SLINGSHOT PURIFICATION TECHNOLOGY

Names, sciper numbers, email addresses

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

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1. Introduction

1.1. The global importance of water

The significance of water has always been an essential element of life on earth. History and archaeological studies always suggest that great civilizations emerged and flourished at riverfronts and other waterways. In recent times, due to climatic, demographic, political and economic reasons there is an increasing strain on water resources. Just recently, we have witnessed alarming news reports about the historical water crisis that people from South Africa and land locked Lesotho. In one example, the dam levels in Lesotho were reported as being in their tenth percentile meaning that water levels were 90% higher in previous years [1]. This alarming depletion of water resources has led to the government issuing directives to the residents of Cape Town to restrict water usage, notably by avoiding long or any showers [2]. California state is considering a fine of $500 for water wastage and considering a permanent water restriction as the state creeps back into drought [3]. Several such contemporary and historical examples can be given. All these news stories occur around the world despite the fact that two-thirds of the world's surface is covered by water, but only 1% of it is portable. What is equally alarming is the annual death of approximately 3.5 million people owing to the consumption of unsanitary water [4].

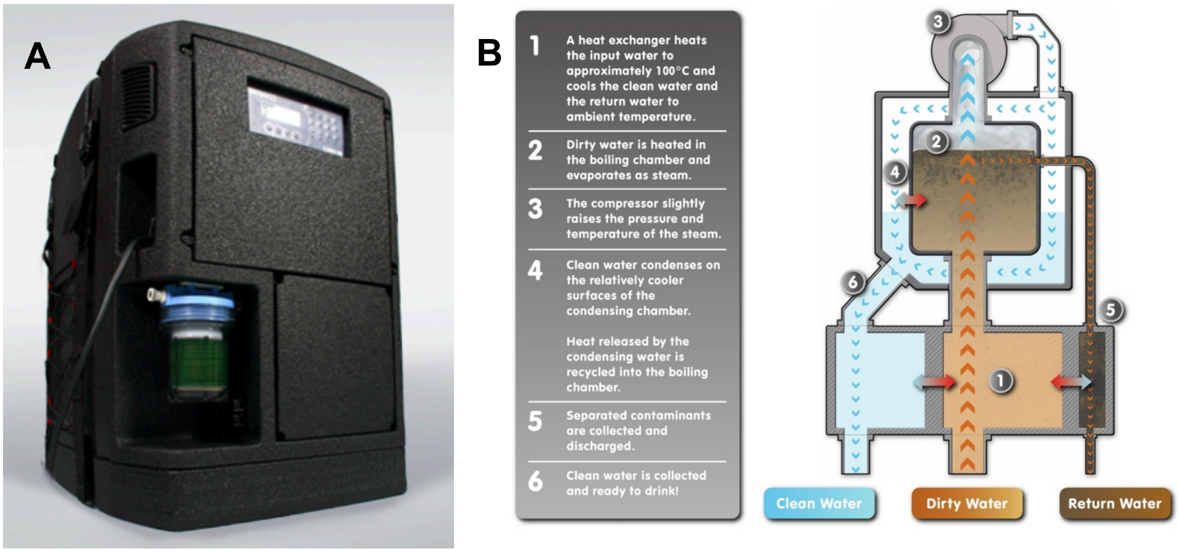


Figure 1: **(A)** The slingshot water purifier with a size comparable to a mini refrigerator and **(B)** its associated operating principle [7].

1.2. Slingshot water purification

In this context, we recently came across this a technology that claims to be able to address this issue: the Slingshot water purification technology [5] (Figure 1A). Named after the famous biblical slingshot story that revolves around the defeat of Goliath (in this case waterborne diseases) by David with a slingshot (their water purifier), this technology introduced in 2010 claims to produce potable water using a relatively simple operation. Specifically they claim that it is possible to produce 1000 liters of clean, distilled water with the power consumption comparable to that of a hair dryer. The system functions based on a vapor-compression distillation mechanism and heat recovery mechanism. It was promoted as a revolutionary breakthrough in the supply of clean water. The soft drink global giant Coco-Cola had even initiated a collaboration with Slingshot increasing the credibility of this technology [6]. It kindled further interest with demonstration setups in rural Ghana, Paraguay, South Africa, Honduras, Bangladesh etc.

The technology can be described as a process, which warms the water to its boiling point, and further boils it by subsequent heat transfer in an evaporator (Figure 1B). This two-step boiling leaves behind the contaminants from the source water, which mimics both the natural water cycle process and the pasteurization process. The saturated steam produced in the evaporator enters the compressor and the resultant supersaturated steam is cooled and condensed to produce liquid water. The key aspect allowing this technology to function is its ability to recover the heat of the supersaturated steam to heat and evaporate the incoming water stream.

Besides the unique selling point of providing clean water, they also claim that the power consumption will be about 1 kilo Watt, the same as that of a coffee maker or a hair dryer. In addition, for regions that are off-grid, they suggest using a Stirling engine, which requires only a hot and cold source, which can be provided by diverse fuels such as cow dung or kerosene with air.

1.3. Objectives

The goal of this report is to evaluate the slingshot technology from both a technology and an implementation perspective. We will first analyze its operating principle from a thermodynamic perspective by building a small systems model. First and foremost, this will allow us to verify that this technology can work without violating thermodynamic principles. Then we will analyze its implementation within the context of a larger water supply network. This will allow us to comment, at least qualitatively, on how this technology compares from an economic and environmental perspective to classic water purification processes like sewage treatment plants.

2. Technology evaluation

2.1. Technology perspective: process flowsheet modeling

Below, we will build a small process flowsheet model in order to better understand the technology and verify its feasibility. As a first approximation, we assume that pure water stream enters the system at room temperature (25°C) and atmospheric pressure. This allows us to treat the system as a one-component system (we can likely ignore the impurities from a thermodynamic point of view). The water then gets heated to 100°C, boils and becomes saturated steam at 1 atm. The steam then gets compressed. We assume that this compression happens isentropically and adiabatically. The steam then cools to its saturation temperature (at some higher pressure P_1), and then condenses. The liquid then further cools to an acceptable temperature (T_2) for consumption. A summary of the system is provided in Figure 2, summarizing what we know from the limited information given in promotional material on the technology.

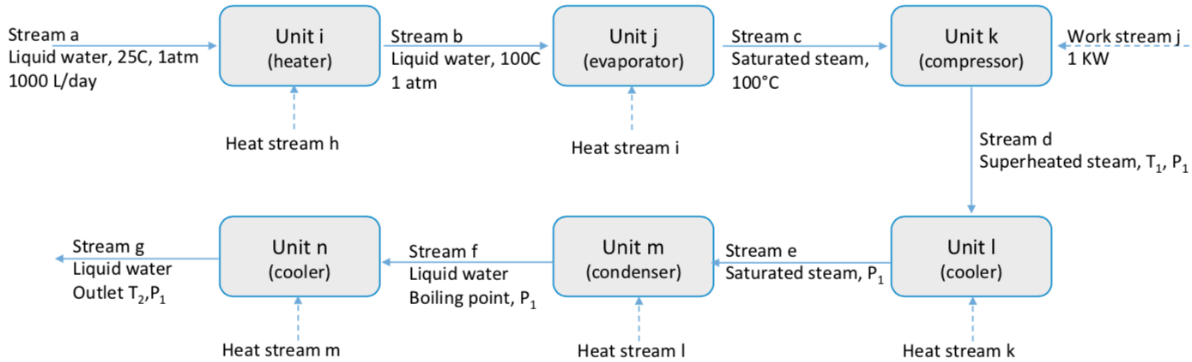


Figure 2: Diagram of the process flowsheet model of the Slingshot water purifier with known specifications

2.1.1. Systems Modelling: Specifications

To ensure that we have sufficient information for characterizing the slingshot system, the following validation was performed.

The number of required specifications are given in equation 1:

$$N_{specifications} = N_{streams,Q} + N_{streams,W_{el}} + 2N_{streams,W_{mech}} + N_{streams,material}(2 + N_c) = 5 + 1 + 7 * (2 + 1) = 27 \quad (1)$$

By comparison with Figure 2, we can count how many specifications were made based on information given found for the Slingshot process or assumptions (Table 1).

Stream	Number of specifications	Remarks
Stream a	3	
Stream b	2	
Stream c	2	Temperature and saturation conditions set the pressure
Stream d	-	
Stream e	2	Saturation T° at P_1
Stream f	2	boiling water at P_1
Stream g	2	T_2 and P_1
Stream j	1	
Streams h, I, k, l, m	-	

Table 1: Number of specifications for each stream fo the slingshot process, with a total of **14 specifications**.

Based on our calculations in Table 1 and equation 1, we are missing 13 specifications. However, this is for isolated streams. We have unit relations that will reduce the number of required specifications. Notably, for each unit we have a mass and energy balance:

$$6\ units \times 2\ balances = 12\ equations \quad (2)$$

For the pump, we also have the relation for isentropic (which leads to a reversible adiabatic transformation) compression, which provides us with one extra equation. Therefore, this will reduce the number of required specifications by 13, meaning our system is fully specified.

2.1.2. Thermodynamic and mass balance calculations

Since our system is fully specified, we should be able to calculate all its properties. Therefore below, we will calculate all the missing information from Figure 2 (i.e. temperature, pressure and enthalpies).

Temperature, Pressure and Volumetric flowrate calculations

We will begin by calculating the temperature and pressure of the fluid after compression. To do so, we will make the following assumptions, which all lead to negligible error:

- The compression is adiabatic
- Steam acts like an ideal gas

For an adiabatic compression, we have:

$$\Delta U = W = C_V(T_2 - T_1) \quad (3)$$

And the quantity of steam becomes:

$$\dot{M}_{steam} = 1000\frac{L}{day} = 0.0116\ kg/sec \quad (4)$$

For the following power:

$$\dot{W} = 1000\ J/sec \quad (5)$$

We can calculate the work used for 1 kg of steam:

$$W = 86.4\ kJ\ per\ kg\ steam \quad (6)$$

Using equation 3 and assuming a C_V of 1.97 kJ/K for steam, we can calculate the exiting temperature of the steam from the compressor:

$$T_2 = T_1 + \frac{W}{C_V} = 100°C + \frac{93.6\ kJ}{1.97\frac{kJ}{K}} = 143.9°C \quad (7)$$

Further calculation will be facilitated by the use of the ratio of heat capacities (k):

$$k = \frac{C_P}{C_V} = 1.31 \quad (8)$$

which allows us to calculate the resulting pressure for an adiabatic compression:

$$\left(\frac{T_2}{T_1}\right) = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} \rightarrow P_2 = P_1\left(\frac{T_2}{T_1}\right)^{\frac{k}{k-1}} = 1\ atm\left(\frac{420.5}{373}\right)^{\frac{1.31}{0.31}} = 1.60\ atm \quad (9)$$

Because we know the quantity of steam and the pressure, we can use the ideal gas law to calculate the volumetric flowrate of the entering and exiting steam:

$$\dot{V}_{steam,1} = \dot{n}\frac{RT}{P} = \frac{10.7}{18}8.314 * \frac{373}{101325} = \frac{0.0182m^3}{sec} = 18L/sec \quad (10)$$

$$\dot{V}_{steam,2} = \dot{V}_{steam,1}\left(\frac{P_1}{P_2}\right)^{1/k} = 12.7\ L/sec \quad (11)$$

Estimation of stream enthalpies and enthalpies

Because we know the state of each stream, we can now use known thermodynamic relations to determine the physical state of the compressed fluid (which is still unkown) and, with this information, we will be able to calculate the entropy and enthalpy. For water, all of these values are directly available from the online NIST database (the chemistry webbook of fluid phase data, https://webbook.nist.gov/chemistry/fluid/). However, we will demonstrate this calculation for the single stream of the compressed fluid (stream d in Figure 2) and the remaining enthalpies will then be taken directly from the NIST webbook.

The necessary coefficients for the Antoine equation and the Cp equation of water and the standard enthalpy and entropy are shown below (these coefficients are also taken from the online NIST webbook).

Antoine's parameters, valid 370-573K:
A = 3.55959 B = 643.748 C = -198.043 (12)

Cp equation coefficients, vapor phase:
A = 30.092 B = 6.832514 C = 6.793435 D = -2.53448 E = 0.082139 (13)

Cp equation coefficients, liquid phase:
A = -203.6060 B = 1523.290 C = -3196.413 D = 2474.455 E = 3.855326 (14)

For this calculation, we also require the standard molar enthalpies and entropies (again taken from the NIST webbook):

Standard enthalpy and entropy, vapor phase:
Standard enthalpy, kJ/mol = -241.83 Standard entropy, J/molK = 188.84 (15)

Standard entropy, liquid phase, J/molK = 69.95 (16)

For liquid phase calculations, we also require various phase change parameters:

Enthalpy of vaporization, water at 100C, kJ/mol = 40.6 (17)
Critical temperature and pressure of water: 647.3K, 221.2 bar (18)

First, using the Antoine equation, we can determine the saturation pressure of our fluid for the its temperature. By comparing this saturation pressure to its actual pressure, we will be able to determine whether the stream is a liquid or gas phase stream and proceed with the appropriate enthalpy calculation.

$$log_{10}(P_{sat,\alpha}) = A_\alpha - \frac{B_\alpha}{T_{sat,\alpha} + C_\alpha} = 3.55959 - \frac{643.748}{430.7 - 198.043} \quad (19)$$

With equation 19, we calculate the following saturation pressure:

$$P_{sat,\alpha} = 6.2\ bar \quad (20)$$

At this temperature, saturation pressure is 6.2 bar. Since our pressure is lower, we know our fluid is in the vapor phase. Therefore, we use the vapor phase Cp coefficients to determine enthalpy and entropy at this temperature from H_0 and S_0.

We know that:

$$C_P(T) = A_\alpha + B_\alpha T + C_\alpha T^2 + D_\alpha T^3 + \frac{E_\alpha}{T^2} \text{, where } T = \frac{temp}{1000} \quad (21)$$

and

$$dH = C_p dT \quad (22)$$

Thus:

$$H = \int_{T_0}^{T_1} C_p \, dT \quad (23)$$

From equation 21 and 23, we integrate to get:

$$\Delta H = A_\alpha(T_1 - T_0) + \frac{B_\alpha(T_1^2 - T_0^2)}{2} + \frac{C_\alpha(T_1^3 - T_0^3)}{3} + \frac{D_\alpha(T_1^4 - T_0^4)}{4} - E_\alpha\left(\frac{1}{T_1} - \frac{1}{T_0}\right) \quad (24)$$

with the correct numerical parameters, we get:

$$\Delta H = (30.09) * (431 - 298) + \frac{\frac{6.832}{1000} * (431^2 - 298^2)}{2} + \frac{\frac{6.793}{1000^2} * (431^3 - 298^3)}{3} + \frac{-\frac{2.53448}{1000^3} * (431^4 - 298^4)}{4} - 0.082 * 1000^2\left(\frac{1}{431} - \frac{1}{298}\right) = 4.51 \frac{kJ}{mol} \quad (25)$$

Therefore, we obtain the desired enthalpy:

$$H_{430.7} = H_{298.15} + \Delta H = -241.83 + 4.508 = -237.3 \ kJ/mol \quad (26)$$

For entropy, we know that:

$$dS = \frac{C_p}{T} dT - \frac{R}{P} dP \quad (27)$$

and we can write:

$$S = \int_{T_0}^{T_1} \frac{C_p}{T} dT - \int_{P_0}^{P_1} \frac{R}{P} dP \quad (28)$$

Using equation 21 and 28, and integrating, we get:

$$\Delta S_\alpha = \left[A_\alpha ln\left(\frac{T_1}{T_0}\right) + \frac{B_\alpha}{1000}(T_1 - T_0) + \frac{\frac{C_\alpha}{1000^2}(T_1^2 - T_0^2)}{2} + \frac{\frac{D_\alpha}{1000^3}(T_1^3 - T_0^3)}{3} - \frac{E_\alpha * 1000^2}{2}\left(\frac{1}{T_1^2} - \frac{1}{T_0^2}\right)\right] - \left[R * \ln\left(\frac{P_1}{P_0}\right)\right] \quad (29)$$

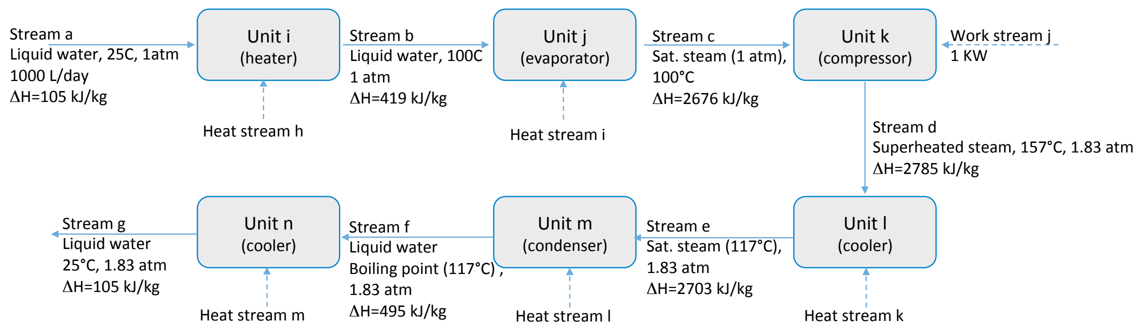
Using numerical values as well as appropriate temperatures and pressures (T_1 = 431 K, T_0=298 K, P_1=1.86 bar, P_0=1 bar), we obtain:

$$\Delta S = 7.338 \ J/mol \quad (30)$$

With this information, we obtain the desired entropy:

$$S_{430.7} = S_{298.15} + \Delta S = 188.84 + 7.3 = 196.18 \ \frac{J}{mol} \quad (31)$$

This type of calculation can be repreated for each stream. The resulting enthalpies are shown in Figure 3.



Note: These enthalpies are based on an enthalpy of zero for liquid water at 0°C, which makes the numbers manageable. If you want to use numbers corresponding to last week's problem set, you need to add -15'880 kJ/kg to the numbers above.

Figure 3: Diagram of the process flowsheet model of the Slingshot water purifier after solving all the heat and energy balances.

2.1.3. Thermodynamic and mass balance calculations

Based on the values calculated in Figure 3, we have all the necessary information to perform heat integration through pinch analysis. This operation will allow us to determine whether or not the system is indeed self sufficient. First, we

Unit i: $T_a = 25°C \quad T_b = 100°C \quad Q = 419 - 105 = 314\ kJ/kg$ → cold stream (32)

Unit j: $T_b = 100°C \quad T_c = 100°C \quad Q = 2676 - 419 = 2257 \frac{kJ}{kg}$ → cold stream (33)

Unit l: $T_d = 157°C \quad T_e = 117°C \quad Q = 2703 - 2785 = -82 \frac{kJ}{kg}$ → hot stream (34)

Unit m: $T_e = 117°C \quad T_f = 117°C \quad Q = 495 - 2703 = -2208 \frac{kJ}{kg}$ → hot stream (35)

Unit n: $T_f = 117°C \quad T_g = 25°C \quad Q = 105 - 495 = -390 \frac{kJ}{kg}$ → hot stream (36)

Interestingly, no streams overlap in temperature. Thus, we can directly use these streams to build our hot and cold composite curves. Because there is supposedly no heat durty for the system, this means the hot composite curve must exactly cover the cold composite curve. Thus, the placement of the hot vs. the cold composite curve is imposed (Figure 4).

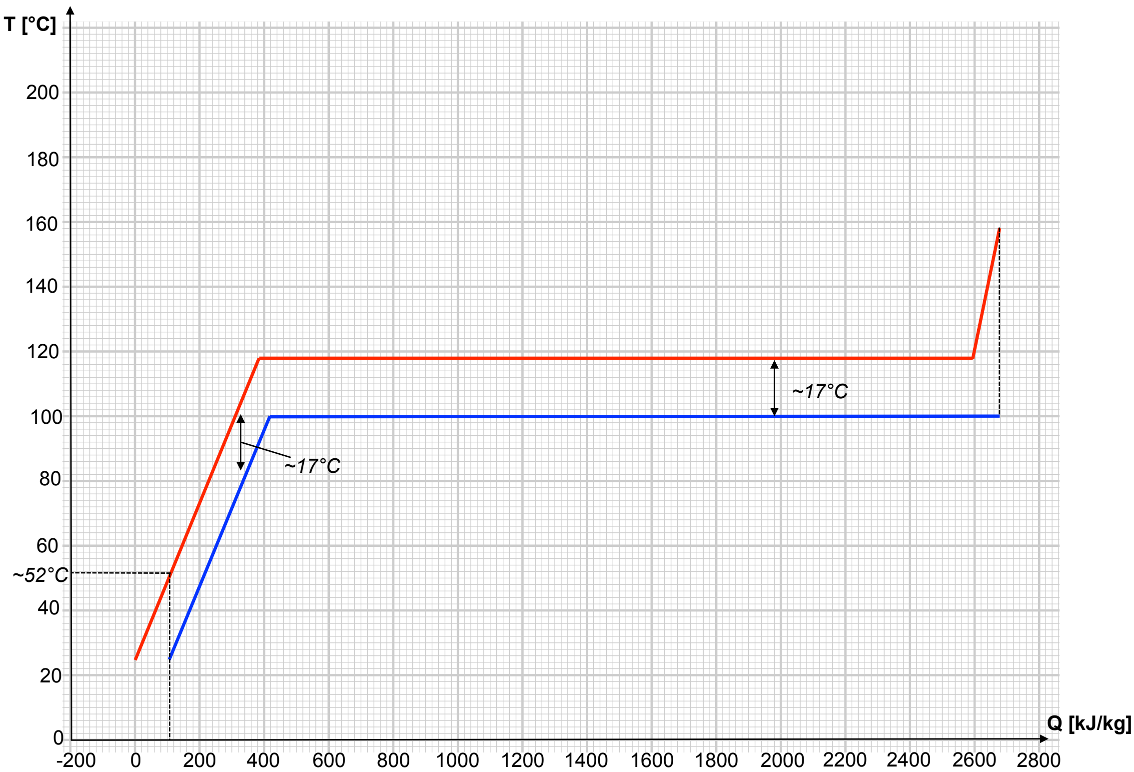


Figure 4: Heat integration by pinch analysis of the Slingshot water purifier.

As construted (Figure 4), the minimum approach temperature is around 17°C both during the boiling/condensing phase and the liquid exchange phase. In both cases, we are well above the recommended minimum approach temperature making this process completely feasible. Notice that there is no true pinch point here because we have too much heat at high temperature.

If we cool the hot stream all the way to 25°C, we would need an external cold utility. To avoid using a cold utility (and violating the specification of self sufficiency), we need the end of the hot stream to be aligned with the start of the cold stream. By interpolation, we can determine that this alignment would correspond to an exit temperature of about 52°C. That being said, in this system, we have assumed that there would be no heat losses to the environment in the process. Since there are likely to be some losses, this final temperature would probably be lower in practice. Either way, as long as the water is pure, it is not considered a problem that the exit temperature is hotter than 25°C.

The conclusion of our technology evaluation is that **the system, as described in promotional material is perfectly feasible based on thermodynamic limits**.

2.2 Systems perspective

2.2.1 Economic evaluation

The fact that the system is feasible does not mean that it can be realistically implemented.To answer assess whether it is a realistic solution or not, we briefly compare the economics of this technology to a cost-effective water supplier in Ghana. The cost of any water treatment system comprises of the purchase cost and the annual operational costs [9]. The latter is inclusive of electricity, repair and maintenance costs of the system. The operational costs depend on the amount of water production per day and the major component of it is electricity.

$$\text{Total cost per year} = Annualized\ cost + Annual\ operational\ costs \tag{37}$$

Wherein,

$$Annual\ operational\ costs = Electricity\ cost + Repair\ and\ maintenance\ costs \tag{38}$$

$$Annualized\ cost = CRF(i, Rproj) \cdot \text{NPC} \tag{39}$$

$$CRF = \frac{i(1+i)^{Rproj}}{(1+i)^{Rproj}-1} \tag{40}$$

Where, the CRF is the capital recovery factor as a function of interest rate (i) and the lifetime (Rproj) of the asset and NPC is the net present cost.

The annualized cost of an asset is the cost that, if it were to occur equally in every year of the project lifetime, would give the same net present cost as the actual cash flow sequence associated with that component. The equivalent annual cost methodology allows a company to compare the cost effectiveness of various assets that have unequal lifespans.

Annualized cost of the Slingshot system, assuming a useful life of 10 years with an interest rate of 5 percent has been estimated to be $259. A power rate of $0.14 per kWh was assumed to calculate the energy costs [10] with the consideration that the Slingshot purifier consumes 1 kW electricity. In addition, repair and maintenance cost were assumed to be 15% of the purchase price of the unit per year i.e. 15% of $2'000. Total cost of the unit is $1'785, estimated by combining annualized cost, operation cost, and repair and maintenance cost which are $259, $1,226 and $300 respectively. From which, the cost per m^3 of the produced water by slingshot was calculated to be $4.89.

Figure 5: The Swiss fresh water water © purifier system

To understand the potential of the Slingshot treatment system, it was compared with four other existing systems. First with a water treatment system developed by the Swiss fresh water company based on reverse osmosis membrane purification and powered by solar technology. Second, a reverse osmosis desalination plant located in Ghana and thirdly with the Ghana water company limited, the major player in the water utility services. Finally, a comparison with the bottled mineral water supplier- Bel-Aqua was made.

Specifically, this comparative study was performed by identifying a similar potable water supplier. A Swiss limited company based in Lausanne "Swiss Fresh Water" develops decentralized water treatment system based on reverse osmosis membrane purification [11]. It can produce 4000 liters per day with an energy consumption of 0.4 kWh (Fig. 5). Annualized cost of the Swiss fresh water system, assuming a useful life of 10 years with an interest rate of 5 percent has been estimated to be $2'408 as the price of one unit is $18'591. A power rate of $0.14 per kWh was assumed to calculate the energy costs with the consideration that purifier consumes 0.4 kWh electricity. In addition, repair and maintenance cost were assumed to be 15% of the purchase price of the unit per year i.e. 15% of $18'591. Total cost of the unit is $5'217, estimated by combining the annualized cost, operation cost, and repair and maintenance cost which are $2408, $20.44 and $2'789 respectively. From which, the cost per m^3 of the produced water by slingshot was calculated to be $3.57.

The direct data (cost per m^3) for the other systems namely, the desalinated water, water supplied by Ghana water company limited and bottled mineral water were obtained from online sources [12-14].

The final comparison (Table 2) suggests that the Sling shot is a very expensive system for fresh water production. However, it is not that dissimilar in price to that of a comparable self sufficient system like the Swiss Fresh Water system. Therefore, it seems that this could be an interesting solution for point of use water purification, and if options for building larger centralized plants are unavailable. Finally, it should be noted that all these solutions are far btetter than bottled water, which is significantly more expensive.

Treatment System	Annualized cost	Electricity cost/year	Repair and maintenance	Total cost/year	Cost/m^3
Sling shot	$259	$1226	$300	$1785	$4.89
Swiss Fresh water	$2408	$20.44	$2789	$5217	$3.57
Reverse osmosis desalination plant					$0.34*
Ghana water company limited					$1.36*
Bottled mineral water Bel-Aqua®					$76

Table 2: The economic evaluation of the slingshot water purifier with other existing systems. *Regulated price

2.2.2 Environmental evaluation

In addition to economic consideration, it is also important to compare these processes from an environmental perspective. To do so, we perfomed a quick estimate of the carbon footprint of the potable water produced by Slingshot technology and a comparison with other technologies was made.

As a first approximation, we decided to neglect the embedded energy needed to produce the aparatus and only focus on the CO_2 emitted during the production of the necessary energy to run the process. Though this might not be entirely accurate, it will at least provide a first estimate of whether or not the Slingshot process is environmentally comparable to others. Since it will definitely include more infrastructure per water produced than a larger plant, the comparison is only likely to get worse for Slingshot as the apparatus is included. The following formula was used to calculate the Kg of CO_2 emission per m^3 of water produced [15].

$$CO_2\ emission\ factor = \frac{Energy\ consumption\ of\ the\ technology}{Volume\ of\ fresh\ water\ produced} * CO_2\ emission\ for\ electricity\ produced \quad (41)$$

As per EPA [16], the statistical figure for CO_2 emission (in kg) for the generation of 1 kWh is 0.744. The per day energy consumption of Slingshot is 24 kWh for a m^3 production of fresh potable water. On the basis of which, the CO_2 emission factor for Slingshot is 17.86 kg CO_2 per cubic meter of water produced. The conclusion is that, from energetic and emissions point of view, and even with this limited analysis, the Slingshot technology appears far worse than competing technologies (though there is a lot of uncertainty) compared to alternatives. However, due to its ability to process virtually any incoming brackish water, no matter how dirty, this might still be interesting in very limited cases where other options are unavailable.

Technology	CO_2 emissions (Kg CO_2 per m^3)
Slingshot	17.6
Multi-effect distillation	0.3-26.9
Multi-stage flash	0.3-34.7
Reverse osmosis	0.08-4.3

Table 3: The carbon footprint evaluation of the slingshot water purifier with other existing systems. The data for the Multi-effect distillation, Multi-stage flash and Reverse osmosis were obtained from [17].

3.Conclusion

In this study, we have performed a quick analysis of the Slingshot water purification technology from both a technology perspective and a larger systems perspective. The latter, was to evaluate what the effect of its implementation on a wide basis. The result of the technology evaluation showed that the presented concept did not violate thermodynamic principles and based on the data provided seems to be feasible. The systems analysis demonstrated that the costs and environmental burden of running the technology are far greater than those associated with classic sewage treatment plant systems and even comparable small scale technologies like reverse osmosis. Therefore, we can conclude that a large scale implementation of this technology would likely would both be economically and environmentally problematic.

That being said, the system's flexibility and ability to function on a very small scale make it an attractive solution for limited punctual uses. This could be an ideal solution to provide an emergency water immediately for a small community when only severely contaminated brackish water is available. Unfortunately, these unfortunate circumstances are not infrequent and, thus, we foresee that the Slingshot could play an important role as an emergency water supply system. However, the way it is portrayed in the associated documentary, as a technology that can rid the world of its water purification issues represents a significant overstatement.

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