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Principles of Siphons

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Abstract

A simple siphon raises water over a crest and discharges it at a lower level. As water flows through a siphon, energy due to pressure and elevation is either lost to pipe friction or converted to velocity energy. For most practical siphons, between 50 and 75% of the elevation energy available to drive flow will be converted to velocity energy.

A standpipe covered with a dome will begin to siphon when the standpipe flows full. During siphoning, the flow rate may be several times higher than the flow through an uncovered standpipe of the same size. Furthermore, the covered standpipe can be designed to lower the water level to a point below the top of the standpipe before siphoning is allowed to stop.

Flow into the covered standpipe can be drawn from the bottom of the reservoir by extending the skirt of the dome. A vent tube allows easy adjustment of the elevation at which air enters the dome and siphoning stops. Flow rate and water level required to start the siphon depend on the pipe diameter. Some flow through the standpipe will occur before siphoning begins. Flow into the reservoir must be greater than the flow required to start siphoning. Maximum flow through the standpipe during siphoning depends on pipe diameter and the elevation energy driving the flow.

Adding a trap to the outlet of the covered standpipe eliminates the leakage flow prior to the start of siphoning. When air bubbles out the trap at the end of the standpipe, pressure inside the dome is released suddenly allowing the water level to jump above the critical level needed to start siphoning. For reliable operation, the crest height of the trap should be about equal to one diameter of the standpipe. The vent tube opening must be below the top of the standpipe to prevent premature overflow of the standpipe. Because a trapped outlet siphon has no minimum flow limit, the standpipe can be sized to carry any maximum flow.

While the trapped outlet siphon eliminates low rate leakage flow prior to the onset of siphoning, the height differential between the start and stop of siphoning cannot be as small or as easily adjusted as with a covered standpipe without a trap. The simple siphon is convenient for some applications, but it does not lend itself to automatic cycling operation. The choice depends on the needs of the situation.

The siphon is a common device used for such mundane purposes as flushing a toilet, metering irrigation water, or borrowing gasoline from a car's tank. The siphon is also used in systems which automatically start and stop the siphon action to cycle the level of liquid in an upstream reservoir. Such devices are used in aquaculture systems to create intermittent rapid flow of effluent to flush debris from tanks and reservoirs (Ebert and Houk 1989). During siphoning, the flow rate may be several times higher than the flow through an ordinary standpipe of the same size. Furthermore, the siphon can be designed to lower the water level to a point below the top of the standpipe before siphoning is allowed to stop.

A siphon is defined as an enclosed conduit for conveying liquid to a lower elevation after raising the water to a higher elevation at an intermediate section of the conduit. It is generally understood that siphon action will begin if the conduit flows full and cease when air is allowed to enter the high point of the conduit. These conditions seem simple enough, but design of a siphon to achieve reliable action with specified flow rates is generally a trial-and-error process. Many attempts have been abandoned in frustration.

This paper summarizes the results of a study aimed at establishing criteria for design of siphon systems for handling water (Garrett 1989). Three types of siphon systems will be discussed. These are: 1) a simple siphon, 2) a covered standpipe siphon, and 3) a trapped-outlet siphon. For each system, general principles will be presented, and the conditions under which siphon action will begin and stop will be defined. Limiting conditions will also be identified, and procedures for predicting flow rate will be given.

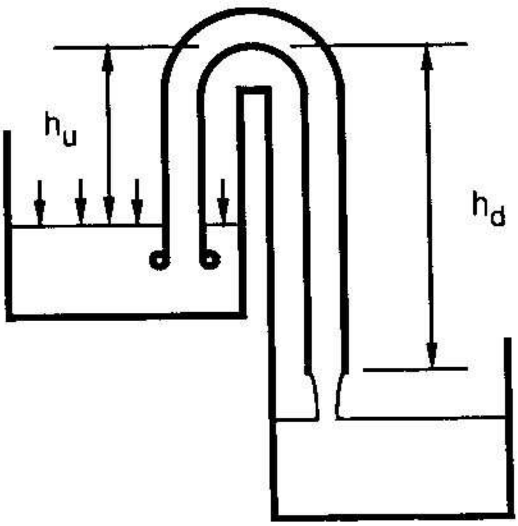

FIGURE 1. *In a simple siphon, the weight of the downstream column of water, h_d, causes negative pressure at the crest, and atmospheric pressure pushes water from the upper reservoir over the crest, h_u. Flow is driven by the height difference, $h_d - h_u$. If the outlet of the siphon is submerged, h_d is measured from the crest to the surface of the downstream reservoir.*

The Simple Siphon

Fig. 1 shows the configuration of a simple siphon formed by a continuous pipe. When the pipe is full of water, the height of the column of water downstream from the crest of the conduit exceeds the height of the column of water in the upstream portion. This difference in height causes the flow. Simple siphons are used in aquaculture to convey water out the top of a reservoir into an external, head box (Huguenin and Colt 1989). The outlet of the siphon is submerged in the head box, and the level of water in the reservoir tends to equalize with the level in the head box. Raising or lowering the outlet of the head box, thus, controls the level of water in the reservoir.

To fully understand siphons, it is instructive to consider the energy in the water at various points along the pipe. Energy is present in several forms. We need only consider those forms of energy which change in magnitude from one point in the system to another. At any point, total energy is the sum of energy due to elevation, to pressure, and to velocity. While energy is neither created nor destroyed, it does change from one form to another. It may also be effectively lost by being converted to heat due to friction and turbulence (Vennard 1954).

Energy Considerations

Water has energy by virtue of its elevation. The magnitude of this energy is commonly referred to as the potential energy head. For the simple siphon, the water at the upper level has more energy of elevation than the water at the lower level. Water would move spontaneously from the upper level to the lower level except for the fact that the path of the tube requires the water to rise to a higher level enroute to the lower level. At that higher intermediate level, the water would have an even higher level of energy of elevation. Where does that extra energy of elevation come from?

Water also has energy by virtue of its pressure. Pressure energy can be related to energy of elevation by converting it to a measure of distance, called pressure head. This can be accomplished by recognizing that water is under pressure from the weight of water above it. Thus pressure, in force per unit area, can be expressed in terms of the height of a column of the water. The pressure at the surface of an open body of water is not really zero; actually, it is equal to the pressure due to the atmosphere above it. At the crest of the simple siphon, the energy due to pressure is less than atmospheric. In fact, the amount of pressure reduction is related to the change in elevation from the surface of the upstream reservoir. As water moves from the inlet of the pipe to the crest, pressure energy is reduced and changed to energy of elevation. As the water moves from the crest to the outlet, energy of elevation changes back to pressure energy.

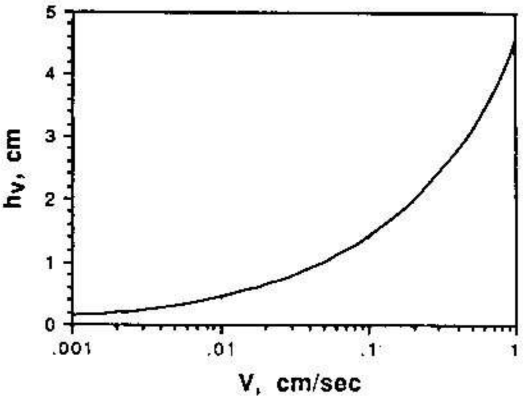

FIGURE 2. *Energy of water associated with its velocity, termed velocity head, h_v, is equal to $V^2/2g$, where V is velocity and g is acceleration due to gravity. Conversely, if the velocity head, in cm, is known, then for velocity in cm/sec, $V = (19.614h_v)^{0.5}$.*

The lower body of water is at a lower elevation than the upper body, yet the surfaces of both bodies are at atmospheric pressure. If energy is not destroyed, what happens to the energy of elevation lost by the water as it moves from the high elevation to the low elevation?

Water also has kinetic energy by virtue of its velocity. This component of energy can be related to the elevation and pressure components by expressing it as velocity head. (Fig. 2 relates velocity and velocity head, $h_v = V^2/2g$, where V is velocity and g is acceleration due to gravity.) If the pipe is of uniform cross section, the average velocity of the flowing water, and hence velocity head, will be uniform along its length. But because velocity is not constant from point to point within the water, real waters experience what may be thought of as friction between the molecules and along the sidewalls of a pipe as the water flows. This friction converts energy of the water into heat. While heat is another form of energy, it is frequently not recoverable. Hence, while energy is not, strictly speaking, destroyed, it is effectively lost to the system. Some of the energy difference between the upper body of water and the lower body is lost at the inlet to the pipe and some to friction along the pipe. The rest of the energy of elevation is converted into kinetic energy which the water carries with it as it exits the tube.

Flow Rate Estimation

Energy differences due to change in elevation are either lost to friction or converted to velocity head. In fact, an upper limit of the flow rate through a simple siphon can be obtained by ignoring the entrance and pipe flow losses and assuming that all of the energy due to difference in elevation of the upper and lower reservoirs is converted to velocity head.[1]

Energy losses do occur, however, due to turbulence at the entrance to the pipe and friction along the length of the pipe. Entrance losses result from a contraction of flow, called a *vena contracta,* as water enters the pipe and subsequent re-expansion of the flow to fill the pipe. The *vena contracta* represents a separation of the flow from the wall of the pipe immediately inside the pipe entrance. Turbulence results in the separation region. This condition is minimal if the pipe entrance is rounded to a radius greater than 14% of the inside diameter of the pipe. Under the best of conditions, entrance losses will amount to about 4% of the velocity head. With a square-edged entrance, as into a thick-walled pipe (wall thickness >0.05 diameters), entrance losses will approach 50% of the velocity head. Screening the inlet would introduce additional losses and reduce the flow rate.

Losses along the length of the pipe result in shear forces between water molecules, especially near the pipe wall. These losses depend on flow velocity and roughness of the inside of the tube. The presence of debris and biofouling on pipe walls increases the roughness and may effectively reduce the inside diameter. Tables of pipe flow losses

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[1] If the siphon is discharging into air, the velocity at the exit is limited by the change in head between the upper body of fluid and the exit of the pipe. Pressure of the flow stream becomes atmospheric at that point.

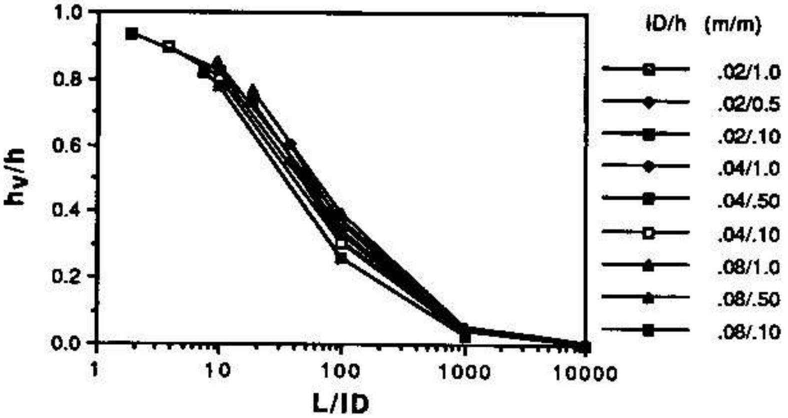

FIGURE 3. *Potential energy of elevation is converted to velocity head in a simple siphon. The portion converted, h_v/h, depends primarily on the ratio of pipe length to inside diameter, L/ID. For a wide range of ratios of inside diameter to total elevation difference, ID/h, the curves tend to run together and may be thought of as a broad line.*

related to pipe size and flow rate are available from pipe suppliers.[2] Even with such tables, design is an iterative process. Pipe diameter and length determine flow rate and head loss for a given driving force (change in elevation), but flow rate and head loss are interdependent. Fig. 3 shows velocity head as a portion of total head over a range of pipe length-to-inside diameter ratios for several conditions of total head and pipe size, assuming entrance losses were 4% of velocity head.[3] The figure can be used to give a preliminary estimate of velocity head that can be expected from a given siphon configuration. From velocity head, velocity, and in turn flow rate, can be determined. It appears from Fig. 3 that for most practical siphons (with L/ID between 50 and 15) velocity head will range between 50 and 75% of the total head available. Considering the uncertainty which results from estimating entrance and pipe friction conditions and the effects of joints and bends in the pipe,[4] estimates of velocity head obtained by using Fig. 3 may be satisfactory.

Limits to Application

The energy of the water at any point includes the combination of its energy components due to elevation, pressure and velocity. If the pressure head at the crest of a siphon should happen to be less than the vapor pressure of the water[5] (part of the total head is embodied in velocity head), vaporization of the water could block the flow over the crest.[6] Vaporization, thus, limits the maximum height of the crest above the outlet of the siphon tube.[7]

Starting Techniques

To start flow in a simple siphon, the pressure at the crest must be reduced sufficiently

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[2] See also "Piping Design and Calculations" (Huguenin and Colt 1989, Chapter 6).

[3] The values in Fig. 3 are based on use of smooth pipe with a well-rounded entrance.

[4] Tables are available from pipe suppliers, which give the effects of joints and bends in terms of equivalent additional lengths of pipe.

[5] 2.34 kPa (0.34 psi) for water at 20 C (68 F).

[6] Gases carried in the fluid stream can also accumulate at the crest of a siphon and result in blockage of flow. This condition is most likely to occur when flow is interrupted for extended periods of time. While fluid is flowing, substantial amounts of gases can be entrained in the flow. Entrained gases reduce the density and weight of the column of fluid, and hence, affect the force driving the siphon.

[7] Note that fluid can free fall from the outlet of the siphon tube to the surface of the lower reservoir without influencing the velocity head in the tube or the pressure head at the crest of the tube.

to cause flow from the inlet to the crest. This condition will exist if the pipe is full of water. Hence, a common way to start flow is to fill the pipe with water. If the pipe is moveable, it can be completely immersed in the upper body of water, then moved into position without losing water or allowing air to accumulate at the crest. It is particularly important to keep the inlet to the pipe submerged. Irrigators become adept at this technique, setting siphons of up to 15 cm (6 in) diameter.

The pipe can also be filled with water through an opening at the crest with the inlet and outlet ends blocked to retain the water. Once the pipe is filled, the opening needs to be sealed securely to prevent air from leaking into the crest and interrupting flow. When the inlet and outlet are opened, flow will begin. Suction can be applied at the outlet (or at the crest if both inlet and outlet ends are submerged) to draw water into the pipe. Flow will begin as soon as water is drawn over the crest.[8]

The Covered Standpipe

Standpipes are frequently used to establish the level of water in a reservoir. As the level rises above the opening of the standpipe, water flows into the standpipe and drains to a lower elevation. If water flows into the reservoir faster than it flows into the standpipe, the level of water in the reservoir will rise and the rate of flow into the standpipe will increase. The flow rate into the standpipe is determined by the height of the surface of water in the reservoir above the inlet to the standpipe.

A standpipe can be converted to a siphon simply by covering the opening to the standpipe with a dome, as shown in Fig. 4. When the flow of water into the standpipe is sufficient to plug the pipe and close the air in the dome off from outside air, the pressure of the air in the dome will drop due to the weight of the plug of water in the standpipe. This causes an increase in the rate of flow into the dome which, in turn, enlarges the plug of water in the standpipe until the standpipe flows full. While the siphon is operating, the flow rate is driven by the height differential from the surface of the water in the upstream reservoir to the end of the standpipe.[9]

If the siphon flow rate exceeds the rate of flow into the upper reservoir, the level of water in the reservoir will decrease. When the water level falls below the lower edge of the dome, air will enter the dome and allow the pressure in the dome to revert to atmospheric. Siphon action will cease. With the level of water in the reservoir below the level of the standpipe, flow through the standpipe will stop. Continuing flow into the reservoir will cause the level of water to rise again until the cycle is repeated. Cycle frequency depends on the relative flow rates.

It is important to recall that siphon action is initiated in a domed standpipe when air in the dome is cut off from the atmosphere by a plug of water in the standpipe. If water flowing into the standpipe has any tendency to swirl, a vortex may be established in the standpipe. This vortex can be very persistent and may maintain an unbroken path for air movement from the dome, through the standpipe, to the atmosphere outside, even though the level of water flowing into the standpipe is well above the critical level normally required to initiate siphoning. Air in the dome will remain at atmospheric pressure until that path is broken. Fig. 5 shows a plate added to a standpipe to reduce the opportunity for establishment of a vortex. A thin plate (18 gage stainless steel) with

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[8] It is not necessary for all air to be removed from the crest; only for the pressure to be reduced sufficiently to cause fluid to flow over the crest. Flow will initiate even though the pipe does not flow full; however, for siphon action to occur, the downstream leg of the siphon must flow full to establish a column of fluid sufficient to maintain the critical low pressure at the crest.

[9] In the case of a submerged discharge, the column length determining siphon flow would be measured to the surface of the lower reservoir.

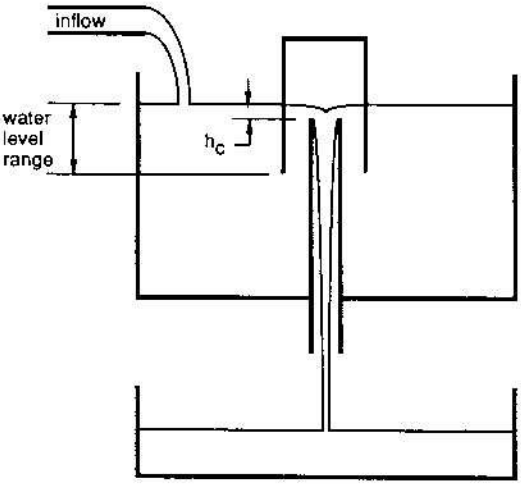

FIGURE 4. *This covered standpipe siphon is just on the verge of starting to siphon. When water rises to a critical height, h_c, above the standpipe, the flow plugs the standpipe. Air in the dome is cut off from outside air. When the plug of water flows down the standpipe, the pressure in the dome will drop suddenly to below atmospheric pressure, and siphoning will begin. Siphoning will continue until air re-enters the dome, restoring the pressure in the dome to atmospheric.*

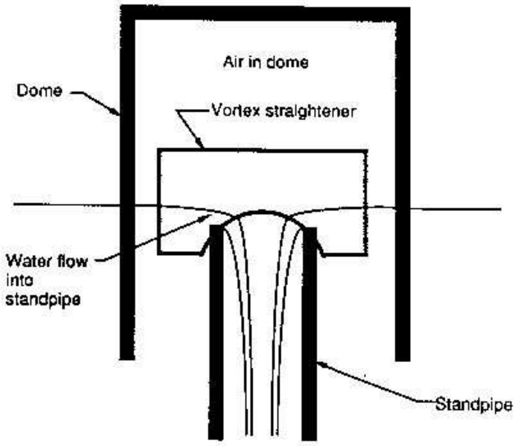

FIGURE 5. *This close up view shows water flowing into a covered standpipe. Circular flow around the centerline of the standpipe can prevent water flow from plugging the standpipe, allowing the air in the dome to remain at the same pressure as outside air and preventing the start of siphoning. A thin plate setting in a groove on top of the standpipe serves to make water flow straight toward the center of the standpipe. The arch in the plate prevents entrapment of an air bubble below the edge of the plate.*

smoothed edges, arching above the entrance to the standpipe, and retained in slots in the end of the standpipe (cut by a hacksaw) has worked well.

At times it is desirable to extend the skirt of the dome to force water flow from lower depths of the upper reservoir. Attempts are frequently made to break siphoning action before the level of water in the reservoir reaches the lower edge of the dome by introducing air vents in the side of the dome. These attempts are not always successful. If the level of water in the reservoir lowers slowly, circular holes may be only partially opened. Air passing through the vent can become entrained as bubbles in the flow stream and be carried through the siphon without stopping the siphoning action. What is needed is a vent which will suddenly open to a large enough passage to ensure adequate air to stop the siphon action. This can easily be achieved by providing a vertical vent tube (>10 mm ID) with a horizontal open end as shown in Fig. 6. A meniscus will cling to the open end of the vertical tube as the water level lowers. When the meniscus breaks, a vertical clearance of 2 or 3 mm will develop between the end of the tube and the surface of the water in the reservoir.[10]

Standpipe Size

For the covered standpipe, the level of the reservoir above the standpipe must be sufficient to cause enough flow into the standpipe to plug the pipe in order to initiate siphoning. During the course of this study, experiments were conducted with covered standpipes, of nominal pipe sizes ranging from ½″ to 1½″ arranged in the configura-

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[10] A horizontal slot in the side of the dome will also work, but it does not offer the ease of adjustment or flexibility of location the vent tube does. The vertical dimension of a slot vent should be greater than 3 mm to ensure that the meniscus breaks cleanly. The length should be sufficient to allow rapid air flow, probably greater than 25 mm.

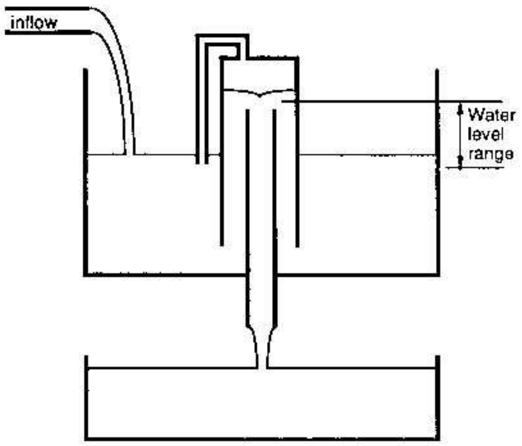

FIGURE 6. *Water flows into the covered standpipe from below the skirt of the dome. By extending the skirt, water can be drawn from near the bottom of the reservoir. Siphoning stops when the water level in the upper reservoir falls below the end of the vent tube. The vent tube opening can be located some distance from the standpipe, and the elevation of the opening can be adjusted easily.*

tion shown in Fig. 6. Based on those experiments, relationships were established between pipe inside diameter, height of water level above the top of the standpipe at onset of siphoning, and flow into the standpipe at onset of siphoning. The values in Table 1 were obtained from those relationships. For the range of sizes tested, siphoning began when the level of water above the standpipe reached 39% of the inside diameter of the pipe.

The flow rate into the reservoir must exceed the value given in Table 1 to start siphoning. A flow rate only slightly larger will approach the start of siphoning slowly. On the other hand, if the flow rate into the reservoir exceeds the flow the standpipe can carry, siphoning will not stop. The maximum a siphon can carry depends on both the pipe inside diameter and on the height differential driving the flow. Using a relationship derived from experimental data, the values in Table 2 were obtained.

TABLE 1. *Conditions to start siphoning in a covered standpipe.*

Nominal pipe size in	Inside diameter cm	Level of water above standpipe cm	Flow through standpipe L/min
½	1.49	0.58	2.8
¾	1.89	0.74	5.2
1	2.87	1.12	14.6
1¼	3.12	1.22	18.1
1½	3.77	1.47	29.0

TABLE 2. *Maximum flow for cyclic siphoning in a covered standpipe.*

Nominal pipe size	Height differential				
in	10 cm	20 cm	30 cm	40 cm	50 cm
	Flow rate, L/min				
½	8.5	12.0	14.7	17.0	19.0
¾	13.8	19.5	23.9	27.6	70.9
1	31.7	44.9	54.9	63.4	70.9
1¼	37.6	53.2	65.1	75.2	84.0
1½	54.8	77.5	94.9	109.6	122.5

A given standpipe can accommodate only a limited range of input flows.[11] If flow rate into the reservoir varies, it must fall within the upper and lower limits for the standpipe if cyclic action is to be achieved. The trapped-outlet siphon can overcome this limitation.

Trapped-Outlet Siphon

A P or S trap can be added to the outlet of a covered standpipe as shown in Fig. 7. When the dome vent is submerged, increases in the level of water in the upper reservoir tend to force air down the standpipe. Water in the standpipe trap, however, blocks the exit of that air. The air becomes compressed and the air pressure acts down on the water in the trap until, eventually, air bubbles out the trap. Air bubbles in the downstream leg of the trap reduce the density of that water-

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[11] Rounding the entrance to the standpipe would allow higher maximum flow while the siphon is functioning, but the rounded entrance would also require higher flow to cause plug flow and initiate siphon action.

air mixture so that it is less able to withstand the air pressure on the water in the upstream leg. As a result, pressure in the dome drops suddenly the instant air bubbles begin to escape from the trap. This sudden reduction in pressure in the dome, in turn, allows the level of water in the dome (and in the vent tube) to rise. If the level of water in the dome rises suddenly to a point above the critical level for initiation of plug flow in the standpipe (as given in Table 1), siphon action will begin. Siphon action will continue until the dome is vented.

Care must be taken in the design to ensure that water in the dome does not overflow the standpipe prematurely; otherwise, that overflow will simply pass through the trap. There will be no further compression of the trapped air, no bubbling to create a sudden reduction in pressure, no sudden rise in water to above the critical level, and no siphoning (unless the inflow rate exceeds the critical value given in Table 1). The critical level for start of siphoning will be exceeded most easily if the level of water in the dome and vent tube is close to the top of the standpipe when bubbling begins.

Siphon Design Considerations

The maximum pressure that can be trapped in the dome depends on the depth of water in the downstream leg of the trap (the crest height of the trap). Pressure in the dome retards the rise of water entering the dome and the vent tube; thus, the level of water inside the dome and vent tube will be depressed below the level of water in the upper reservoir an amount equal to the differential height of water in the trap. That depression approaches the crest height of the trap as the level of the reservoir rises. The depressed water level inside the dome should approach, but must not reach, the top of the standpipe as bubbling begins in the trap. Thus the top of the standpipe should be positioned below the desired maximum level of the reservoir by slightly less than the crest height of the trap.

The crest height of the trap must be greater than the critical depth of flow to start siphoning as given in Table 1. The vent tube opening (or bottom of the dome if no vent tube is used) must be below the top of the standpipe to prevent premature overflow into the standpipe; hence, the level of the upstream reservoir will be slightly below the end of the vent tube (or bottom of the dome) at the end of siphoning.

For the trapped outlet siphon, the stand-

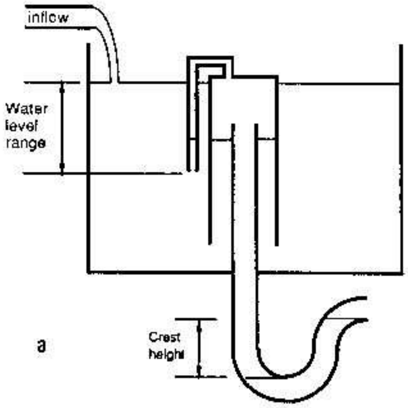

FIGURE 7a. *As water rises around a covered standpipe with a trapped outlet, air trapped in the dome depresses the water in the dome, vent tube and standpipe. When air bubbles out the trap, pressure will be released and the level of water in the dome will rise suddenly.*

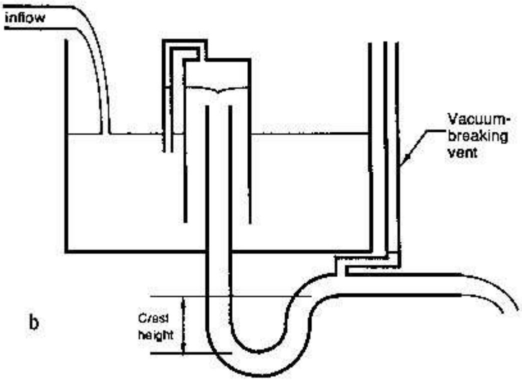

FIGURE 7b. *If the level of water in the dome rises more than the critical height above the standpipe, siphoning will begin and continue until air is vented into the dome. If the trap discharges into a pipe, a vacuum-breaking vent should be provided to ensure that the trap retains water for the next cycle.*

pipe can be designed to provide whatever rate of flow is desired during siphoning; there will be no leakage flow prior to the start of siphoning. The dome will normally be designed to allow flow of water with minimal restriction.

To ensure that the trap remains filled with water at the end of siphoning, static pressure of the flow stream should return to atmospheric at the crest of the trap. If the trap discharges into a pipe, a vacuum-breaking vent should be provided. A pipe extending above the maximum level of the upper reservoir will suffice.

Advantages and Disadvantages of Each

The simple siphon is a portable and manually controlled device, but it is difficult to start and stop automatically.

The covered standpipe siphon provides simple automatic control of the upper reservoir between two levels. The levels can be adjusted simply by changing the location of the ends of the standpipe and vent tube. The magnitude of the difference between the maximum and minimum levels can be small or large, ranging from a few millimeters to almost the full depth of the reservoir. The covered standpipe siphon requires that input flow fall in a particular range dependent on the size of the standpipe. Furthermore, as the level of water in the upper reservoir rises above the top of the standpipe, flow through the standpipe will increase gradually until the critical level to initiate siphoning is reached. This "leakage" flow may be objectionable in some applications.

The trapped outlet standpipe stops the leakage flow, extending the range of input flows for which it will operate. The differential between the upper and lower levels of the upper reservoir must be at least equal to one crest height of the trap. The crest height of the trap, in turn, should be at least equal to one diameter of the standpipe for reliable operation.

The choice of which siphon to use depends, obviously, on the needs of the situation.

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