Siphonic concepts examined: a carbon dioxide gas siphon and siphons in vacuum

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Siphonic concepts examined: a carbon dioxide gas siphon and siphons in vacuum

Joshua J Ramette[1] and Richard W Ramette[2,3]

[1] Ramette Home Education Academy, 7379 Ontario Boulevard, Eden Prairie, MN 55346, USA
[2] Carleton College, Northfield, MN 55057, USA

E-mail: ramette.mn@comcast.net and rwramette@mindspring.com

Abstract
Misconceptions of siphon action include assumptions that intermolecular attractions play a key role and that siphons will operate in a vacuum. These are belied by the siphoning of gaseous carbon dioxide and behaviour of siphons under reduced pressure. These procedures are suitable for classroom demonstrations. The principles of siphon action are summarized.

This article presents novel experimental evidence that intermolecular forces are unnecessary for siphoning and that ambient pressure is required. We also offer ways to teach siphonic principles using classroom demonstrations.

Siphons (from the Greek for a pipe or tube) are used frequently and ingeniously, from gasoline theft and fish tank cleaning to toilet flushing and lake replenishment. Shakhashiri has used a siphon in a demonstration of an instrumental recording of titration curves [1]. The well-known Soxhlet extractor makes use of siphoning for purification of slightly soluble materials [2].

This work deals with the traditional bent-tube siphon shown in figure 1.

Gram has shown [3] how the flow rate of a siphoning liquid in ambient air is predictable from siphon length, height and radius, and fluid viscosity and density. For a basic implementation of Gram's method see this website [4].

Few devices that are so widely used are so poorly understood by the uninitiated. Siphons provoke curiosity because liquids are not expected to 'run uphill'. In a sign of our times, if one enters 'siphon applications', Google first asks if you really mean 'iPhone applications'. Entering

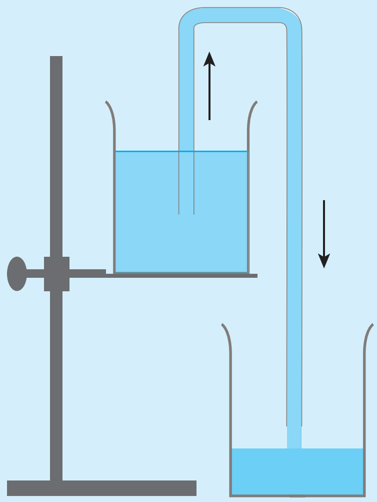

Figure 1. A simple liquid siphon.

[3] Home: 765 W Fountain Creek Dr, Green Valley, AZ 85614, USA.

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'how does a siphon work' yields thousands of hits, but few that are scientifically valid.

Two persistent claims are (a) siphons function through intermolecular attractions and (b) siphons do not rely on air pressure, and will work in a vacuum. These views were recently and forcefully espoused by Hughes [5], who wrote:

> 'In a siphon, the water falling down one side of the tube pulls up water on the other side. The column of water acts like a chain with the water molecules pulling on each other via hydrogen bonds.'

> 'Another seeming ubiquitous misconception is that the maximum height of a siphon is dependent on atmospheric pressure. The maximum height of a water siphon actually depends on the tensile strength of water, i.e. the maximum weight that hydrogen bonds are able to support.'

> 'The chain analogy can be easily implemented in the classroom. A thin metal chain can be placed on a bench with some of the chain draped over a tube, for example a horizontal glass cylinder. The chain will fall to the ground pulling the rest of the chain off the bench. Students can readily see that it is the weight of the downside of the chain that pulls the chain . . .. In this case it is obvious that atmospheric pressure is not pushing the chain up over the cylinder and it is also fairly easy to imagine that this experiment would work on an airless environment, i.e. a vacuum, such as on the Moon.'

Similar assertions have appeared in *The Flying Circus of Physics* [6] and even the venerable *Encyclopedia Britannica* [7].

Procedures

A. Demonstration that siphons do not depend on molecular attractions

The 'chain analogy' is inapt because, for example, when one plunges a hand into a bucket of water, it isn't possible to haul out a big glob. Also, we can siphon non-polar liquids such as carbon tetrachloride. And, if a water siphon functions because of hydrogen bonds, why would the closed tube be necessary? A plastic tube, sliced in half lengthwise, would serve as a tiny aqueduct to siphon water.

Here is a simple proof that intermolecular forces are not required: start up a water siphon in the usual way and, while it is running, quickly raise and lower the input end in the source reservoir. An air bubble rushes in and is readily swept up, separating the water into unconnected sections, and travels over the top and out the exit. Clearly there was no hydrogen bonding making the flow continue.

There is an interesting demonstration involving a high molecular weight polymer, as shown by Shakhashiri, where an aqueous polyethylene oxide solution in a beaker, once pouring is started, will siphon over the edge until the beaker is empty—a 'tubeless siphon' [1]. This is akin to the chain concept, due to molecular tangling, but is not a siphon in the traditional sense.

In the present work, we have found that a gas with essentially zero intermolecular attraction, can be siphoned as easily as water. Carbon dioxide was chosen because it has a greater density than air, is non-polar, can be detected by various methods, and can be procured in the form of dry ice.

The sizes and dimensions of the siphon tube and the upper and lower vessels are not critical. Our siphon tube was a 1.5 m length of plastic tubing, with an inner diameter of 1.3 cm. Milk cartons served as the upper and lower vessels, placed so that the height difference in the tube ends was 75 cm. The tube rose 15 cm above the upper vessel. The latter was filled with dry ice chunks which continuously sublimed to replenish the siphoned carbon dioxide gas. Simple mouth suction on the lower tube end started the siphon.

In the classroom, after showing a simple water siphon, the teacher could ask the class if it makes sense to siphon a gas. After discussion, a dry ice setup (see below) could be described, and the students asked to submit ideas on how to tell if such a siphon actually works, given that the gas is colourless and odourless. The CO_2 siphon would be demonstrated and tested at the next class meeting.

We used several ways to show that carbon dioxide is indeed being siphoned.

(a) After a few minutes of siphoning, the contents of the lower vessel were poured into another container containing a burning candle, which was immediately extinguished. Also, a burning match, held near the end of the lower tube end when it was siphoning, was extinguished.

(b) To measure the flow rate of the carbon dioxide through the siphon, a burning candle was set on a support inside a milk carton. The volume of the milk carton up to the level of the candle wick was about a litre. The lower tube end while siphoning was placed at the inside bottom of the milk carton. Over four tests, the average time it took to extinguish the candle was 13 s, yielding a rate of 80 ml s^{-1}.

(c) Akin to the venerable limewater test to show the presence of carbon dioxide in human breath, the siphon tube was directed to the surface of saturated calcium hydroxide solution while stirring the solution. The solution turned from clear to milky white after about 40 s of exposure.

(d) A thermometer that was adapted to the temperature in the lower vessel sensed a temperature drop in the lower vessel, which indicates that the cold carbon dioxide gas had been siphoned. The change was not dramatic: when the exit end of the tube was directed to the thermometer bulb the temperature dropped from 20.1 to 18.3 °C. Since the dry ice sublimes at −78.5 °C, the low specific heat gas evidently warmed efficiently during its passage through the non-insulated tube.

(e) Another test would be to direct the CO_2 flow to the surface of a stirred slightly basic acid–base indicator solution, so that a weak buffer forms with a pH low enough to change the colour. We did not test this.

(f) A small air-filled balloon in a clear glass bowl might float as CO_2 is collected from the siphon. We did not test this.

B. Demonstration that siphons will not work in a vacuum

The several assertions that a siphon will work in a vacuum trace back to a report by Nokes [8]. Because this article is not easily found, we have posted it for interested readers [4]. Nokes wrote of 'disturbing factors which tend to break the column in an evacuated apparatus', including mechanical shock and turbulent flow, which suggests that his siphons may have been metastable.

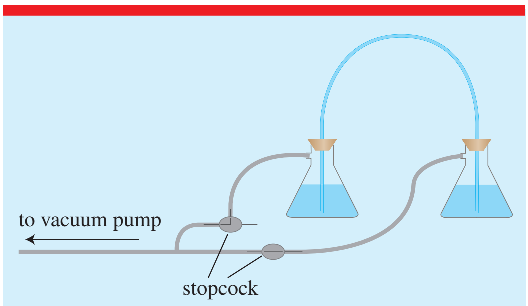

Figure 2. Arrangement for a vacuum siphon.

Good arguments can be made against the possibility of a siphon working in vacuum, in terms of the need for ambient pressure to force the fluid up the intake. Curiously, it seems that Nokes' claim has not been experimentally tested since it appeared in 1948. We performed two studies, one with mercury and one with water.

Mercury siphon

As shown in figure 2, two filter flasks with side arms were fitted with one-hole rubber stoppers that accommodated a plastic tube with a length of 60 cm and an inside diameter of 0.64 cm.

The tube was positioned with its ends near the flask bottoms and rose to a height of about 25 cm. The side arms were fitted with rubber vacuum tubing and attached to a T-connector which in turn was connected by tubing to a vacuum pump good to less that 1 mm of mercury.

Filling a siphon with mercury requires care to avoid trapping air bubbles on the sides of the tube. To minimize such contamination, we did the following: one flask was filled with mercury, the tube and the other flask were left filled with air. The system was evacuated with both flasks connected to the pump. The connection to the empty flask was closed with a stopcock, and then air was gradually admitted into the flask filled with mercury, causing the mercury to flow slowly through the tube and into the previously empty flask. Finally, air was admitted freely into both flasks, resulting in a static siphon, i.e. having equal mercury levels in the flasks. No air bubbles could be seen on the sides of the filled tube.

When the system was then re-evacuated the mercury immediately separated at the top and both columns collapsed. When air was readmitted the two columns rose back to the top of the siphon tube and the static siphon was re-established. A tiny air bubble was present at the top of the siphon, perhaps because evacuation during the filling step had not been perfect.

Water siphon

We observed the effect of reduced atmospheric pressure on static siphons, using water to preserve the possibility that hydrogen bonding might be an important factor. The apparatus was similar to that described above for the mercury siphon. For a partial vacuum source we used a common water aspirator, capable of reducing the pressure to near the vapour pressure of water, which is about 24 cm of water.

Dissolved air in the water is a major problem, because under reduced pressure it forms bubbles in the siphon tube. To minimize this interference, we preconditioned the system as follows: water was boiled for several minutes to remove dissolved air, and while hot was poured into one of the flasks. Gentle ‘suction’ on the side arm of the other flask resulted in flow of the hot water through the tube and into the flask, resulting in a static water siphon. Both flasks were then connected to the aspirator, causing vigorous boiling of the hot water and then were closed off. At this point the system was nearly air free and contained chiefly water and water vapour. The flasks were cooled to room temperature, while under reduced pressure, by bowls of ice and water.

Air was then admitted, and the water in the siphon tube was swept through by action of the aspirator, in order to remove any small air bubbles that may have been present. When the aspirator was restarted, the tube remained filled with water instead of collapsing as expected. However, rapping on the tube with a ruler ‘broke’ the water column and both legs dropped to about 1 cm above the water levels in the two flasks. This result was observed using tubing with inside diameter of 0.32 cm, with heights of 30 and 150 cm.

When 0.64 cm tubing was used, with height of 30 cm, results were similar. Again the tube remained filled under reduced pressure and the siphon broke when rapped. In one trial it broke when normal siphon flow was started by raising one flask.

These results suggest that, despite reduced pressure, water siphons, at least static ones, can persist due to hydrogen bonding. But such persistence seems to be a metastable condition, subject to collapse when disturbed by rapping.

Conclusions

The basic explanation of siphon action is that, once the tube is filled, the flow is initiated by the greater pull of gravity on the fluid on the longer side compared with that on the short side. This creates a pressure drop throughout the siphon tube, in the same sense that ‘sucking’ on a straw reduces the pressure along its length all the way to the intake point. The ambient atmospheric pressure at the intake point responds to the reduced pressure by forcing the fluid upwards, sustaining the flow, just as in a steadily sucked straw in a milkshake.

There are three fundamental requirements for siphon action.

(1) The siphoning fluid must have a density greater than that of the ambient atmosphere.
(2) There must be a gravitational field. In the space station, where orbital motion simulates zero gravity, a siphon and its fluid would all be ‘weightless’ and stationary.
(3) There must be an ambient pressure at least high enough to counter the pull of gravity on the shorter side of the siphon. On the Moon there is gravity, but no atmosphere, so an attempted siphon would collapse in both legs. In a vacuum there is no force to keep the short side filled with fluid. Just as a classical Torricellian barometer, a straight vertical tube longer than 76 cm and filled with mercury, will drop to zero height when placed in a hard vacuum, so does the liquid in both sides of a siphon drop to zero height in a vacuum.

In a partial vacuum a siphon can work to whatever height the reduced atmosphere can support. For example, an evacuated water siphon at 25 °C would work to a height of about 23 cm. (The vapour pressure of water is about 17 mm Hg or 230 mm H_2O.) A mercury siphon no higher than 17 mm should work in an evacuated system saturated with water vapour, e.g., using a water aspirator.

The maximum height of a water siphon is about 10 m, because a column of water that high weighs the same as a column of air with the same cross-sectional area reaching to the top of Earth’s atmosphere. Normal air pressure can support no more—it has nothing to do with a higher column 'breaking under its own weight'. It is not coincidental that vacuum pumps are limited to 'pulling' water no higher than 10 m. The pump is not pulling anything: it is merely removing air from the pipe in the space above the water surface. It is the atmospheric pressure at the intake that is doing all the work of pushing the water up the tube.

Any fluid, liquid or gaseous, can be siphoned in the usual way. It should be possible to siphon air in a helium atmosphere and carbon tetrachloride at the bottom of a swimming pool. Indeed, Pascal is credited with demonstrating the siphoning of mercury under water [9]. However, a water siphon would be static if immersed in water.

In 2010 Hughes [5] startled wordsmiths worldwide with the revelation that the Oxford English Dictionary's definition of 'siphon' has been inadequate for a century by not including gravity as a factor. This holds for most other dictionaries.

We offer this definition.

Siphon

> A device for transferring fluid from one container to another at a lower level, using a tube bent so that it is immersed in the higher container, rises over the rim of that container, and drops a longer distance to the lower container, depending on gravity to pull more strongly on the longer side and air pressure to force fluid into the shorter side.

The experiments described here can be related to gravitational fields, density, viscosity, intermolecular forces, sublimation, precipitation, and air pressure. Also, further experiments with liquid siphons might prove interesting as science fair projects and introductory undergraduate research. For example, Gram's equations might be tested with a variety of liquids and tube diameters. For a long-term project a creamy peanut butter siphon could be set up as an exhibit in a showcase. (Viscosity 100 000–250 000 centipoise [10].)

Acknowledgments

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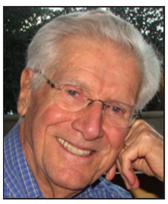
Joshua Ramette is in the eleventh grade at school and took the AP Chemistry test this spring. Over the past year he carried out the experimental work reported here, and has experimented with ammonium perchlorate composite propellants for model rocketry, using his basement laboratory, and has constructed a radio controlled engine ignition system and a gauss meter.



Dick Ramette earned a BA at Wesleyan University and a PhD at the University of Minnesota, and taught chemistry from 1954–1990 at Carleton College, Northfield, Minnesota, with emphasis on novel lab instruction and classroom demonstrations. His research focused on solution equilibria and coulometry. In 1966 he received a Manufacturing Chemists Association award for excellence in college chemistry teaching. In 1990 he received the Sears-Roebuck Foundation award for Teaching Excellence and Campus Leadership, and was the 1991 recipient of the ACS Division of Analytical Chemistry Award for Excellence in Teaching. Wesleyan University honored him with a Distinguished Alumnus Award in 1995. His 1981 textbook, *Chemical Equilibrium and Analysis*, emphasized that these areas should be taught as complementary facets of analytical chemistry. He has published over 70 articles on research and teaching, including an essay defining the term 'exocharmic reactions'.