2006-1891: TWO NOVEL STUDENT-DESIGNED SOLAR THERMAL PUMPS AND A PROPOSED STEAM-DRIVEN DESIGN THAT OPERATES BELOW 100C

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Two Novel Student-Designed Solar Thermal Pumps and a Proposed Steam-Driven Design that Operates Below 100C

Abstract

Two student-designed solar thermal pumps are described. One of them uses water as a working fluid, but uses air to lift water from a well. It features a transparent boiler. The other pump uses an inverted water column to lower the pressure in the boiler, reducing the maximum temperature required during operation. This feature reduces demands on the solar collector. An improved design is proposed in which the working fluid is water boiled well below 100 C. It should be capable of lifting water to heights of a few meters, while allowing the effective use of very simple solar collectors.

Introduction

Solar thermal pumps are of interest as 'appropriate technology' because they can be unusually simple, low-cost devices suitable for undeveloped areas. Numerous designs have been proposed and demonstrated[1,2]. One problem faced by most designs is the need for a working fluid that operates at the low temperatures achievable with simple solar collectors. Two broad approaches have been taken to this problem: Either use water, and design a collector capable of reaching some temperature above 100C, or use some other working fluid that boils at lower temperatures.

Water is the preferred working fluid because it is readily available and non-toxic. Because steam pressure is used in many pump designs to lift water from a well, the pressure of the steam must be above atmospheric, and that implies a boiling point above 100 C. Although this is achievable, it does require some sophistication in solar collector design. Often reflectors must be oriented and used to focus solar energy, or sophisticated flat plate collectors such as the Winston type are needed, but even the best flat plate collectors may not perform well in cold environments. A typical heating curve for water in a crude flat plate collector is shown in Figure 1. The time constant can easily be 10-15 minutes. Heating cycle time can be excessive when the maximum temperature the collector reaches is barely above the boiling point, and most simple collectors fall in this category.

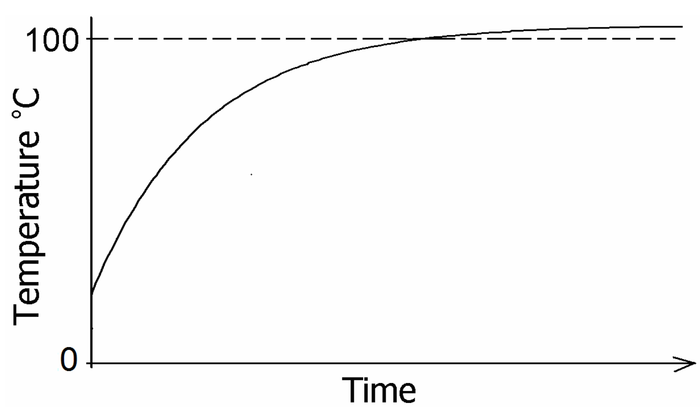

Figure 1: A typical heating curve for a simple flat plate solar collector.

Alternative working fluids such as refrigerants, ether, or other organic fluids with low boiling points[1] have been used in solar thermal pumps to ameliorate this problem. In general, there is at least the potential that these fluids could contaminate the pumped water or otherwise enter the environment. Furthermore, they can be expensive, and are rarely available where ‘appropriate technology’ is needed.

Two separate student-designed pumps are presented that seek to overcome these limitations. They were developed as part of 2-semester ‘Capstone’ design project classes. In one, air separates a small charge of working fluid from well water, reducing the potential for contamination. The other pump is designed to boil water at lower temperatures than might otherwise be necessary, by use of an inverted water column, and is useful when water need only be lifted a few meters. An alternative to this design is also suggested that boils water well below 100C. Other desirable characteristics of 'appropriate technology' are also retained in this design, for instance a limited number of moving parts, and simple construction techniques. It will be introduced after a description of the two student-designed pumps.

A Pneumatic Pump

This pump is named for the pneumatic link between the boiler and the water table, and is shown in Figures 2 and 3. It uses a very small charge of working fluid, in this case water, and it cycles automatically. The well unit is a sealed box with ports as shown. It was built by undergraduate students Bret Armstrong, Mike Bell, Cliff Shin, Jesse Everett, Mark Jenkins, Clay Kelley, Chris Paul, Scott Pobieglo, and Travis Tomlin at Arizona State University’s Polytechnic Campus, who deserve full credit for its design and construction. It works as follows.

Tube 1 is the heating tube in a flat plate collector. In this pump, only enough water is used to fill tube 1; the boiler mostly contains air. Steam compresses the bladder (a foot from a fisherman’s hip wader), forcing air through tube 2 into the sealed well unit. Water is forced upward through tube 3, and fills the upper reservoir. When the upper reservoir fills to the top of tube 4, water will siphon out and flow through the cooling coils in the boiler, condensing the steam and expanding the bladder. As the bladder expands, air is withdrawn from the well unit and well water flows into it, completing the cycle.

When heated with two 200-watt heat lamps placed above the simple flat plate collector, the small demonstration pump raised 3 liters of water per hour to a height of 2 meters. Although the air’s compressibility limits effectiveness for deep wells, it reduces the risk of contamination if an alternative working fluid is used.

A unique feature is the pump’s transparent boiler. Boiler temperatures exceed 100 C by only a few degrees, and an 8-inch polycarbonate cylinder with a 1/8-inch wall stood up to this service, although a thicker wall is advised. Heat loss can be mitigated by the addition of a thin layer of insulation on portions of the inner cylinder wall. External insulation will

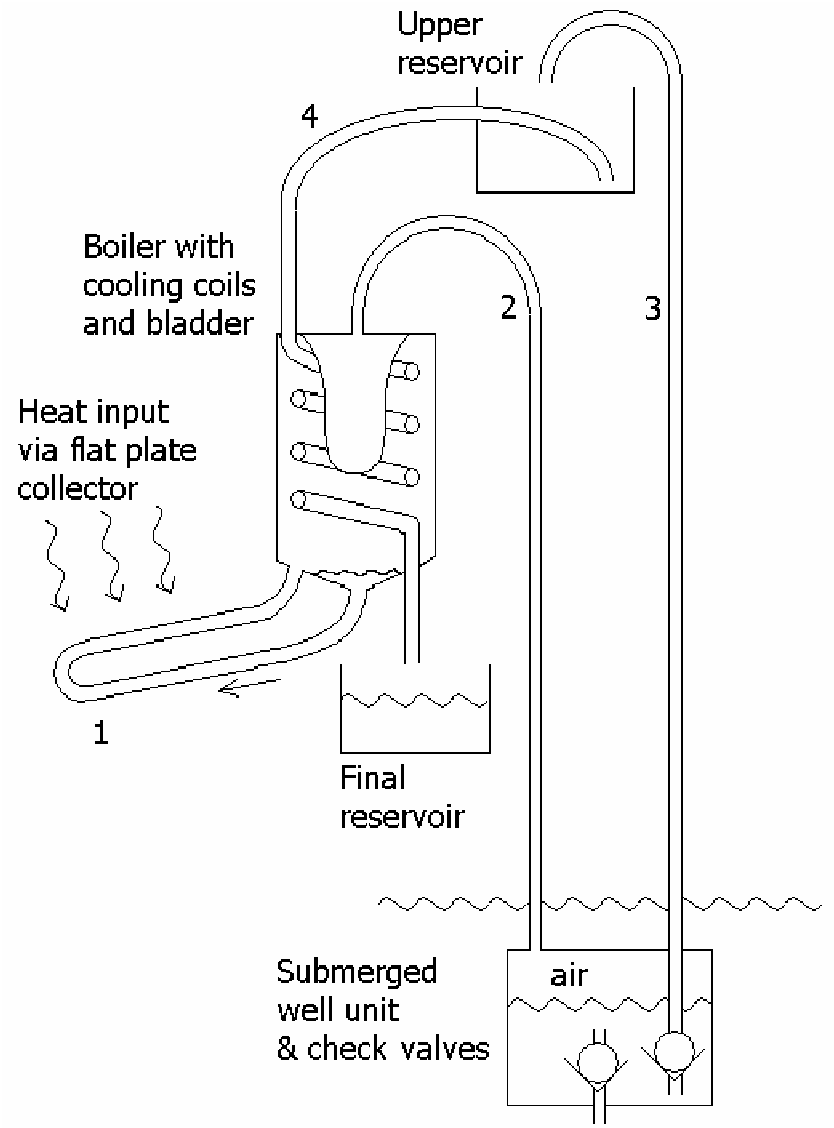

Figure 2: The ‘pneumatic’ pump built at ASU’s Polytechnic Campus.

raise the temperature of the plastic to the point of failure, but is not necessary. In a deliberate failure test, the plastic softened and bulged outward slowly – failure was not catastrophic. The transparent boiler allows students to watch water boil up from the solar collector tube, see the bladder collapse and expand, and watch water condense on the copper coils.

A single line is shown in Figure 3 connecting the collector to the boiler. This was found to work better when a return loop was added as seen in Figure 2. Also note the siphon from the upper holding tank in Figure 2. It is a very simple self-regulating valve. This pump has been used and well received as a heat engine demonstrator in thermodynamics classes. At time of writing, photos of the pump can be seen at <http://ctas.poly.asu.edu/post/capweb/projdir.htm>.

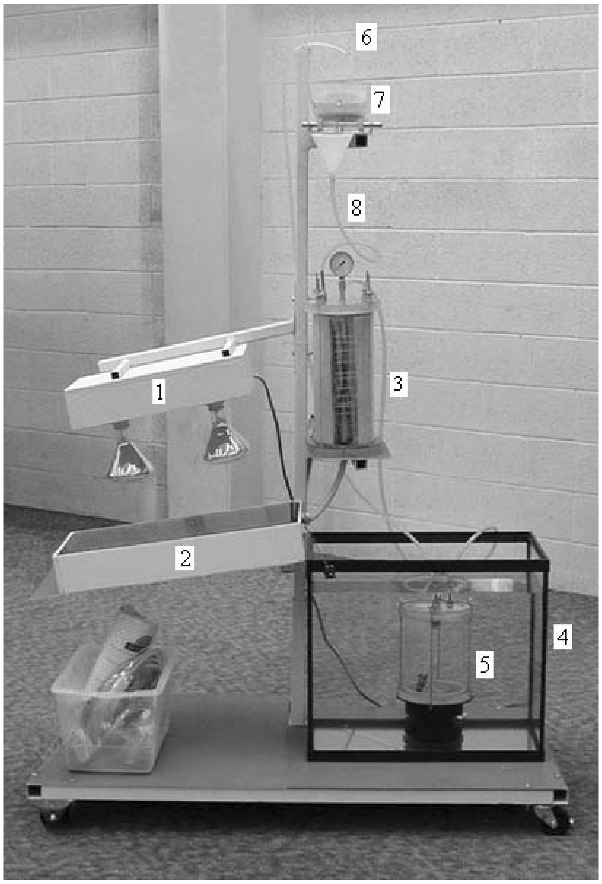

Figure 3: The pneumatic pump. Items are (1) heat lamps, (2) flat plate collector, (3) boiler, (4) aquarium that simulates a 'well', (5) sealed, weighted well unit, (6) pumped water delivery tube, (7) upper reservoir, (8) line to cooling coils from upper reservoir. There is no 'final reservoir' in this demonstration pump; pumped water is allowed to drain back into the aquarium.

A Reduced-Pressure Pump

An inverted water column can be used to reduce the absolute pressure required at the boiler. This concept was proposed and developed by three then-undergraduate students at McGill University, Bruce Constantine, Matthieu Desbois, and Kieran McConnell. They designed and built the pump shown in Figure 4.

This pump is initially filled with water to the level of the upper check valve. The bladder and boiler are completely filled with de-aerated water. When steam is generated in the boiler, water is forced into the bladder, and in turn forces water into the upper tank. When the upper tank fills sufficiently, a flush valve from a toilet allows water to drain through the coil inside the boiler. That quickly condenses the steam in the boiler, causing the boiler to refill. As it does, the bladder contracts, drawing water up from the water table to refill the bladder tank. The boiler is heated continuously, and once the upper tank has drained, steam will again build up and initiate a new pumping cycle[3].

When steam is condensed in the boiler, a vacuum develops that draws water up from the water table. Because of this vacuum, gage pressure in the boiler is negative when steam begins to regenerate. As steam builds, pressure only need be sufficient to lift the water

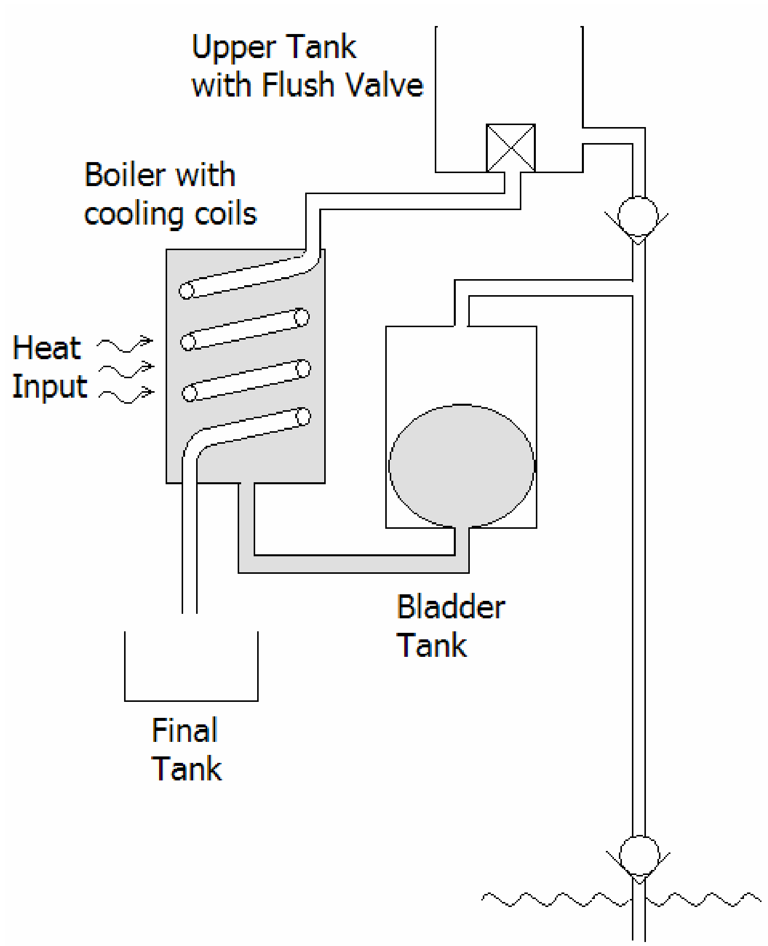

Figure 4: The reduced-pressure pump.

from the bladder tank to the upper tank half a meter above. This requires a gage pressure of + 5 kPa, or a boiling point of 101.1 C. Had the boiler been placed at ground level, without the benefit of a vacuum imposed by the water column, a gage pressure of +44 kPa would have been required to lift the water the entire 4.5 m, which translates to a boiler temperature of 110 C. Therefore this design notably reduces demands placed on the solar collector. The three students named above invented this unique concept on their own, and deserve full credit for developing it as well. They drew on their education in traditional thermodynamics, after the project advisor made them aware of the need for – and the traditional principles behind – "appropriate technology" pumps.

The check valves in the prototype had a cracking pressure of 75 mm of water. The bladder had a capacity of 3 L, and the stroke of the pump was 1.2 L. Heat was provided by a 250 watt heating blanket placed around the boiler and the assembly was well insulated. The pump lifted 3 L/hour to a height of 4.5 m. Note that the flush valve can be replaced with the siphon shown in Figure 2. Aside from the considerable care needed to achieve an airtight system, no problems were encountered in construction or operation.

Toward a Steam-Driven Solar Thermal Pump Operating Below 100C

A proposed design incorporating elements of each of these pumps is shown in Figure 5. This pump uses an inverted water column to develop a near vacuum at the boiler, allowing low temperature boiling of water. When water is raised to some fraction of the height of the boiler's water column, pumping can be achieved at less than 100C, reducing demands on the solar collector.

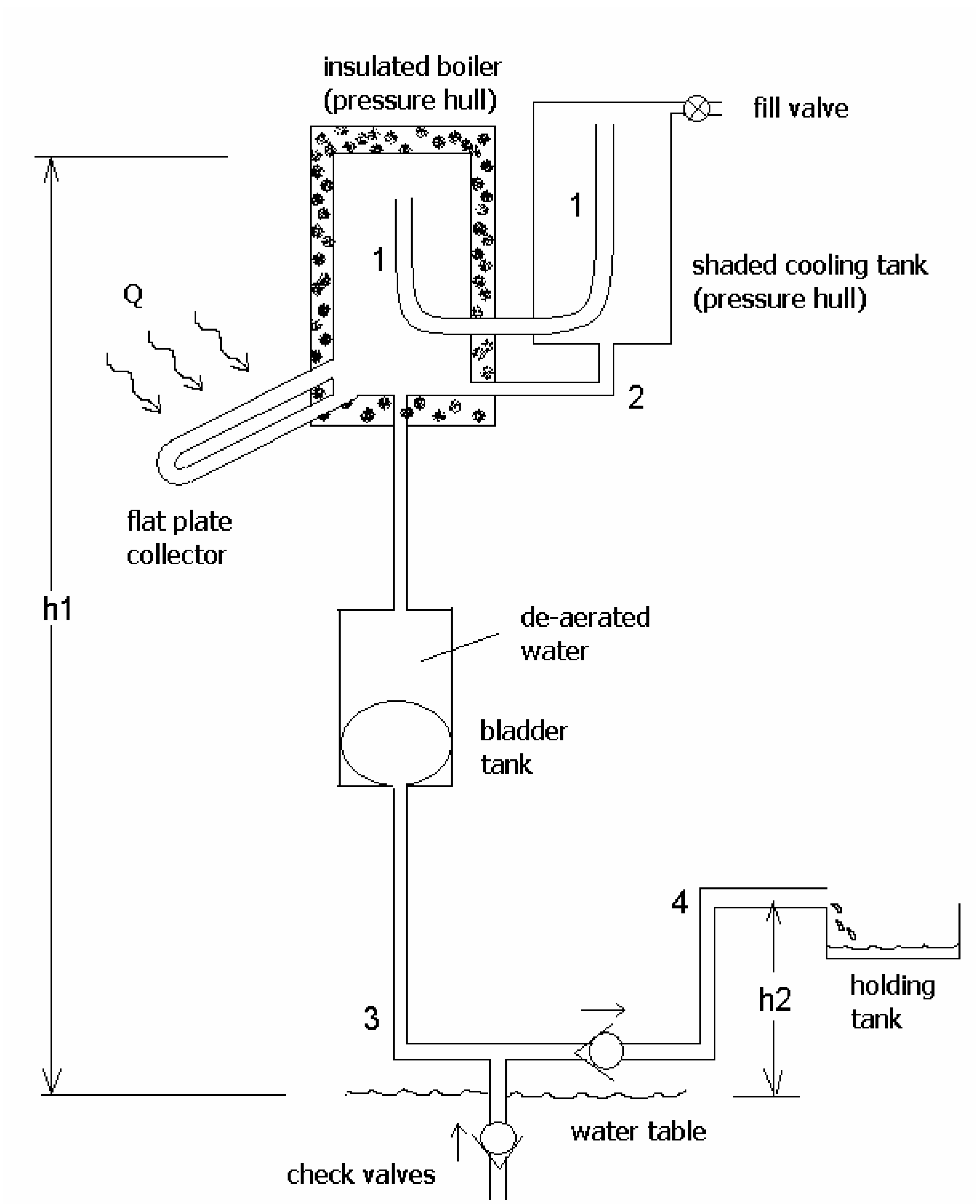

Figure 5: Proposed low-temperature pump.

The boiler, cooling tank, bladder tank and all connecting lines are initially filled with water and raised to the position shown, so that the water column reduces pressure at the upper end of the pump. Line 2 serves to ensure hydrostatic equilibrium between the

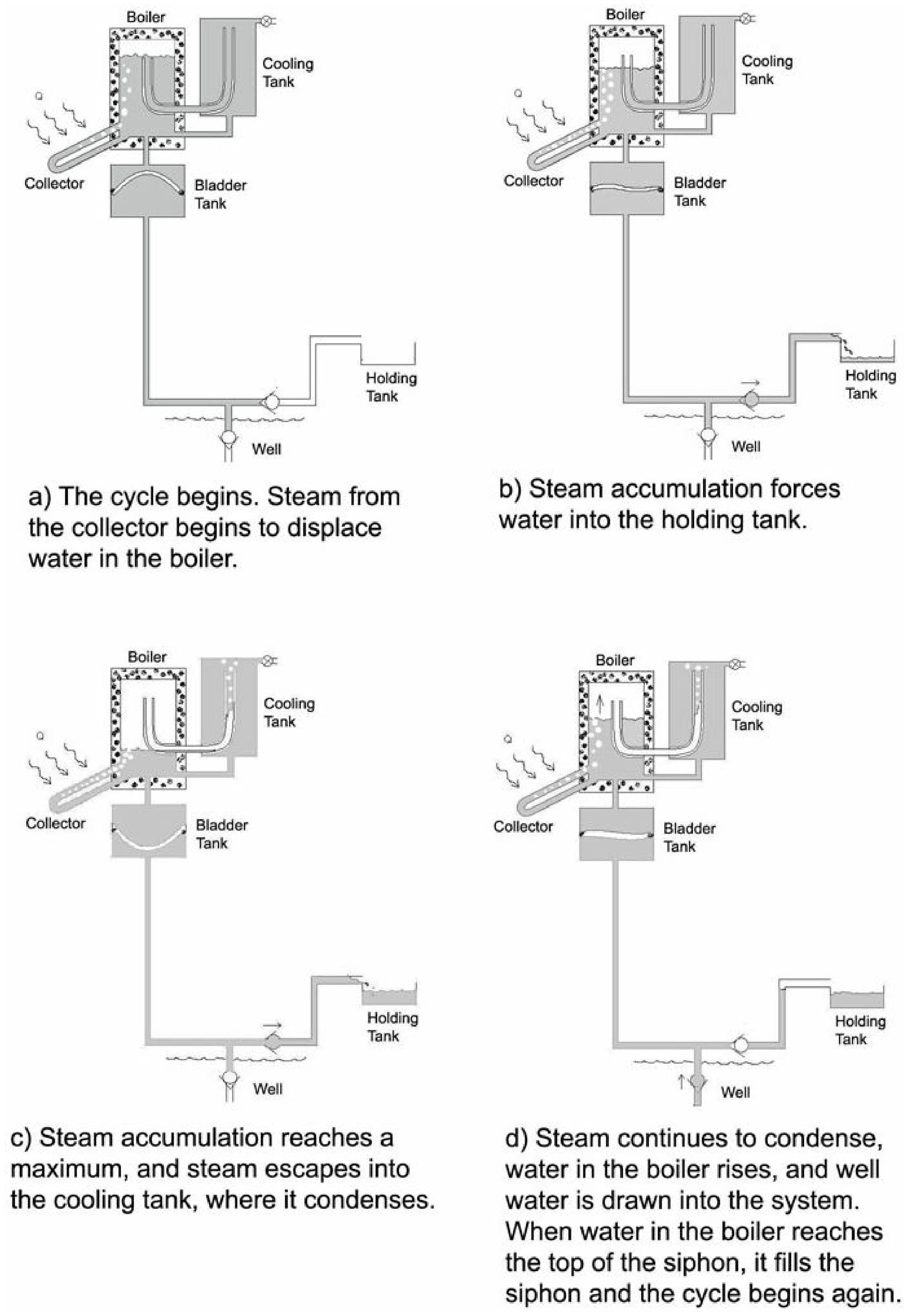

Figure 6: The cycle of the proposed pump.

boiler and cooling tank. Given sufficient heat input, steam will accumulate in the boiler, forcing water down tube 3 and into the holding reservoir. When the water level in the boiler drops below the bottom of tube 1, steam will siphon through tube 1 into the shaded water-filled cooling tank, where it will condense. Siphoning will continue until the water in the boiler rises to the top of tube 1. As this happens, water is drawn from the water table into the system. When water reaches the top of tube 1 in the boiler, tube 1 will fill with water, steam will again begin to accumulate in the boiler, and another pumping cycle will begin.

Although this pump has yet to be built, a mock up of the steam siphon (line #1 in Figure 5) portion was built and tested. In a simplified test with cold water only, it worked as anticipated. However, siphoning was very slow because only a small pressure difference is involved, and perhaps because the size of the line was small. A check valve arrangement might also work in this application.

If the boiler is at a height of h1 meters (h1<10.34 m), then the minimum absolute pressure in it will be

$$P_{B\,min} = \left(1 - \frac{h1}{10.34}\right) x 101.3 \text{ kPa} \ .$$

To raise water to height h2 meters, pressure required in line 3 at the water table must reach

$$P_W = \left(1 + \frac{h2}{10.34}\right) x 101.3 \text{ kPa} \ .$$

To generate pressure Pw, pressure in the boiler must rise by $(h2/10.34)x101.3$ kPa, or

$$P_{B\,max} = \left(1 - \frac{h1\text{-}h2}{10.34}\right) x 101.3 \text{ kPa} \ .$$

For example, suppose h1=9 m and h2=2 m. Then pressure in the boiler will reach a maximum of 32.7 kPa when pumping. At this pressure, water boils at 71C. Comparison with Figure 1 suggests this pump may cycle more quickly than a conventional design, and it may function with even a crude flat plate collector in cooler climates.

Conclusion

Although the proposed pump will only raise water a few meters, this may serve for certain agricultural applications. The reduced temperature requirement for the boiler should reduce heat losses and cycle times. It should also allow the use of simpler flat plate collectors, in cooler environments. The design is simple and should lend itself to applications termed 'appropriate technology'. This pump has not been built, but the design is offered in hope of stimulating further thought about low-temperature steam-driven solar pumps.

Simple heat engines gave rise to modern engineering, but their simplicity can be deceptive. Educationally, the design and construction of a heat engine is a challenge that allows students to exercise their creativity at a high level, and to solve the practical problems that arise in the details. As an educational vehicle, they also focus attention on the need for ‘appropriate technology’, and on engineering topics such as design simplicity, heat transfer, and thermodynamic efficiency.

References

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