Deriving Useful Power from the Osmotic Potential Between Solutions

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Abstract

A device was constructed to enhance mariculture by moving nutrient-rich deep water to the surface. This is done by injecting fresh water at the bottom of a long vertical tube, allowing the fresh water to mix with salt water and having the brackish mixture rise because of buoyancy. While testing prototypes, it was discovered that the mixture flowed through the device much faster than that which could be accounted for by buoyancy or the transfer of kinetic energy. It is presumed that the additional energy comes from the same force that causes osmosis and diffusion. A flow of one cubic meter per second of fresh water into sea water can theoretically generate 3,000 kilowatts.

Introduction

Osmosis is so venerable that it appears in texts from first year biology [1] to graduate level physical chemistry [2]. It is defined as the flow of water through a selectively permeable membrane when there is a difference in concentration between the two sides. It is a colligative property. It is not dependant on the nature of the solute, only on the total molar concentration of all dissolved species. The water flow across the membrane is always from a lower concentration of solute to a higher one. Pure water is defined as having an osmotic potential of zero and all solutions have varying degrees of negative osmotic potential. Many references discuss osmotic potential in terms of pressure across the osmotic membrane since the easiest way to measure the effect is to apply pressure to the side of the membrane with lower osmotic potential until the net flow is canceled.

The original intent of our experiments was to characterize the behavior of a patented device [3] that enhances mariculture (farming of the sea for food and other resources). [4] The device consists of a pair of tubes. A large “UpTube” that carries deep ocean water to the surface and a much smaller “DownTube” that connects a source of fresh water to the bottom of the UpTube. The idea is to pump fresh water through the DownTube, encourage it to mix with as much ocean water as possible, and have the resulting brine travel to the surface because of its increased buoyancy.

We calculated the amount of power available to pump the brine by adding the kinetic energy of the fresh water as it exited the DownTube to the buoyancy of the fresh water. To calculate the efficiency of the energy transfer from fresh water to salt water, we monitored the salinity of the brine exiting the UpTube. In all of our experiments there was more brine flowing from the UpTube than our theoretical maximum. Firmly believing in the conservation of energy, we went looking for the source of this power. It turns out that the device is directing how a fluid with high osmotic potential is flowing into a fluid with low osmotic potential. In the process it allows one to capture useful work.

If this force can be captured with significant efficiency, then it will be possible for electrical power to be generated anywhere a river flows to the sea. If large power plants are commercially viable, this is a pollution-free source of energy that will disrupt the environment far less that the fossil fuel plants it will replace. There should also be lots of fish.

Experimental Design

The experimental apparatus was tested in a large body of salt water. 1800 Kg (2 tons) of sea salt [5] was dissolved into a 50,000 liter (15,000 gallon) tank (in-ground swimming pool). This resulted in a salinity of approximately 35 parts per thousand (ppt). [6] Throughout the experiments the salinity was measured with a Myron L, DS Meter (model 512T5).

The experimental apparatus (see Figure 1) consisted of a pair of vertical tubes, one inside the other. The larger, outer tube was called the “UpTube”. In these experiments, it had an inner diameter (ID) of 15 cm (6 inch, schedule 40 PVC) and was 1.5 meters long. The smaller inner tube was called the “DownTube” and had an ID of 1.8 cm (½ inch, schedule 125 PVC) and was 1 meter long. The end of the DownTube was fastened with two 90° elbows and a short length of pipe such that the fresh water exits upwards. This apparatus was suspended from a float 15 cm below the surface of the salt water tank with nylon cable ties.

The DownTube was connected to a graduated reservoir by means of a flexible rubber hose with the same ID. The reservoir was kept at a constant level by filling to overflowing with fresh (tap) water. Experiments were initiated by opening a valve at the bottom of the reservoir.

There were three independent variables: salinity of the fresh water, salinity of the salt water, and height of the reservoir. The dependent variables were: flow of fresh water through the DownTube and salinity of the water coming out the UpTube.

The salinity meter had two ranges (0 - 5000 ppm and 0 - 50 ppt) and was accurate to ± 50 ppm on the low range and ± 0.5 ppt on the high range. The fresh water measured a consistent 300 ppm of dissolved solids, the salt water varied between 34 and 36 ppt depending on the evaporation from the tank.

Height of the reservoir was measured from the water surface in the reservoir to the surface of the salt water and was measured with a tape measure and is accurate to 2.5 cm. Flow was measured by timing how long it took for the reservoir to lose ~30 liters (two gallons) of water. Accuracy was ± 1 second, which translated into a flow accuracy of ± 3% in the range of our experiment.

Experiments were started by filling the DownTube with water to eliminate air bubbles, adjusting the height of the reservoir, and filling the reservoir with water. When the stopcock at the base of the reservoir was opened, fresh water flowed into the UpTube.

Salinity measurements of the salt water and the fresh water were taken before and after a day of experiments. Salinity at the top of the UpTube was measured either by manually transferring it into the salinity meter with a large bulb pipette or, in later experiments, with a sampling pump.

The temperature of both types of water was the same in any individual experiment (18 to 20 °C) since the salt water tank was set in the ground and the fresh water came directly out of buried pipes. There was no temperature difference between the brine exiting the UpTube and the salt water tank. There were five experiments during a month and a half period.

As the experiments progressed, it distressed us that the effect was only apparent after taking inconvenient measurements and performing much math. We wanted a device that would, all by itself, demonstrate the increase in kinetic energy. To that end we designed the apparatus shown in Figure 3.

The Demonstration Device is a piece of 6" PVC pipe with a 6" turbine roof vent attached to one end. The vent is held in place with caulk and duct tape. The bottom is fitted with a 6" PVC coupling that has been drilled to allow the insertion of a ½" PVC 'U' which is securely glued in place. The entire apparatus is suspended from a float (in this case, a couple of one gallon thermos bottles) with nylon cable ties.

The 'U' is connected to a ¾" garden hose with a hose clamp. The other end of the hose is similarly attached to a reservoir with a valve (beverage dispenser or carboy). One of the vanes of the vent was painted to allow for the counting of rotations.

This device is placed in a body of salt water and the reservoir is continuously filled to overflowing. It is important that all of the air be eliminated from the DownTube. The experiment consists of two operations. First, opening the reservoir valve and timing the revolutions of the turbine. Second, removing whatever is keeping the reservoir full and timing how long it takes for the reservoir to empty. We ran the experiment with salt water in the reservoir and then tested again with fresh water (see Table 3).

The attorneys have requested that it be pointed out that there are patents pending on adapting this device (as well as others) for the generation of power. It is presented here for non-commercial purposes to further the scientific study of this phenomenon, not to place it in the pubic domain.

Analysis

Our original assumption was that a certain amount of power would be needed to overcome buoyant forces as the fresh water traveled from Point 1 to Point 3. Any additional power, in the form of kinetic energy, would be available to move some salt water towards the surface. The complete transfer of kinetic energy from the fresh water to the salt water would result in a flow of salt water at Point 4 equal to the flow at Point 3 divided by the density of the salt water. Therefore, at 100% efficiency, the flow at Point 2 would contain all of the fresh water plus a somewhat lesser quantity of salt water. We assumed that the maximum salinity expected at Point 2 would be dependant only on the salinity of the salt water and its density. Table 1 shows the expected maximum salinity as well as the observed salinity along with the equations based on this assumption.

The observed salinity was far higher than we expected. This implies that far more salt water was being accelerated up through the UpTube than could be explained by buoyancy and transfer of kinetic energy.

Table 2 quantifies the flows and kinetic power output for the points indicated on Figure 1. Since there was a continuous tube from Point 1 to Point 3, their salinity and flow are identical. Since the only inlets to the UpTube are from Point 3 and Point 4, the flow at Point 2 equals the sum of the flows from Point 3 and Point 4.

The equation for the flow at Point 4 is derived from:

If:

Q_i = *Flow at point i*

= W_T / ρ *per second*

S_i = *Salinity at point i*

= (W_S / W_T)

W_S = *Weight of Salt in a Solution*

W_T = *Total Weight of Solution*

Then:

$S_2 = W_{S2} / W_{T2}$

And since the flow past Point 2 comes from either Point 3 or Point 4:

$S_2 = (W_{S3} + W_{S4}) / (W_{T3} + W_{T4})$

Substituting in:

$W_S = S\ W_T$

Results in:

$$S_2 = (S_3 W_{T3} + S_4 W_{T4}) / (W_{T3} + W_{T4})$$

Substituting in:

$$W_T = Q \rho \; seconds$$

Results in:

$$S_2 = (S_3 Q_3 \rho_3 + S_4 Q_4 \rho_4) / (Q_3 \rho_3 + Q_4 \rho_4)$$

Which gives an equation that has one unknown variable (Q_4).

$$Q_4 = Q_3 (\rho_3 / \rho_4) (S_2 - S_3) / (S_4 - S_2)$$

It can be assumed, within the accuracy of this experiment, that:

$$S_3 = 0$$

and

$$\rho_3 = \rho_4$$

Which leaves:

$$Q_4 = Q_3 S_2 / (S_4 - S_2)$$

The power values are derived from:

If:

A = *Cross Sectional Area*

= $\pi \; d / 4$

d = *Tube Diameter*

M_q = *Mass Flow*

= $Q \times \rho$

$\rho = 1 + (S_i / 1000)$

v = *Velocity*

= Q / A

Then:

P_k = *Power from Kinetic Energy*

$= \frac{1}{2} M_q v^2$

$= \frac{1}{2}(\rho Q)(16Q^2 / \pi^2 d^4)$

$= 8Q^3\rho / \pi^2 d^4$

Table 2 shows that the flow of brine at Point 2 cannot be explained by the transfer of kinetic energy between the fresh water at Point 3 and the salt water at Point 4.

Discussion

What had started as a series of engineering experiments in fluid flow had turned into a physical chemistry examination of the possibility of capturing the force behind osmosis. In the course of our experiments we referred to this force as hydrocratic potential energy, or hydrocratic forces.

Consider a hypothetical experiment where a 34 cubic meter container of salt water is supported just under the surface of a large body of fresh water. There is an osmotic membrane between the two types of water and attached to the vessel of salt water, extending up, out of the fresh water, is a tall tube with a volume of exactly one cubic meter (see Figure 2). At the start of the experiment the water level in both containers is identical. The fresh water will flow into the container of salt water through the membrane and raise the level in the tall tube. Clearly the hydrocratic force is doing work on the water in the tube through the mechanism of osmosis. What are the dimensions of the tube if the weight of one cubic meter of water in the tall tube exactly cancels the osmotic pressure? (This is analogous to the 34:1 dilution seen in our device.) How much work has been done?

For small concentrations of an ideal solution, van't Hoff's formula for osmotic pressure (Π) is:

$$\Pi = -CRT$$

Where;

C = *Molar Concentration*

R = *Gas Constant*

T = *Absolute temperature*

In this thought experiment there are two ions per molecule and:

$$w_{NaCl} = 58.5\ g$$

$$T = 20^\circ\ C$$

$$= 293^\circ\ K$$

$$R = 8.3144\ J\ /\ mole\ ^\circ K$$

$$C = 34\ ppt$$

$$= 34{,}000\ g\ /\ m^3$$

$$= (34{,}000 \times 2\ /\ 58.5\ moles)\ /\ m^3$$

$$= 1200\ moles\ /\ m^3$$

$$\Pi = -(1200\ moles/m^3)(8.3144\ J/mole\ ^\circ K)(\ 293^\circ\ K)$$

$$= -2.9 \times 10^6\ J\ /\ m^3$$

$$= -2.9 \times 10^6\ Pa$$

$$= -29\ atm$$

Pascal's Law says:

$$p = \rho g h$$

Setting p (pressure due to the height of a column of liquid) equal to Π (the osmotic pressure) and solving for the height of the column (h) gives:

$$\rho = 1034\ Kg/m^3$$

$$g = 9.8\ m/s^2$$

$$h = (2.9 \times 10^6\ J\ /\ m^3)\ /\ (1034\ Kg/m^3)\ (9.8\ m/s^2)$$

$$= 290\ m$$

The work done to move the water to this height is:

$$W = \tfrac{1}{2}\ Mgh$$

$$= (0.5)\ (1034\ Kg)\ (9.8\ m/s^2)\ (290\ m)$$

$$= 1.5 \times 10^6\ Joules$$

This states that one cubic meter of fresh water, when mixed with 34 cubic meters of sea water in this manner could theoretically produce 1.5 x 10^6 Joules of energy.

Let's take the above example and solve for the work done as a function of initial concentration and initial volume. In this case:

$$C_0 = Initial\ Concentration$$

$$V_0 = Initial\ Volume$$

Setting Π = p results in:

$$\rho g h = CRT$$

$$h = CRT/\rho g$$

Substituting this into the equation for work:

$$W = \frac{1}{2}(Mg)(CRT/\rho g)$$

Fixing the volume of the tall tube at 1 cubic meter, means that:

$$C = C_0 V_0 / V_0+1$$

$$M = \rho \text{ cubic meters}$$

Substituting these into the work equation:

$$W = \frac{1}{2}(\rho g)(RT/\rho g)(C_0 V_0 /V_0+1)$$

$$= \frac{1}{2} RTC_0 (V_0 /V_0+1)$$

While the tall tube thought experiment is analogous to the experimental system, it is not a perfect analogy. The experimental apparatus continuously generates water at the ultimate dilution. Therefore work (W) should be changed to power (P), volume (V) to flow (Q), and the constant (½) to unity (1):

$$P = RTC_0 (Q / Q+1)$$

It is important to remember that

1) Q refers to the flow of solution not the flow of pure water.
2) This equation is true only when the flows are normalized to a fresh water flow of one cubic meter per second.
3) The units are off because of the substitution of density for mass.

A more general form is:

$$P = RTC_4 \ (Q_4 \ / \ Q_4 + Q_3 \ ) \ m^3$$

This states that the potential power available from flowing a cubic meter of pure water into a solution is equal to the gas constant times the absolute temperature times the molar concentration of the solution times the solution's dilution ratio expressed as a fraction. One cubic meter of fresh water, when continuously mixed with 34 cubic meters of sea water, could theoretically produce 3.0×10^6 watts of power.

While the demonstration device is less definitive than our primary experiment, it provides good proof that something interesting is happening. Since the DownTube flows are essentially equal, there is no difference in the input energy, however the turbine spins much faster when fresh water is used.

How is the experimental system capturing this energy? On a macroscopic level there is an osmotic pressure difference between the inside and the outside of the UpTube. Since the fresh water is already flowing in one direction (up) the salt water diffuses into the flow at two points: at the bottom of the UpTube and well away from the top of the UpTube. While the diffusion goes to completion, it is separated spatially and one can capture the net flow through the UpTube to do work.

The experimental apparatus in this paper generates 0.98 watts with a fresh water flow of 2.4×10^{-4} cubic meters. This is equivalent to 4 kilowatts per cubic meter of fresh water per second, about 0.15% efficient. Unpublished experiments indicate that larger devices and smaller salinity differences raise the efficiency.

How would a power generating facility based on this effect compare with other methods? If it is assumed that 30% of the flow from the Columbia River[7] could be funneled through such an underwater device at 100% efficiency, it would generate 6,300 megawatts. For comparison’s sake, the current hydroelectric facility of the Grand Coulee Dam on the Columbia River generates 6,800 megawatts[8]. If the flow from the Weber River[9] into the Great Salt Lake[10] could be funneled through such a device, it would generate 400 megawatts.

Table 1 - Expected vs. Observed Flow at Top of UpTube

Height of Reservoir (meters)	Flow of Fresh Water (10^{-4} m^3/sec)	Salinity of Brine at Top of UpTube (ppt)	
		Expected	Observed
0.23	1.3	17	34
0.55	2.4	17	34

Salinity of Salt Water (ppt) 35
Salinity of Fresh Water (ppt) 0.3
Density of Salt Water (Kg/l) 1.035
Expected Maximum Salinity . . . . $S_4 / (1+\rho_4)$

Table 2 - Flow and Kinetic Energy

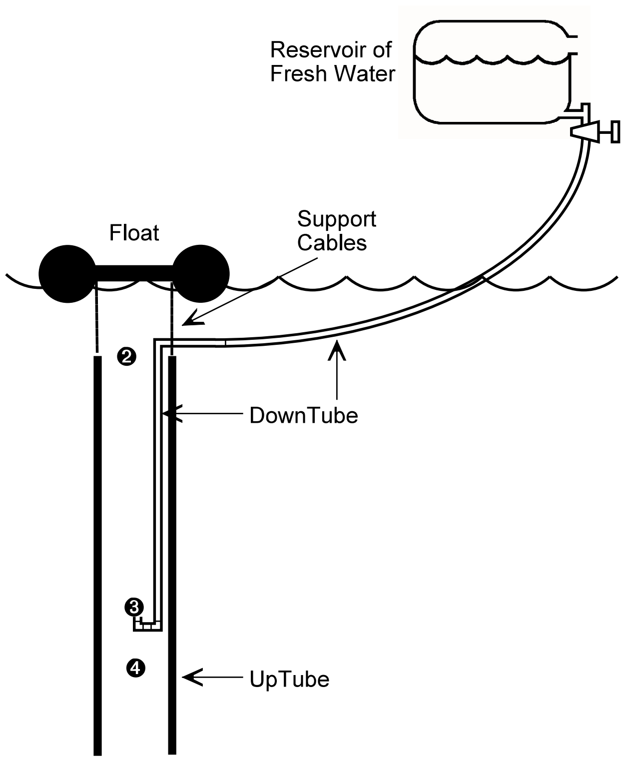
Height of Reservoir (meters)	Salinity at Point 2 (ppt)	Flow (10^{-4} m^3/sec)				Kinetic Power (watts)			
		Point 1	Point 2	Point 3	Point 4	Point 1	Point 2	Point 3	Point 4
0.23	34	1.3	45.5	1.3	44.2	0	0.16	0.02	0.14
0.55	34	2.4	84.0	2.4	81.6	0	0.98	0.11	0.90

Table 3 - Demonstration Device

	DownTube Flow (10^{-4} m^3/sec)	Turbine Speed (rpm)
Fresh Water (0.3 ppt)	2.4	5.6
Salt Water (36 ppt)	2.3	2.3

Reservoir Height (meters) 0.55
Flow (10^{-4} m^3/sec) 2.4

1 **Figure 1. - Cross Section of Apparatus**



❶ Fresh Water Reservoir

❷ Top of Uptube

❸ Exit of DownTube

❹ UpTube Below DownTube

1 **Figure 2 - Thought Experiment Showing Work Performed by Osmosis**

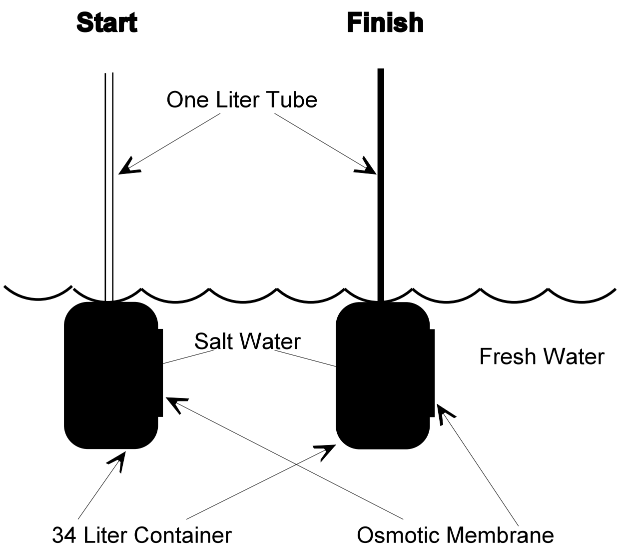
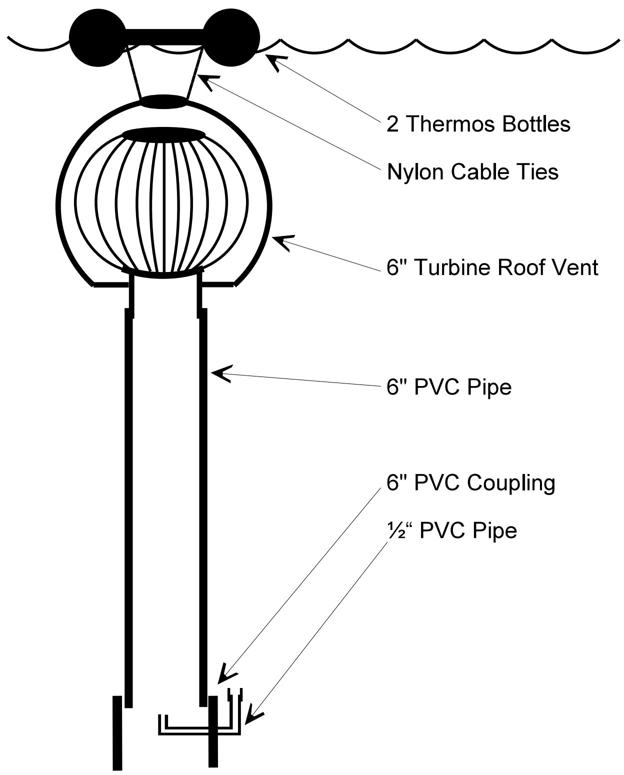


Figure 3 - Demonstration Device



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