Large Scale Solar Desalination using Multi Effect Humidification

Summary

A theoretical proposal is outlined for large scale solar desalination using multi effect humidification. It involves the use of a large area solar collector, multi effect distillation and boiling at reduced pressure. The configuration devised is a circular tank of one kilometre diameter containing water to a depth of 10 metres with a sealed double glazed dome, operating at 0.1 atmosphere pressure with a working temperature below 50°C. A solar absorber placed just above the water level, abundantly perforated but covering the entire area, sets up convection currents that evaporate the sea water and condense the vapour. Incoming seawater recovers energy from outgoing clean water and brine in a counter current heat exchanger. Water flow is driven by solar distillation and hydrostatic pressure. It is estimated that the structure would have 95% energy efficiency and a gained output ratio of 20. In sunbelt countries with average isolation of 6kwh/m^2/day the desalination plant would produce 100,000 m^3/d distilled water at a speculative cost of \$0.28/m^3.

In recent years the author has been working on several theoretical proposals for the large scale generation of electricity from solar energy using natural convection. In correspondence about one such proposal, a retired US professor[1] wondered whether the devices being considered would lend themselves to solar desalination. The author was initially dismissive but after careful consideration has developed the Blue Sky proposal outlined in this paper.

Solar distillation has been used for demonstration purposes for over 2000 years and has been employed in some small scale plants for over 100 years. There has been a great deal of research in recent decades with the growing demand for water and shortage in many areas. Al-Hallaj et al[2] have recently published a comprehensive technical review of solar desalination with a humidification-dehumidification technique.

The present proposal was developed without detailed knowledge of the field and brings together three technologies:

- the use of a solar collector several square kilometres in area has been pioneered for the solar chimney[3]. Transmittance through the glass and absorption of solar energy by a suitably coated metal surface are both over 90% efficient.

- multi effect distillation is very well developed in desalination using fossil fuel energy. The latent heat of condensation of water is efficiently recovered and repeatedly recycled giving 10-20 fold greater output.

- boiling at reduced pressure. This presents enormous practical challenges but if pressure is reduced to 0.1 atmosphere the boiling point of water falls to below 50°C. The low working temperature dramatically reduces energy losses to the environment. The higher energy recovery gives a larger multi effect and greater output.

The configuration devised is shown in Figure 1.

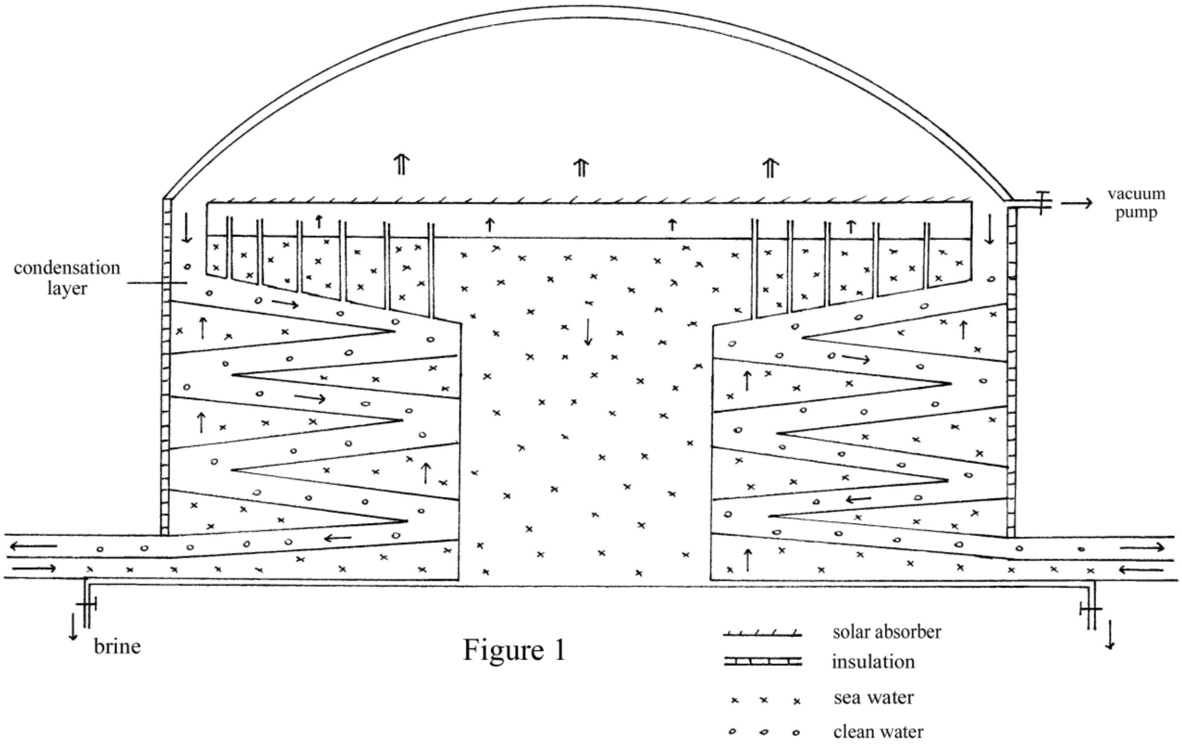

Figure 1

The desalination tank is circular, of diameter one kilometre and is sealed with a double glazed dome. It contains water to a depth of 10 metres and air at a pressure of 0.1 atmosphere. About one metre above the water level, there is a solar absorber covering the entire surface. This is abundantly perforated with millions of small holes to allow the upward flow of air and water vapour.

There are three water flows. There is an inflow of seawater driven by hydrostatic pressure from a storage tank. Second there is a distilled water flow which comes from condensed water vapour and which flows into a clean water store for distribution. Third, the central region of the tank has increased salt concentration and flows back into the sea as brine discharge.

The entire structure is well insulated to minimise energy losses through the containment. The outer circumference has a strong exterior concrete wall and earth bank for insulation and to contain the weight/pressure of the mass of water.

Solar energy passes through the double glazed dome with over 80% transmittance. The solar absorber takes up this energy with over 90% efficiency producing a large hot surface. This is the driver of the distillation process. Air molecules that strike the absorber surface are heated; the hot air expands and rises drawing fresh air and water vapour from beneath. A convection current is set up. Water evaporates from the surface of the seawater, passes through the absorber and is carried into the condensation layer where it forms a clean water supply. The air in the convection current is returned via air channels to just beneath the absorber. The outgoing clean water transfers its heat to incoming seawater in the counter current heat exchanger.

Consider next the surface layer of seawater and the central region of the tank. As the seawater loses water vapour by evaporation, it becomes denser. Its salt content will increase from 3% → 4% → 6% → and as it becomes heavier the saltier water falls to the bottom of the central chamber. Note that boiling water has a density of 0.96g/cc, seawater 1.03 and brine up to 1.1 and greater. The brine discharge surrenders its heat to incoming seawater and a tap on the discharge pipe can allow the brine to be of 5%, 10%, 20% or whatever salt content is considered appropriate. The brine is returned to the sea.

The configuration is designed to ensure maximum energy recovery. Thus the latent heat of condensation is completely recycled and of the energy content of boiling water, the large majority is reabsorbed by incoming seawater in the counter current heat exchanger. The only major energy loss is through the glass of the dome which is reduced by double glazing. This is further dramatically reduced by boiling under reduced pressure. The air in the dome is at a pressure of 0.1 atmosphere; this reduces the boiling point of water and the working temperature of the desalination tank to below 50°C. By such rigorous elimination of energy losses it is expected that 95% of the energy used in heating and evaporating water is recovered and recycled. In that case there will be a multi effect or gained output ratio of 20. (The GOR is defined as the ratio of the energy consumed in the production of condensate to the energy input.)

The above proposal was developed in relative ignorance of what has been achieved in recent years in the field of solar desalination. Multi effect distillation using fossil fuel energy has been a reality for over 40 years and a GOR of 10-20 is commonplace. Multi effect solar desalination is however relatively recent. Tanaka et al[4] achieved GOR 1.6 using successive surfaces for evaporation/condensation. Müller-Holst et al[5] have developed a small commercial plant using one chamber for successive evaporation/condensation by natural convection. This has achieved a daily average GOR of 3 to 4.5 in the field and over 8 in steady-state laboratory conditions. These findings demonstrate that with a large scale commercial plant operating at reduced pressure and much lower temperature, a GOR of at least 20 should be attainable.

Output of Large Scale Solar Desalination Plant

Consider the desalination plant described in Figure 1 of diameter 1 kilometre.

Area solar absorber πr^2 $= 3.14 \times 0.5 \times 0.5$
$= 0.785\ km^2$

In sunbelt countries average annualised insolation is $6kwh/m^2/day$

Assume 80% transmittance through glass
90% efficiency solar absorber

Total solar energy absorbed $= 0.8 \times 0.9 \times 0.785 \times 10^6 \times 6000 \times 60 \times 60$
$= 12 \times 10^{12}$ joules/day

Energy required to heat 1 gram water from ambient temperature to 50°C and to evaporate
$= 30 \times 540$ calories
$= 570 \times 4.2$ joules
$= 2{,}400$ joules

But if there is a gained output ratio of 20
Actual amount of energy consumed per gram water desalinated is 120 joules
Thus mass of water desalinated is $\frac{12 \times 10^{12}}{120}$ grams/day

$$= 100 \text{ million litres/day}$$
$$= 100{,}000 \text{ m}^3\text{/d}$$

Such a capacity would be comparable to some of the world's largest desalination plants. Note that water demand in the UK is 150 litres/day and in developing countries 10 litre/day per person. The desalination plant above would meet the daily demand of 600,000 people in an advanced country or 10 million people in the developing world.

Cost of Desalinated Water

One can only hazard a guesstimate cost for the plant described above to give an order of magnitude figure. The installation is very large but technically very simple with nothing that is high tech. Let us say that construction would cost $100 per square metre giving a total cost of $100 million.

It the capital cost is discounted over 10 years with average production of 100,000 m^3/d, then the capital cost is equivalent to

$$\$ \frac{100\text{million}}{100{,}000 \times 365 \times 10} = \$0.28/\text{m}^3$$

The cost of desalinated water from the world's most recent large plants is about $0.5/m^3

The running costs of the solar desalination plant would be very low with its fuel free. This order of magnitude calculation indicates that large scale solar desalination could compete with present desalination technologies.

Further considerations

The above is only an outline proposal. There are many further points to consider eg

- the solar absorber could be placed immediately beneath the surface of the seawater for more efficient boiling; this has been rejected because of corrosion problems and to facilitate convection currents.

- seawater contains dissolved oxygen and carbon dioxide which would be released on boiling and would accumulate in the dome. This is not a major problem but the partial vacuum would need to be regularly monitored and maintained.

- scaling would be a problem in the central section of the tank and along the brine outlet pipe and would require regular maintenance; note however that with a working temperature of below 50°C, problems of scaling would be far less than for fossil fuel desalination plants.

- dust deposition on the glass dome could substantially cut transmittance; it would need regular washing especially in dry climates.

- it may be worth considering triple or quadruple glazing. Transmittance would be cut to 70% or less but improving the efficiency of energy recovery could give a GOR of 30-50 and higher output.

- the counter current heat exchanger for incoming seawater/outgoing clean water could be constructed in a series of concentric annulus arrangements with lower temperatures as we pass outward. This would improve further energy recovery efficiency and the gained output ratio.

- perhaps the greatest problem in the structure proposed is the strength of the framework needed to support the dome and the 'weight' of air above when it operates at 0.1 atmosphere. With atmospheric pressure of 15 psi or 1033 grams per sq cm the 'weight' of the air above the dome would be about 10 million tonnes. This compares with about 10,000 tonnes weight of glass. The framework for the dome would have to be built of especially strong materials to support such a weight.

<u>Hydrostatic pressure to maintain flow</u>

The arrangements of units in the desalination plant could be as in Figure 2.

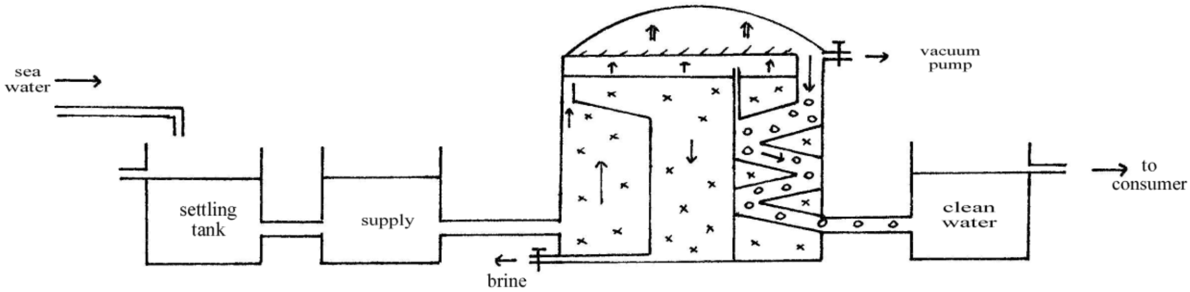

Figure 2 Key as previously

Seawater is pumped into an initial settling tank. Since the settling tank, supply tank and clean water store are each open to the atmosphere, each has water at the same level. The desalination tank is evacuated to a pressure of 0.1 atmosphere. The water level is thus about 8 metres above the level in the other tanks. Once set, this level will be maintained by the vacuum and will be self-regulating. Flow through the series of tanks is driven by distillation and hydrostatic pressure. It should be noted that the volume of water in the desalination tank is

$$\pi r^2 h \quad r = 500\text{ m},\ h = 10\text{m, volume} = 3.14 \times 500 \times 500 \times 10 = 8 \text{ million m}^3$$

If production is 100,000 m^3/d this means that the water in the desalination tank has a turnover period of 80 days.

Pilot Plant → Commercial Plant

The above proposal has been assembled in the full knowledge that for solar desalination to be a serious commercial alternative, very large plants must be considered. But to develop the technology, a stepwise approach is needed eg a pilot plant should first be built – of perhaps 10 metres diameter, 2 metres depth and at atmospheric pressure. The next plant could be 50 metres diameter, 10 metres depth and 0.1 atmos. Then stepwise to a commercial plant. The smaller plants would have a lower GOR and could not be expected to be economic. They are needed however to develop the relevant technologies. The commercial plant would be of 1000 metre diameter, 10 metre depth and 0.1 atmos providing economies of scale, higher GOR, higher output and lower cost.

Conclusion

The above proposal has been devised to demonstrate that large scale solar desalination is technically feasible and that if finance was raised for commercial R & D, solar desalination could provide pure water at a cost comparable to present desalination technologies. This paper is being published in the hope that some individuals, companies and/or government organisations decide to move forward with the proposal.

References

[1] John O'M Bockris, Distinguished Professor, Texas A + M University (1982-1997)

[2] Said Al-Hallaj et al, Desalination, 169 (2004) 167-186

[3] G Weinrebe et al, Solar Energy, 75 (2003) 511-524

[4] H Tanaka et al, Desalination, 130 (2000) 279-293

[5] H Müller-Holst et al, Renewable Energy 14(1-4) (1998) 311-318

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