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Gravity force-driven desalination unit: a sustainable energy substitute of high-pressure pumps

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ABSTRACT

Water shortage is a worldwide serious issue and of great priority. Efforts are being spent to solve this issue and propose alternatives especially in arid and semiarid countries. Along with wastewater reclamation and reuse, desalination has been adopted as a non-conventional water supply alternative in water-scarce regions. Estimates report that reliance on desalinated water is expected to grow in coming decades. However, desalination requires significant amount share of generated electricity. For the time being, most of desalination plants in the Middle East are operated using non-renewable and non-environmental friendly energy options. Hence, investigations to develop effective desalination processes powered by various sustainable energies are prioritized. Thus, a low (energy)-cost seawater desalination system and methods that operate using gravity force are proposed. In this unit, the conventional high-pressure pumps are substituted by a heavy mass (water tank) to generate the pressure needed for seawater filtration (desalination using reverse osmosis membranes), resulting in a massive reduction in the energy needed (about 90%) for this process, consequently, a remarkable lowering in the cost.

Keywords: Desalination; Low-energy; Reverse-osmosis; Gravity force

1. Introduction

Limited water supplies affect economic development, and it is a source of conflicts. Moreover, it results in poor sanitation and severe health impacts. Hence, one of the main development goals of United Nations concerns the sustainable supply of potable water to users around the globe [1]. Along with recycled wastewater, the conversion of seawater to freshwater is among the rainfall independent alternatives to supply fresh water. Thus, seawater desalination and brackish water desalination, a rainfall-independent resources producing non-conventional freshwater, are effective alternatives to meet an ever-increasing water demand, especially in water-scarce countries [1,2]. Seawater and brackish water desalinations are of particular interest in the Middle East and North African countries, which rely heavily on groundwater. More than 15,000 desalination plants operate around the globe to produce approximately

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60 million m^3/d of water, and these values are expected to reach 120 million m^3/d by 2020 [3,4].

Water desalination can be achieved using thermal processes or membrane separation. Greater than 90% of the thermal desalination processes are multi-stage flash (MSF) distillation processes, and more than 80% of the membrane-based processes are RO processes [5,6]. Unfortunately, both methods are typically energy intensive and cause environmental problems because they mainly rely on fossil fuels. An average of 15–20 kWh/m^3 is required for thermal desalination, while 5 kWh/m^3 is needed for reverse osmosis (RO)-based desalination without energy recovery, 3 kWh/m^3 for RO-based desalination with energy recovery, and 1.5 kWh/m^3 for electrodialysis [7–9]. Lower-cost alternatives such as forward osmosis processes are currently under development and not yet commercially in use [10].

Since its early age, desalination is of interest for developing cost-effective methods that provide freshwater for human use. In 1962, John F. Kennedy, the former president of the United States, stated the following: "If we could produce freshwater from salt water at a low cost that would indeed be a great service to humanity and would dwarf any other scientific accomplishment" [5]. Moreover, and because the main energy sources for desalination plants are driven from fossil fuel resources, the rapidly growing energy demand for desalination has become a major concern. Efforts have been made to design less-energy-demanding plants and a renewable-energy powered plants. Membrane-based desalination systems (typically RO) that are associated with renewable energy sources, including wind, solar, and geothermal, are promising, and a number of these plants have been implemented around the world [1–3,7,10–13]. Although advantages exist with the use of the aforementioned renewable energy sources, energy prices for renewable energy are high. In addition, the intermittent availability in space or time of solar, wind, and geothermal resources is a major challenge for the RO desalination plants. Thus, energy that is stored in the form of hydrostatic pressure has been explored as a potential for RO-driven desalination [14–20]. Hydrostatic pressure-driven RO desalination consists of setting the membrane module below a sufficient working depth of the water column. Submarine desalination plants [14,15], underground plants [16], or mountain-foot plants [18] are the three major configurations developed. In these configurations, the high-pressure pumps, which consume the largest amount of energy in RO desalination, are substituted by the hydrostatic pressure, which significantly reduces the energy required for desalination. In submarine and underground plants, energy requirements are mainly required to pump out the product water only, and no pumps are required for feed water or brine discharge. Mountain-foot plants were proposed to overcome the problems associated with the submarine and underground plants (e.g. submerging the entire system in the sea or digging to a depth of approximately 500 m for the underground RO desalination plant) [15,16,18]. If coupled with wind or solar energy when power is available, water is pumped to a water column and is stored as hydrostatic pressure to drive the RO systems when the power is not available. This process is an economically efficient way to store energy. In addition, mountain-foot plants introduce the concept of a feed line and a driving pressure line. In conventional RO systems, water is fed to the membrane and is pressurized using the same high-pressure pump. In mountain-foot innovative design, Al-kharabsheh [17] proposed a driving pressure system composed of a storage tank that is located on top of an adjacent mountain, a water column, a flexible pipe, and an RO module (placed slightly above sea level) with a moving hollow piston (HP) and valves. The feed line is composed of a feed tank, a connecting pipe, a cylinder (lower part of a HP/cylinder), and the RO modules and valves. The perfect opening and closing of the valves controls the cyclic operation of the system (i.e. feeding, pressurization, and brine discharge). This proposed design has a significantly lower energy demand than the conventional RO plants.

The hydrostatic pressure-driven RO plants are promising. However, the main drawback associated with these plants is their construction and maintenance, which are more complicated and costly than conventional plants. Among these three systems, the system proposed by Al-Kharabsheh is the most promising because of its energy efficiency and its relatively simple operation and maintenance. However, its major drawback is that the system is topography dependent and cannot be applied universally. However, the hydrostatic pressure can be exploited by substituting the elevated water column by a pressurized water tank. This option will reduce construction costs and will make the system available for every location.

The purpose of this article is to present the newly proposed mass-driven RO system (Al-Kharabsheh-modified system) along with its energy requirements.

2. Hydrostatic pressure for RO desalination and disadvantages

The use of hydrostatic pressure drew the attention of many researchers in the last few decades [12–15]. Their researches have resulted in new desalination techniques, where the membrane module is set at sufficient operative depth below sea level [12–15]. The water column above the membrane generates the required pressure. In some alternatives, a reservoir is set on a top of the mountain of sufficient operative altitude and connected via a pipe to a membrane module near shoreline [16]. Their efforts have ended up with proposing various configurations. These configurations include submarine, underground, and ground-based plants [17,18], and patents were proposed on this technology [19,20].

Although their importance, these alternative remained limited in use because of the associated technical difficulties, the associated installation costs involved, and their dependence on topography (e.g. a mountain of sufficient operative altitude on shore line).

In conventional RO installations, the required pressure is generated with the use of high-pressure pumps. In the above-mentioned configurations, the water column above the membrane generates the required pressure. In submarine case or underground case, the RO module is in deep sea and only product freshwater is pumped out which reduces pumping energy by up to 80% [14]. With the help of advanced offshore submarine technologies, a pressure vessel containing all apparatus is required for submarine plants, which would raise the installation cost and complicate the maintenance of the plant. A huge cost and complexity are also associated with the installation of the plant on the underground.

For a plant located near mountain [16], freshwater can be produced at a cost of 0.85 kWh/m^3, while it is of 3–10 kWh/m^3 in conventional RO plants. However, this approach is limited by the topography. In flat area, such an alternative cannot be implemented. It is quite limited to find a mountain of sufficient altitude and pumping seawater to a mountain faraway from coastline will increase the cost, and the alternative is no more viable economically.

For a better use of hydrostatic energy for RO desalination, an investigation on developing innovative approach for desalination on ground and near shoreline without requiring a mountain to raise the water column was carried out. In this article, a system based on the concept of mass-driven pressure (MDP) to operate RO desalination is proposed.

Here, we present a way to reduce remarkably these costs, resulting in a cheap desalination technique. The idea is based on the same concept of using hydrostatic pressure to generate the required pressure to operate the RO system to desalinate seawater or brackish water. The innovative idea in the claim is related to the proposed device and equipment that can generate a sufficient level of hydrostatic pressure without the need, neither for a mountain to support the water column nor by placing the membrane module at a sufficient depth below sea level. The claimed system is free of the technical difficulties encountered previously.

3. MDP for RO

The proposed mass-driven RO unit is illustrated in Figs. 1 and 2. In this system, a module including an upper part consisting of a mass (M) that rests on the top of a water column (piston–cylinder) having a relatively small cross-sectional area (A_1) and forming the force of pressure needed for filtration, and lower part consisting of a cylindrical chamber equipped with a moving HP. This HP is connected to the upper water column with flexible pipe. The resulting pressure on the piston is equal to the sum of pressure generated by mass M and the hydrostatic pressure of water column and can be expressed as follows:

$$p = M \times g / A_1 + \rho \times g \times (h1 + h2) \quad (1)$$

where A_1 is the cross-sectional area of water column (upper cylinder cross section), m^2, M is the mass, kg, g is the gravity acceleration, m/s^2, $h2$ is the height of water column, m, and $h1$ is the height from the bottom of HP to the section valve (SV) V1 located beneath the piston–cylinder unit.

The pressure p on HP is transmitted to water contained in the lower cylindrical chamber located beneath the piston. Water is supplied to the cylindrical chamber via a feed pipe connected to the main seawater-feeding tank. During pressurization, water crossflows the membrane modules leading to desalination of the seawater.

The system is also equipped with SV located between the water column and the flexible pipe, a release valve (RV) located just below the SV, a feed valve (FV) located between the feed tank and the cylindrical chamber, and an air RV placed on top of the water column. The system operation depends heavily on the perfect opening and closing of the above-mentioned valves.

4. Operation of the proposed unit

The unit operation depends on perfect opening and closing of a series of SVs and RVs.

4.1. Step 1

FV open (one-way valve), SV closed, and RV open. Water flows from the seawater-feed tank with the higher level into the cylindrical chamber with the lower level and will lift the HP upward until the piston reaches the upper dead end. The upward lift would not be possible without releasing the high

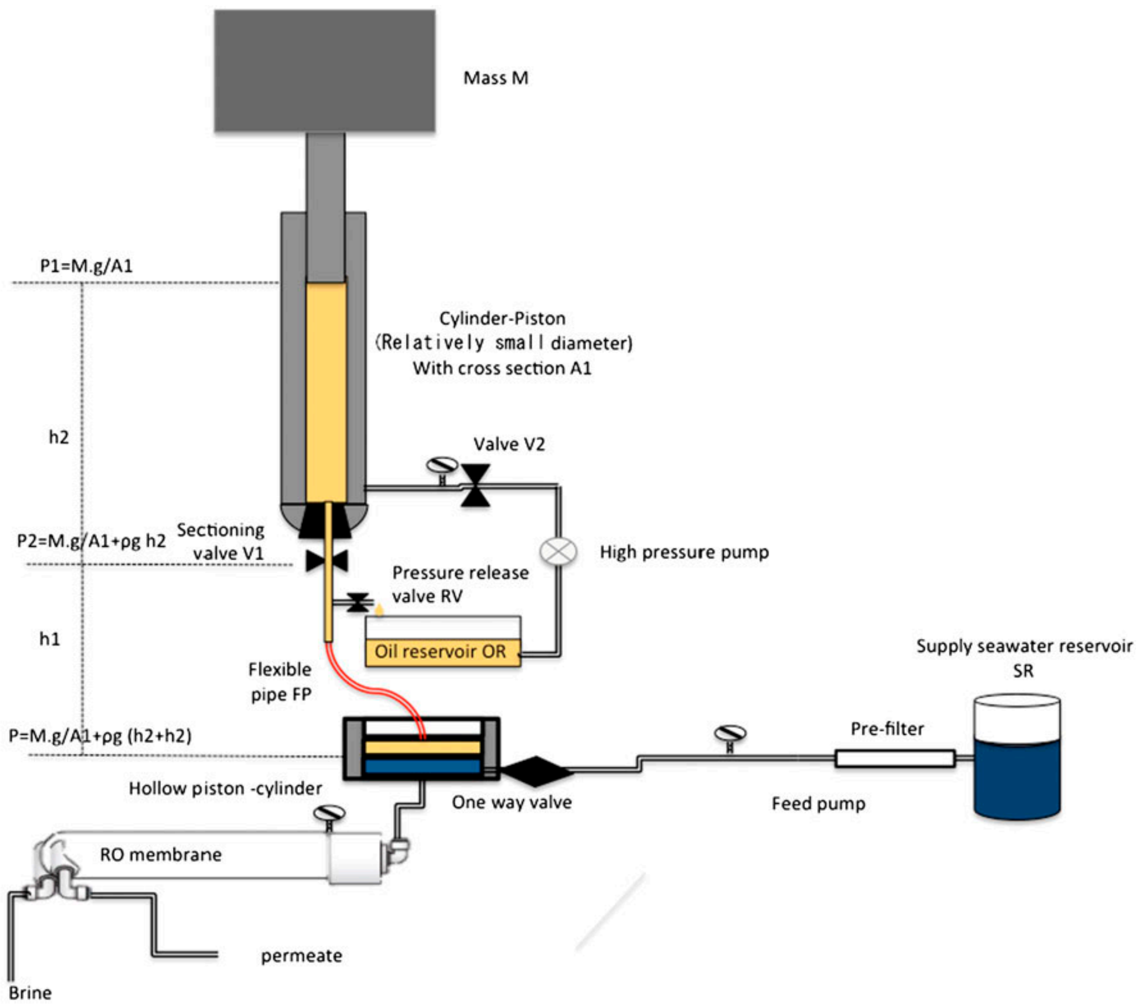

Fig. 1. Mass-driven RO unit sketch.

pressure generated by the mass M and the hydraulic fluid column (e.g. water) and transferred to the top of the HP. Only a releasing mechanism will make the uplifting movement possible. This releasing mechanism will be performed by opening a water RV located in just beneath the SV, and by that, the water in the flexible pipe tends to gain its original volume before being repressurized. The SV divides the system into an upper segment and lower segment. We notice that the hydraulic fluid (oil or water) present between the SV and the HP (i.e. inside flexible pipe) and previously pressurized by the means of the mass M and the hydraulic fluid column tends to gain its original volume when the RV is open, and therefore, a little amount of the fluid will be expelled during this step.

It should be noticed that, during the upward movement of the HP, the pre-pressurized hydraulic fluid (e.g. water) inside flexible pipe (50–70 bar), would tend to gain its original volume before being pressurized. Hence, a certain amount of liquid will be spilled out as the RV opens. The spills are estimated using following equation:

$$\nabla V = -V \cdot \nabla P / E \qquad (2)$$

where ∇V is the spills, m^3, V is the initial volume = volume inside HP + volume inside flexible pipe, m^3, ∇P is the pressure, Pa, and E is the bulk modulus of elasticity for the hydraulic fluid used in the upper piston, Pa.

We assume that the liquid used in the piston–cylinder is water.

4.2. Step 2

FV and RV closed and SV open. The resulting pressure of mass M and the water column pushes the piston downward, and water will flow across the RO

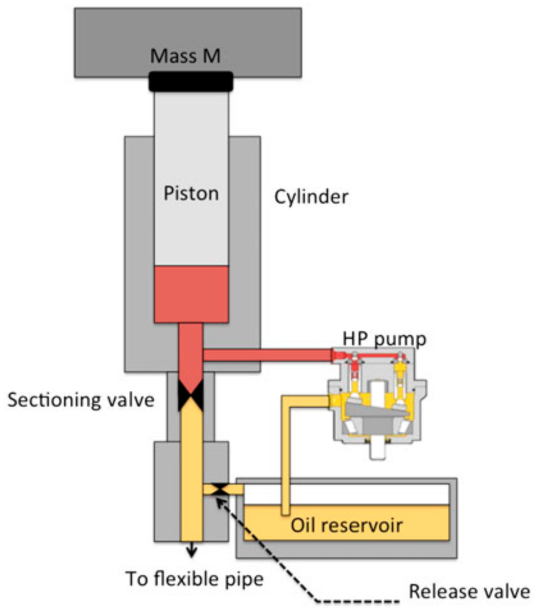

Fig. 2. Details of the driving pressure unit: upon opening of release valve, spills are collected in a reservoir from which oil is pumped at high pressure to lift the mass *M*.

membrane filters. The step 2 ends when the piston reaches the bottom dead end. Then, step 1 is restarted.

When the piston reaches the bottom dead end, the mass *M* would have dropped by a distance "*d*" that depends on the amount of released fluid and the diameter of the upper cylinder. The high-pressure pump 'HP' ensures the lift of the mass *M* through pumping the spilled fluid back to the cylinder, and the system will operate like a hydraulic jack.

5. System's power and energy consumption

Estimation of energy requirements of the system proposed herein depends on the real configuration of the desalination plant. To give an idea on energy needs, hypothetical case studies are considered. They consist of desalination plants operated using the proposed system to generate the power required to pressurize seawater or brackish water and the RO membrane modules. For the operation, power is basically needed to:

- Supply the seawater (fill the feed tank)
- Power required for generating driving pressure: (lift the mass *M* to its original position for every cycle by pumping the spills back to the cylinder beneath the mass *M*).
- Recycle the brine

In the sections below, we estimate the power required to generate the required driving pressure for seawater and brackish water. Energy needs for brine recirculation are ignored in this calculation, as they are not the main energy needs for desalination. Moreover, power required for water supply to the plant is out of the focus of this paper.

5.1. Driving pressure

If separated by a semi-permeable membrane, pure water will tend to move into the saltwater compartment. The pressure required to prevent this inward flow is called osmotic pressure (P_s) and is calculated using van't Hoff equation:

$$P_s = c \cdot R \cdot T \tag{3}$$

where c is the molar concentration of the salt ions, R = 0.082 (L bar)/(deg mol) is the gas constant, and T = 300 K is the ambient temperature on the absolute temperature scale (K).

We shall assume, for simplicity, that all the salts contained in water are sodium chloride (NaCl). The atomic weight of sodium is 23 g and of chlorine is 35.5 g, so the molecular weight of NaCl is 58.5 g. The number of NaCl moles in seawater is, therefore, calculated from the following equation:

$$N = m/\mathrm{MW} \tag{4}$$

where N is the number of moles per liter, mol/L, m is the salinity, g/L, and MW is the molecular weight (g/mol).

When NaCl salt dissolves in water, it dissociates into Na^+ and Cl^- ions. There are two ions per salt molecule, so the ions' concentration is twice the molecules' concentration. $c = 2 \times 0.564 = 1.128$ mol/L. Inserting the values into the van't Hoff formula yields the osmotic pressure as shown in Table 1.

In order to desalinate water (seawater or brackish water), driving pressure must overcome the osmotic pressure *Ps*. Typically, driving pressure is in the range of 10–20 bar for brackish water (P_s = 8 bar) and 40 to 80 bar for seawater (P_s = 27 bar).

To generate the required driving pressure, the required mass *M* is obtained from Eq. (1), and Fig. 3 illustrates the mass diagram as a function of piston diameter, for a given driving pressure. For a piston of 5 cm diameter, (with a total height between the acting surface area and the HP of 1 m height), a mass of 300 kg can generate 15 bar, enough to desalinate

Table 1
Osmotic pressure for various type of water

	Brackish water	Seawater	Brine
Salinity (g/L)	10	33	50
Number of moles (mol/L)	0.17	0.564	0.854
Osmotic pressure (bar)	8.41	27.8	42.1

brackish water. However, a mass of 1,000 kg is required to generate 50 bar to desalinate seawater. As illustrated in Fig. 3, smaller diameters favor the use of smaller masses. Extremely small diameter is not recommended due to the technical problems for installation. In the rest of this paper, we adopt a 5 cm-diameter piston. As aforementioned, the resulting pressure of mass *M* of 1,000 kg is equal to 50 bar (509 water meter head), a pressure large enough to operate seawater desalination system. Under this pressure level and being an incompressible fluid, water's bulk modulus elasticity is equal to $E = 2.2 \times 10^9$ Pa; thus, the change in water volume is equal to 0.226% of the initial volume.

5.2. Power required for generating driving pressure:

As discussed earlier, pressure is generated by the mass *M*, acting on the top of the hydraulic fluid column plus the weight of the hydraulic fluid column itself on the HP. At each cycle, the RV opening spills hydraulic fluid into an adjacent reservoir. The spills cause the falling of the mass *M* by a certain height "*d*" (Fig. 4). After a certain period of operation, the mass *M* and the piston reach the lowest dead end. The high-pressure pump will pump the hydraulic fluid pushing the mass *M* and the piston to the upper dead end to reset the system. It should be noticed that the continuous operation is possible to maintain the mass *M* at a fixed position during operation. In this section, we assume that the hydraulic fluid used is simply water. Then we calculate the amount of freshwater produced at each cycle and the pressure drop due to mass falling. Once the mass reaches the lower dead end, we calculate all the freshwater produced in *N* cycles. Then, we calculate the power required to lift the mass *M* to its original position.

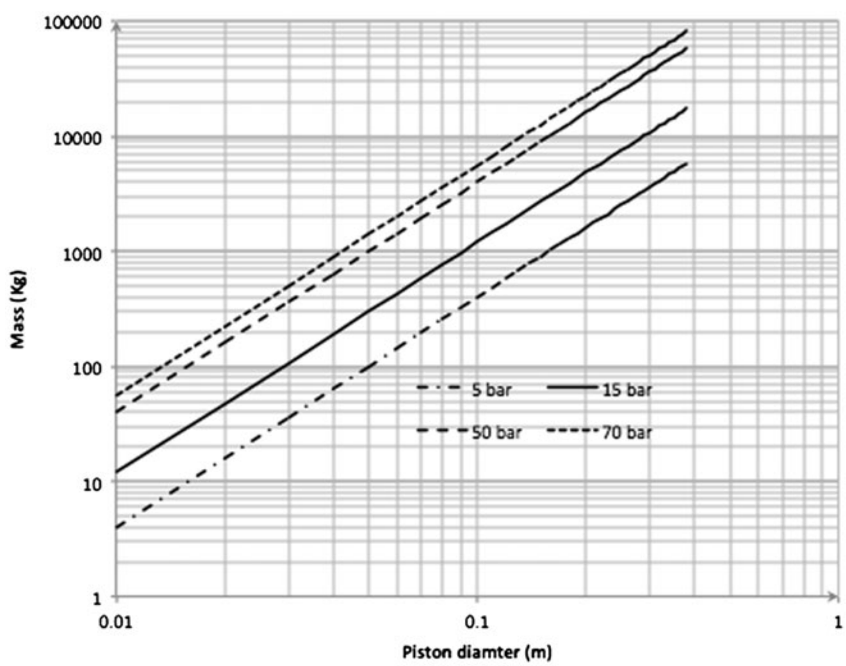

Fig. 3. Calculation of required mass *M*, for a given driving pressure, as a function of piston diameter.

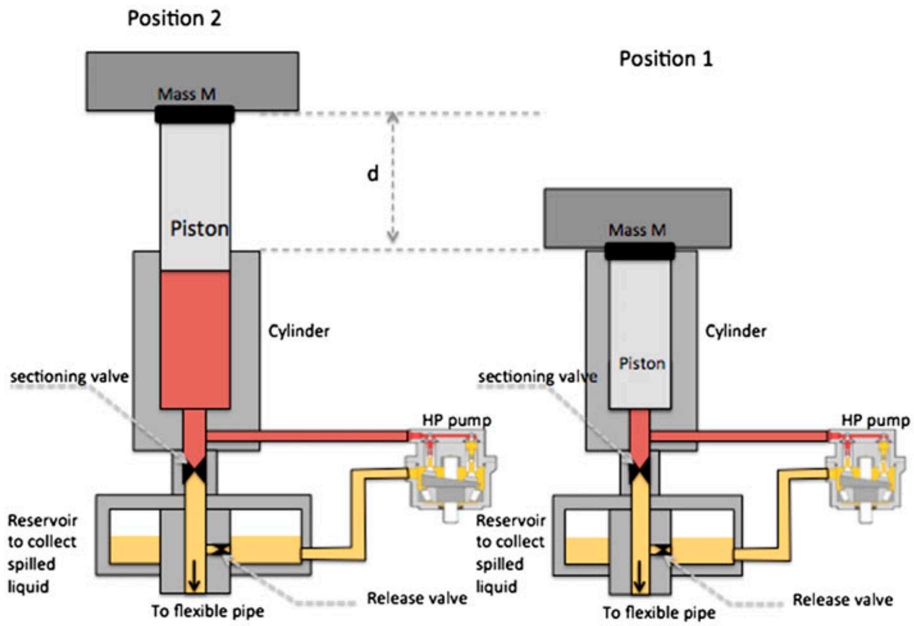

Fig. 4. Mass/piston stroke (lower and upper positions).

$$W = M \times g \times d.\Delta t/r \quad (5)$$

where W is the power, kW/h, g is the gravity acceleration, m/s^{-2}, Δt is the time required to lift the mass M, s, d is the lifting distance, m, and r is the system efficiency, %.

6. Results

Figs. 5 and 6 show the history of the pressure on the bottom of the HP and the position of the mass M during operation. As the upper piston stroke is supposed to be 1 m, when the mass M reaches the lower deadend, the mass M has to be reset to the upperposition.

In the case of seawater, almost in nearly 500 cycles, the pressure has to be reset as the mass M reaches the lower dead end. While in the case of brackish water, the mass M reaches the lower dead end after more than 1,600 cycles.

For each cycle, the freshwater production is estimated using Eq. (5). We assume a coefficient K_f of 0.6E–4 LMH/bar, which leads to a freshwater production of 1.4 L/cycle for seawater and 0.43 L/cycle for brackish water.

$$J = K_f \times (P - P_s) \quad (6)$$

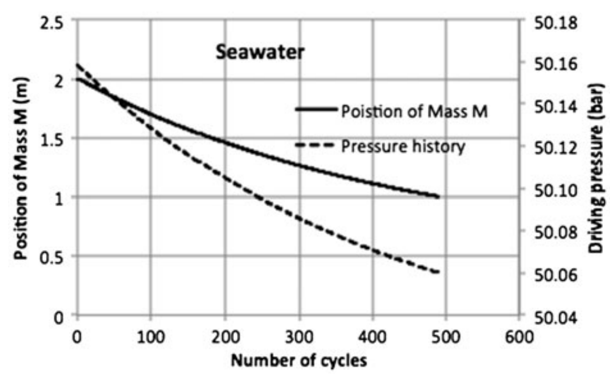

Fig. 5. Driving pressure history and position of mass M—case of seawater.

where J is the flux, P is the driving pressure, P_s is the osmotic pressure, and K_f is the coefficient that depends on the membrane characteristics.

Hence, for seawater and under a starting pressure of 50 bar, 0.69 m^3 of freshwater was produced after nearly 500 cycles, while for brackish water and with a starting pressure of 15 bar, 0.67 m^3 of freshwater was produced after more than 1,600 cycles.

The cyclic operation of this desalination unit is shown in Fig. 7. It reflects that the system will after a certain number of cycles should be reset.

Assuming that setting the mass M to its original position takes place in 20 s, thus, the power required to reset the pressure per cubic meter of freshwater is

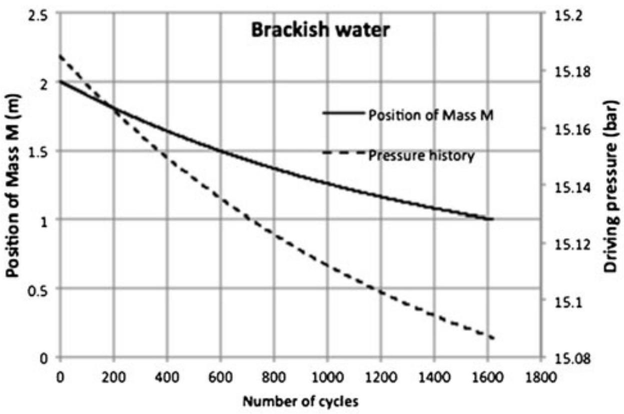

Fig. 6. Driving pressure history and position of mass *M*—case of brackish water.

illustrated in Table 2. In table, conventional practical values (with energy recovery devices) and minimal energy derived by thermodynamic considerations are also shown [21].

7. Discussion

We notice that the amount of energy required in both cases to produce one cubic meter of freshwater (0.23 kWh/m^3 for brackish water and 0.98 kWh/m^3 for seawater) is slightly higher than the minimal energy, derived by thermodynamic considerations, independently of technologies [21,22]. Minimal energy consumption for seawater desalination is equal to the desalinated water volume times the osmotic pressure. The osmotic pressure is nearly proportional to the salt concentration in the water. Because the seawater osmotic pressure is nearly 27 bar, the minimal energy for desalination is approximately 0.77 kWh/m^3 and varies based on water salinity. For brackish water of 15 g/L salinity, the minimal energy for desalination is approximately 0.22 kWh/m^3, and this minimal energy is general and is independent of the technology used. The energy consumed by the proposed design approaches to a great extent to the minimal theoretical values, which can be considered as a significant achievement of the propose unit.

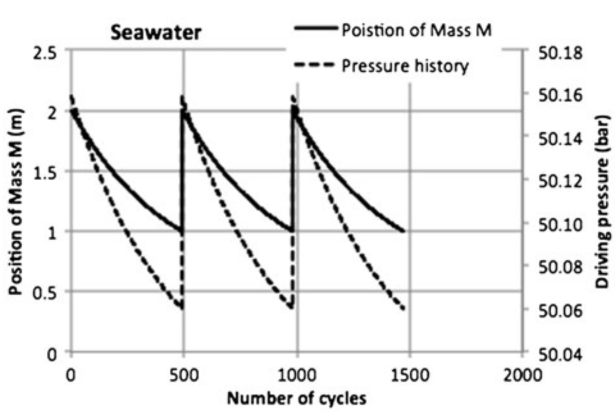

Fig. 7. Illustration of the cyclic operation.

In addition, the energy consumption of the proposed unit is significantly lower than the actual values consumed in real and conventional desalination plants. The thermal desalination plants consume greater than 15 kWh/m^3 [4]. Conventional RO requires 3–10 kWh/m^3 [21]. For a real value illustration, the specific electric energy consumption in the Ghar Lapsi desalination plant (an RO-driven desalination plant) in Malta is 6.12 kWh/m^3 [13]. Despite improvements in the reduction of energy consumption in RO systems by deploying energy recovery devices, feasibility is possible only in large-scale plants, and the energy consumption in small-scale plants without recovery devices is still very high [23].

Conventional desalination plants require from about 3–10 kWh/m^3. This means that this invention will allow an energy lowering of about 82–95% as compared to conventional desalination techniques. This newly proposed method and system is also more cost efficient than the electrodialysis known as the most cost-efficient method for seawater desalination with only 1.5 kWh/m^3. Compared with wastewater recycling, this method and system is 20% cheaper.

8. Conclusions

The findings presented in this paper illustrate the potential for the proposed design to reduce the energy requirements of the high-pressure pumps in RO-driven desalination plants. Theoretically, the proposed design resulted in significant energy savings, and the newly proposed RO unit is energy efficient and economically viable. The energy requirement is considerably low (0.98 kWh/m^3 for seawater and 0.23 kWh/m^3 for brackish water) and approaches the theoretical energy value required for desalination. However, an experimental unit is necessary to prove the aforementioned findings and to provide reliable guidelines for further development. An improvement in the design should follow to overcome the drawbacks associated with this design (e.g. cyclic operation and maintenance). The proposed design can be developed as a large-scale desalination plant or as a portable small-scale unit that can be powered by solar cells or batteries and can deliver sufficient freshwater to supply the needs of a small community.

Table 2
Energy uses of various water alternatives kWh/m^3 of freshwater

	Minimal energy, derived by thermodynamic considerations	Conventional practical values (with energy recovery devices)	Theoretical energy uses of the proposed alternatives
Brackish water desalination	0.22	1–1.5	0.23
Seawater desalination	0.77	2.5–4	0.98

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Nomenclature

A_1	—	cross-sectional area of water column (upper cylinder cross section) in m^2
M	—	mass in Kg
G	—	gravity acceleration in m/s^2
$h2$	—	height of water column in m
$h1$	—	height from the bottom of hollow piston to the section valve V1 located beneath the piston–cylinder unit
∇V	—	spills (m^3)
V	—	initial volume = volume inside hollow piston + volume inside flexible pipe (m^3)
∇P	—	pressure (Pa)
E	—	bulk modulus of elasticity for the hydraulic fluid used in the upper piston (Pa)
Ps	—	osmotic pressure (bar)
c	—	molar concentration of the salt ions
$R = 0.082$	—	(L•bar)/(deg•mol) is the gas constant
$T = 300$ K	—	ambient temperature on the absolute temperature scale (Kelvin)
N	—	number of moles per liter (mol/L)
m	—	salinity (g/L)
MW	—	molecular weight (g/mol)
W	—	power in (kW/h)
g	—	gravity acceleration (m/s^{-2})
Δt	—	time required to lift the mass M (s)
d	—	lifting distance (m)
r	—	system efficiency (%)
RO	—	reverse osmosis
kWh/m^3	—	kilowatt-hour per cubic meter
FV	—	feed valve
SV	—	sectioning valve
RV	—	release valve
HP	—	hollow piston

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