likelihood to happen and amount of water splashed out, Series C would produce most severe geyser, while Series A has the lowest possibility of geyser occurrence. As there is no visual geyser in Series A, this category is not considered for retrofitting.

Table 4.1 is a summary of geyser heights and peak pressures for Series B. For same inflow rate, maximum geyser height and peak pressure would increase as final inflow rate become larger. For the same final inflow rate, the peak pressure and maximum geyser height would decrease as the change in inflow rate is smaller, except for Cases B3 and B6. Although maximum height for Case B3 is 0.6 m higher than that of Case B6, the peak pressure for Case B6 is slightly higher than that of Case B3 at PT2-PT4.

Table 4.1 Summary of maximum geyser heights and peak pressures for downstream full pipe flow (Series B)

Run	Q_0 (L/s)	Q_1 (L/s)	height (m)	p max @ PT 1 (kPa)	p max @ PT 2 (kPa)	p max @ PT 3 (kPa)	p max @ PT 4 (kPa)
B1	20	60	1.48	2.25	11.77	14.89	10.25
B2	20	80	3.18	4.69	38.13	40.09	35.84
B3	20	100	4.20	4.62	46.82	47.97	45.92
B4	30	60	1.07	1.12	10.06	14.79	9.81
B5	30	80	2.64	2.06	37.45	39.16	34.67
B6	30	100	3.58	4.35	48.02	49.02	47.56
B7	40	60	0.70	0.63	6.40	9.33	5.52
B8	40	80	1.43	1.32	14.79	19.78	14.65
B9	40	100	2.11	2.73	24.80	26.81	23.00
B10	50	60	0.28	0.39	2.54	5.91	2.20
B11	50	80	0.78	0.88	7.67	9.57	6.45
B12	50	100	1.28	1.95	10.69	14.45	11.08

Considering the severity of the cases, Case B3 is selected for the test of retrofitting of orifice plate on the top, in the middle and at the bottom of the riser, and WRC on top of the riser. Case B1-B6 are selected to test the effect of an enlarged riser.

Table 4.2 is a summary for geyser heights and peak pressures for Series C. Comparing the case with same inflow rate change but different initial heights of water column in the riser, it can be seen that geyser height and peak pressure would increase as h_r increases. Comparing the case with same h_r, both the maximum geyser height and peak pressure increase when ΔQ is larger.

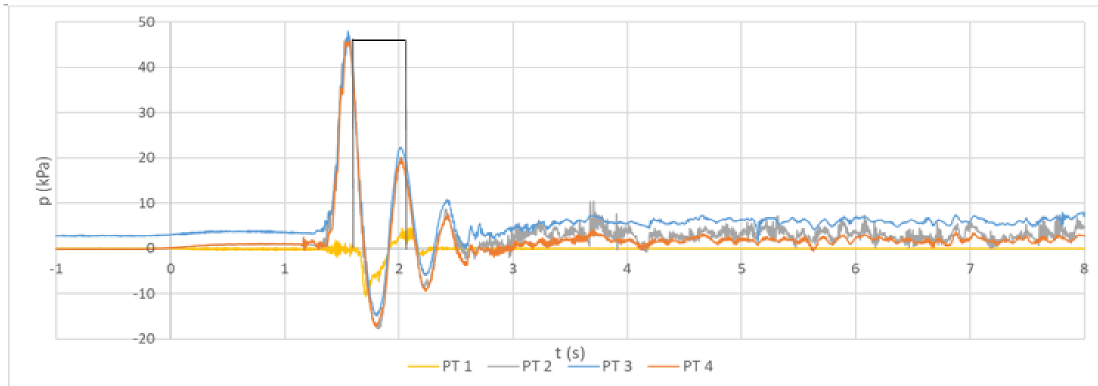
Table 4.2 Summary of maximum geyser heights and peak pressures for downstream full pipe flow with submerged chamber (Series C)

Run	Q_0 (L/s)	Q_1 (L/s)	h_r (m)	h max (m)	p max @ PT 1 (kPa)	p max @ PT 2 (kPa)	p max @ PT 3 (kPa)	p max @ PT 4 (kPa)
C1	15	40	0.1	3.23	11.26	13.77	18.56	13.31
C2	15	40	0.2	3.43	12.37	17.27	21.76	16.94
C3	15	40	0.3	3.70	13.36	20.02	23.03	18.65
C4	20	40	0.1	2.19	7.46	10.37	14.54	11.23
C5	20	40	0.2	2.49	9.21	13.33	17.84	12.61
C6	20	40	0.3	2.64	8.82	14.21	18.86	13.17
C7	25	40	0.1	1.86	4.82	8.19	12.22	8.62
C8	25	40	0.2	1.94	6.95	10.16	14.13	10.99
C9	25	40	0.3	2.21	8.41	11.8	16.49	10.95
C10	30	40	0.1	1.69	3.14	6.41	9.95	6.41
C11	30	40	0.2	1.77	5.13	7.1	11.12	7.29
C12	30	40	0.3	1.90	5.63	8.71	12.26	8.38

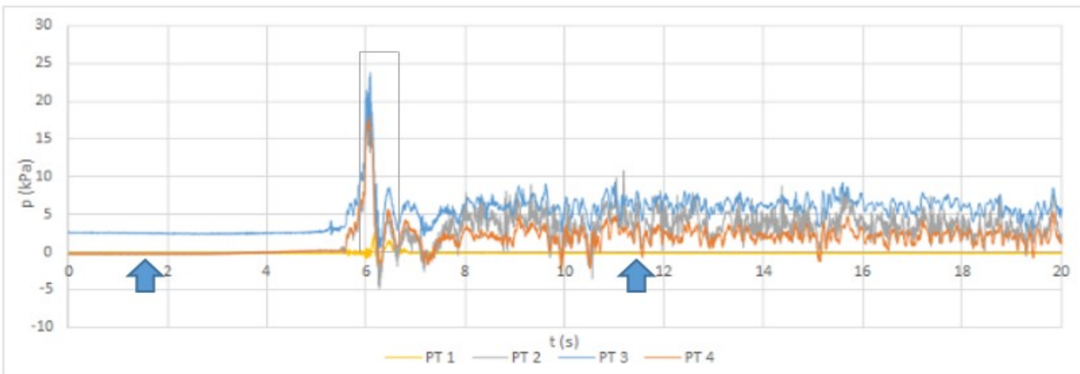
For retrofitting, case C4 is chosen for the test of orifice plate on the top, in the middle and at the bottom of the riser, case C6 is chosen to test the WRC and case C1, C4 to C6, C9 and C12 are chosen to test the enlarged diameter riser.

4.5 Testing of the Impact of Valve Opening Time on Geyser Formation

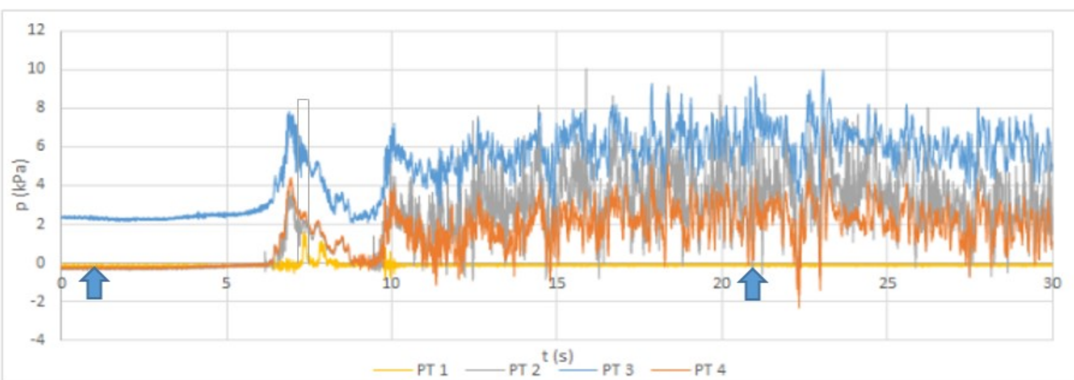
Figure 4.14 shows the pressure variations for Case B3, when different valve opening time of 0.20 s, 10.00 s and 20.00 s was used. The blue arrows in Figure 4.14 (b) and (c) represent the start time for the opening of the valve (left) and fully opening of the valve (right) respectively. It can be seen from the figures that peak pressure at PT3 dropped from 47.98 kPa to 23.79 kPa then to 10.01 kPa when the valve opening time increased from 0.20 s to 10.00 s and 20.00 s. Similar decrease in peak pressure can be found at PT2 and PT4 as valve opening time increases. For the maximum geyser height produced by different scenarios, Figure 4.14 (a) has a geyser of 4.2 m, (b) has a geyser height of 2.14 m and (c) has a geyser height of 1.38 m. As the length of the riser is 1.22 m, only 0.16 m of water was seen above the riser top for Figure 4.14 (c). The duration of this geyser event is short and only small amount of water shoot out through the riser. So if the valve opening time is further increased, it is anticipated that geyser event can be eliminated.



(a)



(b)

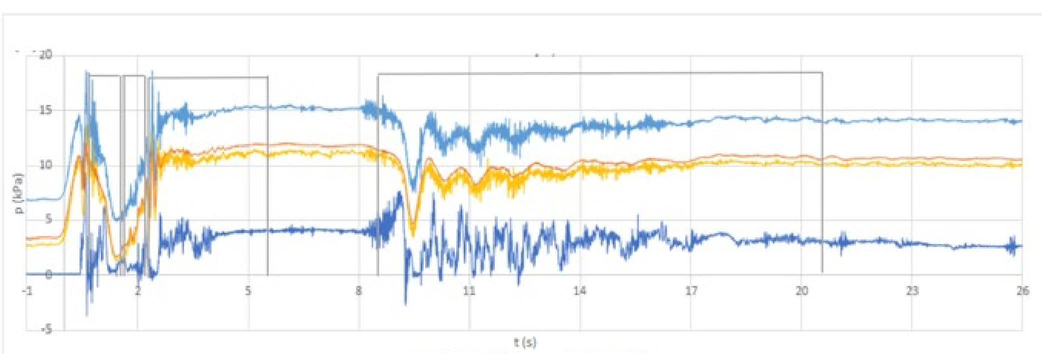


(c)

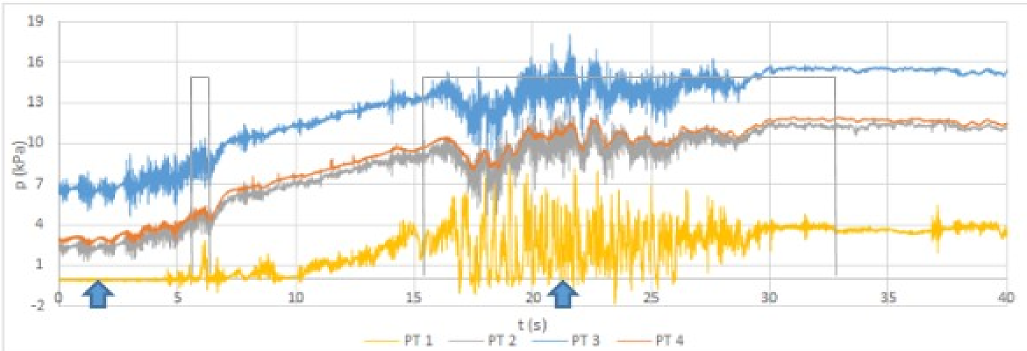
Figure 4.14 Pressure variations for Case B3 under different valve opening times: (a) t=0.2 s, (b) t=10 s, (c) t=20 s.

Figure 4.15 illustrates how valve opening time could impact the pressure process for Case C6. Unlike Figure 4.15 (a), where the maximum geyser height caused by transient pressure pushing the thin layer of air out and the air releasing from air pocket is similar, the maximum geyser height for air pocket release process is much higher than geyser caused by the release of the thin layer of air for Figure 4.15 (b). As the valve opening time increased, it would take longer time for transient pressure to push the thin layer of air into the chamber to form geyser. When the valve opening time is long enough, the geyser caused by transient pressure wave was gone, as seen in Figure 4.14 (c). For Figure 4.15 (a), the pressure in riser raised soon after the opening of the valve, which is followed by the first geyser event. For Figure 4.15 (b), the sudden rise of pressure in the riser coincides with the time of the first geyser event. For Figure 4.15 (c), the geyser caused by transient pressure did not happen, as it was not large enough to push the water column in the riser initially out. The first geyser happened at around 20 s, and it was driven by air releasing from the air pocket. The geyser event in Figure 4.15 (a) has a maximum height of 2.64 m, while the geyser heights for Figure 4.15 (b) and Figure 4.15 (c) are 2.62 m and 2.42 m respectively. It can be speculated that even valve opening time is further increased, geyser event will still happen, with similar geyser height and longer duration.

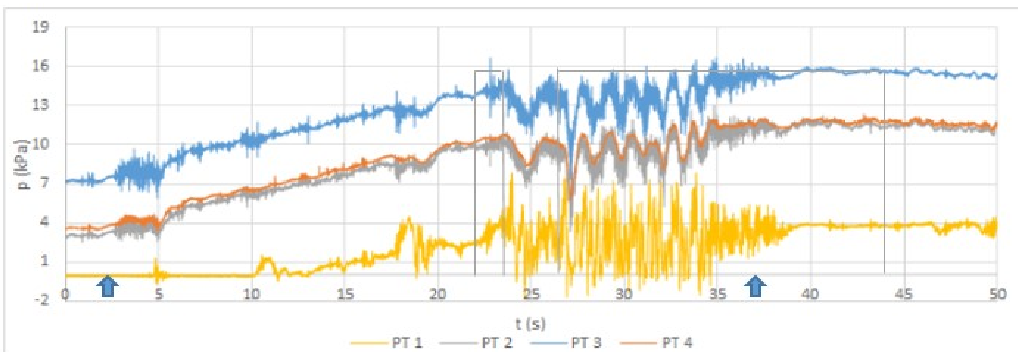
In conclusion, geyser events are greatly mitigated for Series B when a the longer time is used to open the valve in terms of geyser height and peak pressure, but is not much mitigated for Series C.



(a)



(b)



(c)

Figure 4.15 Pressure variation for Case C6 under different valve opening times: (a) t=0.20 s, (b) t=20.00 s, (c) t=35.00 s.

4.6 Spilled Water Volume

In order to gain a basic understanding on how much water splashed out from the riser, selective cases have been chosen for the estimation. The results are summarized in Table 4.3. The $Q_{1\text{-}1}/V_1$, $Q_{1\text{-}2}/\ V_2$ and $Q_{1\text{-}3}/\ V_3$ represents the final inflow rate/spilled water volume of first test, second test and third test respectively and $V_{ave.}$ is the average spilled water volume of the three tests. From the table it can be seen that the amount of water splashed out for the cases in Series B is less than that of the cases in Series C, as only one-shoot geyser event happened for series B but several geyser events happened for series C.

For cases chosen in Series B, the amount of water splashed out depends on the inflow rate increment and the initial condition of water in the upstream pipe. For Case B6 and B9, the amount of water increased by 100% when inflow rate increment increased by 10 L/s and the initial flow condition in the upstream pipe changed from free surface flow to pressurized full pipe flow. For Case B3 and B6, the amount of water increased by 24% when inflow rate increment increased by 10 L/s and the initial flow condition in the upstream pipe are both free surface flow. In can be concluded that the initial upstream pipe condition is the most important factor affecting spilled water volume. For cases chosen in Series C, both a large flow rate change with a higher initial water column height in the riser can result in larger amount of water splashing out. Comparing C4 and C7, when the inflow rate increment decreased by 5 L/s while the initial heights of water column in the riser are the same, the spilled water volume was decreased by 506%. For case C7 and C8, when the initial height of water column in the riser increased by 0.1 m while the inflow rate changes are the same, spilled water volume was increased by 178%. For same initial inflow rates, as the difference are made by adjusting the height of the gate to limit the flow capacity in the system, it can be concluded that both the initial height of water column in the riser and the inflow rate change can impact the spilled water volume.

Table 4.3 Measured spilled water amounts

Run	Q_0 (L/s)	Q_1 (L/s)	h_r (m)	1 st test		2 nd test		3 rd test		$V_{ave.}$ (L)
				$Q_{1\text{-}1}$ (L/s)	V_1 (L)	$Q_{1\text{-}2}$ (L/s)	V_2 (L)	$Q_{1\text{-}3}$ (L/s)	V_3 (L)	
B3	20	100	-	98.7	0.65	100.6	0.78	101.3	0.82	0.72
B6	30	100	-	100.5	0.63	101	0.65	99.5	0.55	0.58
B9	40	100	-	98	0.22	98.6	0.215	99.3	0.27	0.29
C4	20	40	0.1	40	10.8	39.2	9.3	40	8.02	9.7
C7	25	40	0.1	40	1.55	40	1.65	40.7	1.8	1.6
C8	25	40	0.2	39	4.1	39.1	3.8	39.5	4.42	4.45

5. Experimental Results on Geyser Mitigation Measures

5.1. Results and Discussions on Mitigation Methods Applied to Series B

5.1.1 Orifice plate applied to Case B3 (Series D)

For case B3, the orifice sizes of 6 mm, 12 mm and 30 mm have been applied to the top, middle and bottom of the riser. The fully sealed case on the top end of the riser is also tested.

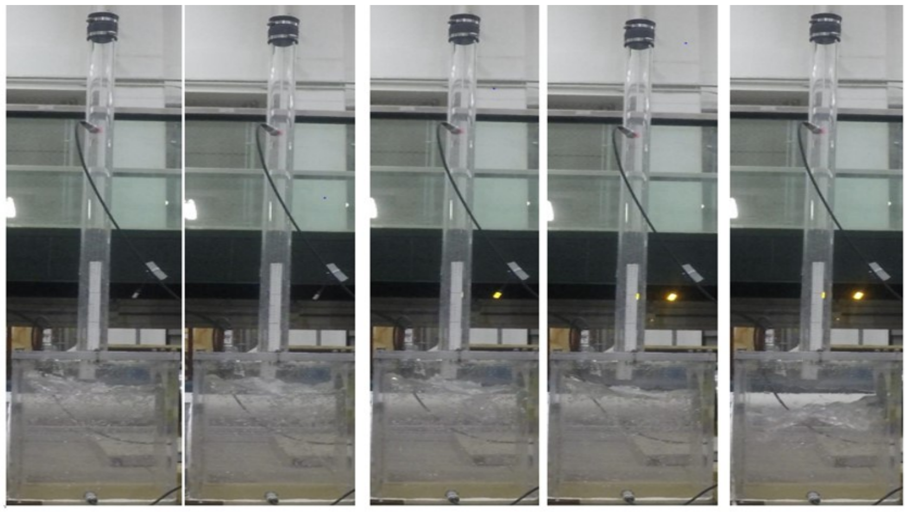
5.1.1.1 Adding orifice plate on top of the riser for Series B (Case D1-1 to D1-4)

Figure 5.1-Figure 5.4 show how orifice plate at the top of the riser could influence the pressure variation for case B3.

For cases D1-1 to D1-4, one phenomenon worth noting is that the pressures at all pressure measurement locations started to rise at around -0.15 s, which corresponds to the starting time of opening valve. The reason behind that is the air in the riser, chamber and upstream pipe has already been compressed before further turning up of the valve, as the air was constrained to escape from the top of the riser.

Figure 5.1 is the pressure process and air-water movement in the chamber and riser for Cases D1-1. As the top of the riser is fully sealed for this case, water could not shoot out through the riser. A rise in water level in the chamber was seen at -0.11 s, which caused the compression of air, and resulted in pressure rise at PT1-PT4. When the ball valve is fully opened, the rapidly filling front would propagate towards the chamber, as the air in the chamber, riser and upstream pipe is connected, the pressure variations at PT1, PT2 and PT4 are identical. At around 0.41 s, the compressed air started to expand and pushed some of the air into the downstream pipe, resulted in pressure decrease. The air was compressed for the second time from around 1.17 s to 1.52 s, when the flow with increased inflow rate was continuously fed into the chamber, the pressure riser caused by the compression of air was less than that in the first time due to the smaller upstream transient pressure. More air was brought into the downstream pipe along with a chaotic mixture of air and water from around 1.86 s, and pressure dropped again at PT1-PT4. This process of air compression and expansion stopped at around 4.00 s, when most of the air had been expelled from the system, and the chamber gradually became clear.

(a)



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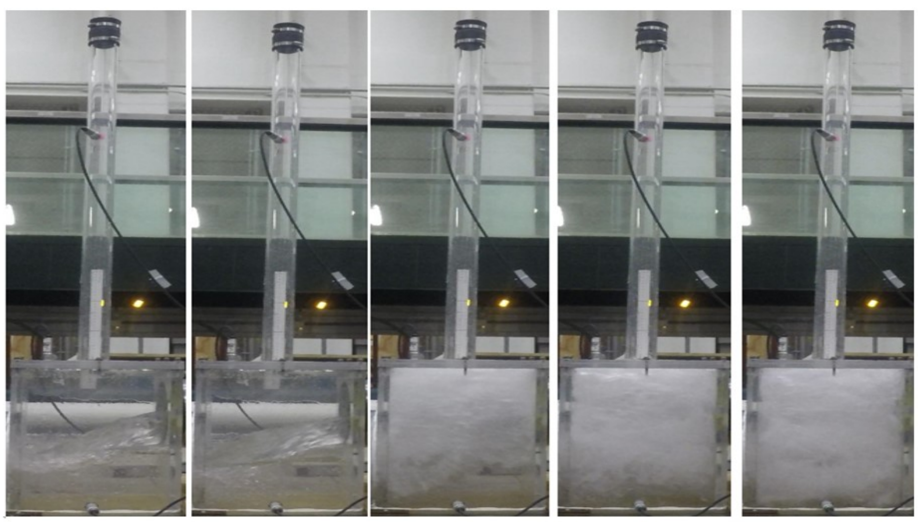


t=0.81s t=1.17s t=1.52s t=1.86s t=2.11s

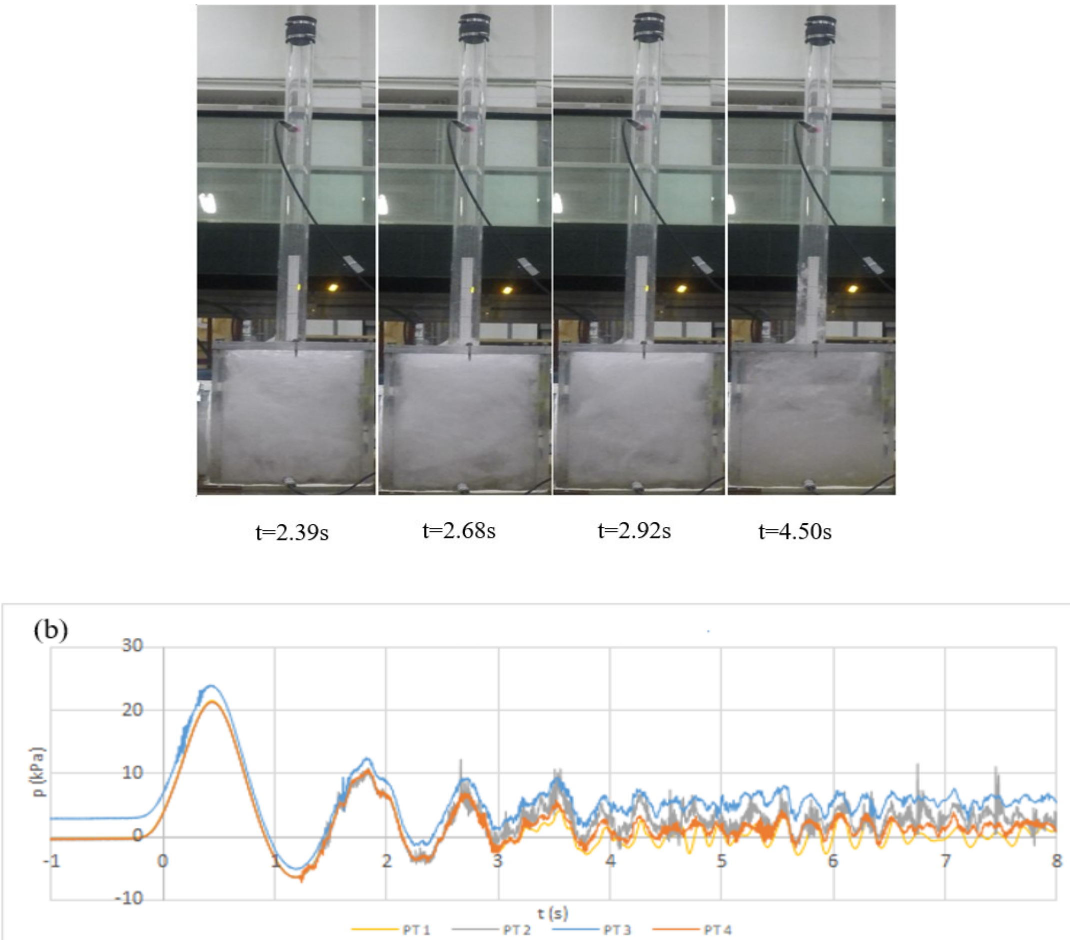
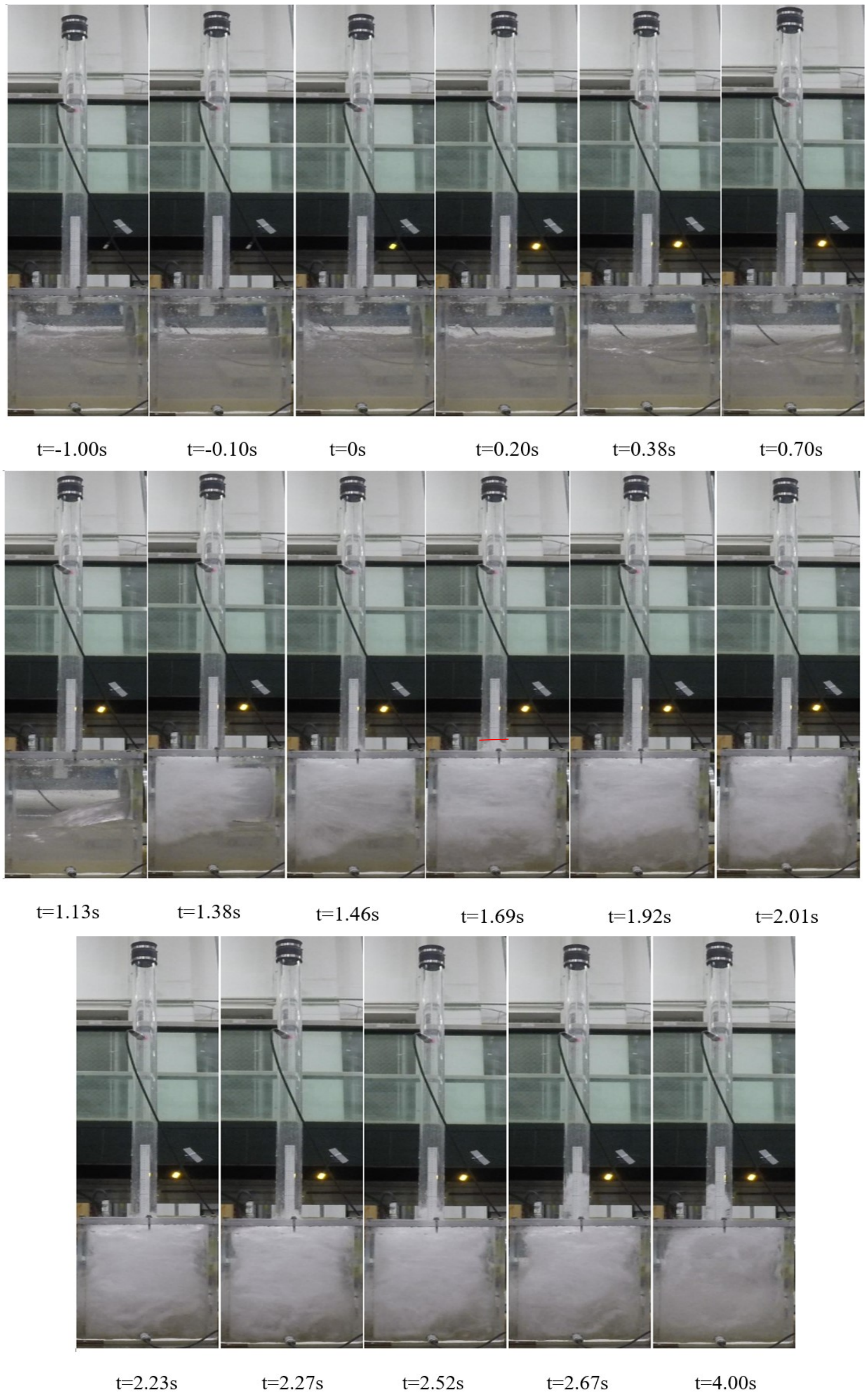


Figure 5.1 Experimental process of Case D1-1: (a) air-water movement in the chamber and riser, and (b) pressure variation

Figure 5.2 is the pressure history and air-water movement in the chamber and riser for Case D1-2. The duration of pressure oscillation period is shorter for Case D1-2 compared with Case D1-1, as air was less compressed because small amount of air can be released through the riser from the opening. Water started to appear in riser at around 1.92 s, and the oscillation of water column in the riser could cause compression and expansion of the air in the riser, which resulted in several non-periodical pressure oscillations from 1.92 s to 4.00 s.

(a)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(b)

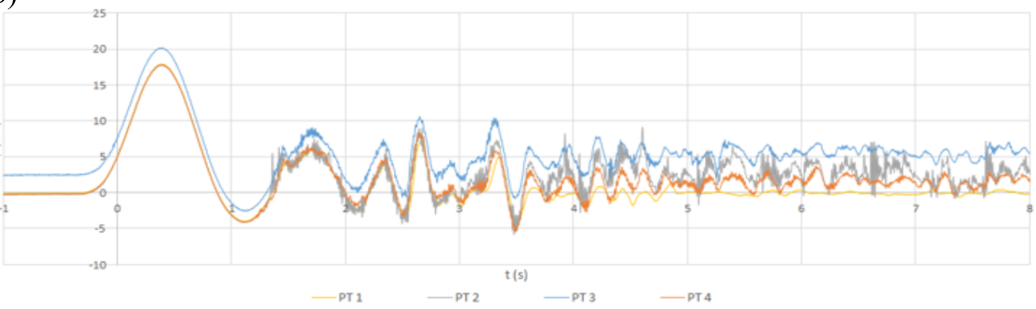
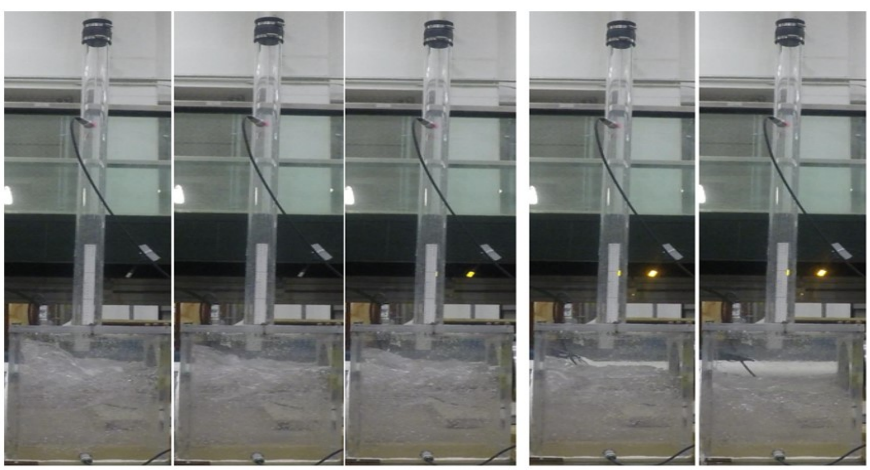


Figure 5.2 Experimental Process of Case D1-2: (a) air-water movement in the chamber and riser, and (b) pressure variation

Figure 5.3 is the pressure history and air-water movement in chamber and riser for Cases D1-3. As the opening size further increased, air was less compressed compared with Case D1-1 and Case D1-2 and it would take shorter time for the pressure to reach its final steady state. Water started to appear in riser at around 1.56 s, which was earlier compared with Case D1-2, as the air pressure in the riser is smaller. This is the only case which resonance phenomenon happened in the pipe and a large sound was heard during the experiment.

(a)



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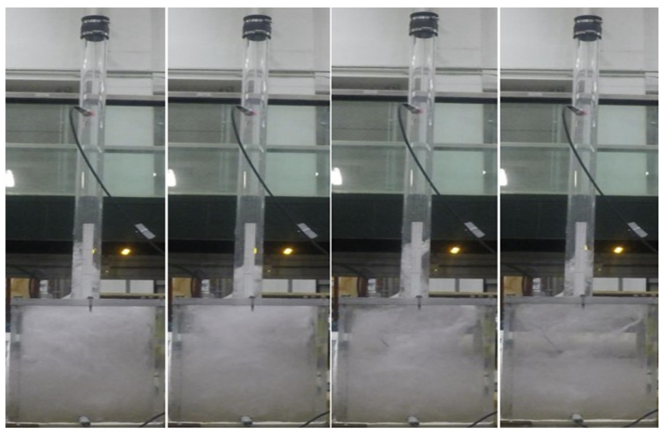
t=0.75s t=1.01s t=1.56s t=2.11s t=2.70s



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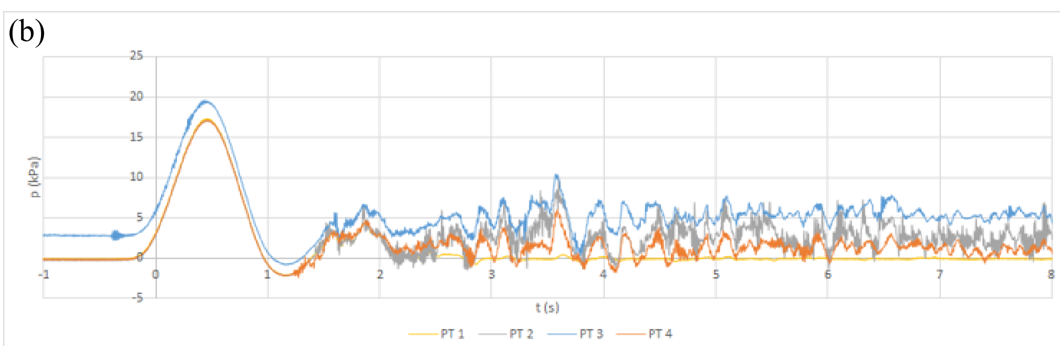
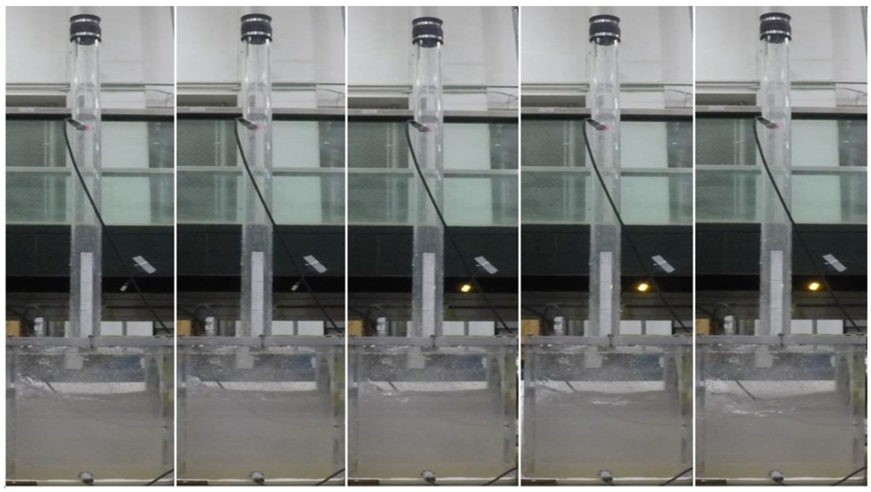


Figure 5.3 Experimental process of Case D1-3: (a) air-water movement in the chamber and riser, and (b) pressure variation

Figure 5.4 is the pressure history and air-water movement in chamber and riser for Cases D1-4. No periodic pressure oscillation to negative was seen for case D1-4, as air initially in the system was gradually released from the top of the riser before the arrival of the rapid filling front at around 1.3 s. As the orifice size increases, more air can be released through the riser. Although the pressure in the riser (PT1) was high initially, it soon dropped to 0 kPa after the inflow rate increased, as the air was mostly expelled from the system and the pressure at PT1 was approximately equal to the atmospheric pressure.

(a)



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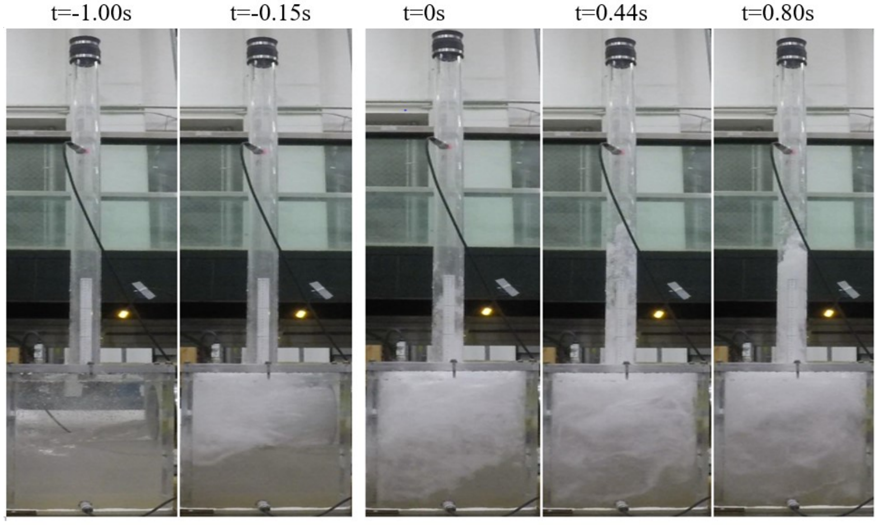

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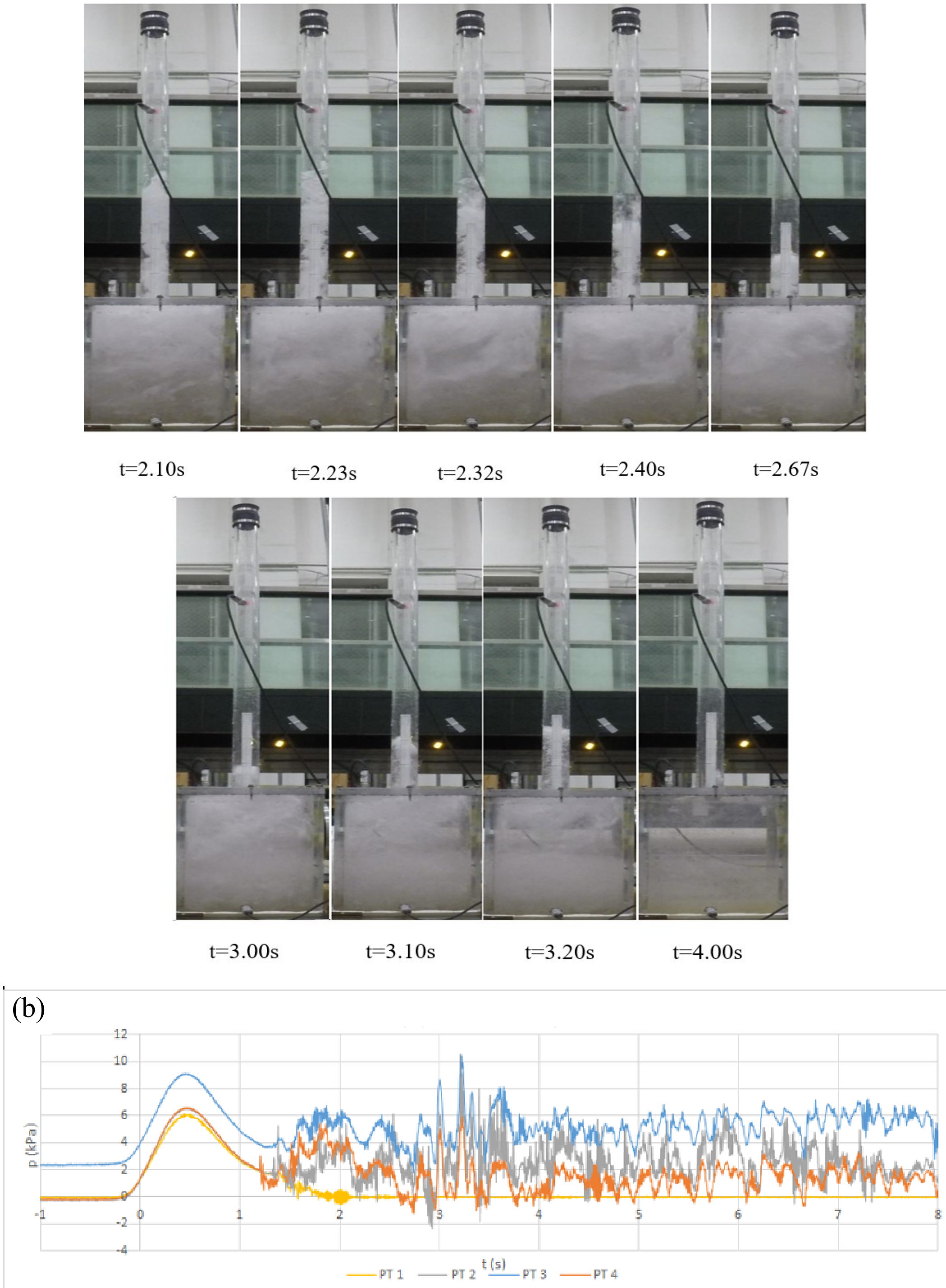


Figure 5.4 Experimental process of Case D1-4: (a) air-water movement in the chamber and riser, and (b) pressure variation

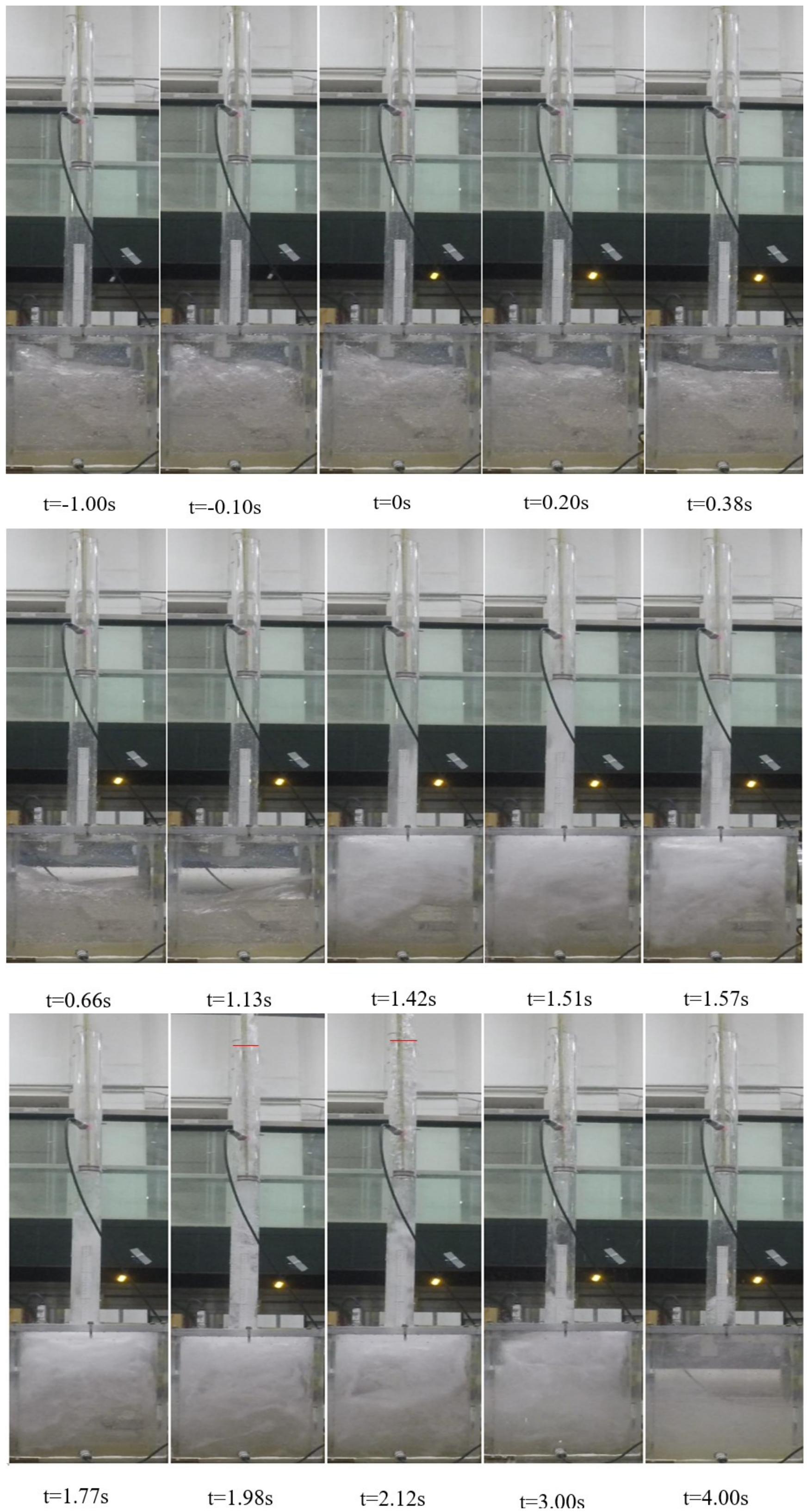
In summary, geyser event did not happen for D1 cases. From Cases D1-1 to D1-4, it can be concluded that the peak pressure in the riser decreases as the orifice size increases, as smaller orifice plate could impede air release more. All the air in the chamber, riser and upstream pipe was pushed into the downstream tank for D1-1, and the amount of air pushed into the downstream tank decreases as the orifice size increases for Case D1-2 to D1-4. Lack of ventilation on top of the riser could be a potential hazard to downstream pipes, as air can be transferred the far downstream.

5.1.1.2 Adding orifice plate at middle of the riser Series B (D2-1 to D2-3)

Similar to using the orifice plate on top of the riser, the pressures at PT2-PT4 also started to increase at around -0.15 s when the orifice plate is installed at the middle of the riser. Unlike D1, where the entire riser, chamber and upstream is connected initially, PT1 records the atmospheric pressure for D2 cases, as the location of the transducer is higher than the orifice plate.

Figure 5.5 is the pressure history and air-water movement in chamber and riser for Case D2-1. One geyser event happened 1.98 s to 2.12 s, in the form of mist. This geyser event was caused by the air pushing the water column that existed in the riser upwards, and when water column in the riser reached the location of the orifice plate, it would squeeze into the small opening and shoot out. Comparing Cases D2-1 with D1-2, the only difference is the length of the air column in the riser that existed before the experiment, as much longer air column for Case D1-2, water column could not make it happen to reach the location of the orifice plate, so that geyser did not happen for D1-2.

(a)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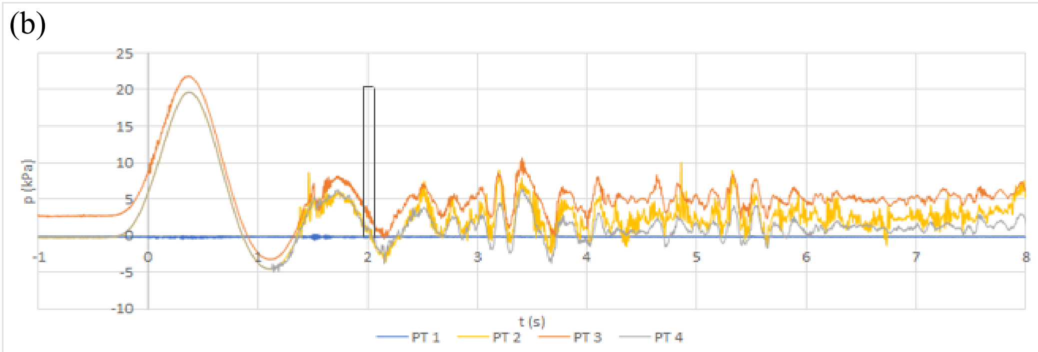

Figure 5.5 Experimental process of Case D2-1: (a) air-water movement in the chamber and riser, and (b) pressure variation

Figure 5.6 is the pressure history and air-water movement in chamber and riser for Cases D2-2. During the rapid filling process of 0 s to 1.00 s, the air in the riser was continuously squeezed into the orifice, pressure oscillations can be seen at PT1. As less column of air was entrained in the riser for D2-2 compared with D1-3, only one periodical pressure oscillation was seen for D2-2.

(a)

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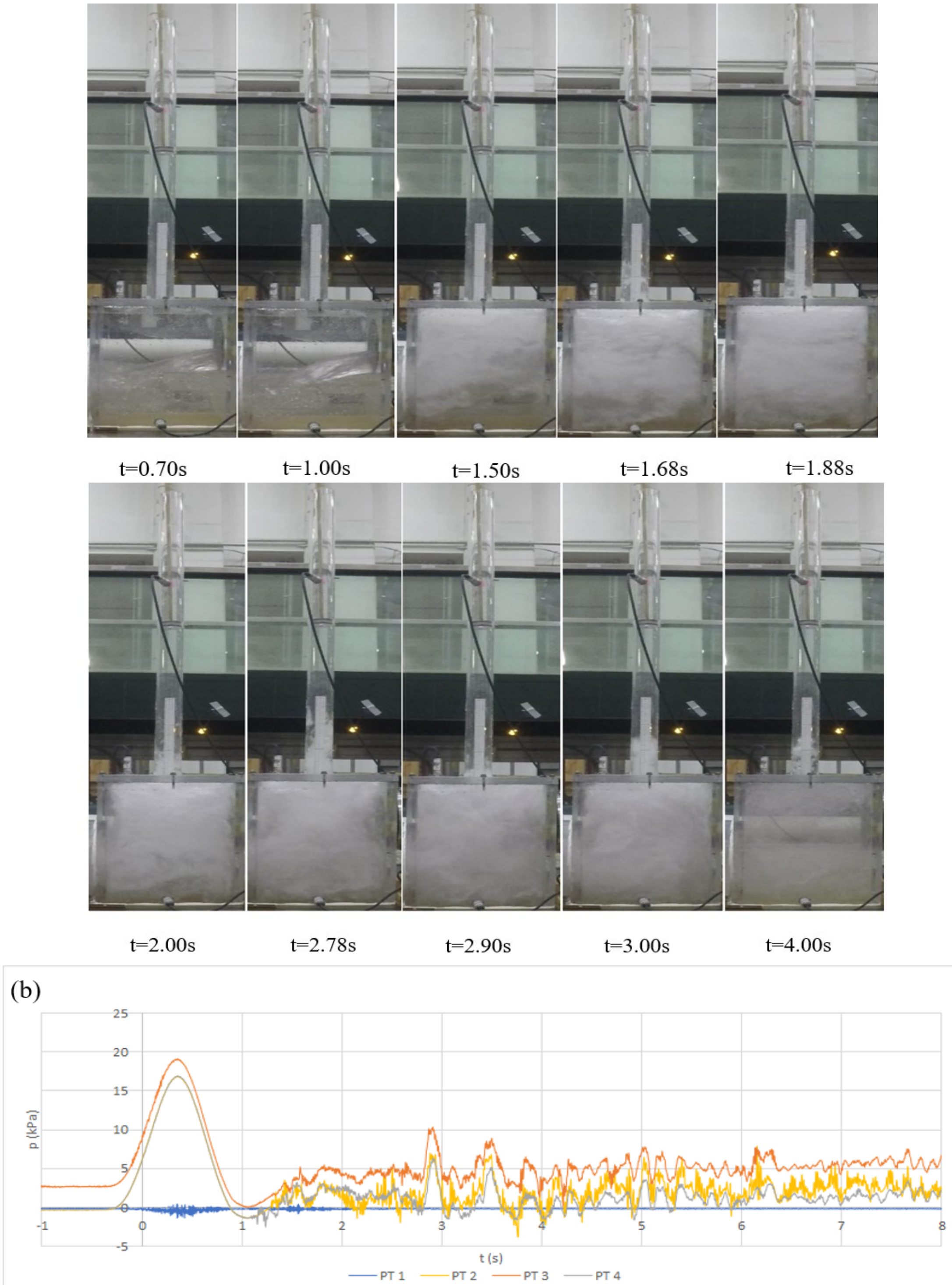
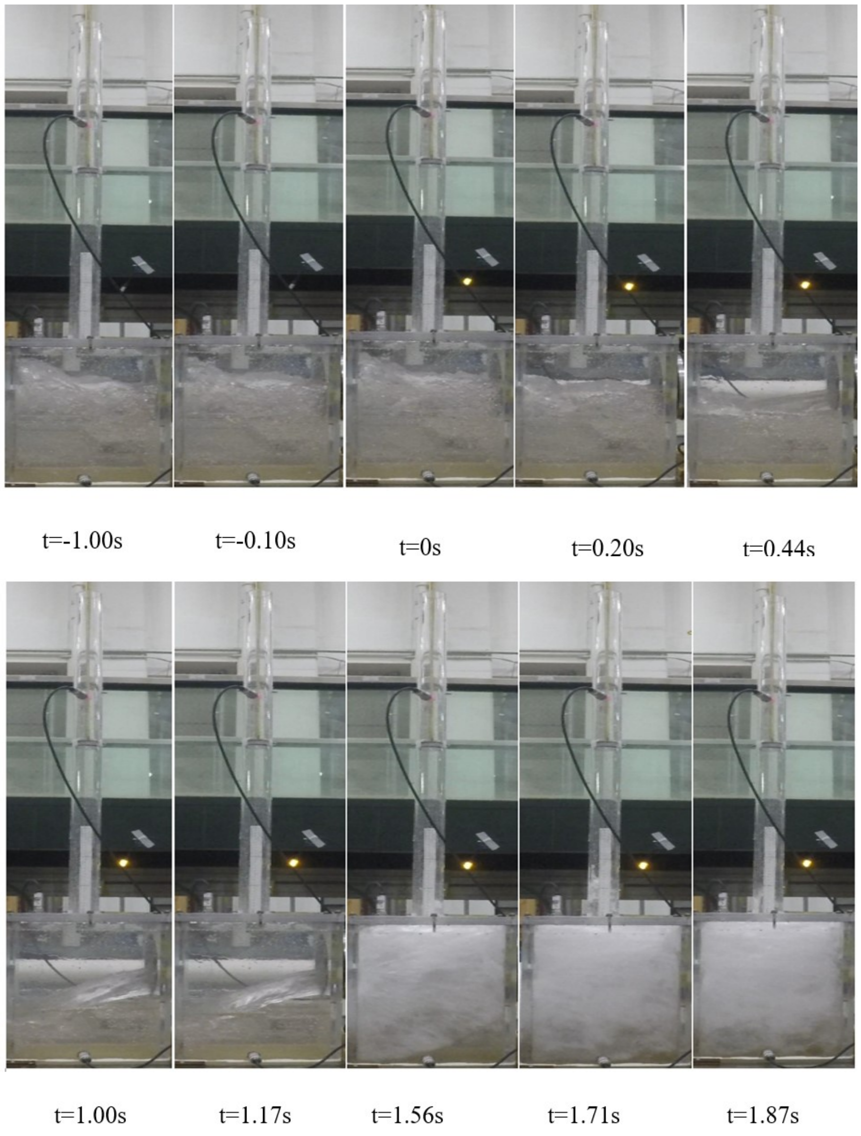
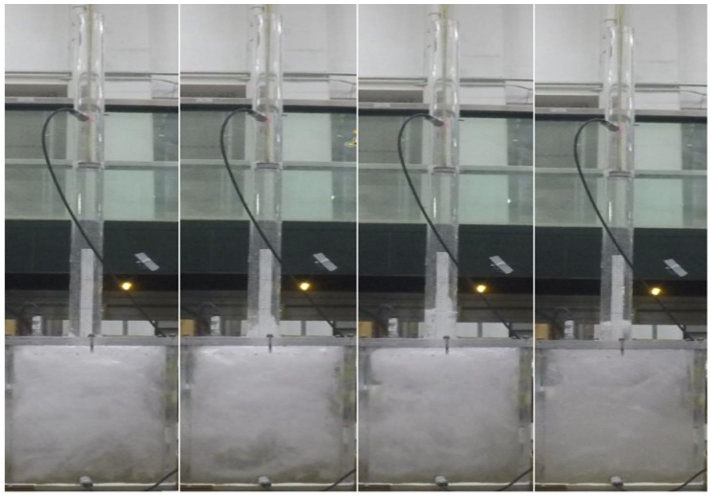


Figure 5.6 Experimental process of Case D2-2: (a) air-water movement in the chamber and riser, and (b) pressure variation

Figure 5.7 is the pressure history and air-water movement in chamber and riser for Case D2-3. As the orifice size increased, the ability to prevent air release from the riser decreased, first pressure peak due to compression of air was lower compared with Cases D2-1 and D2-2. After the rapid filling flow filled the chamber at around 1.56 s, water started to appear in riser due to minimized air cushion effect, which caused the second pressure peak.

(a)





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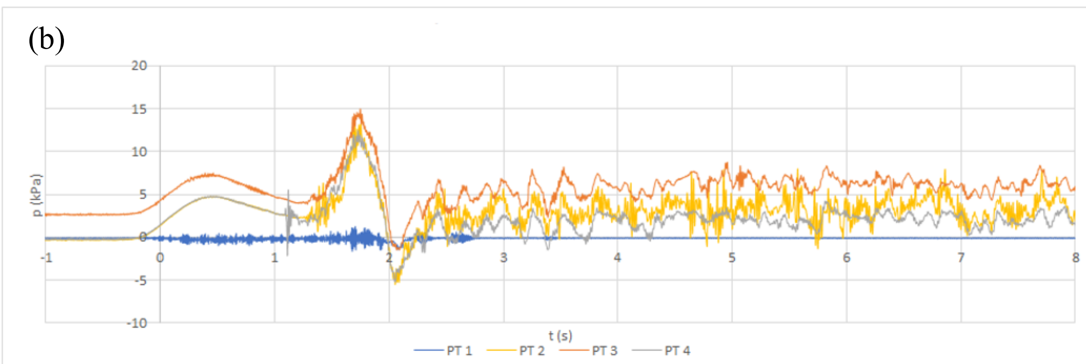


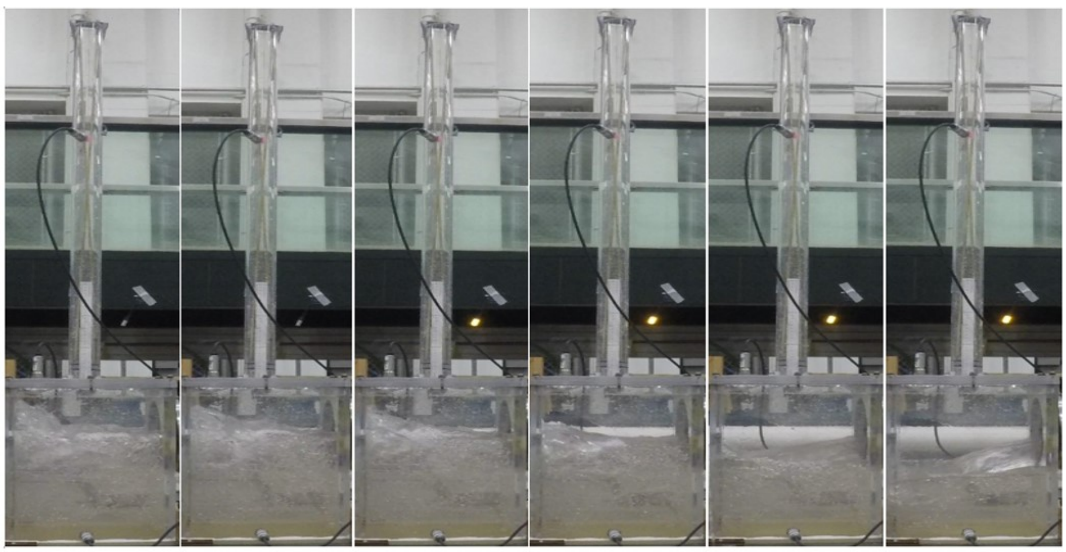
Figure 5.7 Experimental process of Case D2-3: (a) air-water movement in the chamber and riser, and (b) pressure variation

In summary, geyser only happened when 6 mm orifice plate was used for D2 cases. As for the air being pushed into the downstream tank, Cases D2-1 and D2-2 have the similar amount as the orifice size is too small for air to go out through the riser, while much less air is pushed into the downstream tank for Case D2-3. Just like D1 cases, where the largest pressure decreased as orifice size increased the peak pressure during the periodical oscillation period reduced as the orifice size increased for D2 cases. The time for periodical oscillations lasted shorter for D2 cases compared with D1 cases, as less column of air was entrained in the riser when the flow is flowing from the upstream pipe into the downstream pipe. The duration of the periodical pressure oscillation period decreased as the opening size increased, as less air can be stored in the riser. The steady state was reached after most of the air was expelled from the system.

5.1.1.3 Adding orifice plate at bottom of the riser for Series B (D3-1 to D3-3)

Figures 5.8 and 5.9 are pressure history and air-water movement in chamber and riser for Cases D3-1 and D3-2. As they are similar to Cases D2-1 and D2-2 respectively, except that the frequency of the pressure oscillations becomes higher due to its smaller air space, the detailed analysis is not shown here. Geyser did not happen in D3-1 when the air-water mixture was squeezed into the riser, as the velocity of the air-water mixture was not high enough for it to reach the riser top, as compared with Case D2-1.

(a)



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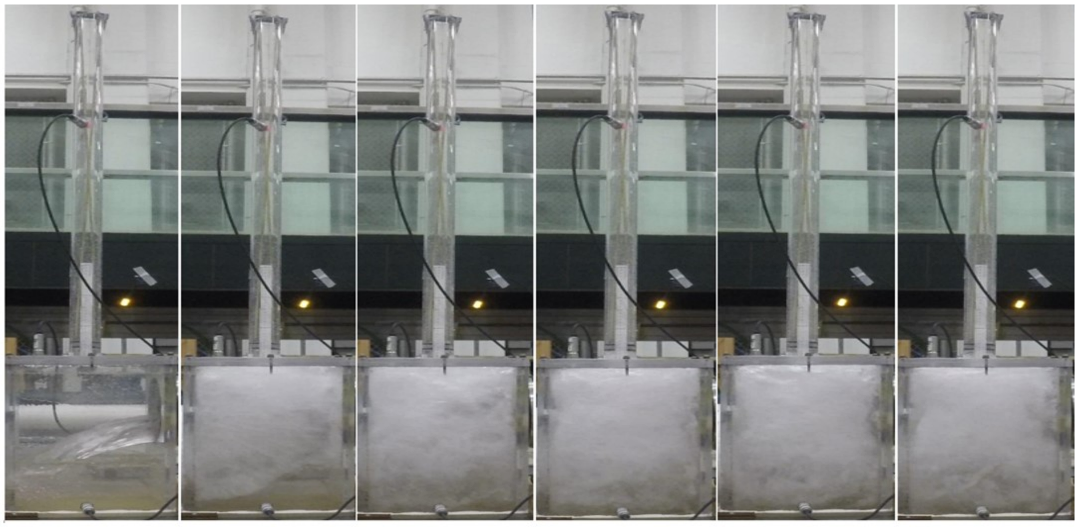

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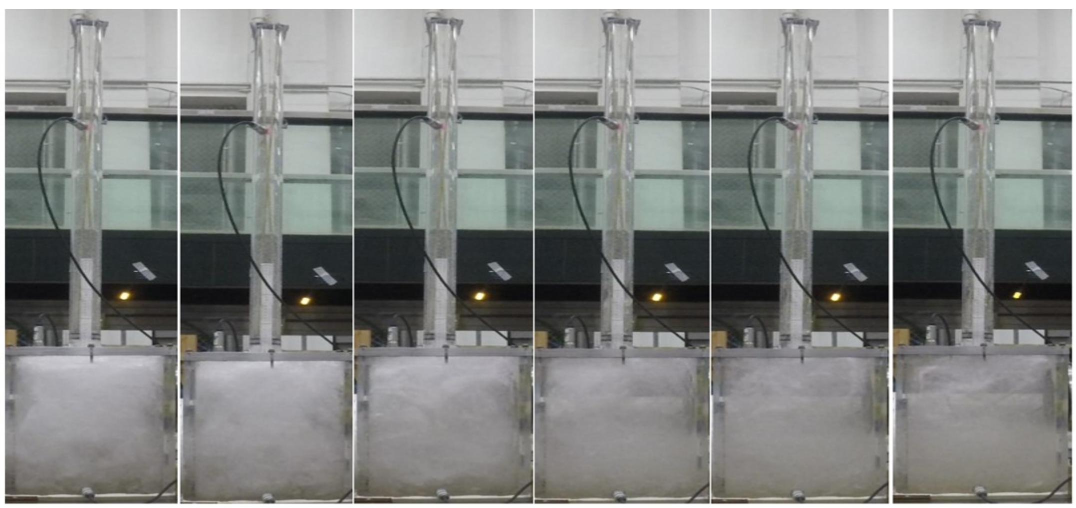
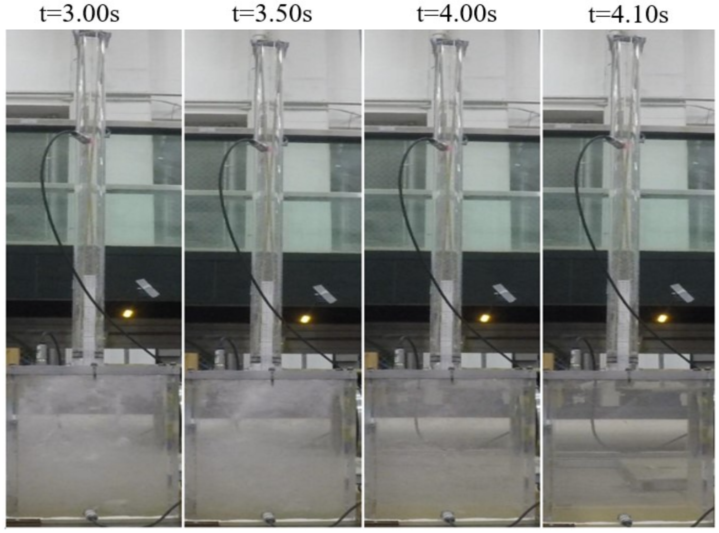


t=2.52s t=3.00s t=3.50s t=4.00s t=4.10s t=4.20s



t=4.30s t=4.40s t=5.00s t=7.00s

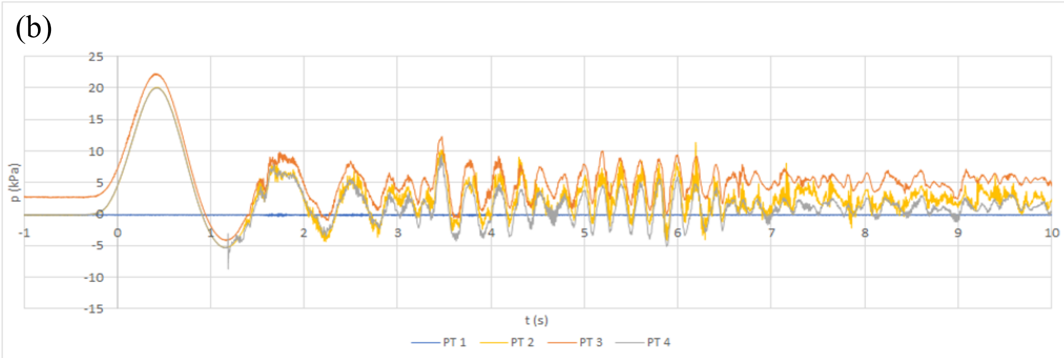
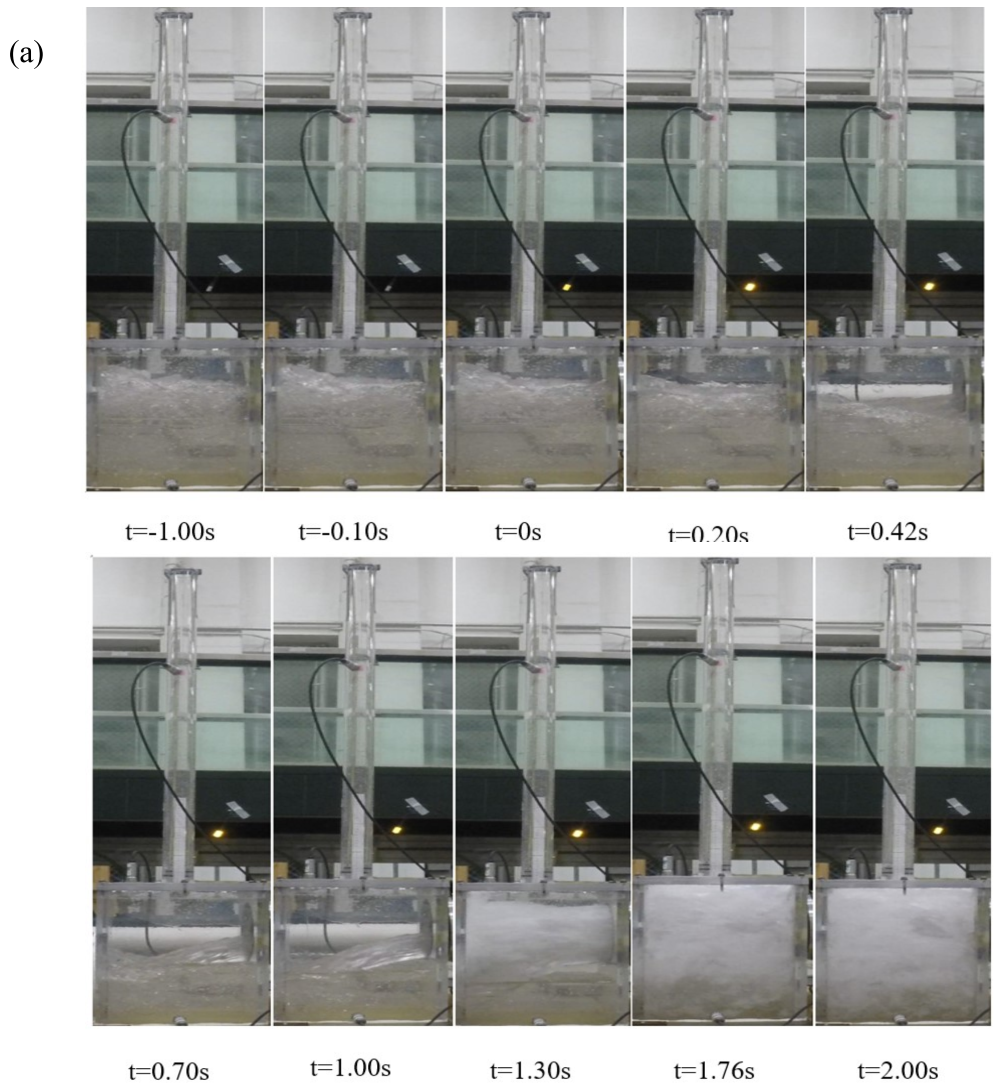


Figure 5.8 Experimental process of Case D3-1: (a) air-water movement in the chamber and riser, and (b) pressure variation.



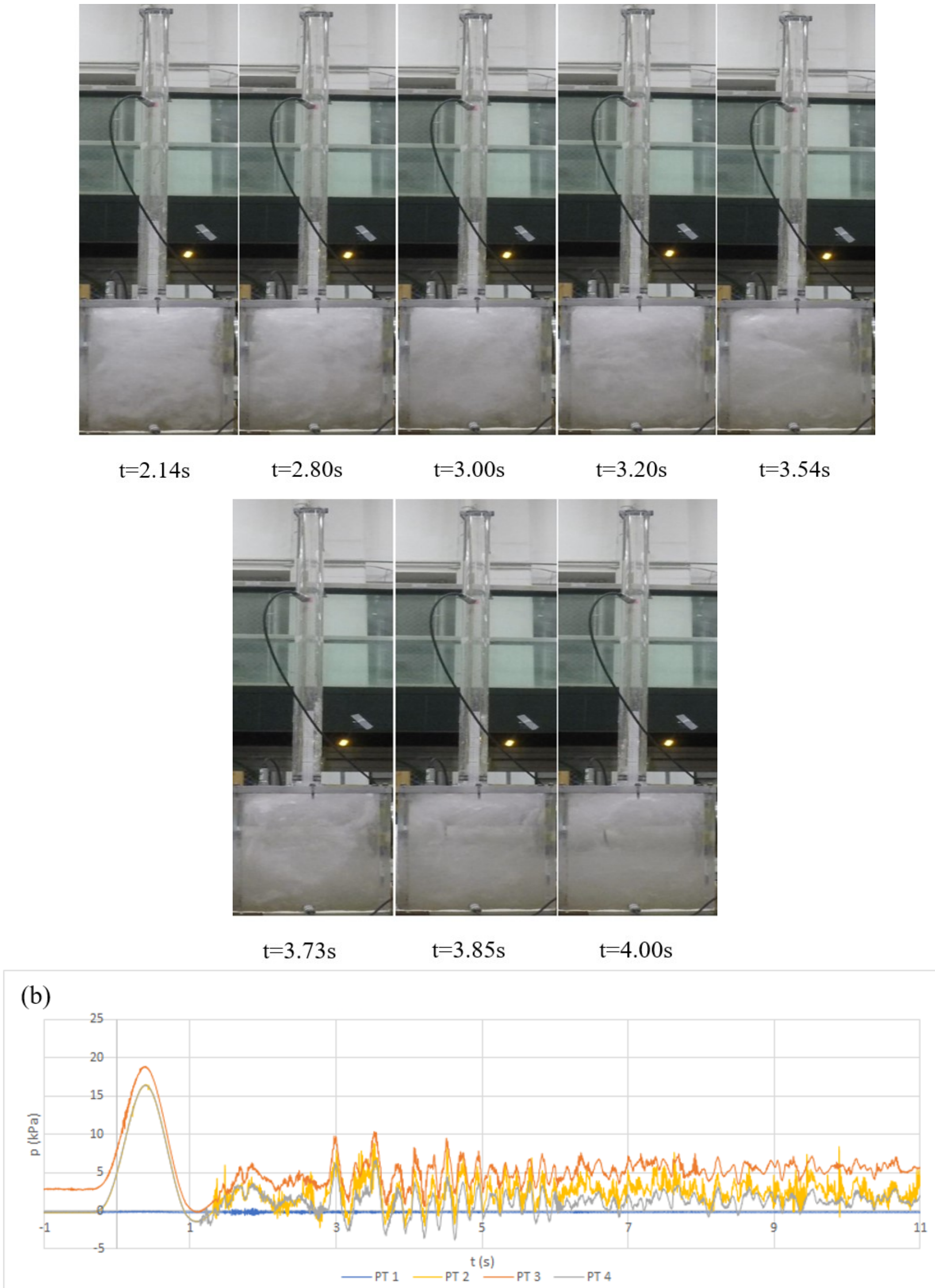
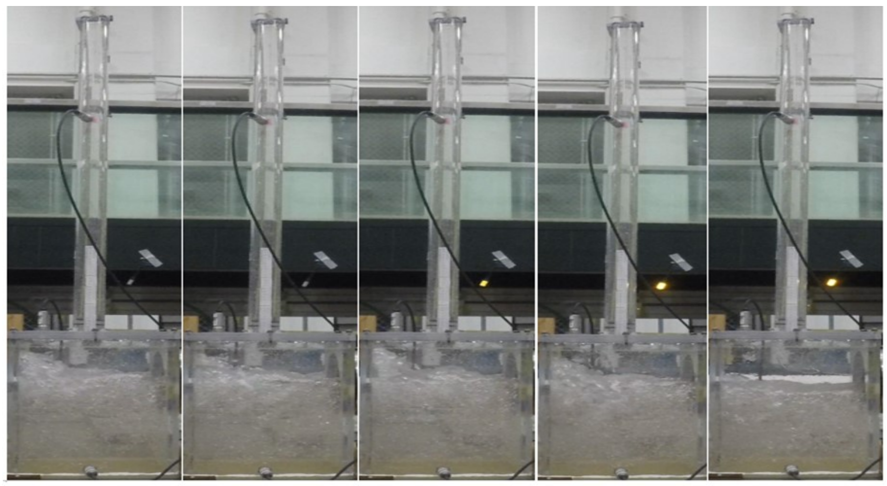


Figure 5.9 Experimental process of D3-2: (a) air-water movement in the chamber and riser, and (b) pressure variation.

Figure 5.10 is the pressure history and air-water movement in chamber and riser for Cases D3-3.

Comparing Case D3-3 with Cases D2-3 and D1-4, it can be seen that the second sharp peak pressure appeared when the orifice is used at middle and bottom of the riser, but did not appear when the orifice plate is used on top of the riser. As the only difference between those cases was the air volume in the riser under the orifice plate, it can be concluded that the sudden pressure peak was caused by minimized the air-cushioning effect. A trivial geyser event was seen in case D3-3 around 1.64 s to 1.78 s, where water shot out from the riser in the form of mist, and the orifice plate can be treated as a smaller diameter riser.

(a)



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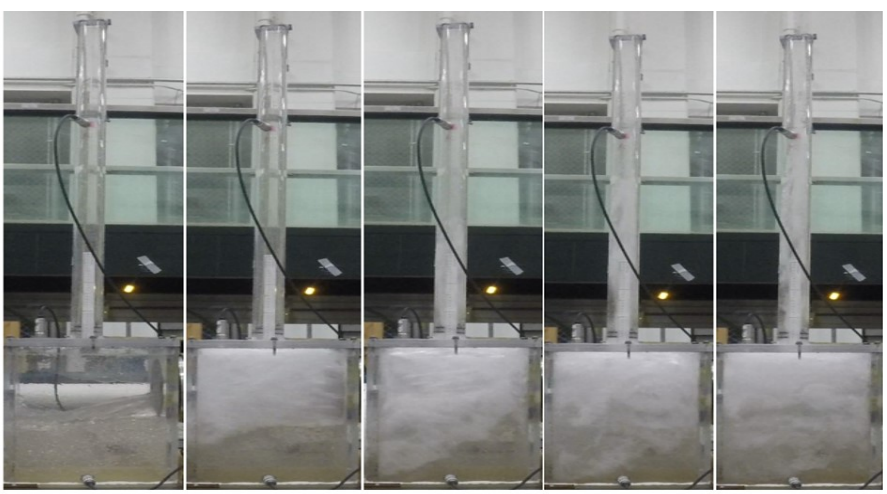


t=1.00s t=1.34s t=1.50s t=1.64s t=1.78s

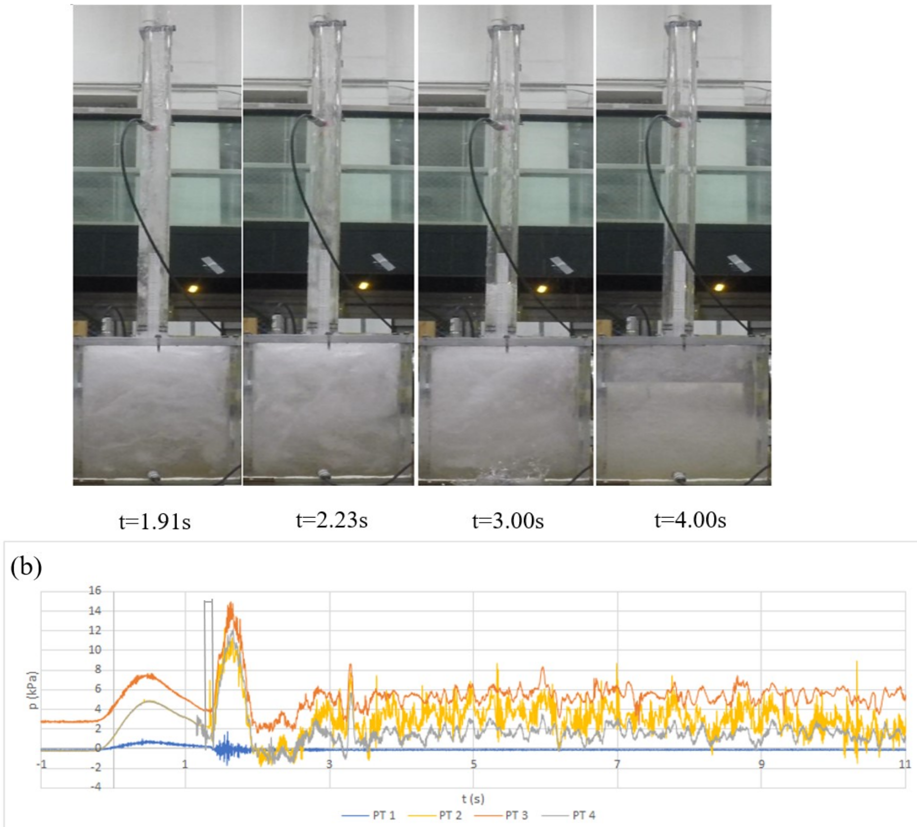


Figure 5. 10 Experimental process of Case D3-3: (a) air-water movement in the chamber and riser, and (b) pressure variation.

In conclusion, using orifice plate is effective in preventing geyser, as it decreased the geyser height and narrowed down the magnitude of pressure oscillation. Seen from the pressure variation, combined with height data, it can be concluded that smaller opening orifice plate at the bottom of riser is most effective in preventing geyser. For all the cases, it takes 4.00 s-5.00 s for most the air in the chamber be released into downstream pipe. The summary of jetting height and peak pressure change for the original case and with orifice plate cases are shown in Figure 5.11 and Figure 5.12. From Figure 5.11 and Figure 5.12, it can be concluded that both the pressure at different locations and the geyser height decreased after the orifice plate was used, and the geyser event was beat mitigated when 6 mm orifice plate was used at the bottom of the riser.

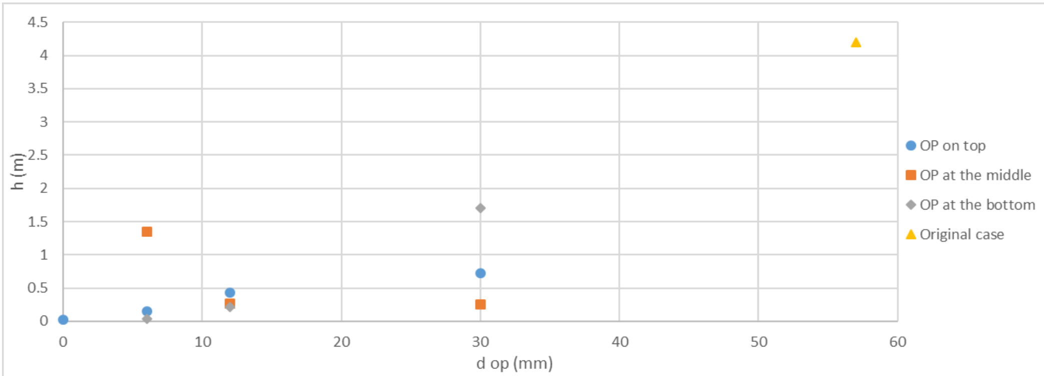
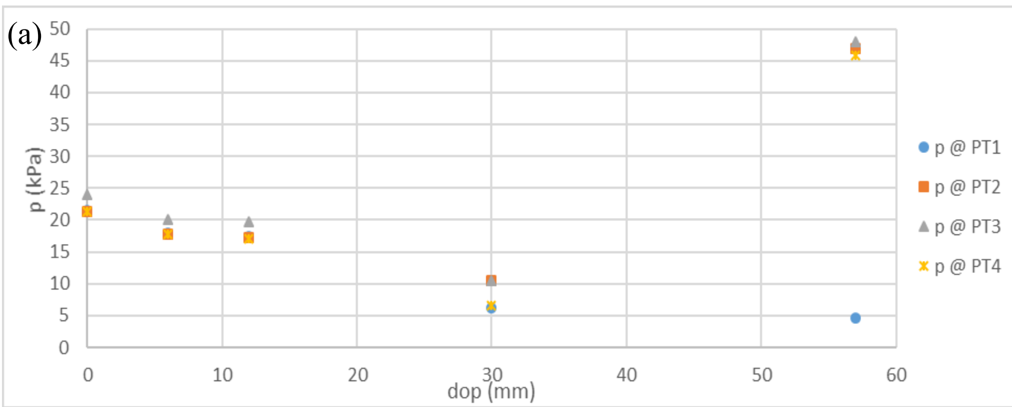
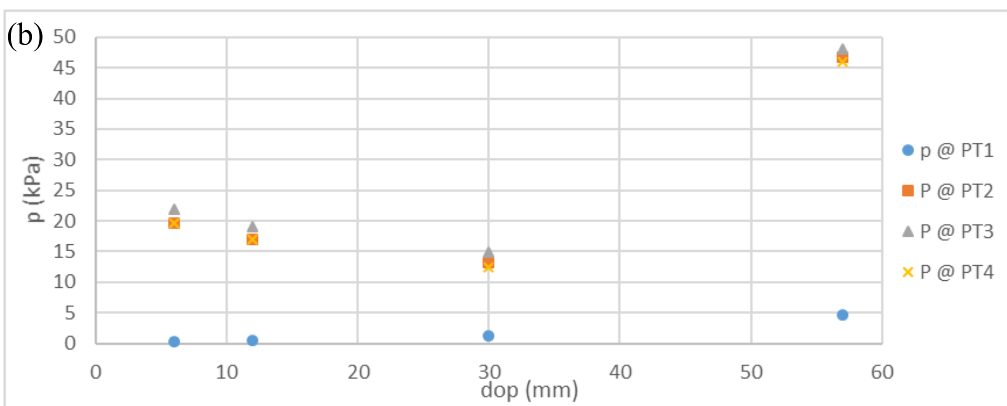


Figure 5.11 The impact of orifice plate on the geyser height for Case B3 and orifice plate applied to B3





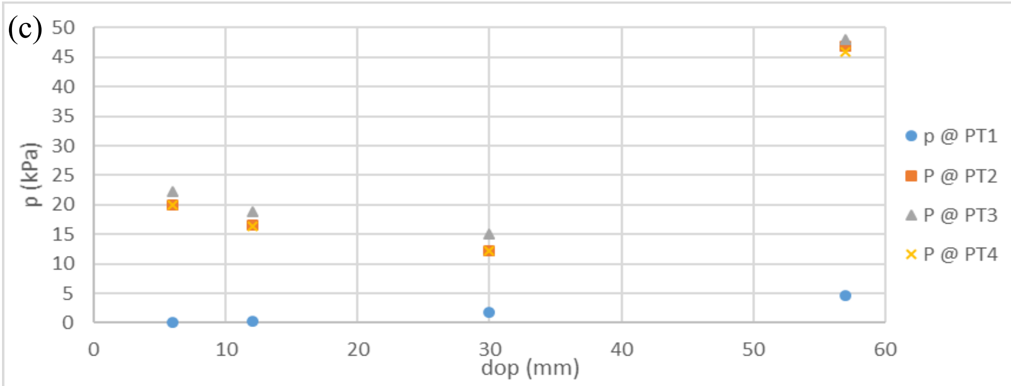
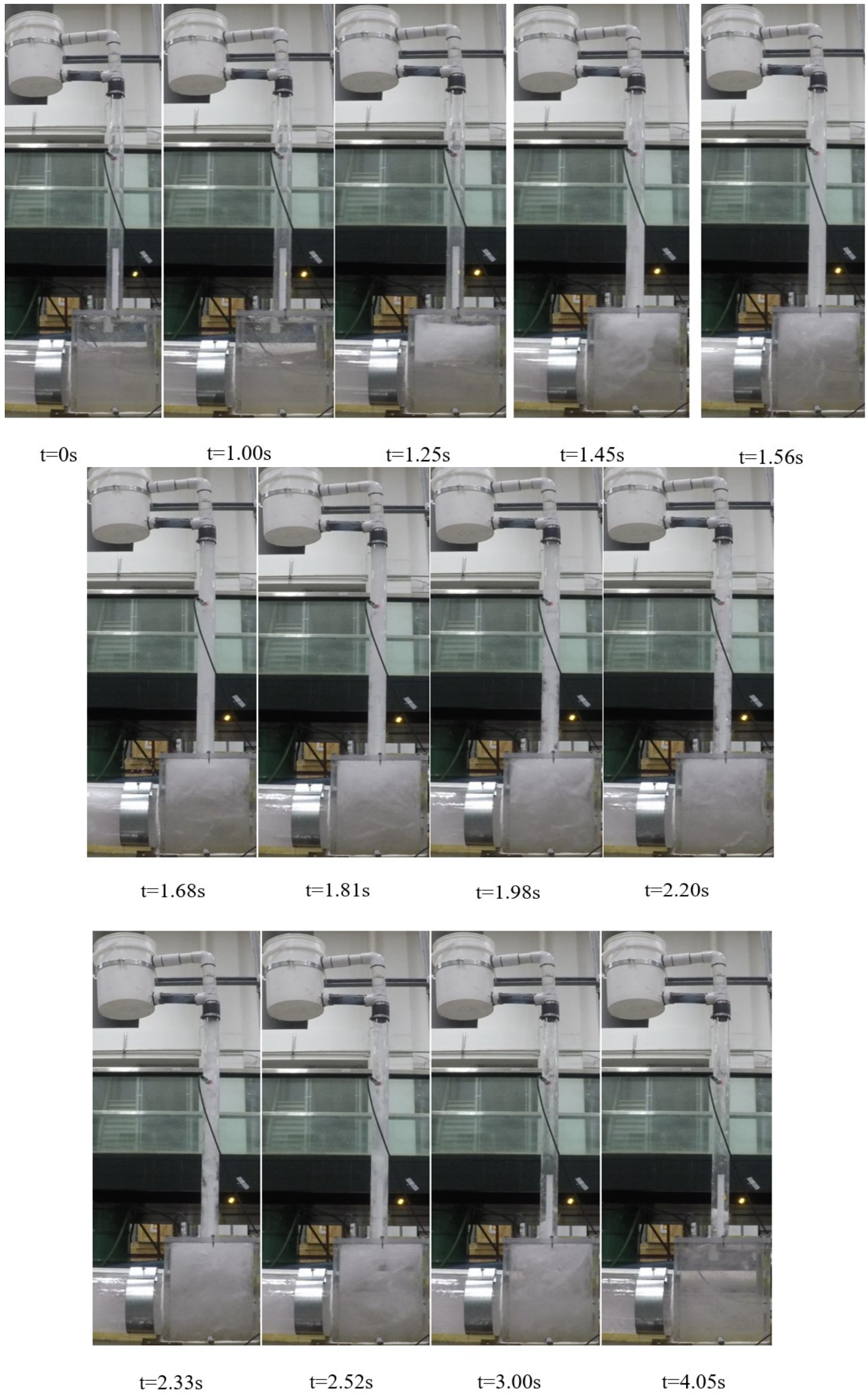


Figure 5. 12 The relationship between orifice plate size and peak pressure at different locations for Case B3 and orifice plates applied to B3: (a) orifice on the top of the riser, (b) orifice on the middle of the riser, (c) orifice at the bottom of the riser

5.1.2 Adding WRC on top of the riser for Series B (H1)

The pressure variations and movement of air and water in the chamber and riser for Case H1 is shown in Figure 5.13. Unlike Series D, where the orifice plate restricted air from going out through the riser, air in Case H1 can go out through the riser freely as WRC has an opening top. WRC has no obvious effect on the flow before the rapidly filling front arrived at chamber around 1.25 s. Air-water mixture reached the top of the riser at around 1.56 s, instead of directly shooting upwards, it was redirected by the bend to go horizontally into the recirculation chamber. Due to density difference, the air-water mixture could be separated in the recirculation chamber, so that air would be directly released from the WRC while water would flow back into the chamber.

(a)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t=2.52s
t=3.00s
t=4.05s

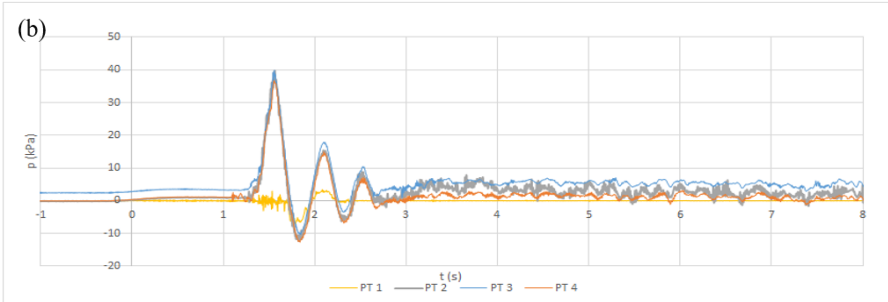
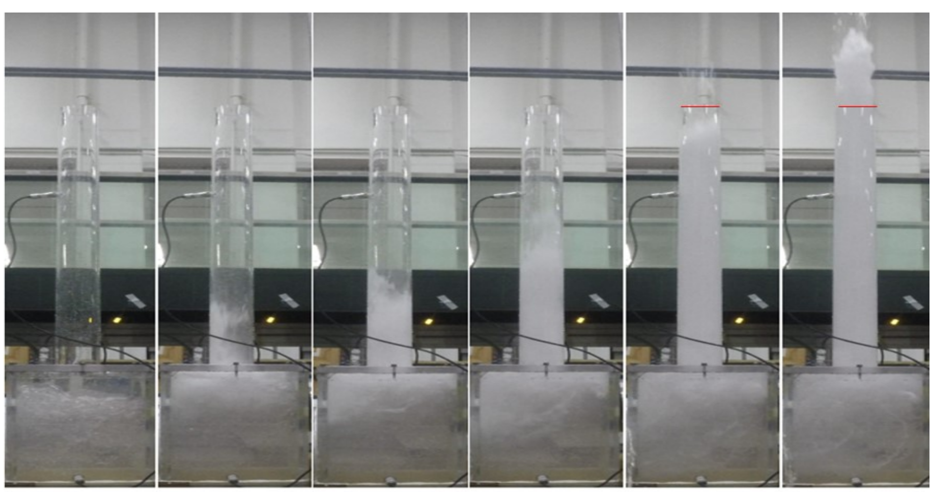


Figure 5.13 Experimental process of Case H1: (a) air-water movement in the chamber and riser, and (b) pressure variation

5.1.3 Using enlarged riser for Series B (F1-F6)

Six cases were chosen to test how the riser with a larger diameter could influence the geyser process. The pressure variations and movement of air and water in chamber and riser for Case F3 is shown in Figure 5.14. For Case F3, when riser diameter changed from 57mm to 100mm, the cross-sectional area is about 3 times bigger. Water filled the chamber more quickly for this case compared with Case B3, as the air brought into the chamber by rapidly filling flow could be pushed more easily into the chamber and go out through riser. The starting time of geyser is earlier compared with Case B3. Compared with B3, higher pressure oscillation frequencies at PT2-PT4 with non-negative readings are observed. Most of the air was expelled from the chamber at around 4.00 s, when the chamber became clear.

(a)



t=0s t=1.19s t=1.24s t=1.29s t=1.40s t=1.49s

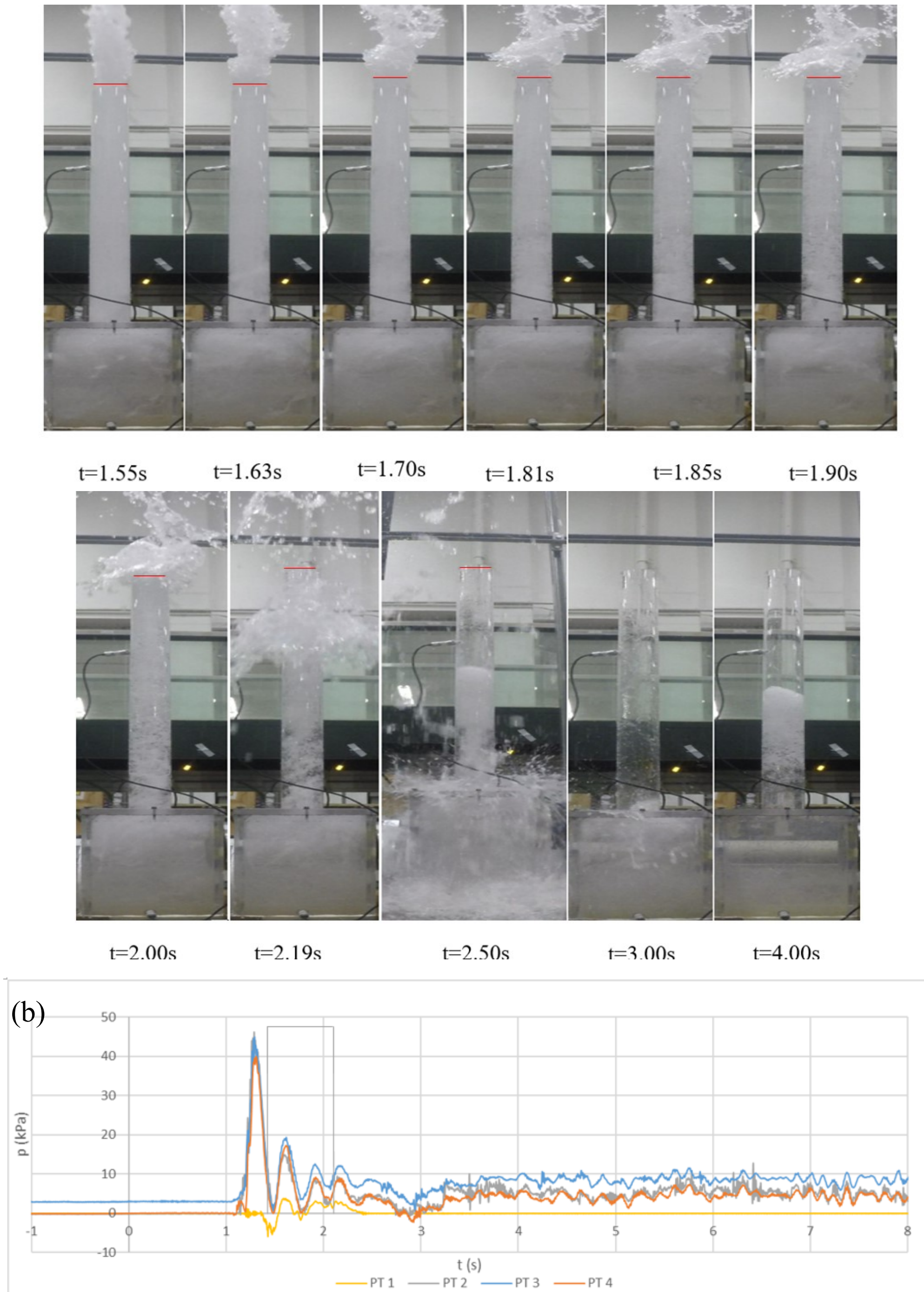


Figure 5.14 Experimental process of F3: (a) air-water movement in the chamber and riser, and (b) pressure variation

For all the six cases, larger diameter riser could help lower the peak pressure, but the pressure at the stable stage is higher because more water was held when the height of the mixture columns are the same in the riser. The amplitude of pressure oscillation during the periodical oscillation period is smaller when larger diameter riser is used.

5.2. Results and Discussions on Mitigation Methods Applied to Series C

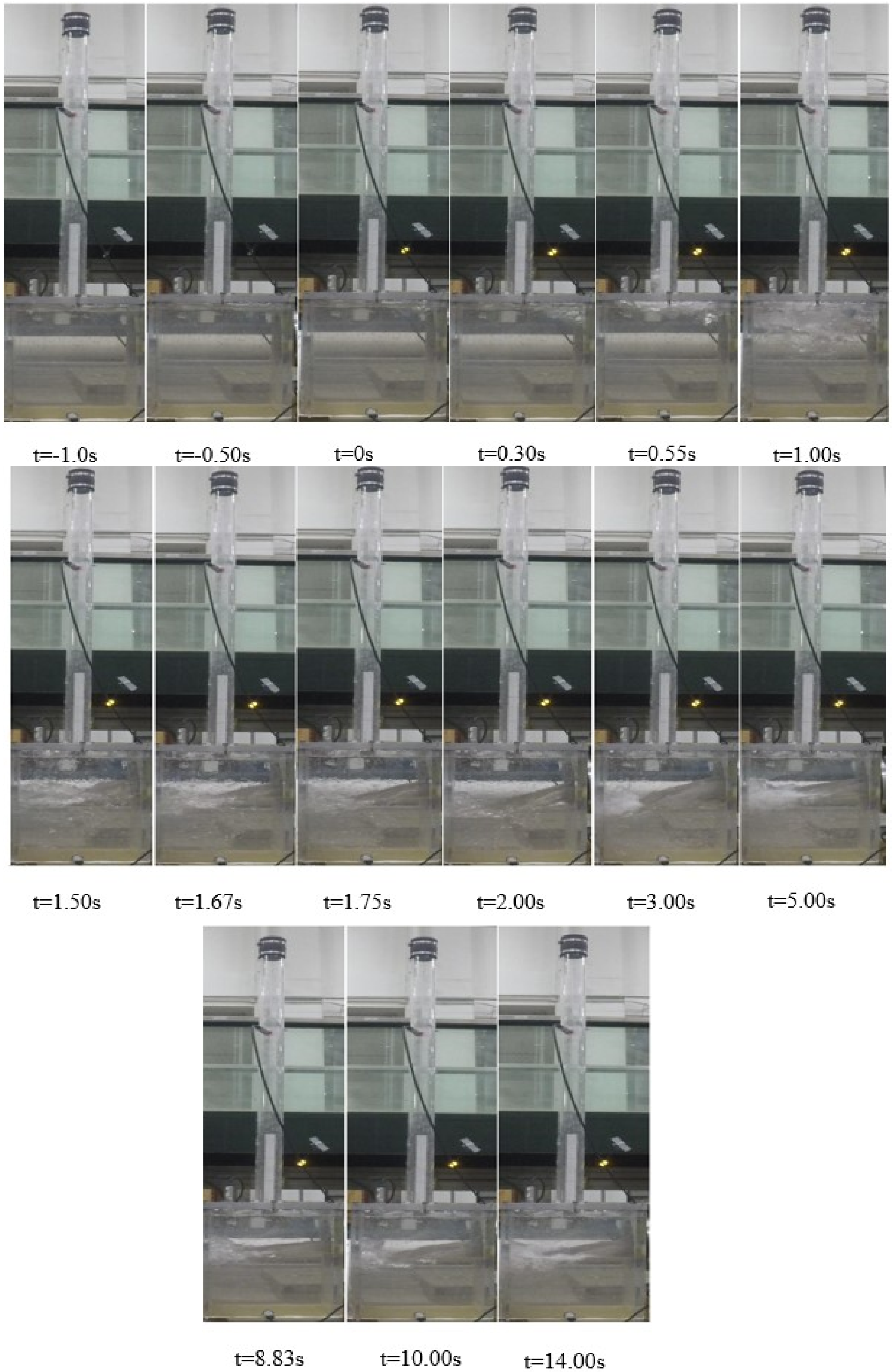
5.2.1. Orifice plate applied to Case C4 (Series E)

A total of 18 cases were tested to see how the pressure process and geyser events would be affected when the orifice plate was placed on the top, in the middle or at the bottom of the riser for cases C4 and Case C6, one additional test of fully sealed on the top end of the riser was also conducted. Retrofitting methods based on Case C4 were chosen for analysis in detail.

5.2.1.1 Adding orifice plate on top of the riser for Series C (E1-1, E1-3, E1-5 and E1-7)

Figure 5.15 is the pressure history and air-water movement in chamber and riser for Cases E1-1. No geyser phenomenon is observed in this case because of the completely sealed riser top. When the water in the system was flowing at the initial rate of 20 L/s, the sudden blockage of air passage on the top of riser would cause air in the system became pressurized. For this case, upon sealing the riser top, the air which accumulated at the upper portion of riser would push water column that existed in the riser initially into the chamber, so that the air in riser, chamber and upstream pipe was connected together to form a big air pocket before conducting the experiment, and the pressures at PT1, PT2 and PT4 are all air pressure. The sudden increase of inflow rate would induce a transient pressure wave which moved rapidly towards the chamber, causing the large air pocket further compressed, resulting in a pressure rise in the system and the increasing of flow rate in the downstream pipe. The pressure reached its peak value at around 0.55 s, when the transient pressure exerted force on the water in the chamber, causing small amount of water pushed into the riser. As the air passage from the riser top is blocked, all the air had to go out through the downstream pipe, which resulted in large splashing of water in the downstream tank.

(a)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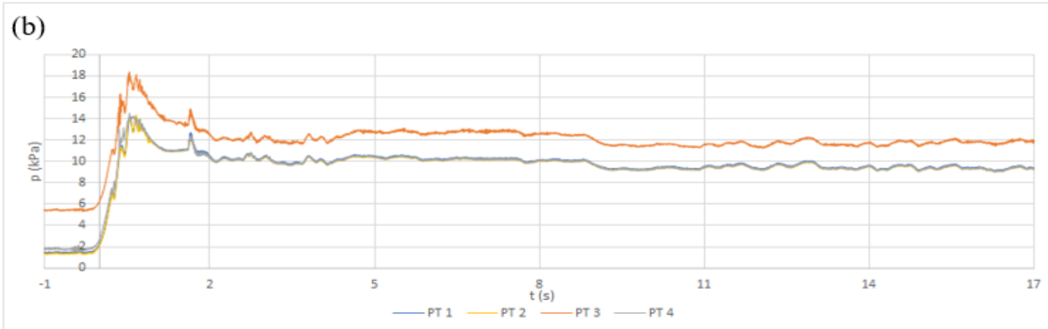
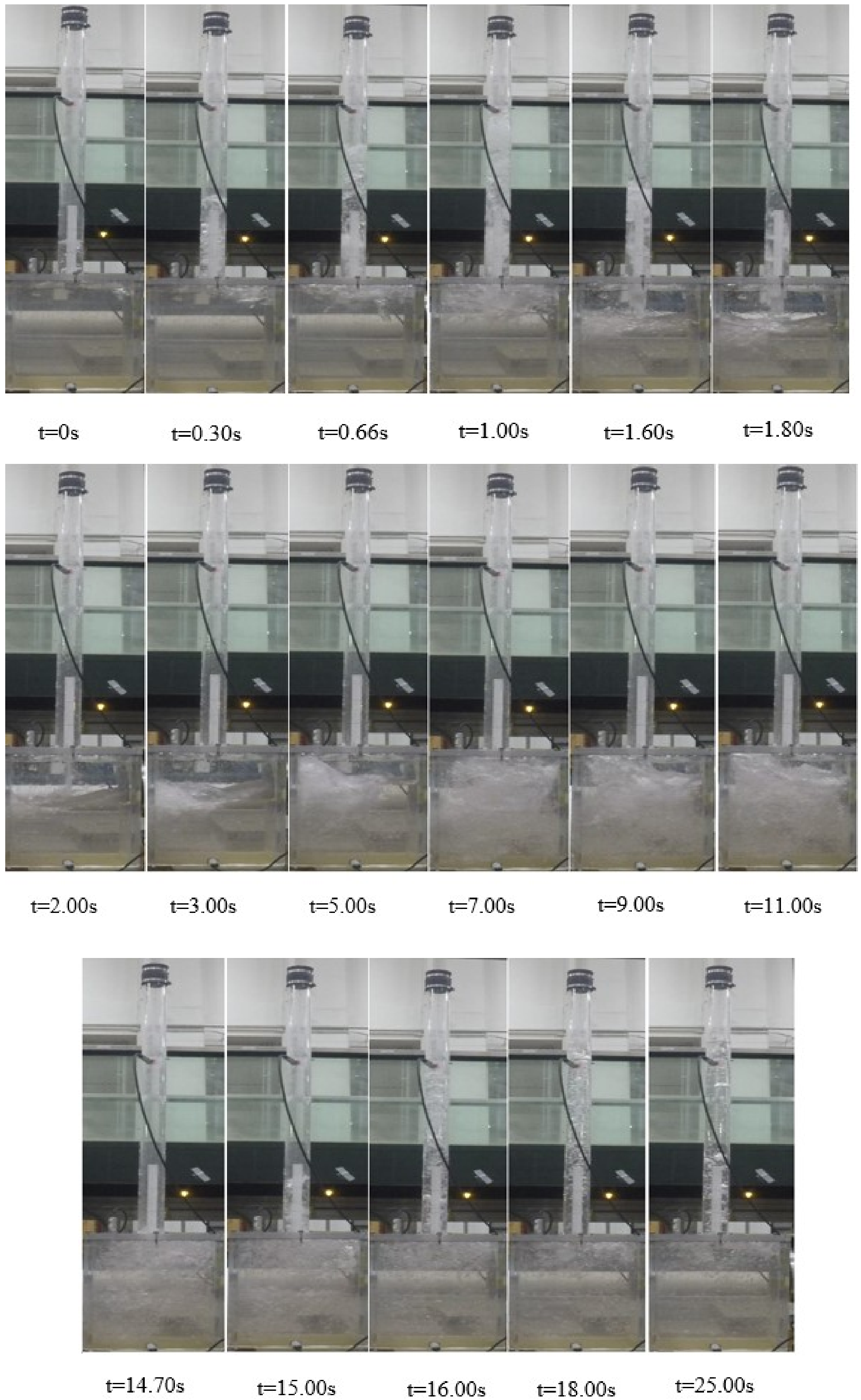


Figure 5. 15 Experimental process of E1-1: (a) air-water movement in the chamber and riser, and (b) pressure variation

Figure 5.16 is the pressure process and air-water movement in the chamber and riser for Case E1-3. No geyser was observed in this case because of the air cushioning effect. Water column in the riser started to rise at around 0.30 s, as air at the upper portion of riser gradually escaped from the riser top. Air cavity happened in the chamber at around 1.50 s, which tends to move upwards due to buoyancy, then water in the riser would drop back into the chamber due to gravity, causing fluctuation of pressure at PT1. The process of this was shown in the picture from 1.00 s to 2.00 s. Until 2.00 s, all the water had dropped back into the chamber, so that the air in the riser and chamber reattached again, and steady pressure variation was seen from 2.00 s to 5.00 s. After the air cavity happened, unlike Case C4 where water coming from the upstream pipe had enough strength to make air compress so that water in the chamber and in the riser could reconnect, air pressure in the system is big for this case, so that a large air pocket formed which connected air in the riser with air in the upstream pipe. Although the orifice size is small, air can still be released from the top of the riser gradually. At around 14.70 s, as more air in the riser was slowly released from the riser top, water column was seen in the riser again, which resulted in pressure decrease at PT1. At the final stage, when most of the air had been released from the riser top, the height of water surface in the riser became stable, and Taylor Bubble can be seen rising steadily in the riser.

(a)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t=15.00s
t=16.00s
t=18.00s
t=25.00s

(b)

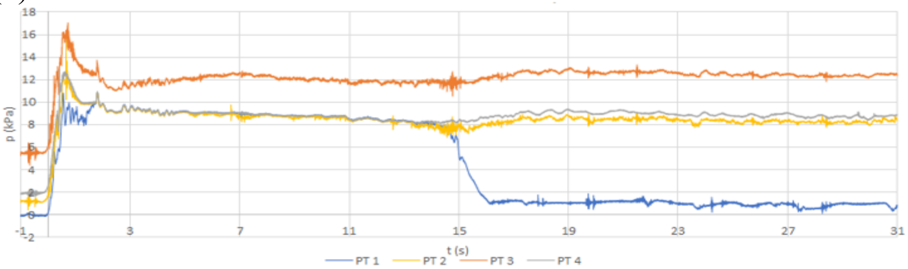
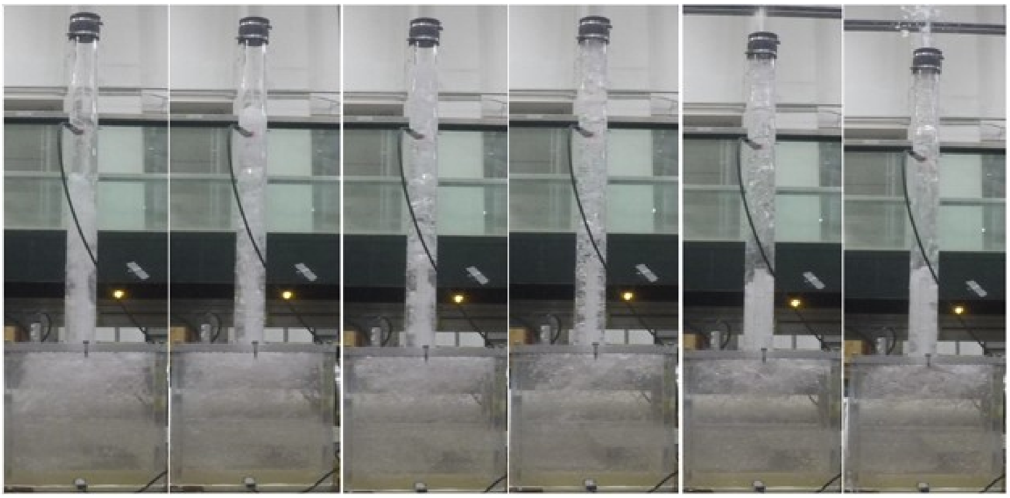


Figure 5.16 Experimental process of E1-3: (a) air-water movement in the chamber and riser, and (b) pressure variation

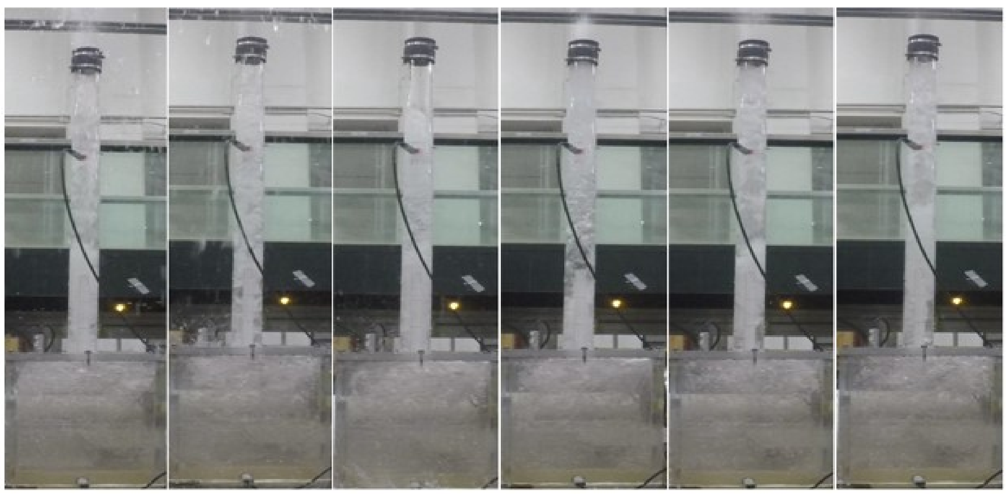
Figure 5.17 is the pressure process and air-water movement in the chamber and riser for Case E1-5. Pressure variation of this case resembles the original Case C4 without retrofitting, except a water-hammer pressure was found at the initial inflow rate increasing stage. Upon fully opening of the valve, the water surface in the riser would rise due to transient pressure forcing flow to accelerate. The first geyser event happened at around 0.76 s, which was accompanied by a sharp water hammer pressure recorded at PT1, when the free surface stroke on the riser top. The remaining splashes were caused by air releasing from the air pocket into air bubbles and rising up in the riser along with water. Water shoot out mostly in the form of thin water jet for this case due to the small orifice.

(a)

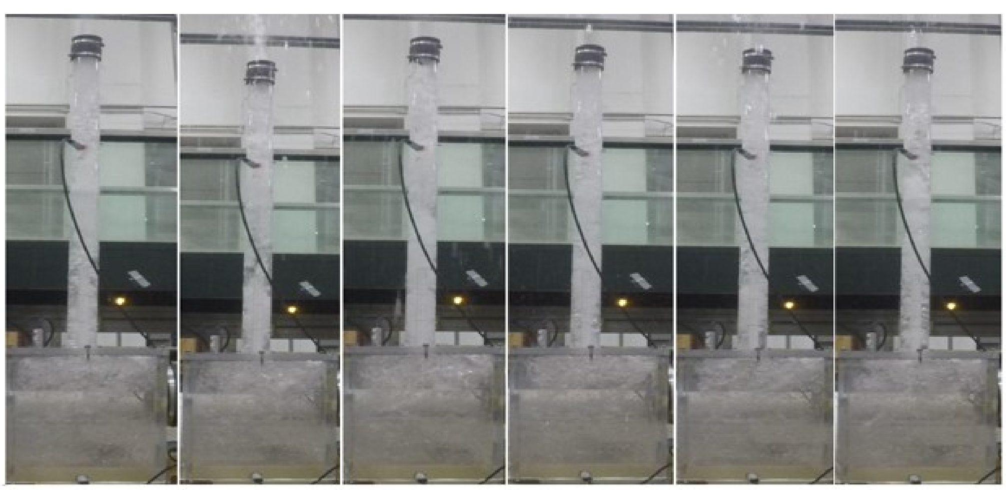
t=0s t=0.20s t=0.51s t=0.76s t=2.19s t=4.00s



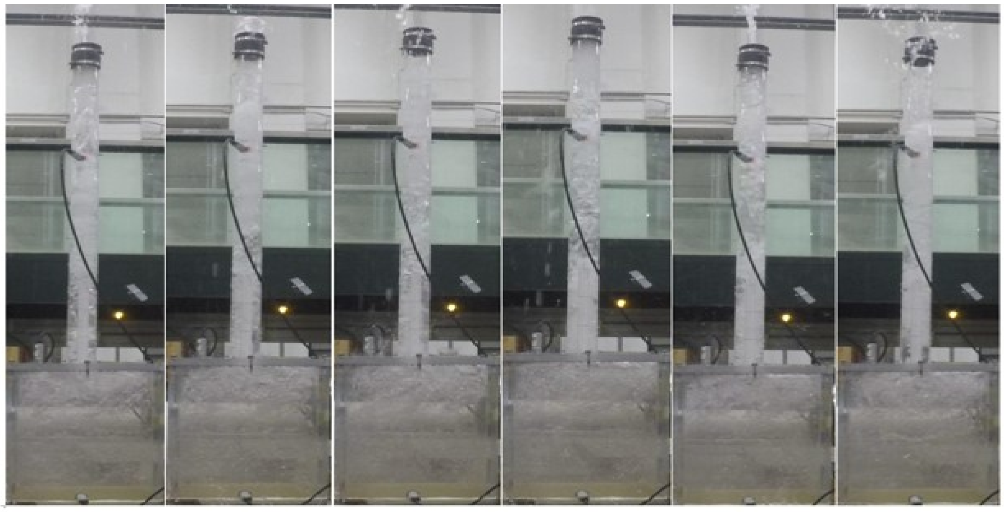
t=5.00s t=5.29s t=5.50s t=6.00s t=7.19s t=8.20s



t=9.00s t=9.42s t=9.89s t=10.43s t=10.78s t=10.80s



t=11.24s t=11.51s t=11.65s t=12.07s t=12.24s t=13.03s



t=13.16s t=13.50s t=13.65s t=13.88s t=14.16s t=14.58s

t=15.36s t=22.00s

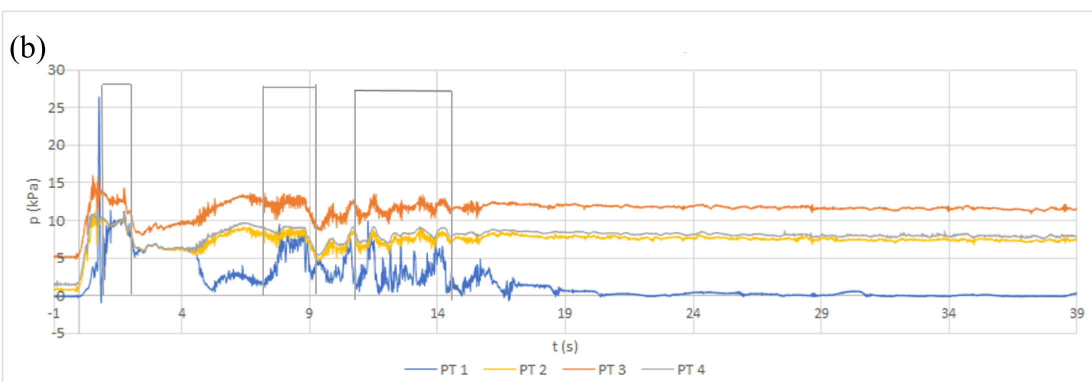
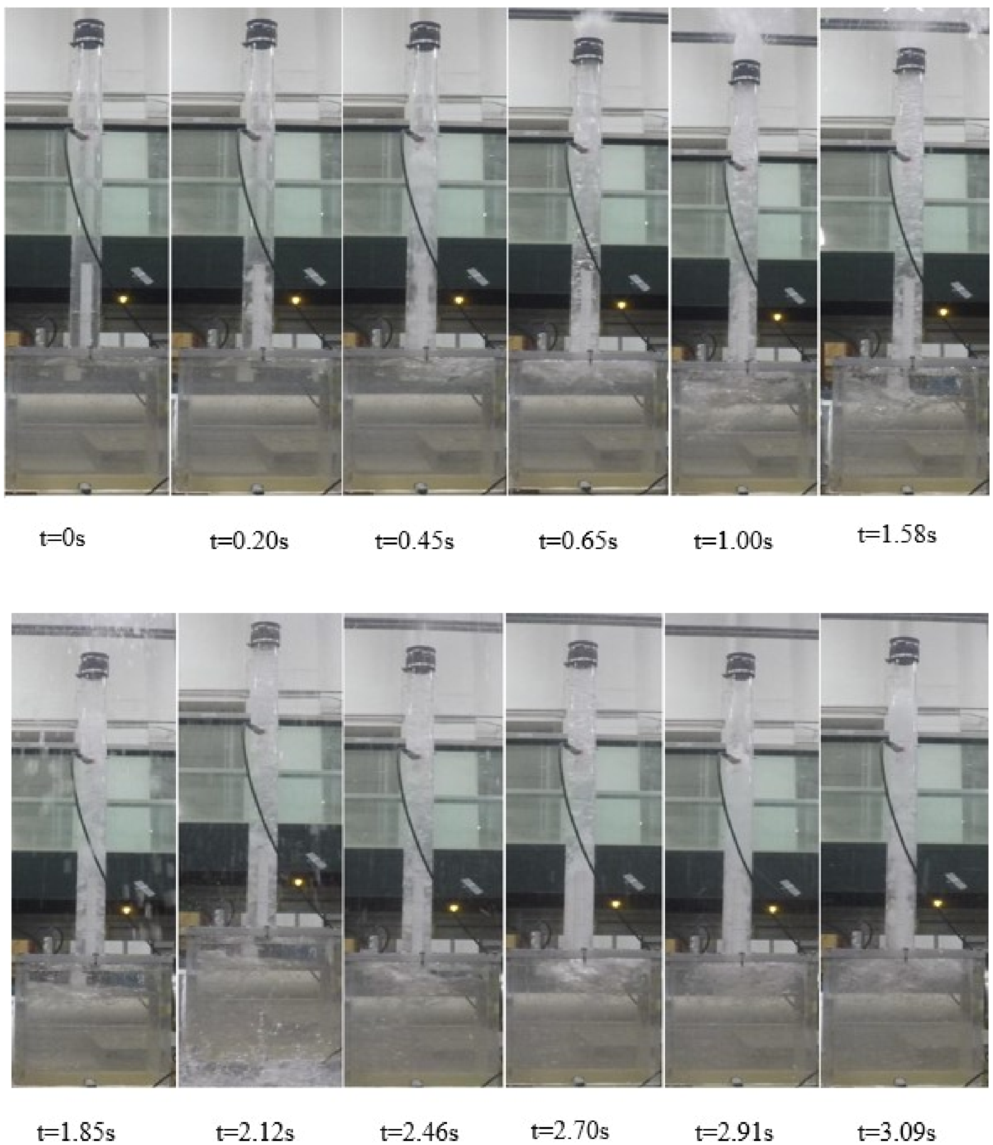


Figure 5.17 Experimental process of Case E1-5: (a) air-water movement in the chamber and riser, and (b) pressure variation

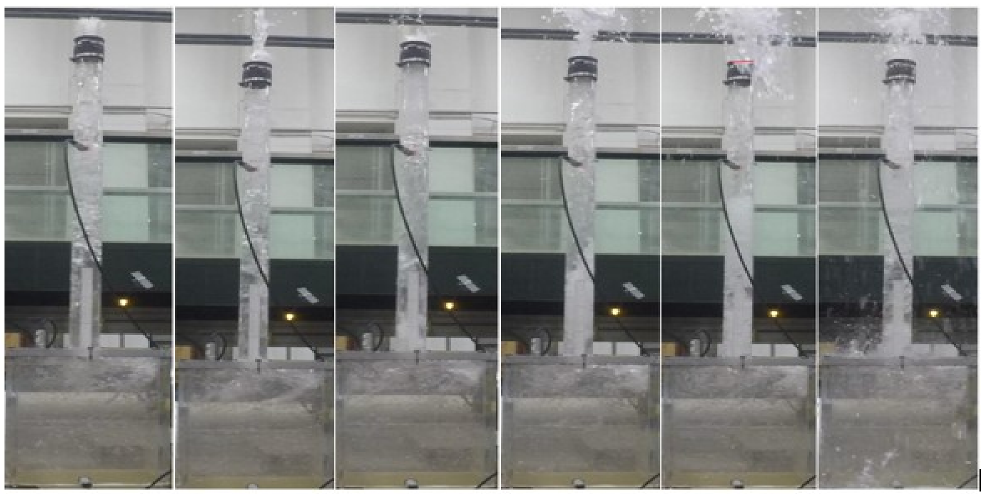
Figure 5.18 is the pressure process and air-water movement in the chamber and riser for Case E1-

7. For this case, geyser phenomenon is quite intense, as the orifice plate size is biggest compared with E1-3 and E1-5. The cause of splashing is identical to the Case C4, with first two caused by transient pressure which accelerated the flow and the third one was caused by continuously air releasing from the air pocket. The third splashing was intermittent, but as the time interval is too small, it was treated as one big splash. As orifice size is big for this case, compared with Case E1-5, air-water mixture splashed out in the form of jet surrounded by mist.

(a)



t=3.31s t=3.86s t=4.45s t=5.00s t=6.45s t=6.86s



t=7.23s t=7.39s t=7.52s t=7.70s t=7.88s t=8.95s

t=11.53s t=12.15s t=12.78s t=13.26s t=13.53s t=14.04s

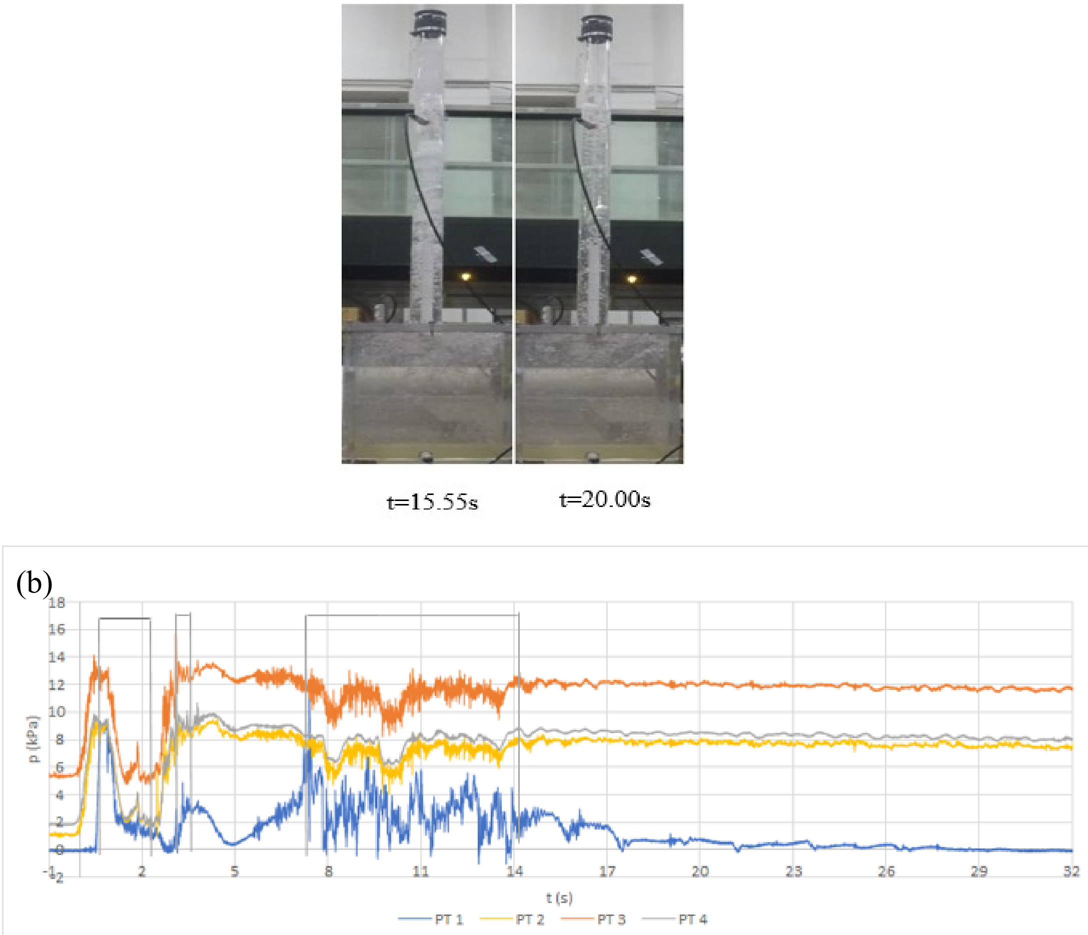


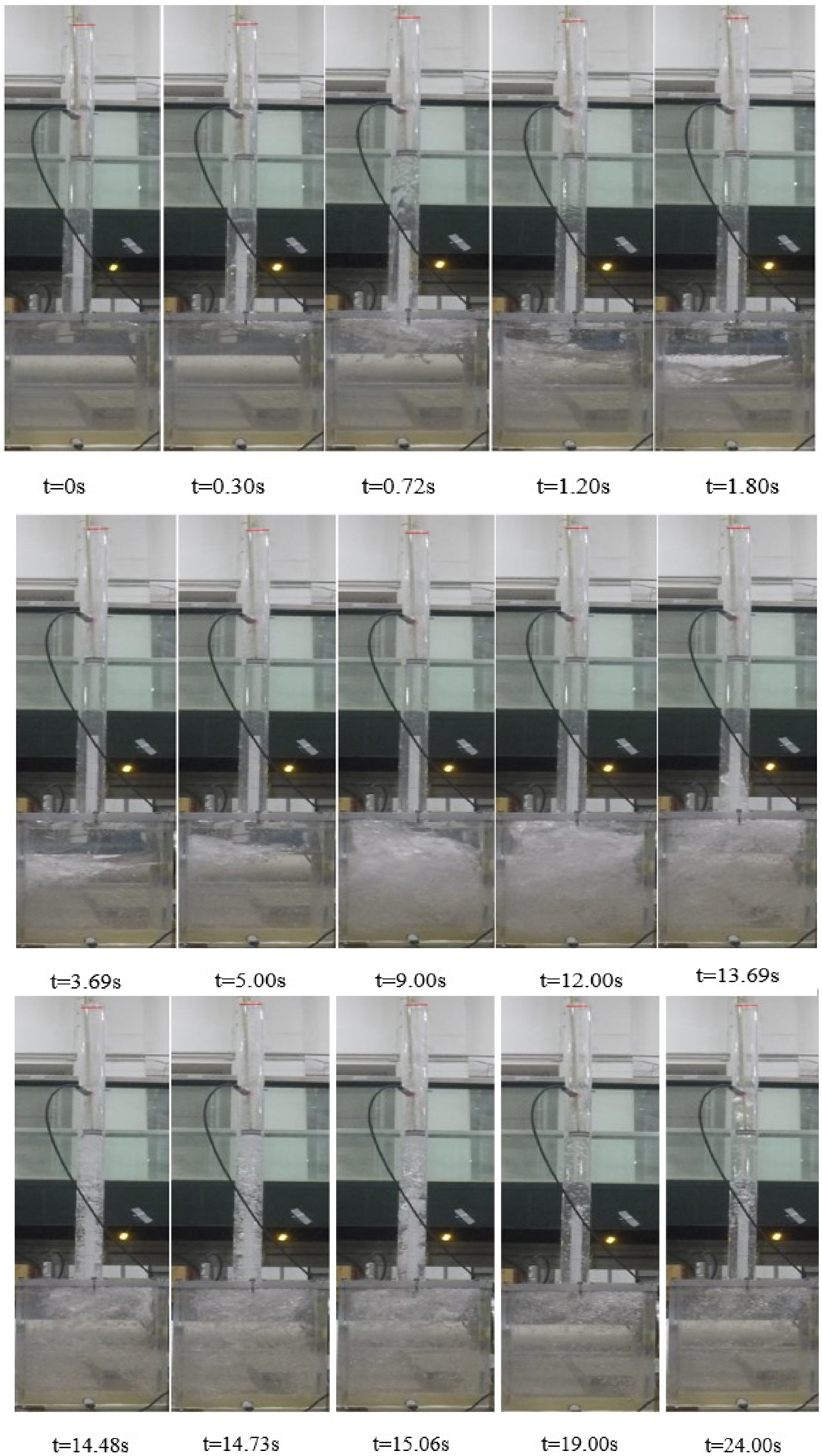
Figure 5.18 Experimental process of Case E1-7: (a) air-water movement in the chamber and riser, and (b) pressure variation

<u>5.2.1.2 Adding orifice plate in the middle of the riser for Series C (E2-1, E2-3 and E2-5)</u>

Figure 5.19 is the pressure history and air-water movement in the chamber and riser for Case E2-1. From the pictures, it can be seen that 6 mm orifice is small enough to block the airflow from escaping the system, causing long time air cavity in the chamber and the pressure resemblance at PT2 and PT4, which is similar to Case E1-3. When small amount of air was released from the orifice, water level in the chamber started to rise until 12.00 s, water filled the chamber again. After the water level in the riser raised above the orifice plate at around 14.00 s, the water surface raised to the location of PT1 at around 14.48 s. The movement of Taylor bubble can be seen in the

pictures from 29.00 s to 29.37 s, and pressure oscillation was recorded at PT1 when Taylor bubble passed the pressure measurement location.

(a)



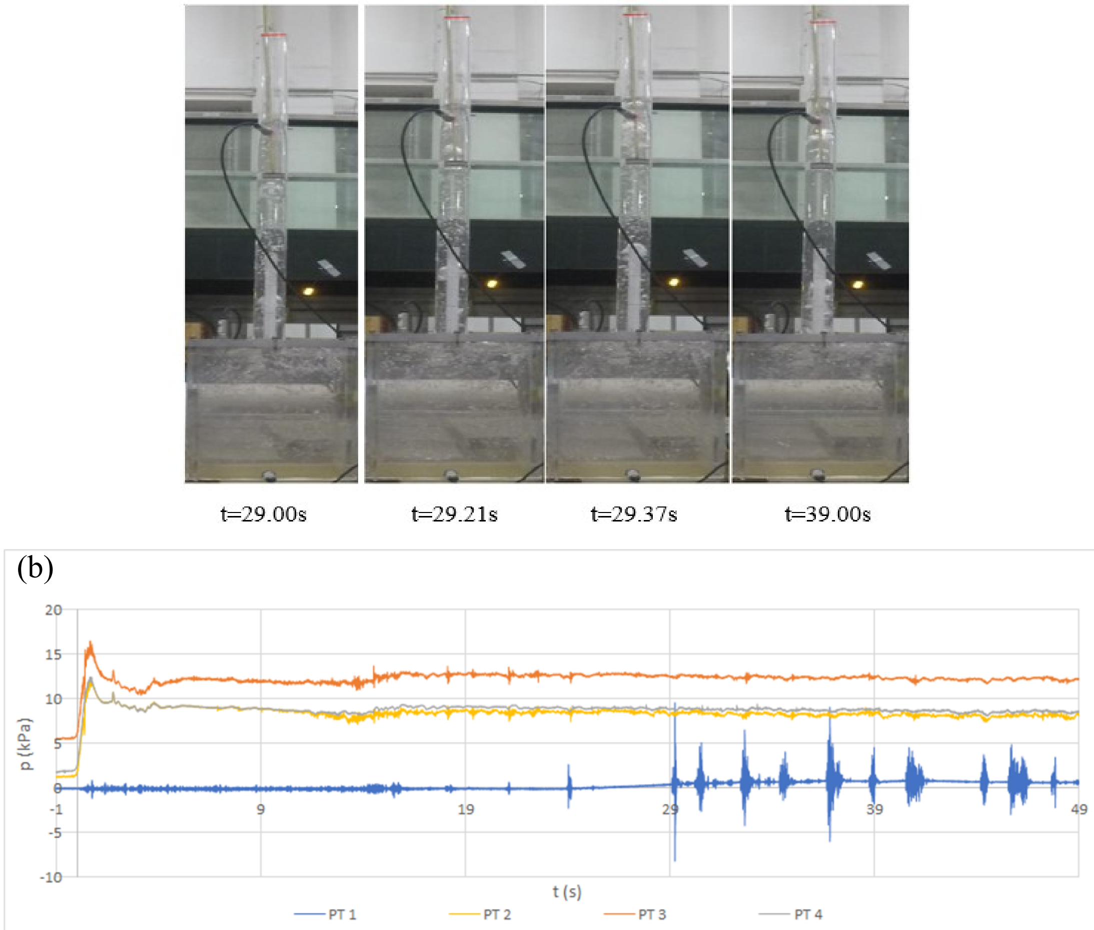
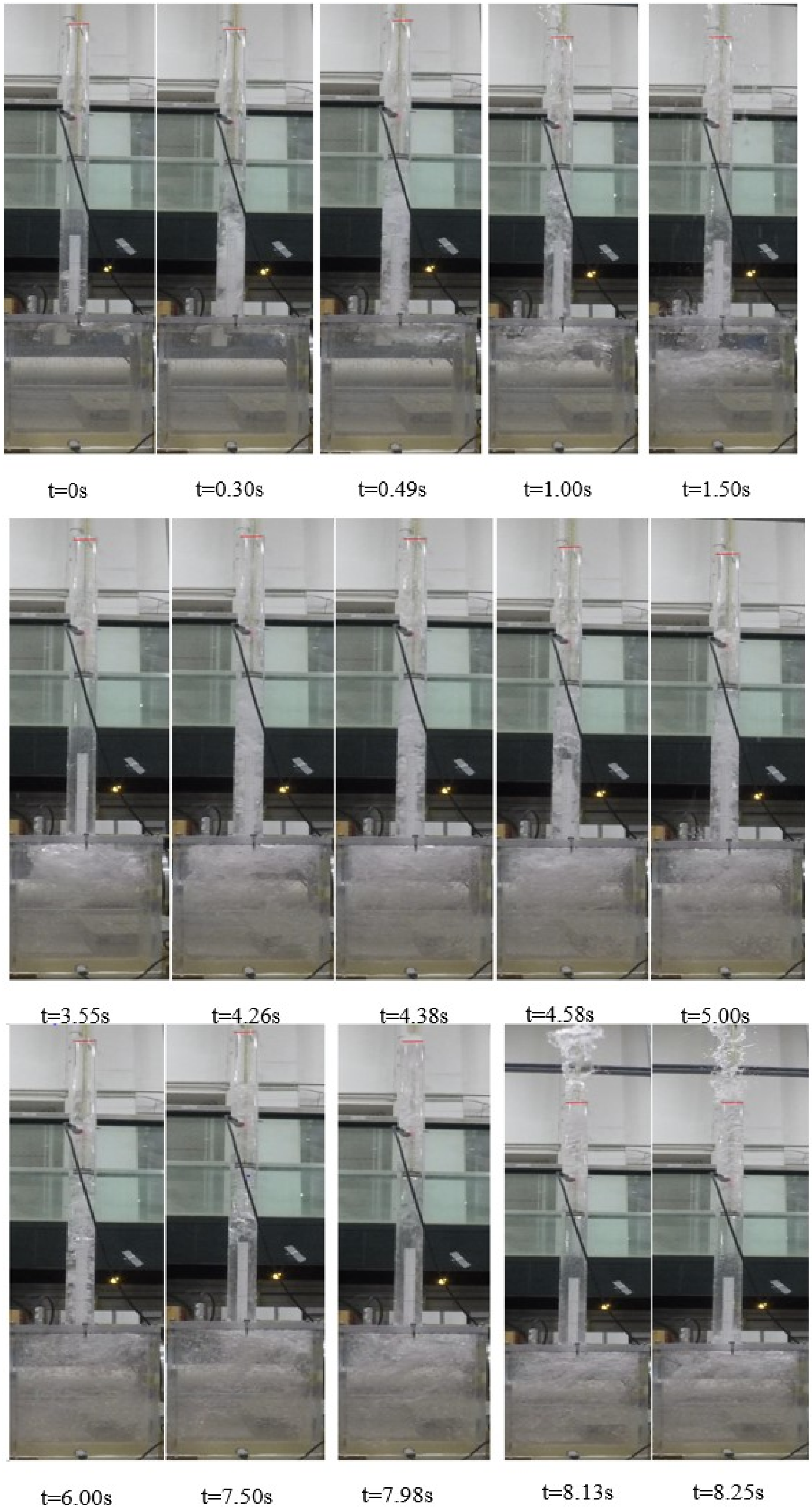


Figure 5.19 Experimental process of Case E2-1: (a) air-water movement in the chamber and riser, and (b) pressure variation

Figure 5.20 is the pressure history and air-water movement in the chamber and riser for Case E2-3. Geyser event happened three times for this case, with first two caused by transient pressure which accelerated the flow and the third one caused by continuously air releasing from the air pocket. The third splashing was intermittent, but as the time interval is too small, it was treated as one big splash. Unlike Case E1-3, no sharp peak pressure was seen at PT1 for this case. Only a few drops of water splashed out of the riser for the first two geyser events and in the form of mist. The third intermittent geyser events were intense, one representative geyser event is shown in pictures from 7.98 s to 8.70 s. As air bubbles were continually released into the riser, it would accumulate around the bottom of the orifice plate to form a short column of air, which was then pushed out by the water below to form geyser.

(a)



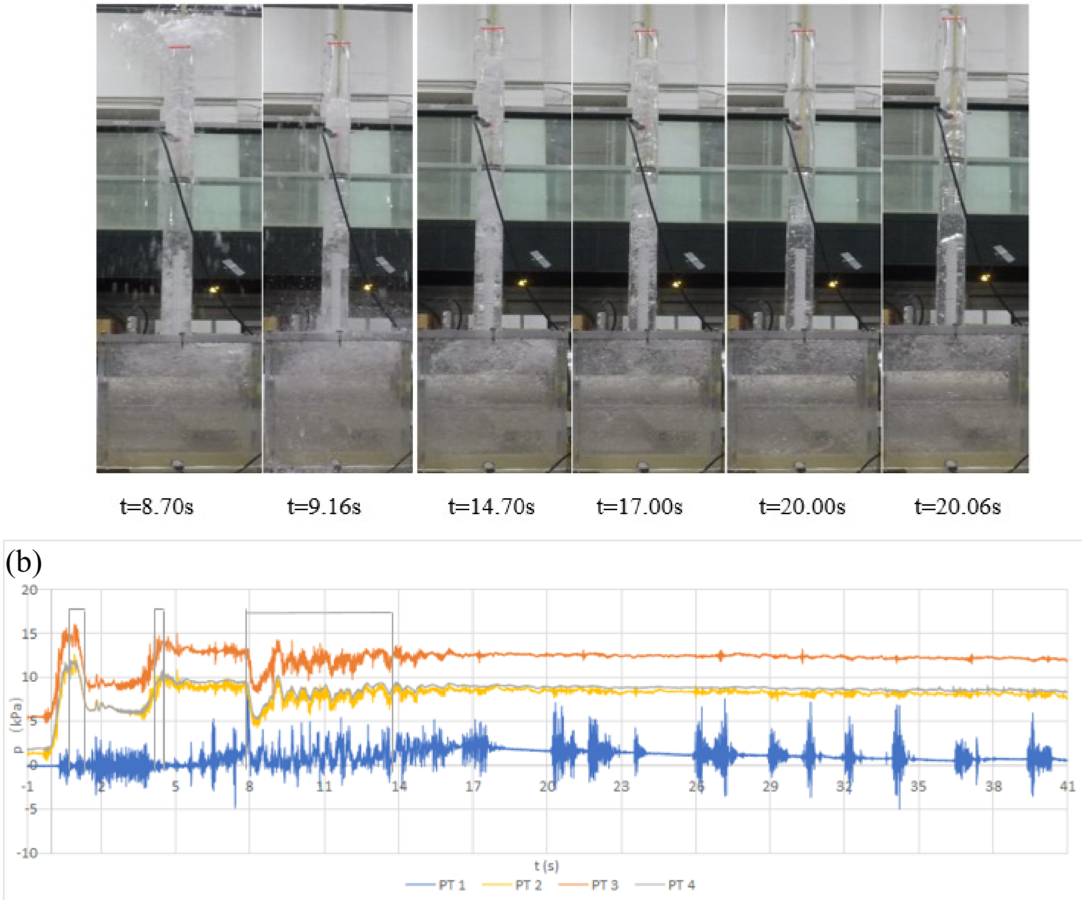
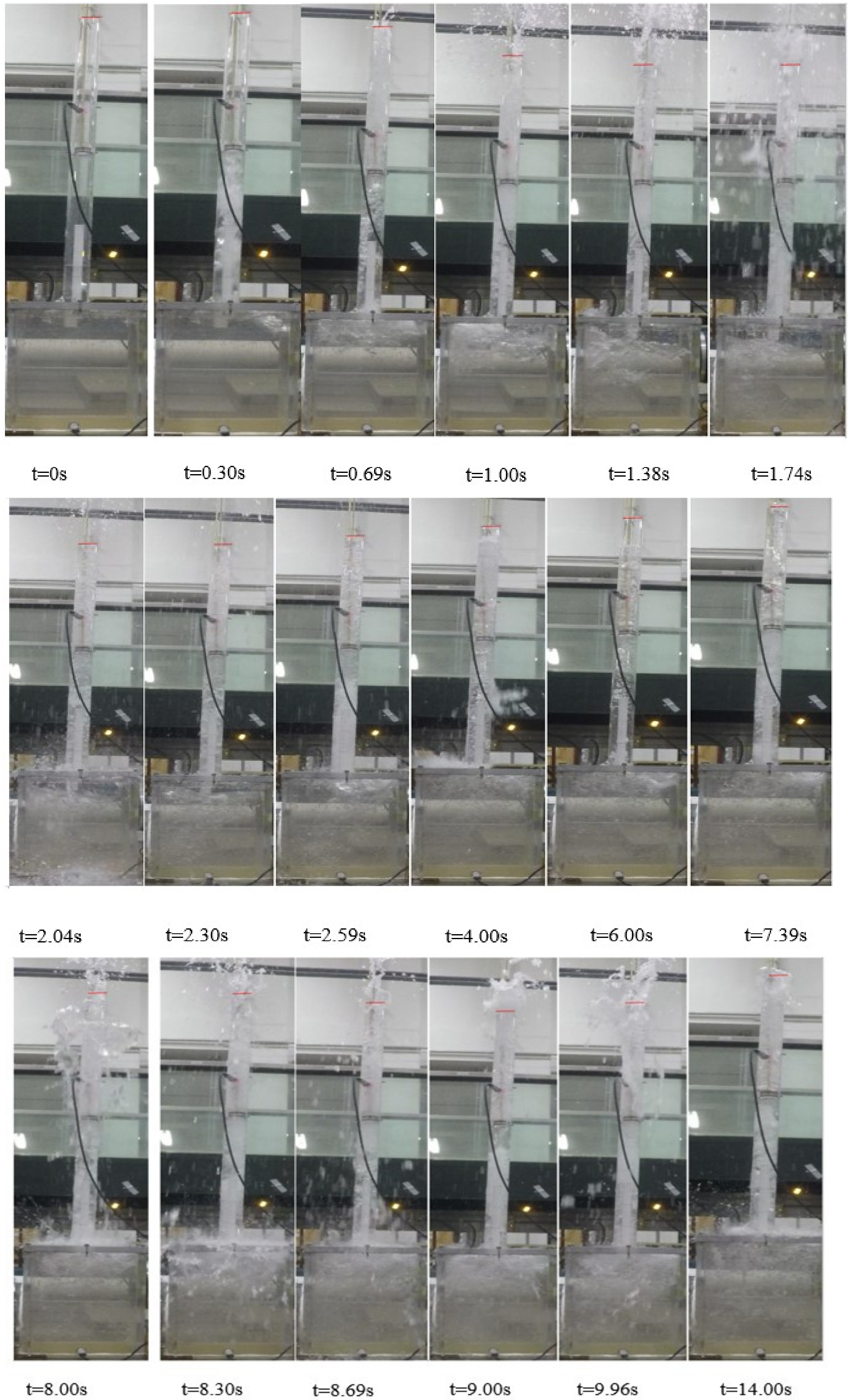


Figure 5.20 Experimental process of Case E2-3: (a) air-water movement in the chamber and riser, and (b) pressure variation

Figure 5.21 is the pressure history and air-water movement in chamber and riser for Case E2-5. Geyser event happened twice times for this case, with the first one caused by transient pressure which accelerated the flow and the second one caused by continuously air releasing from the air pocket. Large amount of water splashed out during the second geyser event, as air in the riser below the orifice plate was continuously compressed through the opening and pushed water above orifice plate out.

(a)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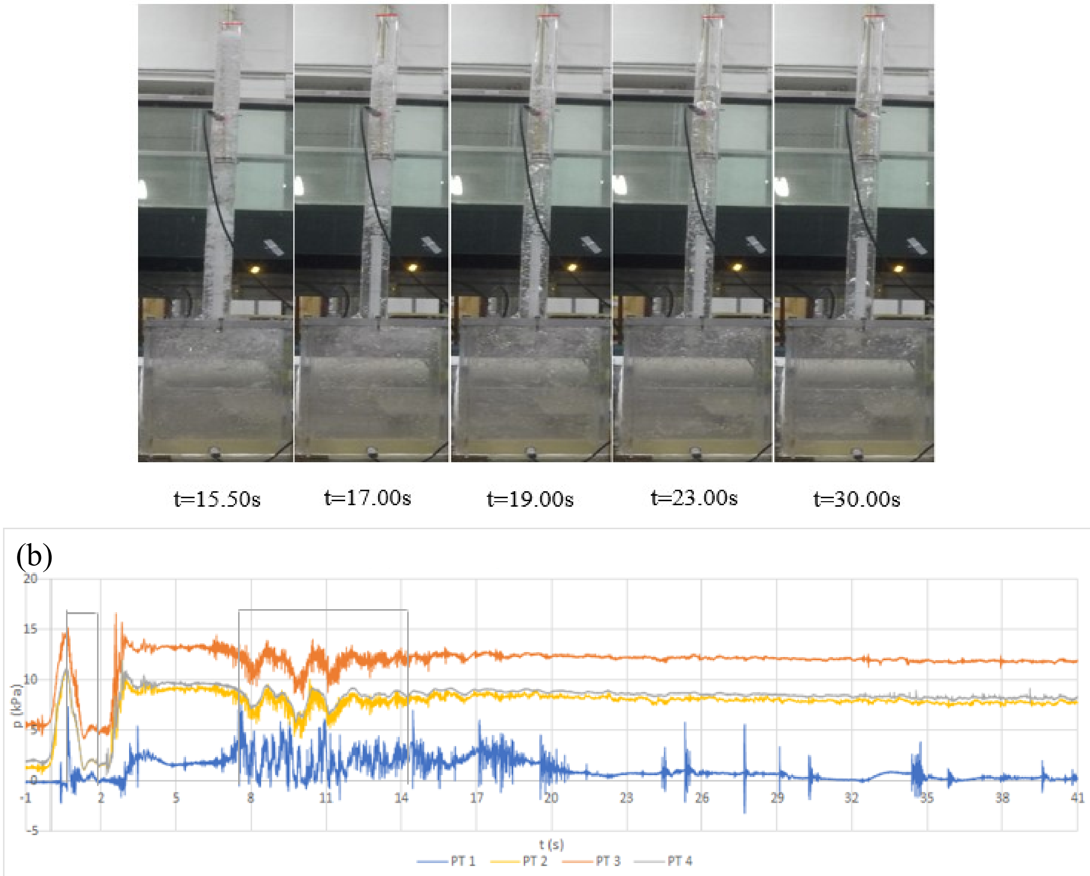
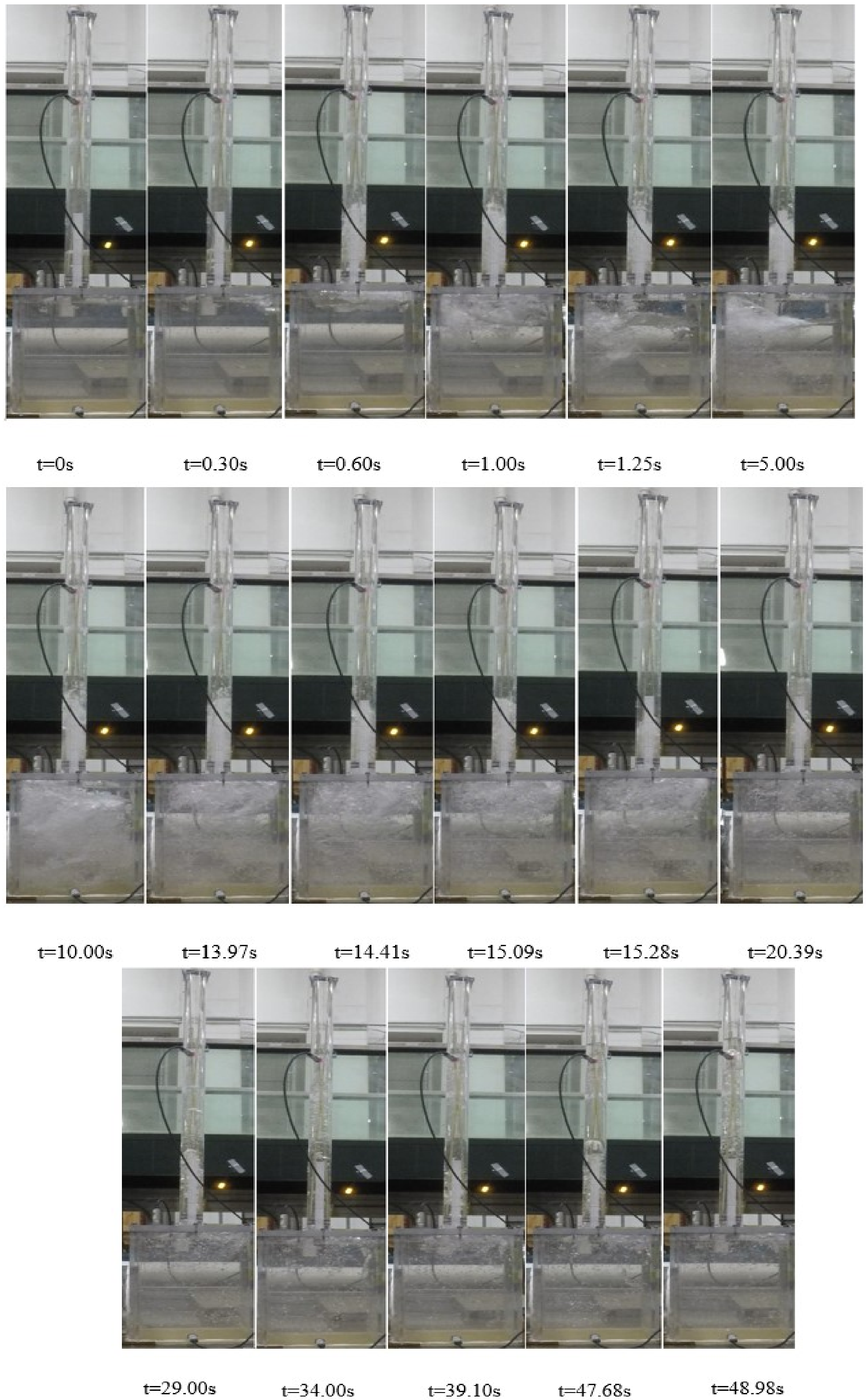


Figure 5.21 Experimental process of Case E2-5: (a) air-water movement in the chamber and riser, and (b) pressure variation

5.2.1.3 Adding orifice plate at bottom of the riser for Series C (E3-1, E3-3 and E3-5)

Figure 5.22 is the pressure process and air-water movement in the chamber and riser for Case E3-1. For Case E3-1 with 6 mm orifice plate at bottom of the riser, no geyser was observed. When the air pocket arrived at the riser, air would enter the riser in form of air bubbles, as orifice plate could throttle the flow. When air bubbles was continuously released into the riser, the bottom of the water column in the riser would become turbid, as seen in the picture at 0.60 s. This chaotic movement of air and water caused the fluctuation at PT1 from 0.60 s to 15.00 s. As the orifice is small, the movement of the turbid air-water mixture in the chamber persisted until air cavity vanished in the chamber. After the water in the chamber reached the location of the orifice plate, water column in the riser became clear as no more air could be released into the riser. The sudden fluctuation of pressure at PT1 was caused by bypassing of the Taylor bubble.

(a)



(b)

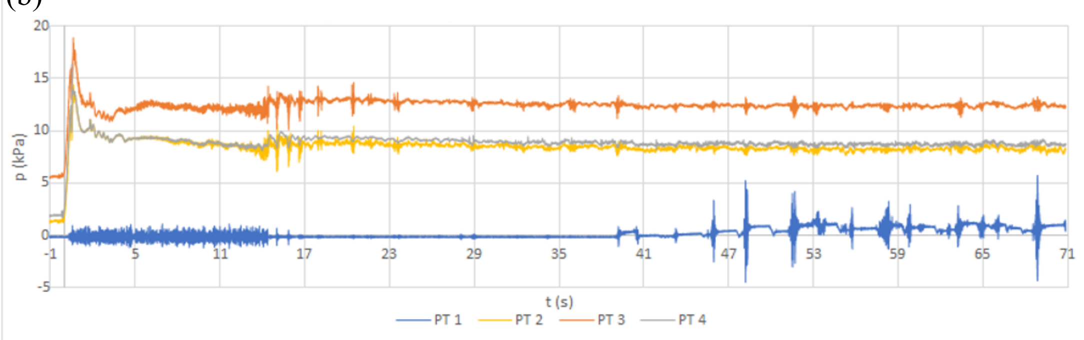
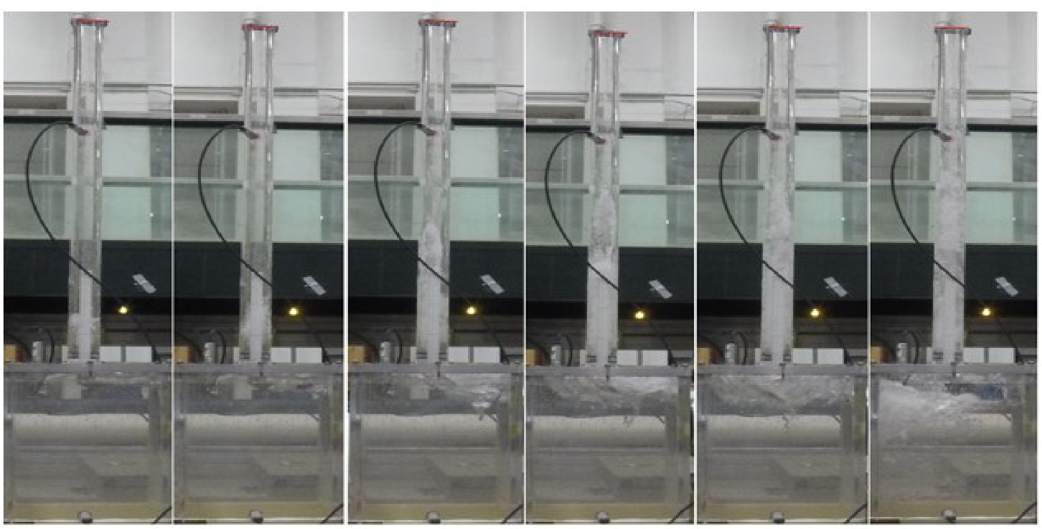


Figure 5.22 Experimental process of Case E3-1: (a) air-water movement in the chamber and riser, and (b) pressure variation

Figure 5.23 is the pressure process and air-water movement in the chamber and riser for Case E3-3. For this case, one geyser event happened during the air pocket release process. Geyser happened after air bubbles were squeezed into the riser through the orifice. Due to buoyancy, when air bubbles entered the riser, it forced the water in the riser to go upwards. The chamber became transparent at around 27.71 s, when most of the air had been expelled from the downstream pipe.

(a)



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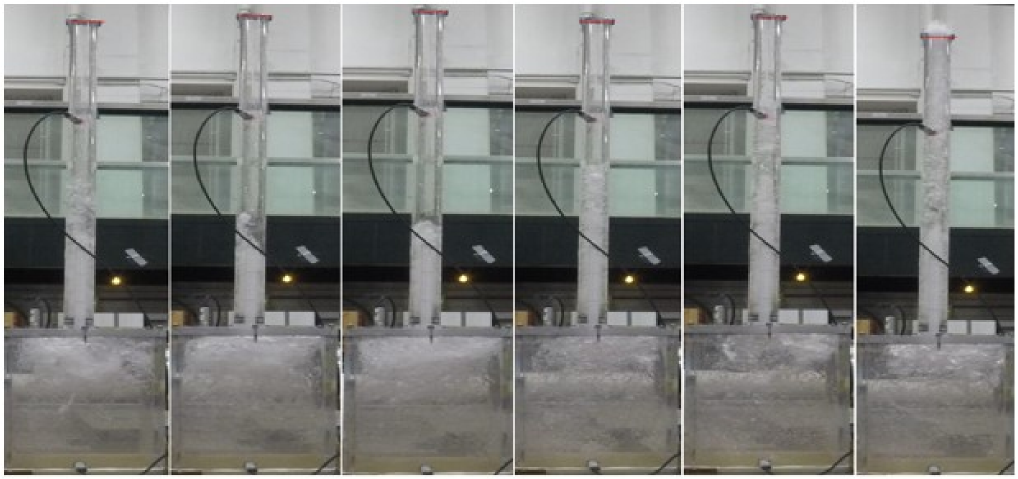

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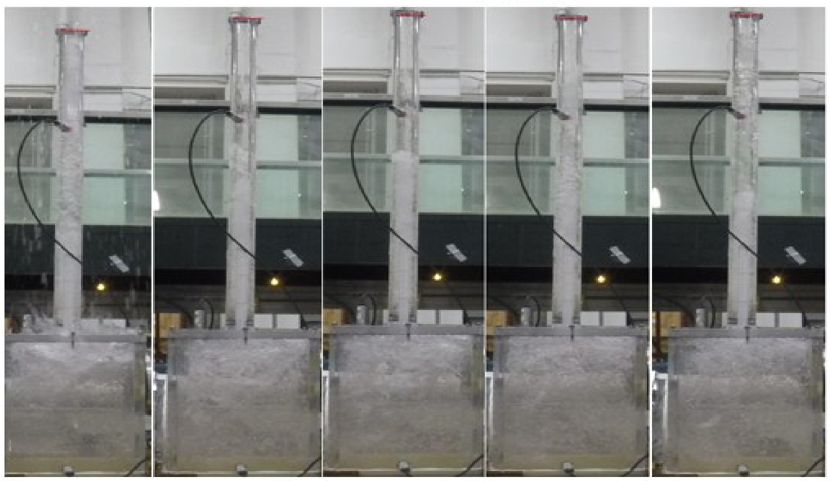

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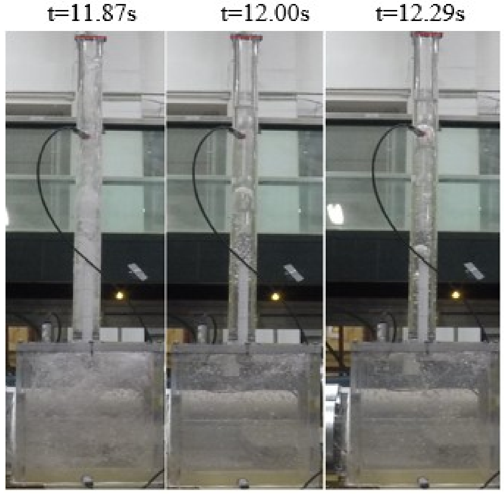


t=12.74s t=26.95s t=27.71s

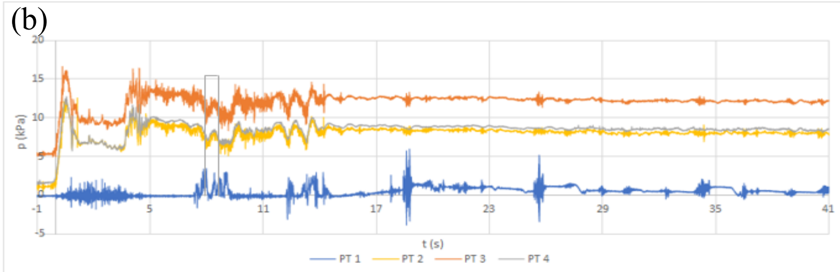
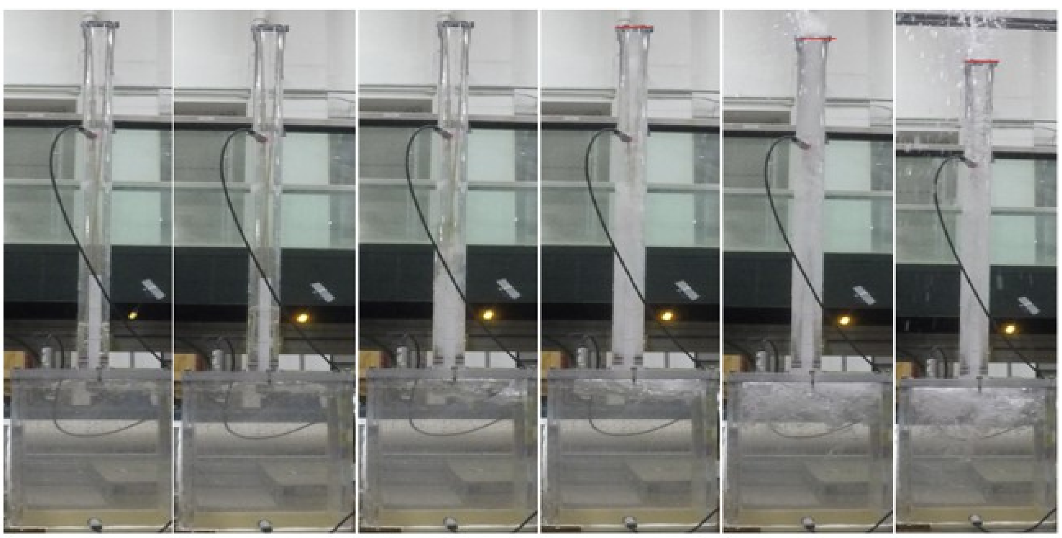


Figure 5.23 Experimental process of Case E3-3: (a) air-water movement in the chamber and riser, and (b) pressure variation

Figure 5.24 is the pressure process and air-water movement in the chamber and riser for Case E3-5. Three geyser events happened in Case E3-5 as 30 mm orifice plate is least effective in holding air compared with Cases E3-1 and E3-3. The sharp peak in the figure at chamber bottom occurred randomly, and could be caused by water suddenly struck the bottom chamber wall. Geyser was severe for this case, as orifice plate acted as a smaller diameter riser when air-water passed through it.

(a)



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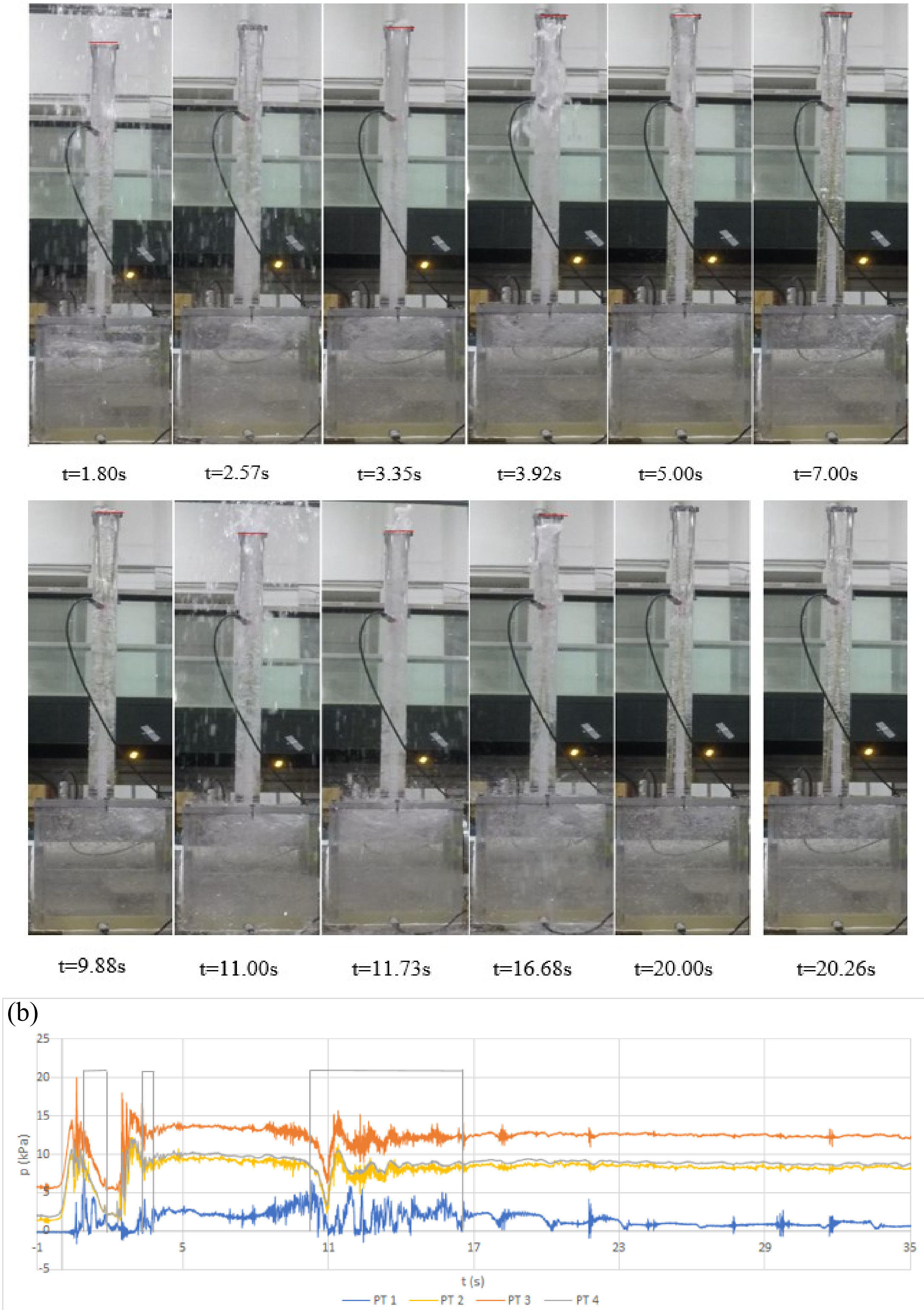


Figure 5.24 Experimental process of Case E3-5: (a) air-water movement in the chamber and riser, and (b) pressure variation

In conclusion, most of the orifice plate is can mitigate geyser events for Series C. The pressure pattern and geyser events are more like the original process without retrofitting as the orifice size increases. Comparing the cases with same size orifice plate, orifice at the bottom is more effective in preventing geyser in the amount of water splashed out, while the orifice plate at the middle is least effective in preventing water from splashing out. The orifice plate can influence the pressure process, but the final steady state pressure at all locations are identical for same inflow change and initial h_r cases. The summary of jetting height and peak pressure change for the original case and with orifice plate cases are shown in Figure 5.25 and Figure 5.26. From Figure 5.25 and Figure 5.26, it can be concluded that the geyser height decrease with the decrease of orifice size and lowered down of the orifice plate location, while the pressure at different locations had a minor change after the orifice plate was applied.

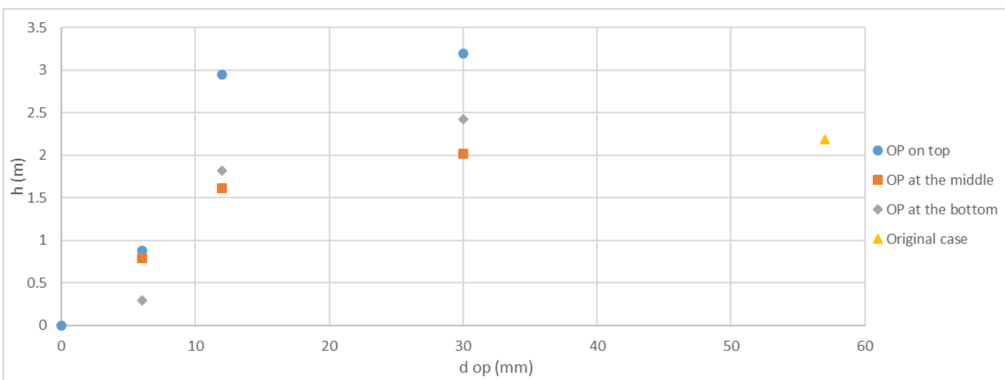
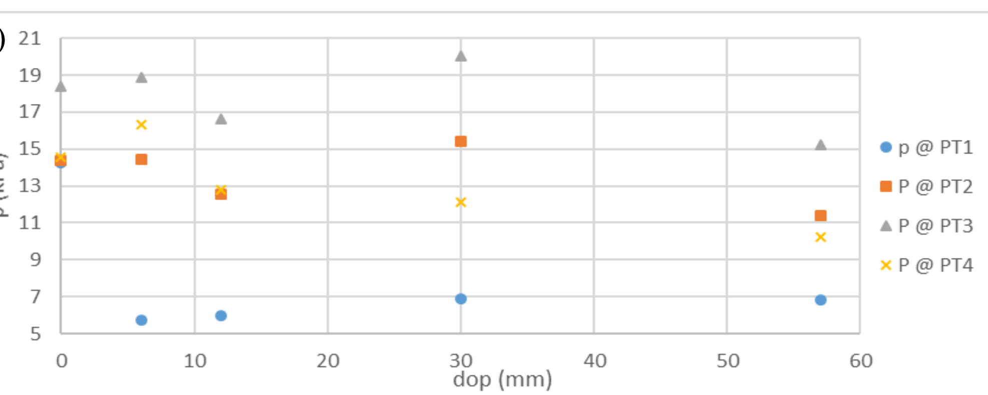


Figure 5. 25 The impact of orifice plate on the geyser height for Case B3 and orifice plate applied to B3

(a)



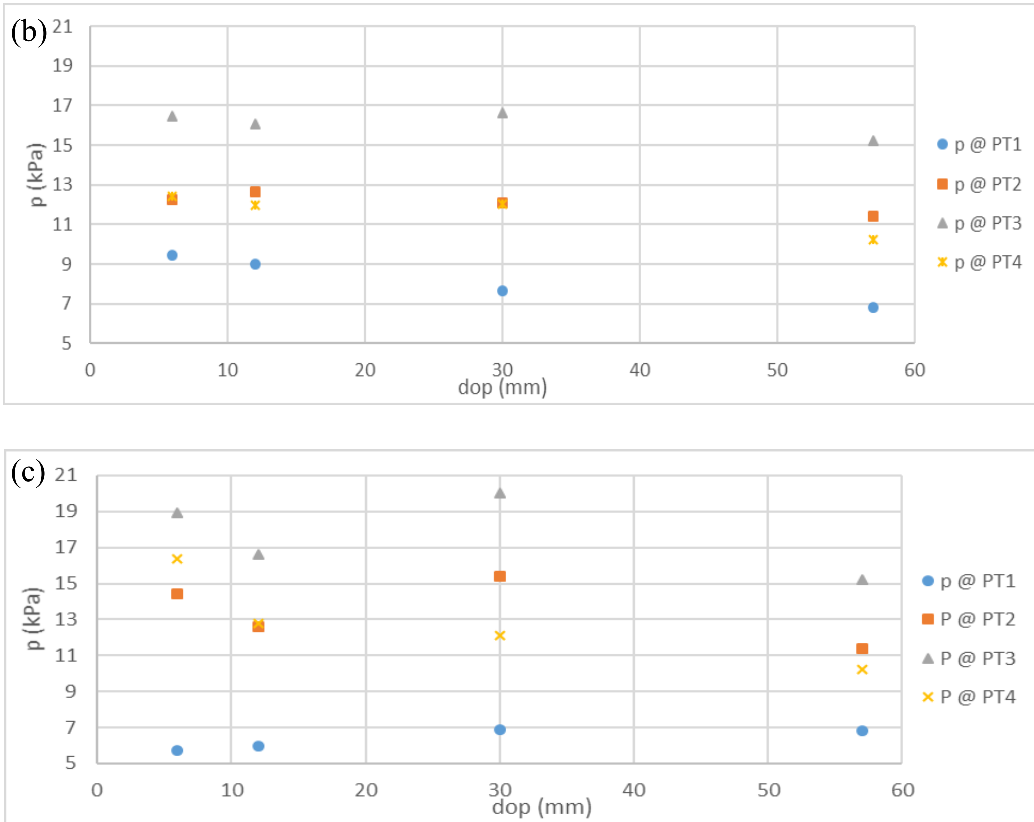


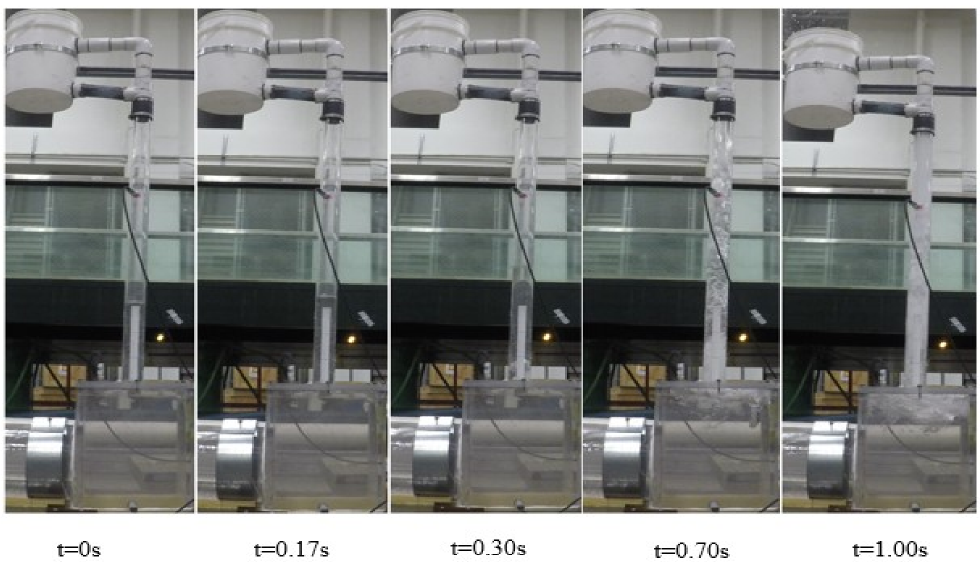
Figure 5.26 The relationship between orifice plate size and peak pressure at different locations for Case C4 and orifice plates applied to C4: (a) orifice on the top of the riser, (b) orifice on the middle of the riser, (c) orifice at the bottom of the riser

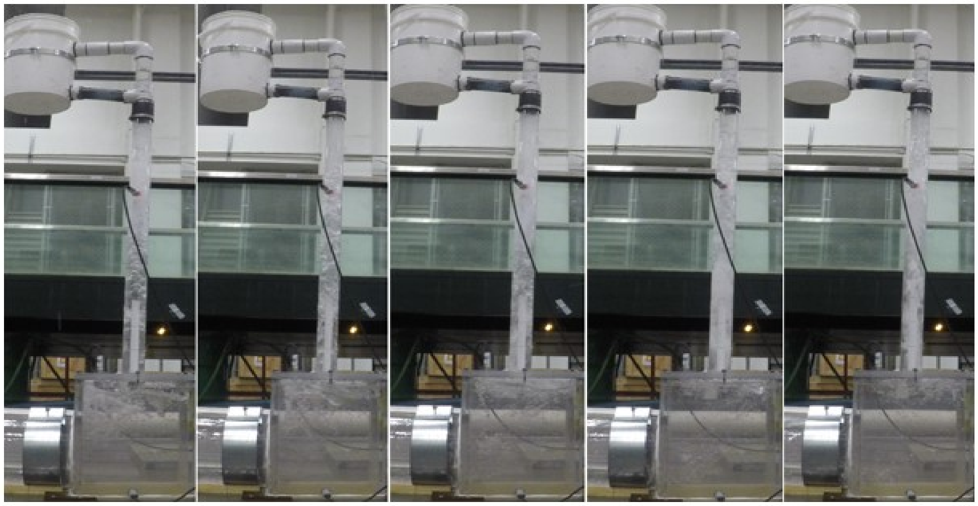
5.2.2 Adding WRC on top of the riser for Series C (H2)

Figure 5.27 is the pressure process and air-water movement in chamber and riser for Cases H2. As WRC has an opening on the top, air can still be released from the riser, so that the pressure process/peak is similar to Case C6. Similar to Case C6, the first geyser was caused by the transient pressure wave, which happened from around 1.00 s to 1.81 s. Unlike Case C6, the air-water mixture could not escape from the riser when it reached the riser top for this case, as the bend would lead it to go directly into the recirculation chamber. Due to the density difference of air and water, the air-water mixture was separated in the chamber, and only small amount of water splashed out after air-water mixture struck the recirculation chamber wall. After air escaped the system through recirculation chamber, water would flow back into the system from the riser. The pressure at PT2-PT4 raised around 1.38 s, but geyser event did not happen as the upwards moving air-water mixture encountered the downward moving flow. Second splashing event happened after the head of the air pocket arrived at the chamber and a portion of it entered the riser.

The pressures at all the locations increased by a small amount after the system reached a steady state, meaning adding a WRC did not help in reducing the pressure. Unlike Case C6 where a large amount of water shoot out through the riser, only a few drops of water came out for Case H2, as WRC is useful in redirecting the flow and to automatically separate the air and water in the recirculation chamber due to the density difference.

(a)





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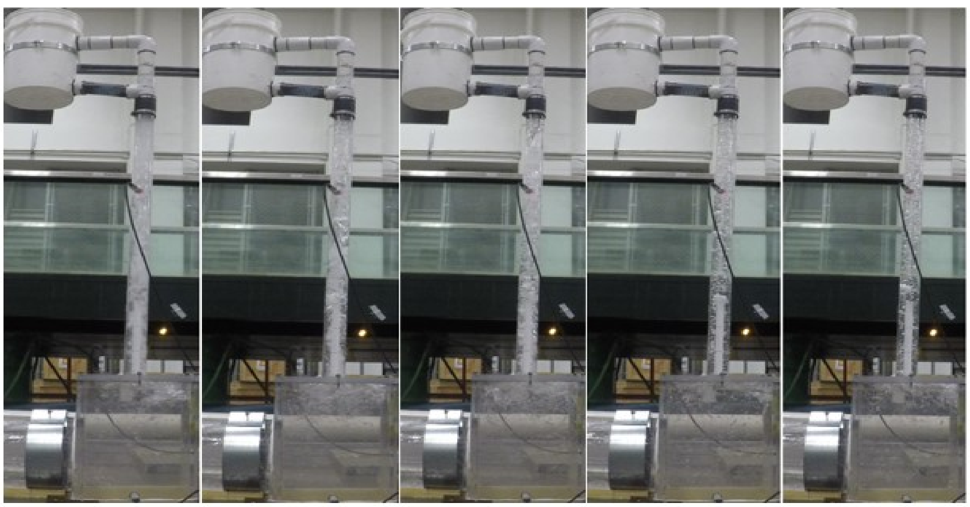

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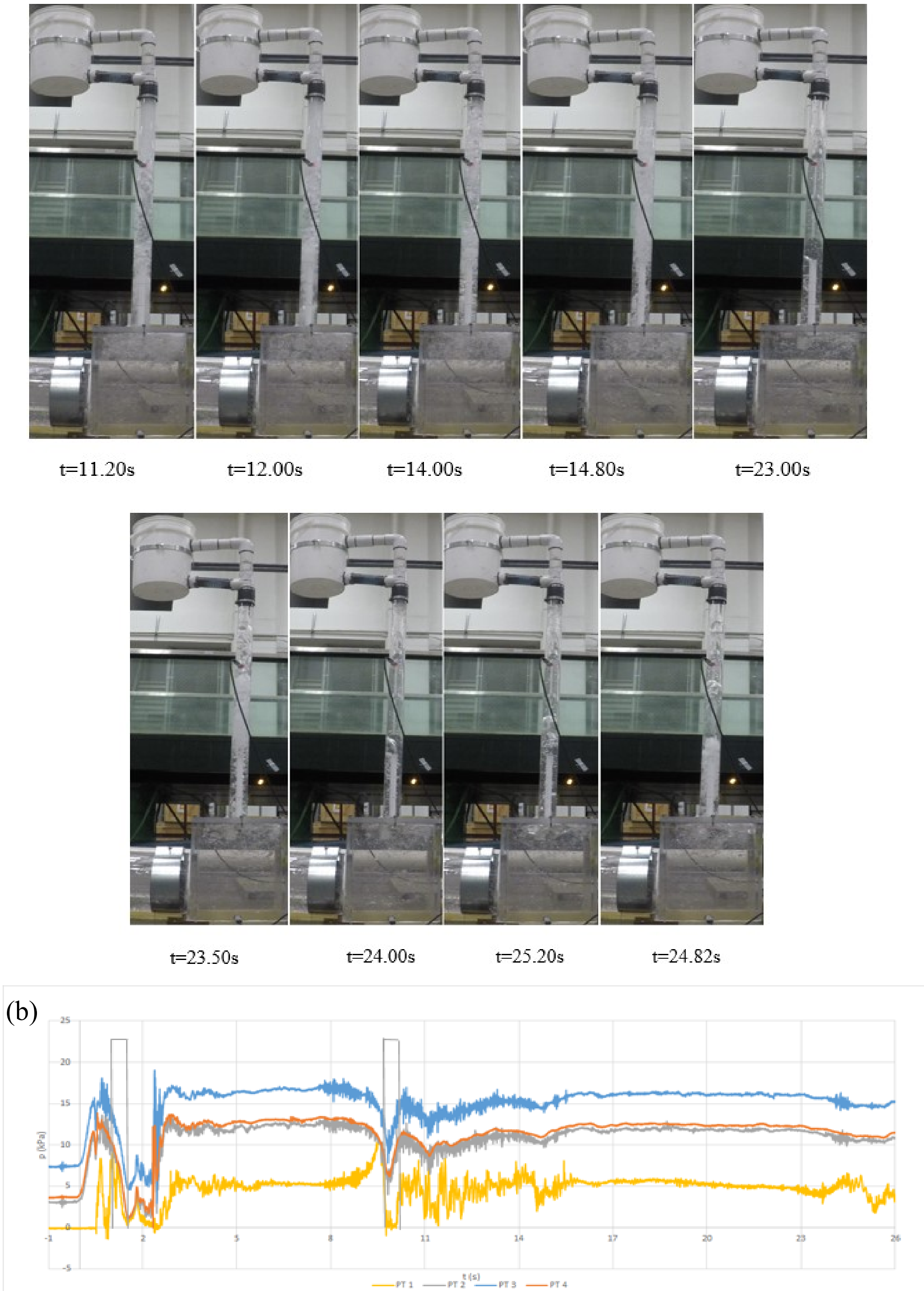
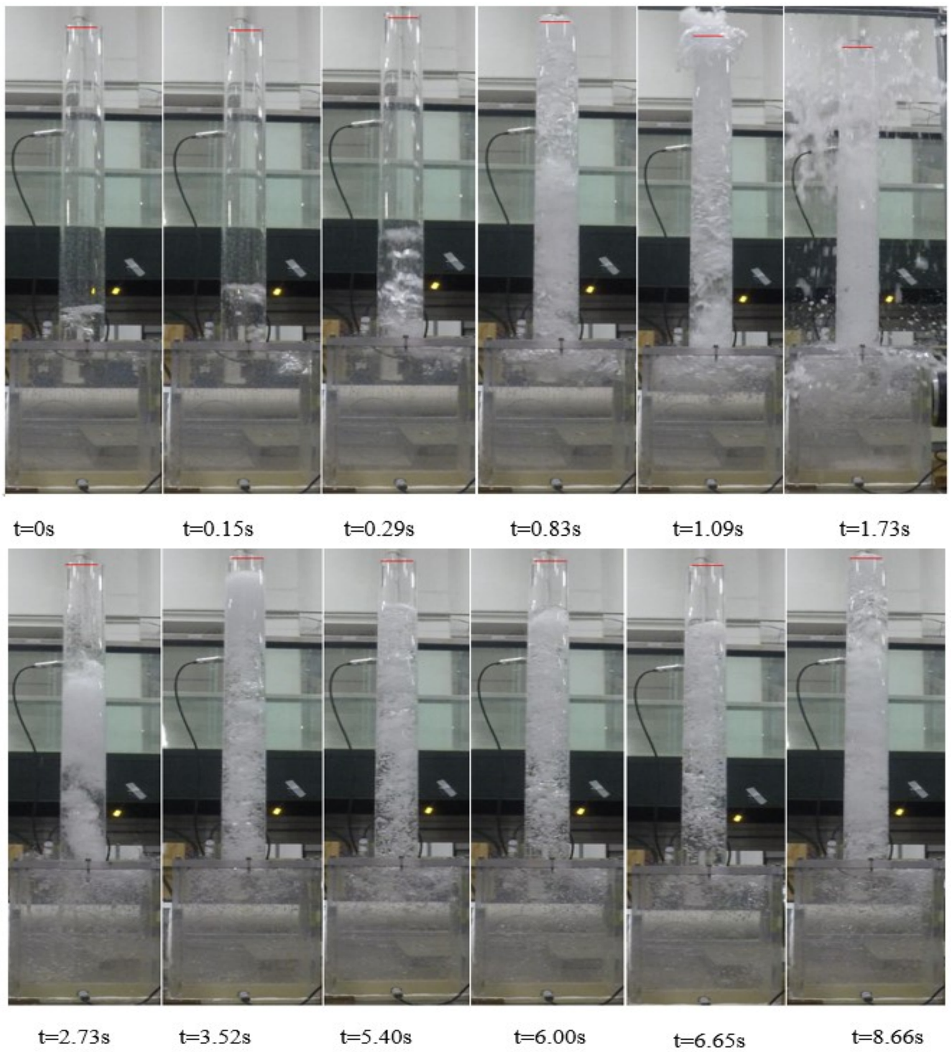


Figure 5.27 Experimental process of Case H2: (a) air-water movement in the chamber and riser, and (b) pressure variation

5.2.3 Using enlarged riser for Series C (G1-G6)

Six cases were chosen to test what impact larger diameter would have on geyser process. One representative case of C4 was chosen to show the difference, as shown in Figure 5.28.

(a)



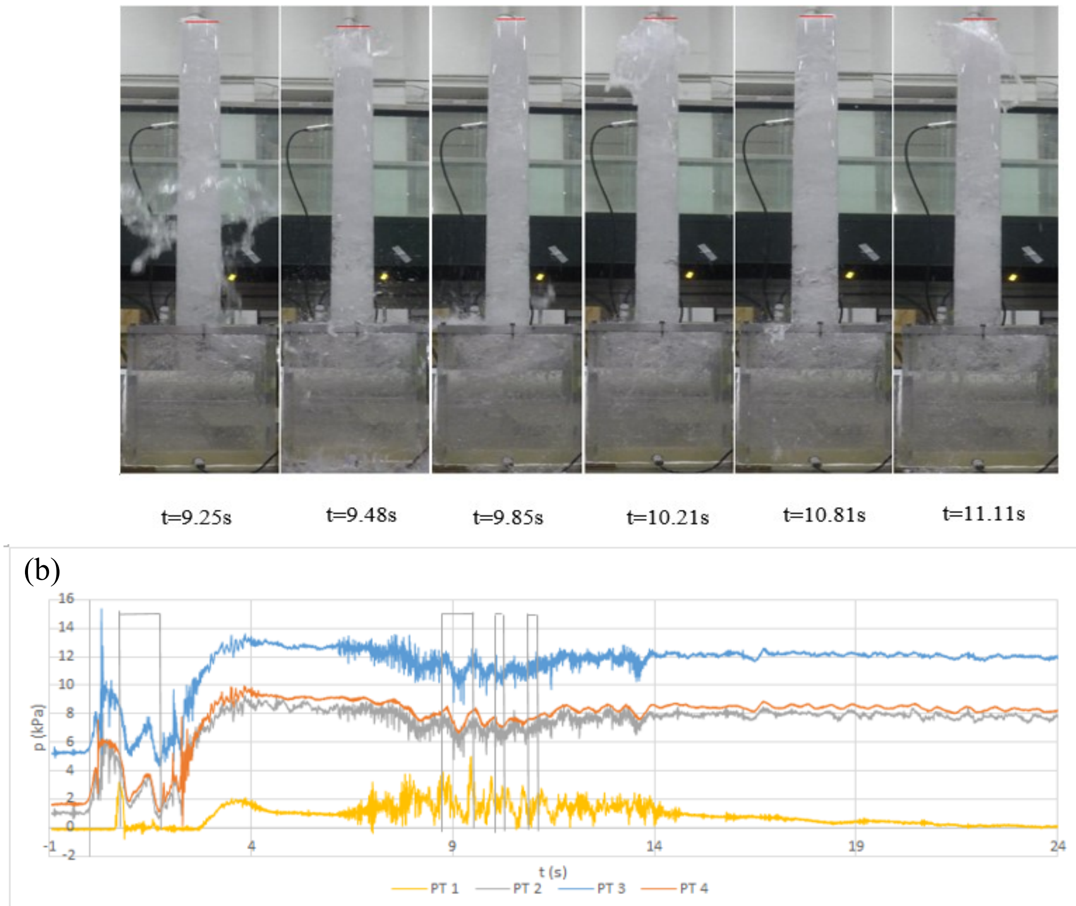


Figure 5.28 Experimental process of Case G4: (a) air-water movement in the chamber and riser, and (b) pressure variation

When larger diameter riser is used, more energy would be required to lift the same height of water column. Upon fully opening of the valve, the water level in the riser started to increase until 0.83 s, water first appeared out of riser, causing the geyser event. After the first geyser event, the water column was oscillating in the riser from around 2.00 s to 8.50 s. Second geyser event happened from 8.66 s, when the head of the air pocket arrived in the chamber, a portion of it entered the riser and rose up along with water. Second geyser event stopped at around 9.25 s, which was directly followed by the third geyser event induced by air releasing from the air pocket, after another smaller air bubble from the main air pocket entered the riser. Last geyser event happened from 10.81 s to 11.11 s, after last smaller air bubble was pushed into the riser.

Compare Cases C4 with G4, the duration of geyser event is shorter for Case G4. The peak pressures of the two cases were similar, with a reading of 15.20 kPa and 15.39 kPa respectively. Due to gravity, more energy would be required to lift up the same height of water column in a larger diameter riser. As air-water mixture in the original and enlarged riser possessed same energy when it entered the riser, the existing velocity at the riser top for larger riser was smaller than that of the original riser, which resulted in lower geyser height and reduced amount of water splashed out for Case G4. The bubbles at the final steady stage would rise in the riser in the form of the oblate bubble, instead of Taylor bubble, as gas viscosity is smaller for the bigger riser (Kajero et al. 2012).

5.3 Summary

5.3.1 Summary on retrofitting for Series B

The peak pressures and geyser heights for Case B3 and different retrofitting methods applied to B3 are summarized. When an orifice plate is used on top of the riser, it can be seen that the peak pressure decreased at PT2, PT3 and PT4, while increased at PT1, as the riser is pressurized, compared with Case B3. Comparing Case B3 with Cases D1-1 to D1-4, Case D1-4 is the most effective way in reducing peak pressures at PT2-PT4. For the geyser heights produced when different orifice plates were used, Case D1-4 produced 0.70 m geyser while Cases D1-1, D1-2 and D1-3 all produced less than 0.15 m geysers, which are all significantly lower than the original Case B3 case of 4.20 m. It can be seen that the peak pressures at all the pressure measurement locations increase when the size of orifice plate decrease. For Case D1-1, the peak pressure recorded in the riser is about 5 times larger compared with Case B3. When orifice plate is used at the middle of the riser, one geyser event happens when the orifice plate size is 6 mm. This happens when water enters the riser and squeezes out from the small opening during air compression process. When orifice plate is at the bottom of the riser, the peak pressure is similar to orifice plate at the middle, but maximum geyser height is reduced, except for 30mm case, where the orifice plate acts as smaller diameter riser. Case H1 produces a geyser that is approximately 1.3 m and Case F3 produces 2.82 m geyser, so that WRC is more useful in mitigating geyser compared with larger diameter riser, while the peak pressures at different pressure measurement locations are similar compared with Case B3.

From the pressure data at PT6, peak pressures dropped for all the retrofitting tests, compared with Case B3. The usage of WRC and larger diameter riser showed a minor decreasing in peak pressures at PT3 from 45.11 kPa to 39.43 kPa and 36.84 kPa respectively. When orifice plate is installed at top/middle/bottom of the riser, the pressures at PT6 dropped to below half of the regular value of 45.11 kPa. The pressure at PT 6 for Case D1-4 is lowest at a reading of 7.78 kPa.

When a larger diameter riser is applied to cases in Series B, peak pressures drop at all pressure measurement locations as shown in Table 5.1. It can be seen that geyser height decreases significantly after a larger diameter riser is used. PT3 is chosen to show the difference between maximum pressure for original and enlarged riser diameter cases. From the table, it can be seen that peak pressure did not reduce by a great amount when the larger riser is used for Series B.

Table 5.1 Geyser heights and peak pressures summary for Series B and Series F

Run	Q_0 (L/s)	Q_1 (L/s)	h (m)	P_{max} at PT3
B1	20	60	1.48	14.89
F1	20	60	0.91	14.69
B2	20	80	3.18	40.09
F2	20	80	1.83	28.37
B3	20	100	4.20	47.98
F3	20	100	2.82	44.96
B4	30	60	1.07	14.79
F4	30	60	0.71	12.07
B5	30	80	2.64	39.16
F5	30	80	1.58	24.34
B6	30	100	3.58	46.02
F6	30	100	2.68	41.49

In summary, using smaller size orifice plate (6mm) at the bottom of the riser is the best for Series B in reducing peak pressure along the pipe and lowering maximum geyser height. However, more air would be pushed into the downstream pipe and downstream tank as the orifice plate size decreases, so the 6 mm OP case would push more of air into the downstream, compared with 12 mm and 30 mm OP cases.

5.3.2 Summary on retrofitting for series C

The peak pressures and geyser heights for Case C4 and different retrofitting methods applied to C4 are summarized. When orifice plate is used on top of the riser, orifice plate with different orifice size would not help lowering peak pressure, especially for Case E1-5, where the water hammer pressure at PT1 is about 7 times higher than the original Case C4. For all orifice sizes, Case E1-7 has lowest peak pressure overall. The peak pressures at PT1 are similar for all the cases, except for Case E1-5, in which the water hammer effect causes a pressure increase and larger amplitude of pressure oscillation. When orifice plate is used at the middle of the riser, the peak pressures at the same locations for all orifice sizes are similar, except that maximum pressure at PT1 for Case E2-5 is smaller, because less air in the chamber is compressed before air-water mixture came out through the riser. When orifice plate is used at bottom of the riser, although the peak pressure for Case E3-1 is slightly higher than Cases E3-3 and E3-5, it produce much lower geyser of only 0.3 m.

6mm orifice plate produce the lowest geyser for all orifice plate locations in Table 5.3, and as peak pressures at same locations are similar among the cases, 6 mm orifice plate is the best retrofitting choice for Series C. As for the location of orifice plate, it should be used at the bottom for lower height of geyser.

The peak pressures and geyser heights for Case C6 and different retrofitting methods applied to C6 are summarized. This case is chosen as representative for Series C to study the peak pressure in the downstream pipe, so that pressure at PT6 is measured. When orifice plate is used on top of the riser, unlike D1 cases, where a gradual increase of pressure in the riser is seen as the orifice size decreases, the pressure at PT1 for Case E1-6 is higher than Case E1-4 for this category, which is due to resonance phenomenon that happens for Case E1-6. The variations in pressures are small for different orifice sizes, so are the geyser heights. Water shot out from the riser for all the orifice plate cases except for the fully sealed case, where no air or water can escape from the riser. Case E1-4 produce a geyser height of 2.7 m in the form of mist. For orifice plate used at middle and bottom of the riser, 6 mm OP is the best choice in terms of lowering geyser height and peak pressure.

For use of a larger diameter riser, the height of geysers and peak pressures at different locations both show a decreasing trend, but geyser still happen, and as a larger volume of water would be splashed out from the riser for same height of water with a larger cross-sectional area, larger diameter riser is not as effective in preventing geyser as orifice plate. When the larger diameter riser is used to conduct the experiment (Case G6), both the geyser height and the duration of the geyser is reduced.

The pressure peak is similar for Case C6 and Case H2, but as the geyser height is reduced from 2.60 m to 2.12 m, it do help in reducing the geyser height. The problem is that as the WRC is directly attached to the top of the riser, it increased the distance water can travel from riser length of 1.22 m to around 1.60 m.

Seen from the pressure at PT6, the value is similar for all the cases, with or without retrofitting method, except for Case E3-6. Case E3-6 is worth noticing, as the geyser event is intense and the maximum geyser height is 2.90 m. The reason for that is the orifice acting as a smaller diameter riser rather than a blockage to prevent air from entering the riser.

In summary, from experiment point of view, using a small size orifice plate (6mm) at bottom of the riser is the best retrofitting method for Series C, although a large amount of air was pushed into the downstream. For use of WRC, although adding it on the top of the riser helped alleviate geyser height, it did not help reduce the pressure in the system. When larger diameter riser is used, peak pressures drop at all pressure measurement locations, but the peak pressures at different pressure measurement locations are similar, as shown in Table 5.2.

Table 5.2 Geyser heights and peak pressures summary for Series C and Series G

Run	Q_0 (L/s)	Q_1 (L/s)	h_r *(m)*	*h (m)*	P_{max} at PT3
C4	20	40	0.1	2.19	15.19
C5	20	40	0.2	2.49	17.84
C6	20	40	0.3	2.64	18.86
C1	15	40	0.1	3.23	18.56
C9	25	40	0.3	2.21	16.49
C12	30	40	0.3	1.90	13.08
G1	20	40	0.1	1.68	15.39
G2	20	40	0.2	1.75	16.09
G3	20	40	0.3	1.80	17.10
G4	15	40	0.1	1.88	17.15
G5	25	40	0.3	1.52	14.08
G6	30	40	0.3	1.31	12.40

When a larger diameter riser is used, the geyser phenomenon is alleviated in terms of height. All the maximum geyser data are summarized in Figure 5.29. It can be seen that when the maximum geyser height is the same, the peak pressure is smaller when riser diameter is larger. As all the geyser height decreased for all cases with a larger diameter, peak pressure would decrease more.

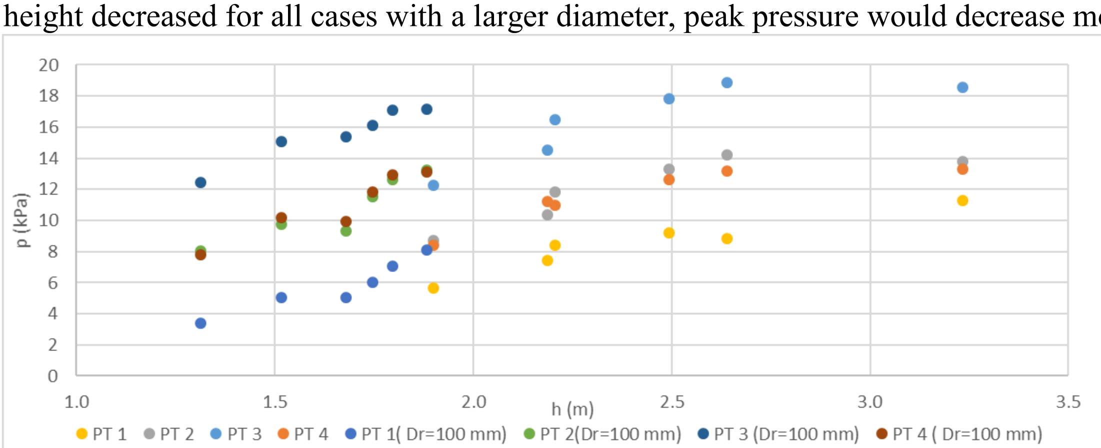


Figure 5.29 Peak pressures vs. maximum geyser heights with original and larger size riser

6. Conclusions

6.1 Summary of the Present Study

This thesis reports an experimental investigation of two important aspects related to geyser events in stormwater drainage systems: geyser mechanism and retrofitting methods. A physical model, which consists of an inclined upstream pipe at a slope of 1%, a chamber with a vertical riser and a horizontal downstream pipe, with a scale of around 1:20, was built in the T. Blench Hydraulic Laboratory at the University of Alberta. In the experiment, four pressure transducers were used to record the pressure data in the upstream pipe crown, chamber bottom, chamber top and riser, one additional transducer is used to measure the pressure in upstream pipe bottom for some of the cases, and the sixth one is used to measure the pressure in downstream pipe for selected cases. Four cameras were used, with two tracking the water movement in the upstream pipe, one focused on air/water interaction in chamber and riser and another one recording the height of geyser. Bulbs were used along the pipe and connected to the data acquisition board, so that the pressure measurement could be synchronized with the video recording.

Eight series of experiments have been conducted, with three series focused geyser mechanism and five on geyser mitigation. Two geyser formation mechanisms have been studied, which are the propagation of rapidly filling front and the air releasing from the air pocket. The rapid filling regime is divided into two categories, downstream initially open channel flow or downstream initially full pipe flow. Three geyser mitigation methods have been tested, which are orifice plate on top, in the middle or at the bottom of the riser, water recirculation chamber on top of the riser and enlarged diameter riser.

Based on the physical experiments, several conclusions can be summarized as follow:

- Geyser events are not likely to happen when a filling front is advancing from upstream to downstream while downstream is open channel flow with a lower water level. As the inflow rate suddenly increases, the downstream pipe is large enough for all the air to pass quickly. Water column can be seen in the riser after surge front strikes the chamber wall and reflects back to fill the chamber.

- Geyser events can be triggered by a rapidly filling front while the downstream pipe is full. As the downstream pipe is full, when the inflow rate is suddenly increased, it would take some time for the downstream pipe to adapt to the new flow rate, so that water could fill the chamber rapidly and shoot out vertically through the riser.
- Geyser can also be triggered by the movement of an entrapped air pocket in the upstream pipe. As the air pocket is formed when a tailgate is lowered down to partially block the outflow at the downstream pipe outlet, the capacity of outflow in the system is limited. When inflow rate increased to the desired value, the thin layer of air that existed on top portion of the upstream pipe between chamber and head of the air pocket would be pushed into the riser, followed by main air pocket advancing towards the chamber, entering the riser and cause geyser. This type of geyser formation is commonly seen in the field, and the geyser events would go on intermittently as air pocket was separated into smaller discrete air bubbles.
- Installation of the orifice plate is effective to decrease the geyser strength for Series B. In series B, only two geyser event were captured in the form of mist. As for the peak pressure produced by same size orifice but different location of orifice plate at PT1, orifice plate on top of the riser would produce higher pressure as the entire riser is pressurized. As for the orifice plate with different orifice size installed at middle/bottom of the riser, a smaller peak pressure at PT1 and larger peak pressures at PT2-PT4 are seen for smaller opening orifice plate.
- Using orifice plate is effective in mitigating geyser for Series C. When orifice plate is used on top of the riser, the height of geyser is higher than the original case for 6mm and 12mm orifice plate, but in a form of thin water jet or mist, so that the amount of water shooting out is greatly reduced. An orifice plate with a 12 mm orifice size (1/5 riser diameter) is dangerous

to the riser, as a sharp peak pressure is recorded, along with a large sound heard in the riser. Geyser height is lowered when the orifice plate is installed at the middle of the riser for same orifice plate size cases, while the pressure at different locations remain the same. No sharp peak pressure at PT1 is recorded when orifice plate is used at the middle of the riser. When orifice plate is used at the bottom of the riser, the pressure at PT1 is lowest among the three locations, while a small increase in pressure can be seen at PT2-PT4. Of particular importance, the larger orifice plate (30 mm) should be avoided to be installed at the bottom of riser, as it would act as a smaller diameter riser and cause more severe geyser.

- The enlarged diameter riser is helpful in reducing geyser height because the larger cross-sectional area could provide more room for air ventilation. In terms of lowering the pressure, however, larger riser does not help much as it does not change the way water flows in the system, i.e. no bent is used to redirect flow, water is not pressurized, etc. Even if the pressure is not a big concern, making the dropshaft larger can still be difficult for construction.
- No visual geyser is observed when a WRC is used on top of the chamber for Series B. As geysers in Series B is caused by rapid filling of water, WRC provides a chamber where air and water can be separated. The bent which redirects water from shooting up vertically to going horizontally into the WRC is also helpful because energy can be dissipated through the process. WRC does not help in lowering the pressure at all locations. Several droplets of water splashes on the ground when WRC is applied to Series C. Although geyser height and maximum pressure stays the same as the original set up without WRC, the amount of water shooting out is greatly reduced, so that it would still be useful in the field.
- From the experiment, smallest size (6mm) of orifice plate installed at the bottom of the riser is the most effective way for geyser retrofitting, but a large amount of air travelled downstream, which might be a concern for prototype sewer system.

This study is based on a real scale model, so that the practicality can be expected from this research. As most of the studies on geysers only focused on the mechanism, the study of both mechanism and retrofitting using the same set up is more comprehensive and complete in understanding geyser.

6.2 Recommendations for Future Works

This study is focused on finding out the mechanism and retrofitting methods of the geyser. In this study, the different combination of inflow rates for each series are tested. For severe cases from Series B (rapid filling regime), the geyser could go up to several meters in height, with a peak pressure of nearly 50 kPa, measured at bottom of the chamber. For severe cases from Series C (release of air pocket), the explosive nature of geyser events is seen, with a mushroom-shaped pocket of water released into the air and dropping down to the ground. After retrofitting, geysers are mitigated either by not shooting out through the riser or by shooting out in the form of mist. Although this is an extensive study on the geyser, the essence of unsteady two-phase flow in the stormwater system is still limited, and there are many opportunities to extend the research to understanding the geyser better, both in the lab and in the field, which are listed as follow:

- Despite that the result of experiments for Series C coincides with the large-scale experiments done by Muller (2016), the scale effect could still affect the result as the riser diameter is still too small to simulate the real air-water interaction, especially for retrofitting methods.
- In all the experiments, the valve opening time is around 0.20 s, but this is not the case in reality, as the rapid filling of the stormwater into vertical shafts is expected to take some time, so that experimental study combined with hydrograph is necessary.
- The pipe joint of the upstream pipe could prevent the entire air pocket from going into the chamber, so that the tail of the air pocket would always stuck at the pipe joint, which could have an impact on the overall duration of geyser event for air pocket release cases.

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