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EXPERIMENTAL STUDY OF VOID FRACTION EFFECT ON FLOW CONTINUITY IN A SIPHON

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ABSTRACT

A siphon is a Ƞ-shaped conduit employed to transfer liquid from a higher elevation to a lower elevation via gravity. It has application when the liquid is required to be transferred without an external pump as a power source. All siphon applications require initial priming, followed by a natural siphoning process to continue the liquid flow without interruption. However, when the fluid is at the saturated condition or contains an abundance of dissolved gases, the suction process will produce a large amount of gas or vapor bubbles that may eventually disrupt the natural siphoning process. The motivation for this study is to prevent the discontinuity of the siphoning process by investigating the critical void fraction (CVF) of gas/vapor bubbles that can suspend in the liquid flow before the natural siphoning is interrupted. The volume and weight methods are used to determine the amount of air bubbles inside the liquid siphon before the flow is interrupted. The experimental results show that the natural siphon can sustain up to 65% of the void fraction before the flow is interrupted. A series of qualitative experiments are performed on the siphon to present means of rejuvenating (or repriming) a stalled siphon. The results from this study will help in determining the operating characteristics of two-phase flow necessary to sustain a naturally siphoned condition in many applications associated with two-phase flow transports. Understanding of the physics with the quantitative data obtained from this study can help reduce the pumping power and reduce the energy consumption of two-phase flow transports.

KEY WORDS: Two-Phase Siphon, Bubbly Flow.

1. INTRODUCTION

1.1 Background

A siphon is a Ƞ-shaped conduit employed to transfer liquid from higher elevation to lower elevation via gravity. The flow is usually sucked from the source on one side of the conduit by the low pressure created at the highest point in the siphon and flows down the other side via gravity. The flow speed is directly related to the elevation difference.

A siphon has application when the liquid is required to be transferred without an external pump as a power source. Siphons are employed in many industries such as water and waste water systems, nuclear power plants, and the paper industry. In the fermentation process, siphons are used to transfer liquid from one container to another and to prevent the flow of bubbles or foam. In irrigation systems, siphons are commonly used to transfer water over a ditch or elevation with a simple application of initial priming. The groundwater can be transferred using siphons; however, an important factor is the degassing of the flow that can interrupt the natural siphoning process. In nuclear power plants, siphons breakers are used to prevent the natural siphoning of liquid water out of the reactor pool, thus, preventing the loss of coolant accident (LOCA). In the pulp and paper industry, blow-through steam is used to remove condensate from inside high-speed rotating dryers using siphons. The condensate removal process consumes a large quantity of steam to entrain the condensate out of the siphon. The steam consumption in a stationary siphon, a rotary siphon, and Yankee dryers is 10 to 15 % [1], 15 to 25% [1], and 40 to 90 % [2] respectively.

All the siphon applications require initial priming, followed by the natural siphoning process to continue liquid flow without interruption. However, when the fluid is at the saturated condition or contains much dissolved gases, the suction process may produce a large amount of vapor or gas bubbles via cavitation or flashing that may eventually

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disrupt the natural siphon process, adversely impacting the operation or even causing hazardous accidents. For example, in paper dryer applications, flashing of saturation condensate [3] requires more steam to push the condensate out of the siphons. An efficient transport of fluid through the siphon will help reduce energy consumption in irrigation systems, the paper industry, and water and waste water systems.

In the current study, experiments are performed on the flow of air bubbles entering a simple siphon. This simplification is performed to experimentally measure the amount of air bubbles that can sustain the natural siphoning process under atmospheric pressure conditions. Moreover, a series of qualitative experiments are performed to study the repriming of a stalled siphon.

1.2 Motivation and Objective

The motivation of this study is to achieve an uninterrupted flow inside a siphon and use the natural siphoning process to remove the fluid for a two-phase flow inside a siphon in order to save energy. When a two-phase flow is considered, it is always intriguing to inquire what role bubble dynamics will play in affecting the flow behaviors that are not seen in a single-phase flow. The curiosity is usually raised by questions like, for example, "Will the bubbles coalesce to form a bigger bubble and block the natural siphon process?" or "Will more power or suction force than that required in a single-phase flow be required to rejuvenate the natural siphon when it is stopped?" To this end, the overall objective of this study is to conduct experiments to understand the fundamental behavior of vapor/gas bubbles inside a natural siphon and its impact on sustaining or interrupting the natural siphon processes under various conditions. To achieve this objective, the following specific tasks are established (a) determine the critical void fraction (CVF) — the maximum volume ratio of air/vapor bubbles — that can sustain the bubbly siphon flow before the siphon flow is interrupted and (b) explore the means to rejuvenate (or reprime) the flow.

2. THEORY OF THE SIPHON

A simple siphon is shown in Fig. 1. It consists of a simple tube that is used to transport liquid from point B to D, such that B is a higher elevation in the gravitational field than D. In the siphon, point C is the apex point which is the highest point in the siphon. The pressure at point A and point D is atmospheric pressure, P_{atm} = 1 atm. The flow of liquid moving under atmospheric conditions at point A to the other location (point D) where the same atmospheric conditions exist seems to be uncommon as compared to, for example, a pipe flow where flow moves from a higher pressure to a lower pressure. To initiate a simple liquid siphon without bubbles, the liquid is first sucked at point D to fill the tube with water and establish the flow field and accompanying pressure distribution in the siphon—this is basically **priming the siphon**. As the initial pressure field is established the liquid starts to flow. Figure 1 shows the pressure at different locations in the siphon. At the apex point C, the pressure is the lowest, thus, liquid flows from atmospheric pressure at A to below atmospheric pressure (i.e., vacuum) at point C, which is a pressure driven flow. However, from point C to D, the liquid flows due to gravity. The elevation difference between A and D as shown in Fig. 1 as $h_{D,}$ is the driving potential of the siphon flow. To maintain the same flow speed, the elevation head (h_D) should be maintained at a constant value. The siphon with continue the flow of liquid from the tank as long as the level of liquid in the tank is maintained, thus, the tank should be continuously replenished at the rate of flow through the siphon.

To obtain the baseline pressure distribution in a conventional liquid-only siphon, apply the frictionless Bernoulli equation at points A and D of the system shown in Fig. 1 and neglect the frictional effects in the siphon, to obtain

$$\frac{P_A}{\rho g} + \frac{v_A^2}{2g} + h_A = \frac{P_B}{\rho g} + \frac{v_B^2}{2g} + h_B \tag{1}$$

Substituting $P_A = P_D = P_{atm}$, $v_A = 0$, and $h_A = 0$, Eq. (1) gives the velocity at the exit of the siphon as a function of height, neglecting the friction, as

$$v = \sqrt{2gh} \tag{2}$$

In the literature two theories co-exist which explain the operation of the siphon. In some research work the driving forces for the siphon are the atmospheric pressure and gravity. However, other research work has explained the siphon operation using the chain model that signifies the cohesion and gravity responsible to operate a siphon. According to the chain model of the siphon, the intermolecular forces between the water molecules play a larger role while atmospheric pressure does not. The earliest work in support of the chain model of the siphon [4] shows that the siphon cannot operate under vacuum conditions due to the discontinuity caused by expansion of air bubbles as water flows inside the siphon. In the work of Potter et al. [5] it was concluded via an explanation based on Bernoulli's equation that the atmospheric pressure is not required for operation of the siphon. In the literature, there are various studies that support either of the two theories for explaining the working of a simple siphon [4–13].

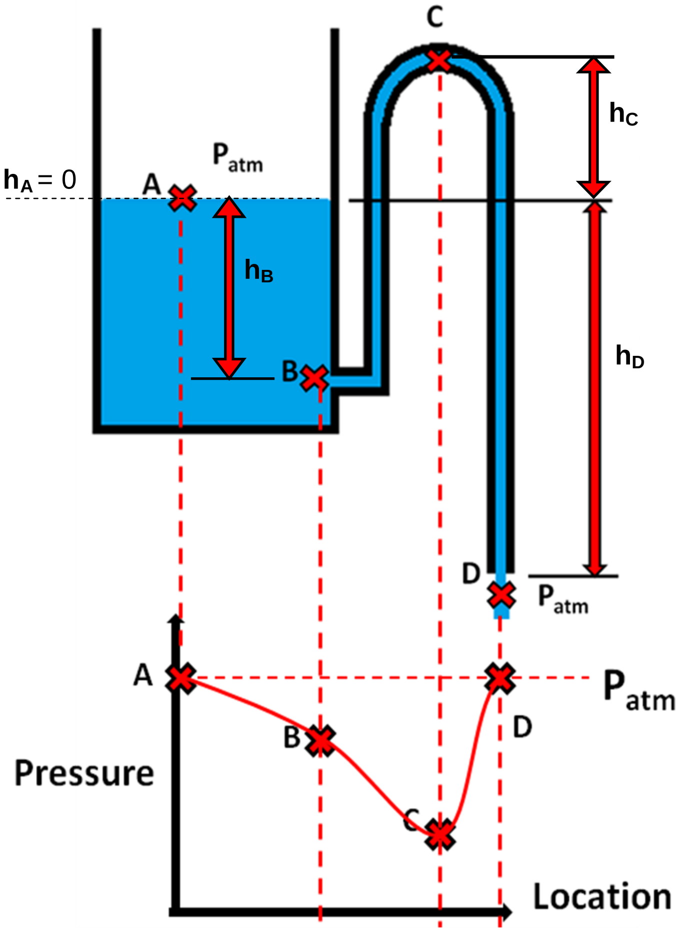

Fig. 1 Pressure profile in a siphon.

Ganci et al. [6] discussed the controversies surrounding the operation of the siphon. Ganci's research presented a brief time history of siphon development in both experiment and theory. The role of cohesion in the operation of the siphon was disproved by Ganci et al. [6]. An experiment was performed to show a train of bubbles added to the siphon still continued the siphon operation. However, as the size of the bubble added to the apex becomes large the siphon ceased.

Hughes [7] performed experiments to support the chain model of the siphon. In this work, the flow rate in the siphon was shown to depend on the pressure difference between the inlet and outlet of the siphon and not on the atmospheric pressure. According to Hughes [7], atmospheric pressure cannot be the driving force of the siphon operation. Planinšič et al. [8] disapproved of the chain model of the siphon and conducted experiments to disprove the chain model. Ramette et al. [9] did an experiment with CO_2 siphon to disprove that intermolecular force plays a part in the operation of the siphon. Moreover, they performed experiments to claim that the siphon can operate under vacuum conditions and does not rely on air pressure.

Hughes [10] conducted an experiment to show that the siphon operates due to the gravity effect. This research work discussed the situation of bubbles inside the siphon where both gravity and atmospheric pressure have a role. Richert et al. [11] disproved the chain model of the siphon and showed that both gravity and pressure play a major role in the operation of the siphon. Four set of experiments were conducted by Richert et al. to show that siphon operation depends on the atmospheric pressure and that the chain model of the siphon is erroneous. Hughes et al. [12] performed an experiment under low pressure conditions and observed a waterfall effect in the siphon flow after the apex point when pressure was reduced below 0.18 atm. In this work, the flow in the siphon was shown to break into two barometers as the pressure was reduced. Boatwright et al. [13] studied the height of siphon when the apex is at 15 m from the siphon inlet using water which was initially degassed. They claimed that the siphon operated due to molecular cohesion and gravity. Although the above discussions were all related to a single-phase siphon, the fundamental theory is identical with two-phase flow siphons, i.e., the siphon flow is driven by the hydraulic head and gravity and the lowest pressure occurs at the apex. Due to the vacuum condition at the apex, cavitation or flashing can occur during the uprising part of the siphon flow, resulting in two-phase siphon flow. In this research paper, our focus is not on explaining the working of the siphon but to perform experiments on two-phase flow and the repriming of a two-phase siphon. The following section explains the details of the experimental setup used in the experimentation.

3. EXPERIMENTAL SETUP

3.1 Experiment Test Facility to Determine the Critical Void Fraction (CVF)

The simplified experimental setup using an air-water mixture was designed in the laboratory to simulate the vapor-condensate mixture. The first task is to determine how much air (in terms of volume fraction) is allowed in the natural siphon flow before the flow is interrupted. The following diagram in Fig. 2 illustrates the layout of the experimental stand and its associated components, including the reservoir tank, water tank, siphon, valves, and liquid-receiving bucket.

The experimental setup consists of two valves. The air valve, as shown in Fig. 3, is used to control the amount of air added to the siphon. The air valve is operated manually and the graduations are reported in the experiment. The water valve is used to control the flow of water from the reservoir tank to replenish and maintain the fixed water level in the tank. Ideally, the water level in the tank should be maintained at a constant height just above the siphon tip. The reservoir tank is replenished with water from a faucet.

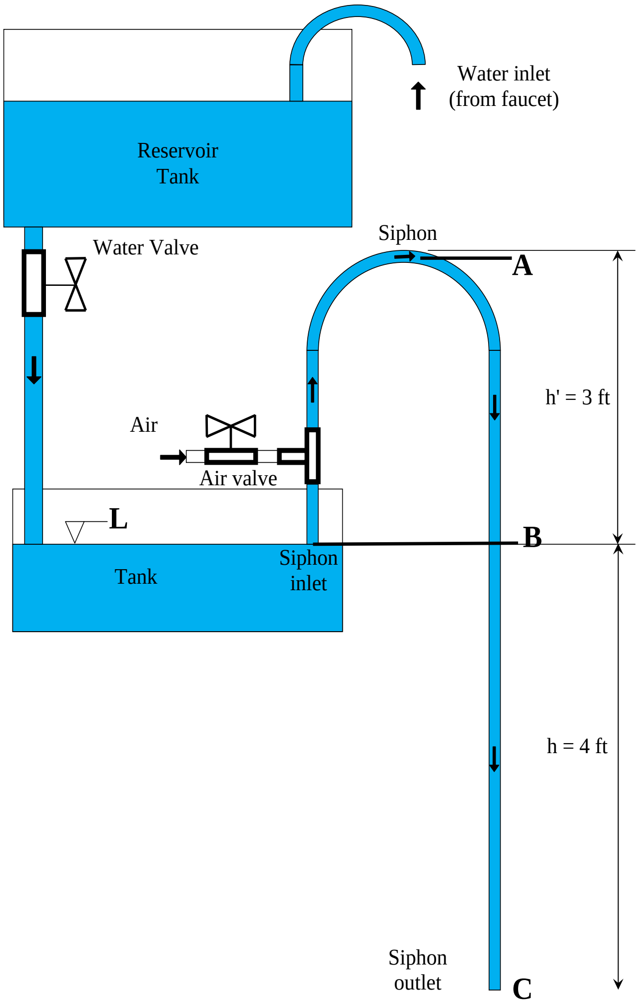

Fig. 2 Schematic of the siphon experiment. The locations of A, B, and C correspond to those marked in the experimental setup shown in later figures.

The operation of the experiment started with filling the reservoir tank. The water valve was completely opened to fill the tank up to the marked height just above the tip of the siphon. The siphon was initiated by suction at the outlet end of the siphon. The water flows from the tank and is siphoned to the bucket placed at the siphon outlet. The volume flow rate was measured by specifying the volume of water collected in 180 seconds. The water valve was adjusted such that the water level is maintained in the tank to ensure a constant head to the liquid flow in the siphon. The air valve was slowly opened to allow ambient air to be entrained into the siphon due to the negative gauge pressure (vacuum) in the siphon. The air broke up into bubbles as it entered the siphon. Two methods were used to quantify the air bubble in the siphon namely the volume method and the weight method. The volume method measured the volume of water collected after 180 seconds per trial for different air flows introduced by the air valve. In the weight method, the weight of the water collected after 180 seconds was measured for different air flow rates. For each different procedure, three to five trials were performed at five different angles in the air valve. Starting at zero degrees, which is the baseline case (no air in the siphon); the valve angle was increased until the air flow interrupted the siphon flow. Each subsequent trial was compared to the baseline case to determine the volume of air passing through the siphon in 180 seconds. The results from both methods are compared and discussed in a later section.

Fig. 3 Air valve with graduations.

The volume method offered a straightforward way of calculating the volume of air flowing through the siphon by simply subtracting the volume of water per trial (V_t) from the total volume of water in the initial baseline case (V_b), as Eq. 3 shows,

$$V_a = V_b - V_t \tag{3}$$

The percentage of air inside the siphon is calculated as,

$$V_a(\%) = 1 - \frac{V_{avg}}{V_b} \tag{4}$$

The weight method used the same approach but with an additional step. For each trial, the mass of water collected was converted into volume using density (Eq. 5). Then Eqs. 3 and 4 were used as in the volume method.

$$V_t = \rho_w \times m_w \tag{5}$$

The effect of the height of the siphon, represented by the distance of the apex point to the siphon inlet, h’ in Fig. 2, is investigated for a siphon with apex height of 1.542 ft, 2 ft, 2.5 ft, and 3 ft respectively. In all cases the distance between the siphon inlet and outlet (the hydraulic head of the siphon) was fixed to represent a constant driving force for the siphon. The experiment was repeated for each siphon height and reported as the average of the trials. The weight method was repeated and compared for each siphon height.

3.2 Experimental Test Facility for Re-Priming of a Two-Phase Siphon

To allow the convenient application of different re-priming methods, another set of experimental setups was constructed. In this second setup, the air was not aspirated into the siphon as in the previous setup; rather, the air was drawn from a compressed air source. A water spout was attached to the water tank and was turned facing upwards so that the siphon tube can fit into it from the top, instead of from the bottom, creating a conventional, simple siphon. The siphon is made of a PVC tube of 0.25” inner diameter and was fixed onto the supporting frame. The water tank is fed with water from the reservoir at the back of the support structure. Figure 4 presents the initial level of water inside the water tank (L), the level of inlet of the siphon (B-B), the level of the apex height (A-A), and the outlet of the siphon (C).

Fig. 4 The experimental setup to study re-priming of a two-phase siphon.

4. RESULTS AND DISCUSSIONS

This section presents the results in three sub-sections: the maximum volume of air to interrupt the water flow in the siphon, the effect of apex height of the siphon, and the repriming of a stalled siphon.

4.1 Critical Void Fraction (CVF)

In this study the maximum air/vapor volume ratio, known hereafter as the critical void fraction (CVF),that will interrupt the water flow in the siphon is determined. The apex height of the siphon is fixed to 1.524 ft. The baseline case is the case when water flows in the siphon with no air bubbles i.e. the air valve is closed at 0°. As the valve is opened to a specified degree, air enters the siphon and is carried by the water flow into the siphon in the form of air bubbles. Both the volume method and the weight method, described in the section above, are used to estimate the volume of air. The results for the void fractions (volume percentage of air) added to water flowing in the siphon before it stopped are shown for the volume method and the weight method in Table 1.

Table 1 Void Fraction (Air percentages) for the volume method and the weight method.

Volume method			Weight method		
Angle, θ (degrees)	Average Volume of Water (L)	Void Fraction (%)	Angle, θ (degrees)	Average Volume of Water (L)	Void Fraction (%)
0	6.9	-	0	7.45	-
11	6.5	5.8±1.9	12	6.82	8.5 ± 0.39
15	3.9	45±0.35	18	5.36	28 ± 0. 34
20	2.7	57.9 ± 0.4	20	4.09	45.1± 0.26
25	2.3	66.7 ± 0.3	25	3.09	58.1 ± 0.19

The comparison of volume of water with the baseline case is used to estimate the percentage of air added to the siphon. The results show that the air percentage increases with higher air valve angles. The maximum percentage of air that can be sustained in the siphon is 66.7 % and 58.1 % for the volume method and weight method respectively. This result is significant as it shows that approximately **67 % of air by volume** can sustain the natural siphoning process. Or it can be more conservatively stated that the critical void fraction is about **62%** with a mass flow rate of 38% of the original liquid-only single phase siphon. The results in this study are for a fixed apex height of 1.524 ft. It will be interesting to know if the apex height will affect the critical void fraction, which will be presented in the following section.

4.2 Effect of Apex Height

In the simple siphon shown in Fig. 1, the pressure drops to the lowest value at the apex of the siphon. As mentioned in the theory of the siphon, the strongest vacuum is created at the apex point that creates the suction required to move the water column upward from the inlet to the apex point and the flow beyond the apex point. For a single phase liquid siphon, the flow rate is determined by the hydrostatic head between the siphon inlet and outlet, so the apex height will not affect the flow rate. However, it is not clear whether in a two-phase flow siphon the apex height would affect the CVF and flow rate. In this study, the effect of apex height of the siphon, h' in Fig. 2, is investigated. The results in Table 2 do not show a clear trend or conclusion. The CVF value decreases as the apex height increases from 1.524 ft to 2.5 ft, but it is clear that, at h' = 3.0 ft, the CVF is up to about 71%. It seems that increasing apex height will create more suction inside the siphon, thus, more air is added to the siphon flow, though the current results for 2ft and 2.5ft are not conclusive.

Table 2 Volume fraction of air for increasing siphon apex height.

Angle, θ (degrees)	h' = 1.542 ft	h' = 2 ft	h' = 2.5 ft	h' = 3.0 ft
10	3.3 ± 4.3	5.3 ± 3.6	7.7 ± 0. 5	8.4 ± 11
11	31 ± 0.4	19.7 ± 0.5	36.7 ± 0. 4	22.4 ± 0.5
13	51 ± 0.3	48.2 ± 0.4	54.1 ± 0.3	43.7 ± 0.3
14	60 ± 0.3	60 ± 0.5	54.9 ± 0.4	51.4 ± 0.3
16	62.8 ± 0.3	-	-	70.9 ± 0.3

4.3 Repriming of the Siphon

The previous set of experiments shows that the liquid siphon can sustain as high as a 67 % void fraction of air. This is a very favorable outcome as it could mean that for applications involving two-phase flow due to cavitation or flashing, the siphon can still be applied without using external power to move the two-phase. In this next set of experiments, a basic siphon study was performed to investigate the re-priming phenomenon and the methods of a simple two-phase flow siphon. The objective of these set of experiments is to look into different approaches to re-prime the siphon if it is interrupted. The experiments are presented in the sequence that they were performed, each with an initial hypothesis on the physics that could occur, followed by using the actual experimental results to support, modify, or even deny the initial hypothesis. The experiments were performed with the single liquid phase first, followed by using two phase air-bubbly flow.

<u>*4.3.1 Experiment 1 – Initial water level lower than the apex of the siphon.*</u> In this first experiment, to simulate the most common practice of siphoning, the initial water level was set lower than the apex and the siphon tube was empty at the beginning. Before performing the experiment, it was thought that the natural siphon would not occur unless a suction force was applied at the siphon tube outlet. After the spout was opened in the experiment, the water entered the siphon tube and only rose up to the same level as the water in the tank. No siphon was formed. This hypothesis was obviously right! After suction was applied to raise the water over the apex, a natural siphon was initiated. In this experiment, it was believed that the pressure distribution as shown in Fig. 1 has been established by the externally applied suction force so that the lowest pressure can be achieved at the apex (location C) in Fig. 1.

In some real applications involving **saturated** liquid, the practice of applying **suction** at the rear end of the siphon is a concern, because more saturated condensate will flash into vapor, making it difficult for the siphon to start or to be stable at the beginning. Thus, it is thought to be a better approach if a high pressure source, like a compressed air or nitrogen gas, can be applied at the siphon inlet inside the container for a short instant as needed. Furthermore, it was thought that this high pressure source could raise the overall pressure field in the siphon in such a way that the pressure at the apex could become higher than the atmospheric pressure, and hence flashing phenomenon of the saturated condensate might be removed. However, the means to connect a compressed air source to the existing open-top water tank setup required the water tank to be sealed. This would have been inconvenient to the experiment because the ambient pressure would be cut off from the siphon inlet. Thus, more water was added into the tank to raise the water level, which will provide an effect similar to the application of compressed air. The overall-raised pressure distribution inside the siphon is hypothesized in Fig. 5. This led to Experiment 2 as explained in the following section.

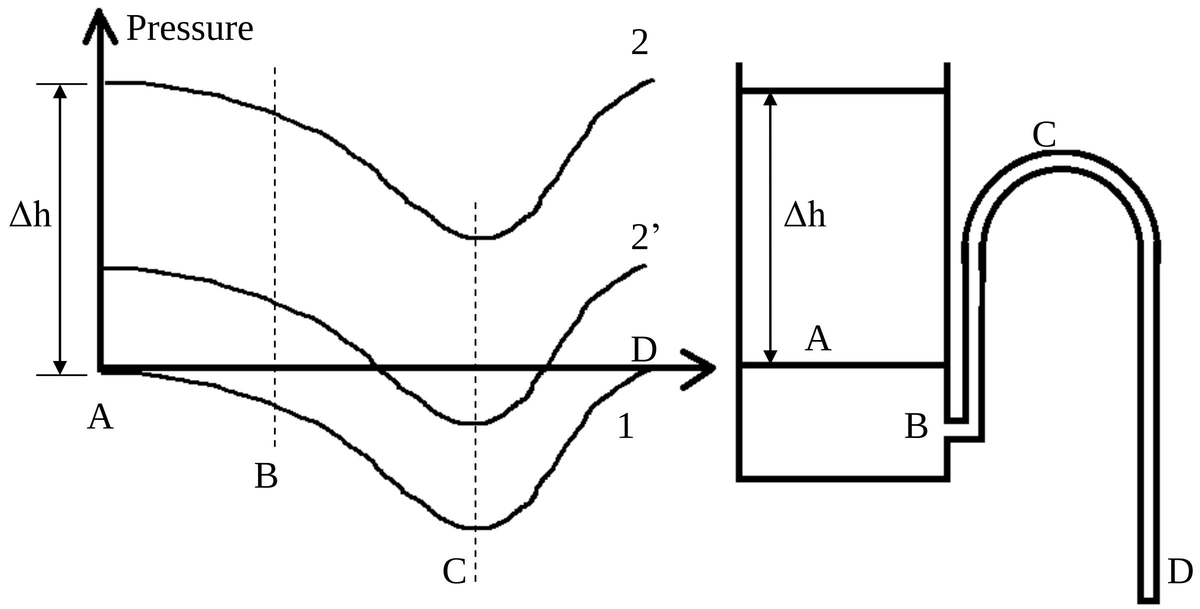

Fig. 5 Hypothesized pressure distribution inside the siphon when the water level in the tank is higher than the apex and its variations as the water level continues to descend to below the apex level. (Note: This hypothesis is wrong and will be corrected later in the paper).

<u>*4.3.2 Experiment 2 – Initial water level is higher than the apex of the siphon, but no make-up water is added until the water level descends below the apex.*</u> In this second experiment, the water tank was initially filled with a water level higher than the apex of the siphon as shown in Fig. 5. The siphon tube was empty in the beginning. As the spout was opened, the water entered the siphon tube and rushed past the apex of the siphon because the water level in the tank was higher than the apex—i.e. the natural siphon started. The water head at the inlet of the siphon represents the pressure head required to push the water through the siphon as shown in Fig. 5.

Now, the next question arose: if the water level in the tank moves below the apex, **will the siphon continue or discontinue?** *It was hypothesized that the natural siphon will continue even though the water level in the tank reduces to lower than the apex elevation because as the apex pressure dips below* P_{atm}*, the lowest pressure at the apex will produce a suction force to lift the water column to the apex to allow the siphon flow to continue*.

The experiment was conducted and the result was consistent with our hypothesis: the siphon flow continued even though the water level became lower than the apex (Fig. 6). More specifically, it was further observed that not only did the liquid flow continue, even when the water level descended to below the upper edge of the spout—about 50% of the inlet of the spout started to be exposed to the air—but also the flow still continued with air bubbles moving in the flow. This was very similar to the phenomenon observed in the experiments for determining the CVF in previous section 4.1. Meanwhile, a loud noise could be heard from the suction of the air-water mixture at the inlet of the spout, the bubbly flow moving along the siphon, and the bursting of the air-water mixed flow sputtering out intermittently from the outlet of the siphon. **This loud noise was impressive and important because it manifested the strong suction mechanism generated at the apex. It strengthened the core concept of this study by using the natural siphon principle to remove liquid water even though flashing/cavitation occurs and the inlet is only partially flood with liquid. It also further emphasized the importance of executing adequate priming of the siphon to ensure the required pressure distribution for natural siphon is established**.

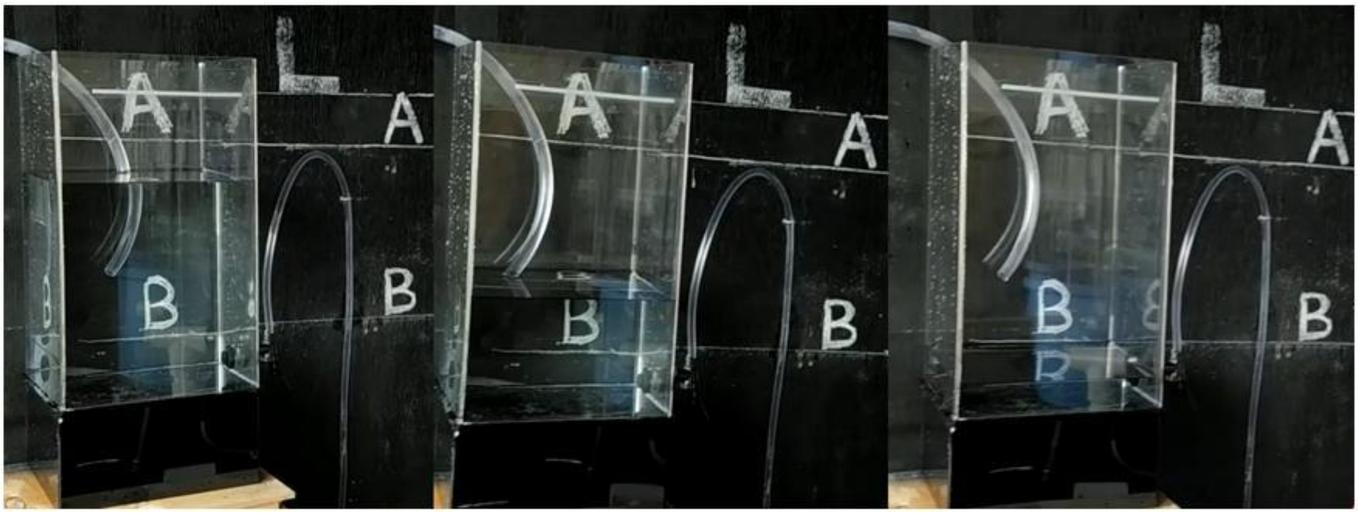

Fig. 6 The water level in the tank is lower than the apex height and the siphon continues.

Fig. 7 Close-up of water level lower than the top edge of the spout in the tank (left) and air-water mixture sputtering out loudly at the siphon outlet (right).

<u>*4.3.3 Experiment 3 – Reprime after shut off of the flow when the water level in the tank is lower than the apex.*</u> In Experiment 2, the siphoned flow continued even though the water level in the tank reduced to below the apex. Then there are two questions to consider: (a) If the spout is shut off what will happen to the flow in the pipe? (b) If the spout is reopened, will the siphon flow continue? Responding to these two questions, *it was hypothesized that (a) the water in the right leg would split at the apex and fall off under gravity, while the water in the left leg would stay in the tube because it had no place to go after the spout is shut off; (b) after the spout is reopened, the water in*

the left leg would flow back to the tank until it reaches the equilibrium level with the water surface inside the tank; no siphon flow will occur.

However, it turned out that these hypotheses were completely wrong! As the spout was turned off, the siphoned flow stopped but the water liquid in the right leg of the siphon did not fall under gravity. The water was actually stuck inside the siphon tube, fully supported by the atmospheric pressure at the siphon outlet. When the spout was opened again, the siphon continued without requiring any repriming. This phenomenon can be explained as follows: when the spout was opened again, the water in the right column of the siphon fell off, creating a low pressure or suction region at the apex. This suction effect lifts the water in the left leg of the siphon to the apex and continues the siphon. This experiment showed an interesting physics that contradicted the earlier intuition.

The complete failure of the hypothesis for Experiment 3 has prompted to re-exam the understanding of the fundamental physics of the siphon flow. During this re-examination process, a question arose: how strong is the suction at the apex after the spout is reopened? Will the strength of this suction head change as the water level in the tank changes? Earlier in Fig. 5 in experiment 2, it was hypothesized that Curve 1 is the pressure distribution along the siphon with the water level in the tank at 1; Curve 2 is the pressure distribution for Experiment 2 with a water level higher than the apex of the siphon; and Curve 2' is an intermediate pressure distribution when the water level in the tank is decreasing from level 2 to level 1. Based on the relationship of these three pressure distribution curves, it seems that the apex pressure changes with respect to the water surface level inside the tank, but Experiment 3 showed that after the spout was shut off, the pressure inside the siphon did not correlate with the water level information inside the tank. **This means that the pressure distribution inside the siphon filled with stagnant water is in hydrostatic equilibrium with the atmospheric pressure and it should be the same for all the situations regardless of the water level in the tank.** This means that only one pressure curve in Fig. 5 is correct and this unique pressure curve should be curve 1. **Therefore, the hypothesized curves for 2 and 2' are wrong!** But where did it go wrong? A further examination discovered that the hypothesis mistakenly applied the hydrostatic equilibrium concept to a dynamic flow condition by incorrectly adding the additional hydrostatic head Δh for condition 2 (water level above the apex case) to the static pressure at locations B and C. **Actually, the additional hydrostatic head Δh was 100% converted to the velocity head when the siphon flow starts: the larger the hydrostatic head, the higher the velocity or the flow rate, resulting in the same static pressure distribution inside and outside the siphon independent of the water level in the tank**.

<u>*4.3.4 Experiment 4 – Duplicating Experiments 1-3 with air-water two phase flow.*</u> The above three experiments were for 100% liquid water repriming studies. These three experiments were duplicated with an air-water mixture. The air bubbles were added at the siphon inlet through a tube supplying compressed air. Figure 8 shows the air bubbles added inside the water tank.

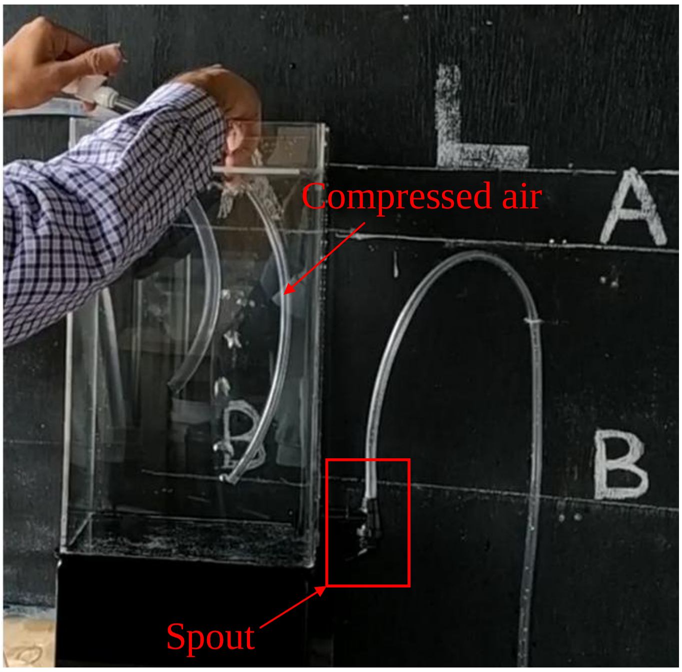

Fig. 8 Air bubbles added to the water tank via a tube supplying compressed air.

The experiment started with a water level, L, higher than the apex of the siphon. The spout was turned on and the natural siphon started as in the previously established single-phase experiments. The amount of air bubbles was qualitatively controlled by moving the compressed air tube closer or away from the spout inlet. Individual air bubbles were seen to move along with the flow in a well-organized, sequential manner in the ascending (left leg) and descending (right leg) parts of the siphon, whereas bubble coalescence and breakups were seen around the apex. Figures 9 to 11 show the close-up views of the air bubbles inside the siphon tube captured in a high-speed video in the left leg (before the apex), around the apex, and in the right leg (after the apex) of the siphon respectively.

Fig. 9 Air bubbles inside the siphon at the siphon's left-leg (before the apex).

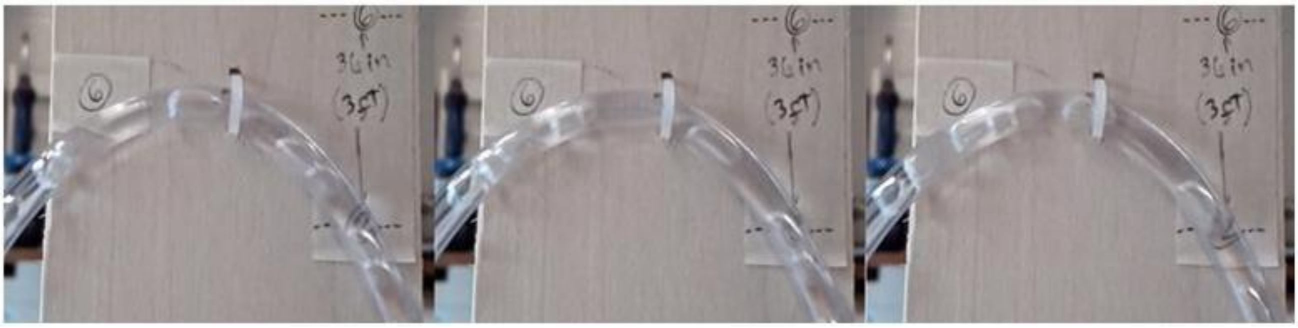

Fig. 10 Air bubbles inside the siphon tube at the apex of the siphon.

When the water level in the tank descended below the apex, the natural siphon continued with bubbly flow, until the water level reached as low as the inlet of the spout. If the spout was shut off when the water level in the tank was still higher than the apex, a natural siphon could restart without any problem. Moreover, when the water level descended lower than the apex, as the spout was shut off, the air-water mixture was stuck in equilibrium in the siphon with no fluid motion. Three key features were observed: (a) the water column with bubbles did not fall off from the right leg of the siphon; (b) all of the air bubbles in the left leg of the siphon slowly moved upwards to the apex and coalesced into a bigger bubble; (c) some of the air bubbles from the right leg also moved up (in the opposite direction) to the apex and coalesced to form a bigger bubble, but most of the bubbles stayed in the right leg stuck in the water column. Conclusively, after the spout was shut off and the two-phase flow settled in equilibrium, there were no air bubbles in the left leg of the siphon, a large air bubble presenting at the apex, and discrete air bubbles presenting motionlessly in the right leg of the siphon. As the spout was re-opened, the water in the right leg of the siphon fell down and the siphon continued. This behavior is shown at the apex in Fig. 12 below. This is an important phenomenon that can help formulate the automatic valve control algorithm in real applications with the understanding that the two-phase fluid will stay in the piping if the connection to the original hydraulic head is disconnected by turning off a control valve.

Fig. 11 Air bubbles inside the siphon at the siphon's right-leg (after the apex).

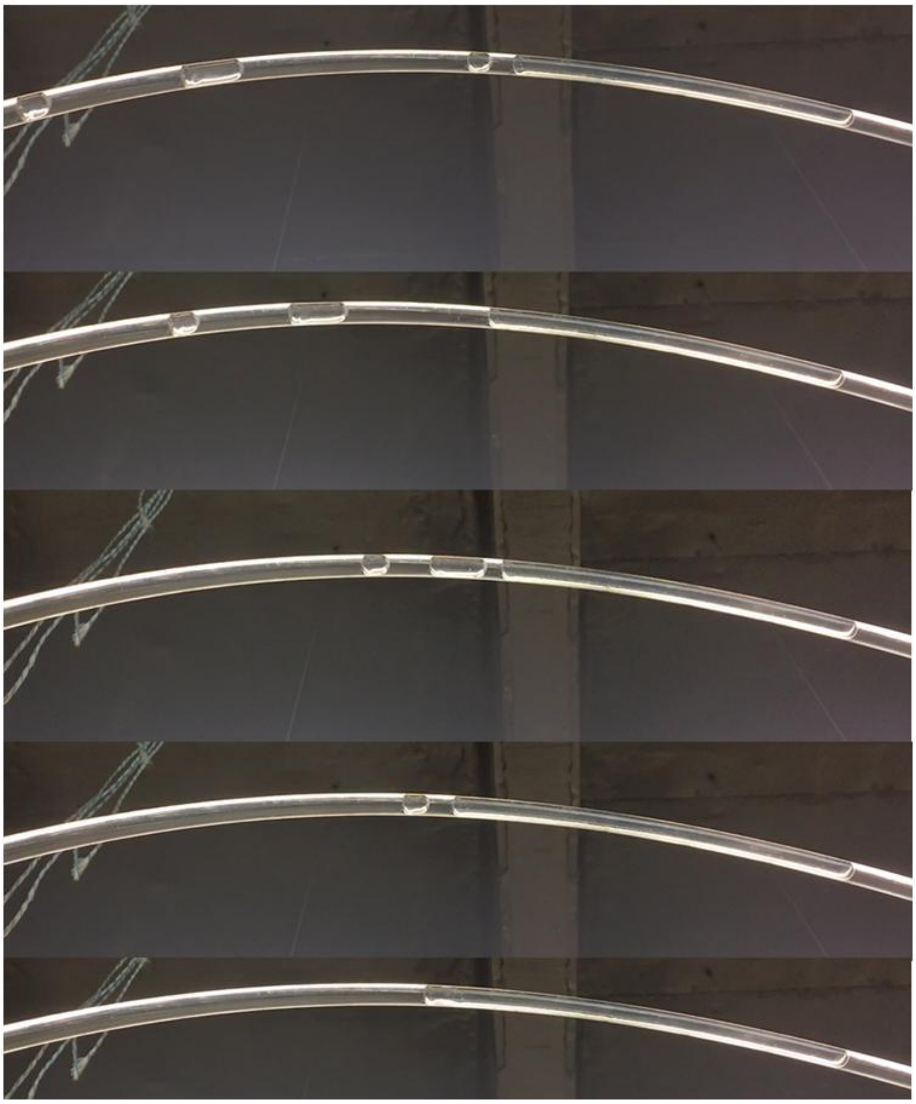

Fig. 12 Air bubbles in the siphon moving towards the apex (time is increasing from top to bottom) as the spout is turned off and finally reaches the equilibrium (last snapshot).

4.3.5 Experiment 5 -- Repriming the bubbly siphon by compressed air inside the tank. As shown in the previous experiment (section 4.1), as the air bubbles inside the siphon went beyond the critical void fraction (CVF) the natural siphon stopped. The experiment performed was similar to the setup shown in Fig. 8 wherein the liquid level is below the apex and the compressed air was added inside the open tank close to the inlet of the siphon with the objective of entraining the liquid water through the siphon. Noting that the tank is open to the atmosphere, the purpose is to guide the compressed air to flow inside the tube and, in the meantime, to entrain the liquid with it. This is different from the earlier idea of using the compressed air as a high-pressure source in a sealed tank to push the fluid through the siphon tube as discussed as a motivation for Experiment 2 via Fig. 5. However, in this experiment 5 it was concluded after numerous experimental trails that the compressed air added inside the water tank close to the siphon inlet cannot entrain the liquid water, thus, the siphon was not reprimed.

4.3.5 Experiment 6 – Repriming from outside of the tank using compressed air. The approach in Experiments 1-4 was to use a higher hydrostatic pressure (i.e., higher water levels) inside the water tank to reprime the siphon to simulate the operation of adding high-pressure steam or inert gas in a real application. However, even though higher-pressure steam can be easily obtained, it still is costly to generate and maintain it at a stand-by condition to make it available whenever it is needed. Another thought for reducing the operational cost was to consider whether it would be possible to use compressed air from outside the tank to restart or reprime the natural siphon flow. Compressed air at about 100 psia is easy and cheap to generate and store. Thus, in this last set of experiments, the compressed air was added via the T-connector outside the water tank**.** Figure 13 shows the apparatus for this experiment with the T-connector supplying compressed air from outside the water tank. The flow rate of the compressed air was controlled by a valve connected to the compressed air tube.

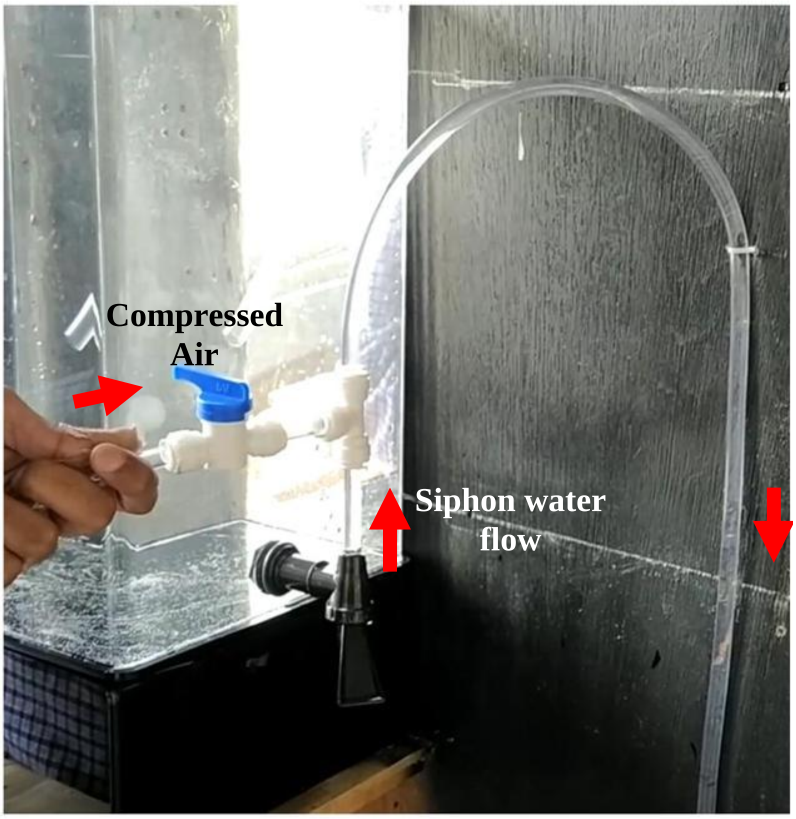

Fig. 13 A second compressed air tube added to a T-connector to the siphon to study repriming the siphon from outside the water tank.

This experiment started with setting the water level inside the tank initially higher than the siphon apex. The siphon tube was empty and the compressed air valve was closed. As the spout was turned on, the liquid water was naturally siphoned. Compressed air was added in the form of bubbles inside the tank to provide a bubbly flow, similar to the previous experiment. As the water level in the tank was descending below the siphon apex at marking "1" in Fig. 14, the compressed air valve for the outside compressed air tube was quickly turned on and immediately off, creating an impulse of compressed air surge to stop the natural siphon by purging all the liquid in the siphon. Since there was no flow at this point, the spout was turned off. It is known from the previous experiment that the water in the tank can't reprime the siphon in this situation because the water level inside the tank is below the apex. Now to explore if the siphon could be reprimed by the compressed air outside the water tank the air valve controlling the compressed air was opened slightly and gradually until it was observed that the compressed air was entraining the liquid condensate and restarted the natural siphon of the bubbly flow. This experiment was repeated four times with the water level changing from marking "1" to "5" as shown in Fig. 14. All the experiments successfully demonstrated the feasibility of using the compressed air to "jump start" the natural siphon process from outside the tank. Figure 15 illustrates the entraining mechanism induced by the compressed air injected from a side branch. This is a very exciting result since in some actual applications large amounts of high-grade steam is wasted in entraining the condensate from inside the container. Since the compressed air is only used for a very short instant during the repriming process, the amount is small and can easily be separated from the liquid later in a real application.

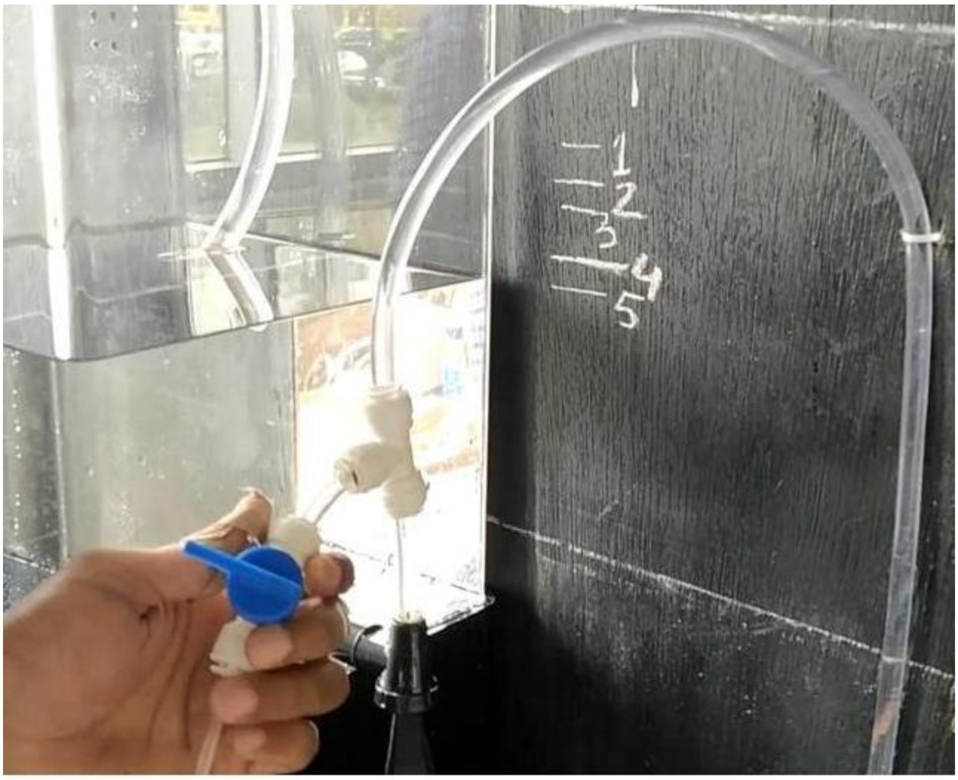

Fig. 14 Siphon primed by compressed air outside the siphon with initial water level 1 to 5 inside the water tank.

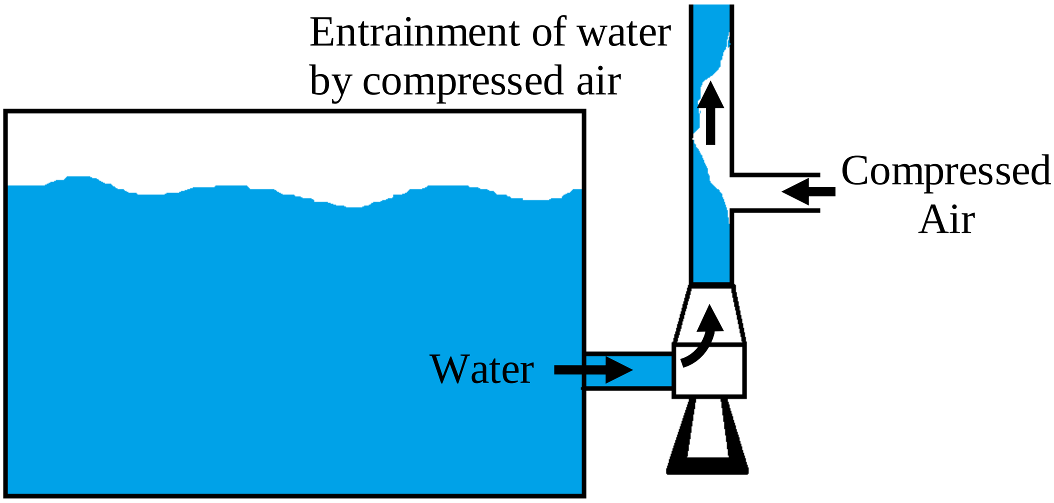

Fig. 15 Illustration of **e**ntrainment of water into the siphon by compressed air fed from outside the tank.

6. CONCLUSIONS

The study in this paper has application in transporting the two-phase flow using the natural siphon principle such as removing saturated condensate when flashing can occur or transporting liquid through a low pressure region when cavitation can occur. In this paper, two sets of experiments were performed: (a) measurement of the critical void fraction (CVF) or the maximum volume of air that can sustain the natural siphoning process and (b) study various repriming methods and the associated flow behaviors. The experiments were performed with single phase liquid flow first, followed by air-water bubbly flow. The conclusions for only the two-phase bubbly flow are presented below:

- The natural siphon flow can sustain a **maximum of 67%** of air by volume once the pressure field is established. This result is significant as it means that the saturated condensate can be removed via a natural siphon flow even though high volume void fraction bubbly flow can occur via flashing or cavitation.
- After the flow and pressure field was established in the siphon, it continues to flow even after the water level in the water tank was below the apex of the siphon and, furthermore, flow continues even the siphon inlet was only partially flooded. The latter is an important phenomenon that provides evidence to support a safety operating margin allowing the siphon inlet to be partially exposed to the air (or vapor).
- During two-phase flow operation of the siphon flow, an impressive loud noise was heard. This manifested the important behavior of a strong suction mechanism generated at the apex. This strong suction strengthened the core concept of this study by using the natural siphon principle to extract the condensate even though flashing occurred and the inlet was only partially flood with liquid. This loud noise was not heard during the single phase siphon experiments.
- The two-phase bubbly siphon was primed and restarted under conditions similar to a single-phase siphon even with large amount of air bubbles added at the inlet of the siphon.
- When the siphon flow was shut off by closing the valve, the two-phase mixture stayed in the siphon without falling off by gravity. This is an important phenomenon that can help formulate the automatic valve control algorithm in real applications with the understanding that the two-phase fluid will stay in the piping if the connection to the original hydraulic head is disconnected by turning off a control valve and the natural siphon can be restarted without priming, immediately after the valve is opened.
- The compressed air added at the inlet of the siphon did not prime the siphon by employing the tactics of entrainment.
- The final experiment showed that the compressed air supplied outside the water tank could reprime the siphon. This can have a significant impact in real applications because compressed air is cheaper to generate and store than high-pressure steam and that the application of priming from outside the tank can significantly reduce the manufacturing and maintenance cost and simplify the operating procedures.

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NOMENCLATURE

CVF	Critical Void Fraction
P	Absolute Pressure (N/m^2 or Pa)
g	Acceleration due to gravity (m/s^2)
h	Height (ft or m)
m	Mass of water (kg)
v	Velocity (m/s)
V	Volume (L or m^3)

Greek Letters

ρ	Density, (kg/m3)
θ	Position of the air valve (degrees)

Subscripts

a	Air
avg	Average of all the trial cases
b	Baseline case
t	Trial case

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