Siphons, Revisited

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he siphon is a very useful example of early technology, the operation of which has long been well understood. A recent article¹ makes the claim that established beliefs regarding this device are incorrect and proposes a "chain model" in which intermolecular forces within the fluid play a large role while atmospheric pressure does not. We have carefully tested, and disproved, this claim using four simple experiments employing inexpensive, easily available apparatus. We complement the experiments with a discussion of conceptual issues related to the device and by invoking earlier studies and observations.^{2–8} Our findings fully support an explanation based on Bernoulli's equation in which both gravity and pressure play important roles, but intermolecular forces do not.

Introduction

There appears to be a consensus in the earlier literature²⁻⁸ that the operation of a siphon can be satisfactorily explained using Bernoulli's equation,

$$P + \rho g h + (\frac{1}{2})\rho v^2 = \text{constant}, \tag{1}$$

which is a conservation of energy statement for incompressible, inviscid flows along streamlines: the three terms respectively quantify work done on or by a fluid parcel at its boundary, potential energy, and kinetic energy.

A recent paper by Hughes¹ contains the following statement: "A very common misconception is that siphons work through atmospheric pressure pushing water through the tube of the siphon, not [...] a single dictionary [that] correctly referred to gravity being the operative force in a siphon." The author proposes a chain model: "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." These statements appear to be at odds with established beliefs, so we wish to reexamine this problem with our own experiments and arguments. In particular, we note that Bernoulli's equation applies to fluids without cohesion forces, implying that Hughes' explanation requires mechanisms that go beyond this equation.

Experiments

To test the relative contribution of pushing (pressure-based) and pulling (gravitation-based) forces in a siphon, we performed four simple experiments, at least two of which have previously been proposed in the earlier literature. These experiments require water, food coloring, two 2-L plastic soda bottles (caps included), sealant, and an assortment of plastic tubes and valves available at a typical hardware store.





Fig. 1. (a) Siphon under normal operation, and (b) after the stopper at the upper bend has been pulled out.

Experiment 1. The siphon bend has an attached valve that can be opened at any time, putting the fluid at the top in direct contact with atmospheric pressure. If the chain model is correct, this should not affect the operation of the siphon; if pressure drives the siphon, the latter should stop operating due to the loss of a pressure gradient, and the fluid column on each side should fall down under its own weight. We found the second outcome to consistently take place, as shown in Fig. 1.

Experiment 2. The siphon was prepared so that the short leg was filled with air and the long leg with water, as in Fig. 2(a). As there is no continuity of water in the siphon, the chain model predicts that it will not operate. Bernoulli's law does not give a conclusive prediction. We observed that water was pulled up the short leg, as seen in Fig. 2(b), contrary to the prediction of the chain model. If enough water







Fig. 2. (a) Siphon with water (green) on its long leg, (b) after the blue valve is opened, and (c) after it reaches full operation. Part (b) is inconsistent with the chain model.







Fig. 3. (a) Siphon under normal operation, (b) once upper bottle is sealed, and (c) after upper bottle is fully crunched and siphon operation stops.

was pulled over the bend and into the long leg, normal operation was established, as seen in Fig. 2(c).

Experiment 3. The siphon was primed and allowed to reach normal operation, as seen in Fig. 3(a). At this point, the cap of the top bottle was fully closed and tightened, with the siphon-cap assembly having previously been sealed. The chain model predicts that, as the gravitational driving force has not been altered, the siphon will continue to operate. Bernoulli's law predicts that, once enough fluid is drawn out of the top bottle, pressure of the gas trapped inside it will lessen until at some point the siphon stops operating. We observed that the walls of the plastic bottle caved in as the pressure within the bottle decreased, as seen in Fig. 3(b); once the pressure inside the top bottle was low enough, as shown in Fig. 3(c), siphon operation stopped.

Experiment 4. The top bottle was filled quite high, the end of the leg inserted in this bottle was pushed near the bottom of the bottle, and the siphon was primed. As long as



Fig. 4. Configuration in which hydrostatic pressure at the opening of the longer leg is higher than that at the opening of the shorter leg. The siphon operates by drawing fluid from the longer leg through the bend and out of the shorter leg.

Conceptual considerations

Bernoulli's equation contains *both* a gravity and a pressure term, so asking whether one of the two "drives" the operation of a siphon may not be a meaningful question. Moreover, additional forces (such as surface tension) may play some role in a real siphon, although they are not explicitly included in Bernoulli's equation.

the opening of the siphon leg in contact with atmospheric pressure was raised above the level of the other opening, but still below the surface of the fluid in the top bottle, fluid flowed through the siphon (see Fig. 4). This was the case even if the leg on the side drawing fluid was longer. This observation is inconsistent with the chain model, as a shorter column of water would be pulling a longer one. It is, however, consistent with pressure driving, as hydrostatic pressure at the bottom of the bottle is higher than atmospheric pressure.

This said, the simple and easily repeatable experiments performed here consistently rule out the chain model as the mechanism for siphon operation (except, perhaps, in near-vacuum conditions). A serious concern with the arguments in Ref. 1 has to do with its reliance on the presence of hydrogen bonds. If the Bernoulli equation explanation is correct, one expects fluids held by much weaker London-type forces, such as hexane, to be able to move through a siphon. Perhaps the most spectacular case of this is a physical science textbook example from 1894 (reprinted in Ref. 3) showing that carbon dioxide gas (which has negligible cohesive forces) can be siphoned, with the visible effect of extinguishing a flame.

Experiment 2 sheds some light onto what may actually be happening in a siphon: as the fluid initially primed on the long leg of the siphon rushes down due to gravity, it leaves behind a partial vacuum that allows pressure on the entrance point of the higher container to push fluid up the leg on that side. If enough fluid flows past the bend of the siphon, continuous operation of the device is established. Once a steady-state flow is reached, one can imagine a mechanism for continuous operation in which the fluid passing through the siphon goes through analogous steps, but without the air bubble. This points to a combined mechanism in which *both* gravity and pressure contribute to siphon operation, but without the need of forming a "fluid chain." In further support of this mechanism, pressure below atmospheric at the siphon bend has been documented in Ref. 6.

Returning to the issue of dictionaries, an updated entry for "siphon" may read: "A pipe or tube made of inelastic material, shaped as an inverted 'U' placed between fluids with their surfaces at different heights, which continuously transfers fluid

over the bend from one end to the other through the combined effect of pressure and gravity." This is only a few words longer than the current *Oxford English Dictionary* definition, and far more accurate.

Note: After acceptance of this manuscript we learned about a recent paper⁹ that implements and analyzes a siphon experiment inspired by the work of Hero of Alexandria, different from the four we performed, and that also challenges the chain model.

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