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ESTIMATING EXTRA WATER FROM SPRAY TURBINES AS A FUNCTION OF BOUNDARY LAYER TEMPERATURE AND HUMIDITY

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ABSTRACT

A previous paper described the mechanics of spray turbines and estimated the amounts of seawater that could be sprayed by a machine with a 1000 square metre rotor as a function of wind speed. The objective was to increase the rate of evaporation of seawater so as to increase the probability of rain over downwind landmasses. This paper presents an estimate of an upper limit to the amount of water that a country could 'import' across its coastline. It represents the distilled results of some hastily-learned meteorology and evaporation physics and has yet to be checked by professionals in those areas.

Keywords: Spray turbine, Sea evaporation, Marine boundary layer, Drought relief, Enhanced rainfall.

1. INTRODUCTION

The atmosphere immediately in contact with the sea consists of a few millimetres of air with low turbulence and very high humidity which chokes evaporation. Csanady[1] says that the airside resistance to evaporation is about 100 times greater than the water side.

Above the surface is a region several hundred metres thick called the marine boundary layer. In normal conditions it has considerable turbulence which mixes everything fairly evenly but, because of the steady temperature of the sea, does not have the more violent convecting updrafts that occur over land during hot parts of the day. The pressure declines as we move upwards and this leads to a reduction of temperature. In the dry places where spray turbines may be used, this reduction will be about 9.8 C per thousand metres of altitude. The reduction means that the amount of water that can be held in the air falls with increasing height.

A previous paper, Salter [2], described the design of a floating vertical-axis wind turbine (see figure 1) which would spray finely divided drops of sea water at a height of about 10 metres. The rate of fall of small drops is determined by Stokes law. The drop diameter would be controlled so that there would be enough time for evaporation but not enough for the salty residues to reach land.

The pumping was achieved by using hollow blades which reached below the surface of a moon-pool breaking the water surface at a gentle slope up which water was moved by centrifugal force. This made a very efficient pump with no pistons, valves or machined parts.

The need for creating the very large extra surface area of water drops and the nozzle losses meant that about 60% of the power taken from the wind was used doing work against gravity. Each machine would lift between 0.5 and 2 cubic metres a second so that an array of them could spray enough to make significant contributions to the national water requirement of entire countries.

2. LIMITATIONS

The latent heat for evaporation can only come from the air. No matter how many spray turbines we install and no matter how fast the wind blows, we cannot put more fresh water into the marine boundary layer than would be enough to raise it to 100% relative humidity. With normal strength sea-water the limit would be about 98% and with the stronger salt solution left behind after evaporation it will be lower still. Our estimate is 94 to 96%.

Above the marine boundary layer is a temperature inversion cap which separates it from the much less turbulent higher air. Without turbulence, the diffusion of water vapour is slow. We argue that the maximum transfer of water from a near-shore array of spray turbines will occur when the entire marine boundary layer crosses the coast with a relative humidity of 95%.

3. DATA SOURCES

To make a prediction of the amount of water in air we need numbers for the temperature and relative humidity of the marine boundary layer. Unfortunately sea observations of the humidity gradient are rare. A few are available from [3], [4] and [5]. Temperatures over land will be higher at midday and lower during a clear night and so we should choose points as close as possible to the sea and use some intelligence in picking times of observation.

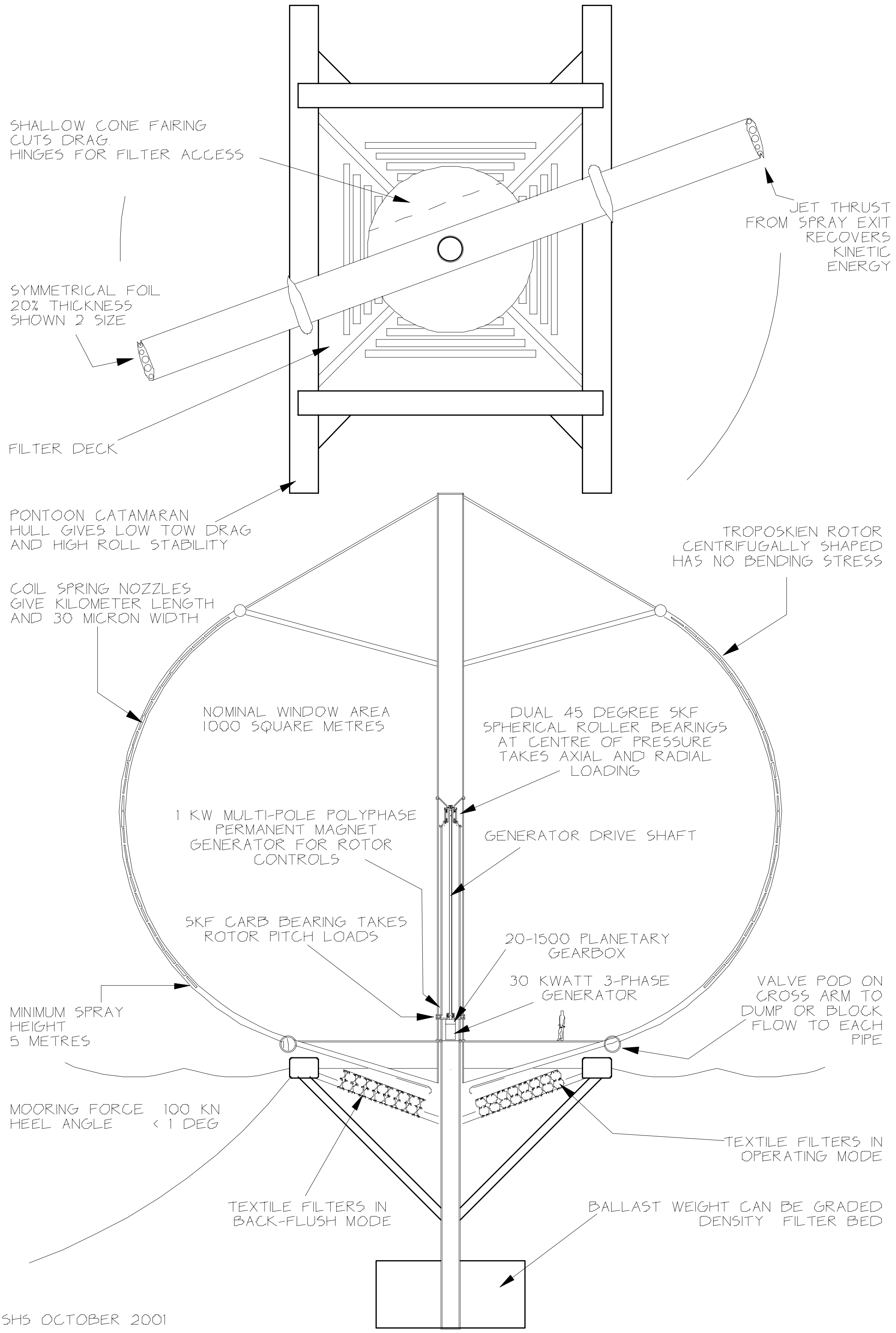

Figure 1. The Spray Turbine may be able to increase atmospheric humidity. Depending on rotor size and wind speed the volume of sea water sprayed is between 0.5 and 2 m3/sec.

There is also meteorological information measured by satellites, available on the web from [6], [7] and [8].

Meteorologists often measure pressure instead of height because this is more easily measured from a balloon and automatically applies several useful corrections. A pressure of 1013.3 millibars corresponds to ground level.

With enough latent heat the maximum mass of water that a kilogram of air can hold depends only on its temperature. The amount rises very steeply with temperature but we have the problem that the temperature of the air in the boundary layer will fall as the water evaporates. The properties of air and water combinations behave in ways which make it hard to use directly solved mathematical equations, and so much of the work used to be done with psychrometric charts. These can be found in textbooks on air conditioning or chemical engineering such as Perry's Handbook. The calculations done with software that you can buy or use free over the web by browsing 'psychrometric'. Interestingly the results from different programs are not in perfect agreement. My favourite is by Reza Zakeri [9]

4. THE PSYCHROMETRIC CHART

Even if you automate the calculations it is much easier to understand what is happening by looking at a hard copy of the chart. The complete chart is a bewildering maze of lines so the newcomer should take things slowly. A simplified version is given in figure 1. It looks like the outer side of a left-footed ski-boot. Along the bottom is a temperature scale. We start by finding the point along this scale for the temperature of the air upstream of the wind turbines. We follow it vertically upwards until it crosses a curve for relative humidity coming in from the lower left.

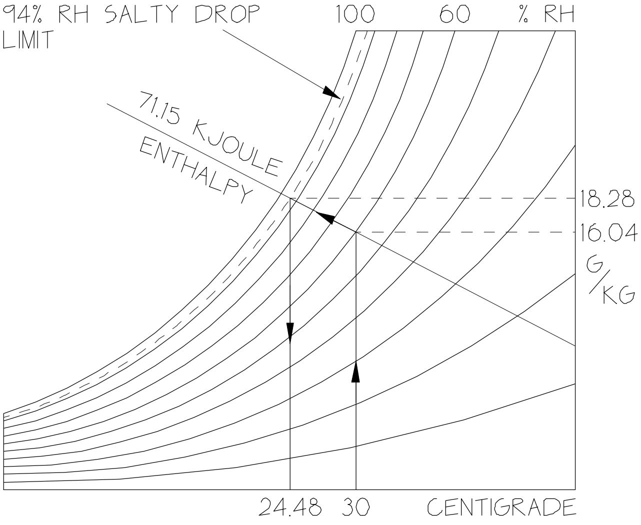

Fig 2. A simplified version of the psychrometric chart showing the path from input temperature to the relative humidity curve of the incoming air-stream and on to water gain and output temperature.

From the point of intersection of the temperature and relative humidity lines we move horizontally to the right edge of the diagram to a scale of absolute humidity which will give the amount of water in the air. This can be given as either grams of water per kilogram of air or per cubic metre of air. For example at a temperature of 30 C and a relative humidity of 60% the turbine input would have 16.04 grams of water per kilogram of air.

If we ignore the energy of sunlight hitting the top of the cloud of drops, the only source of the 2.25 Megajoules per kilogram of latent heat needed for evaporation is the air itself. Air has a rather low specific heat of only 1000 Joules per kilogram C and so we have to mix the drops with lots of air. With no energy from outside this would be described as a system of constant enthalpy. The chart shows that the value of enthalpy corresponding to 30 C and 60% relative humidity is 71.15 kilojoules per kilogram.

From the intersection point of temperature and relative humidity we follow the sloped line of constant 71.15 enthalpy coming from the lower right towards the upper left until it crosses the 94% salt-limited relative humidity line. Probably there will be lines at 90% and 100% so you will have to interpolate to get 94%. This now represents the air which can take no more water from the salt drops. If we follow a line vertically downwards to the temperature scale we can read the new temperature downstream of the turbines as 24.48 C. If we move horizontally right to the absolute humidity scale we can see that the new amount of water in the air has risen to 18.28 grams per kilogram, an increase of only 2.24 grams or about 13%.

As we are dealing with distances and wind speeds it will be more convenient but (because of the variation of atmospheric pressure) less accurate to convert to grams of water per cubic metre of air. This has been done in figure 3 by dividing by the nominal density of 1.15 kg per cubic metre. Assuming that evaporation is limited by latent heat supply from the air and that it stops at 94% relative humidity, the result for our 30 C 60% RH input is 1.95 grams per cubic metre as the maximum that the air could take.

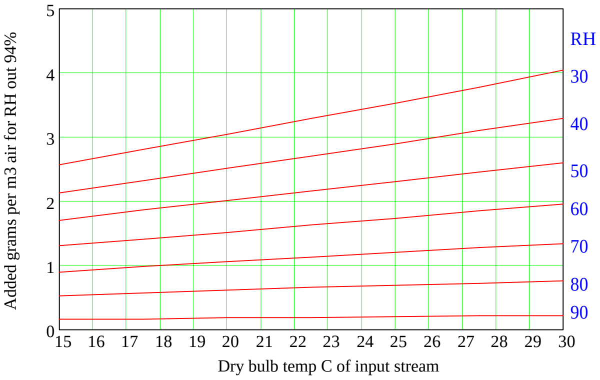

Fig 3. The gain in water per cubic metre of air.

Next in figure 4 we plot the outgoing temperature reduction of the downstream air flow as a function of the upwind temperature and humidity.

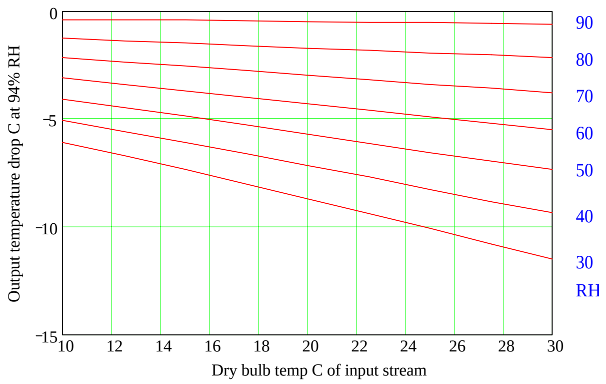

Fig 4. The estimates for the temperature drop of the saturated output stream.

The addition of a few grams of water per cubic metre of air does not sound very much. But the summer values along the southern coast of Australia and other drought-afflicted places are between 3 and 7 gm per cubic metre and fortunately there are lots of cubic metres of air available. To estimate an upper limit for the extra water crossing a coast for each slice of boundary layer we take water gain per cubic metre from the graph and multiply by the following:

1. A mean wind velocity at the level of the slice. This will be higher than the value of the usual measurement height of 10 metres.
2. The cosine of the angle between wind direction and coastline. This can change with height in ways that are well understood.
3. The length of the coastline along which the array is deployed.
4. The depth of the marine boundary layer slice over which we can assume steady mean values of temperature and relative humidity. Temperature will usually fall with increasing height at a rate of 9.8 C per thousand metres and relative humidity will usually rise, especially if there are any clouds in which case it will approach 100% at the cloud base. If a wind has blown over high mountains and salty deserts the humidity may be very low through the whole layer.

Data from the University of Colorado [10] show marine boundary layers round the world with typical depths of 630 metres. However there are accounts of higher local values, up to 2000 metres and some as low as 200 metres.

Balloon observations using radiosondes are made at many airfields and the University of Wyoming has a useful collection [11]. Unfortunately data on relative humidity profiles close to the sea surface are not collected on a regular basis.

If we take the 30 C and 60% relative humidity point giving a gain of 1.95 grams per cubic metre, multiply by a wind speed of 8 metres per second perpendicular to the coast, multiply by a slice depth of 630 metres but halve this because of the change of conditions with height, we get nearly 4900 cubic metres of water a second from a thousand kilometre coast line. In some narrow seas with drier input air we may be able to double this.

If this were to be spread evenly over a thousand kilometre square over six months of the year there would be an increase of *new* atmospheric moisture equivalent to 77 mm of rain on the ground. Some of this will blow on to countries downwind but none of it can disappear. Rain gauges are carefully designed to prevent subsequent evaporation. However, much of the rain which falls on the ground is evaporated and may fall again downwind to be recorded a second time. In Israel the evaporated fraction is 75%. To calculate the gain in rainfall which would be recorded by a rain gauge requires knowledge of the multiple accounting correction, possibly a factor of three of four.

This approach using available latent heat from the air does not allow for the heat which could be supplied from solar radiation hitting water drops in any cloud or mist in the turbine wake. Although this is effective for only a few hours a day, the area of mist spray could be quite large. The magnitude of the correction is being calculated.

There may be a further correction involved with the alternation of land and sea breezes. The cosine rule would not predict any useful gain from the night breeze flowing from the land. However, if there is enough wind, the spray turbines will continue to work at night and some of this air and the water in it will come back to land on the following day after a second passage.

If we consider offshore arrays with large dimensions along the direction of the wind, there is a chance for water vapour to diffuse through the boundary layer cap and for a gain in temperature from solar energy. Any travel over land will give rise to convection currents, which are an efficient way to get water to higher levels, making room for more lower down. The most obvious site for such an installation is parallel to coasts of Yemen and Oman when the south-west monsoon is blowing towards Pakistan and Iran. Spray turbines here could move conditions towards those at Burma and Assam, which have some of the highest recorded levels of rainfall.

General information on monthly mean values of temperature and relative humidity from many land sites round the world is given by Pierce and Smith [12]. For example Jeddah, which will use observations taken close to the coast, has values relative humidity values ranging from 52% to 63% with an annual mean of 55%. Adelaide in Australia has lower values ranging from 31% to 65% with an average of 46%. Remember that measurements taken close to the ground in the early morning, especially after a clear night, may be misleading.

5. COMING ASHORE

Spray turbine enthusiasts must never claim that they can make rain certain. All we can do is to nudge probabilities nearer to the conditions which favour rain and perhaps give an additional nudge with cloud seeding. It is useful to list these mechanisms:

- With cooler air and higher humidity, the cloud base will be lower and rain can form on lower hillsides or need less updraft.
- Even if the height of the cloud top is unchanged, the cloud depth will be greater.
- The drops of condensed water in the cloud will be closer together so that they have a better chance of meeting others and growing.
- Any which grow big enough to fall will have a longer path in cloud and will encounter more small drops.
- When they leave the cloud base they will have a shorter distance to fall to ground and will be falling through cooler air with a higher humidity so that they will lose less through evaporation.
- The lower temperatures and higher humidity at ground will reduce the rate of evaporation of previous rain.

Every factor seems to favour the chance of rain but a great deal of work with computer-based regional climate models will be needed to calculate a value for the change in probability. One way to express the results of the work would be in the form of a map of the region split into four categories of effect. These are as follows:

1. Places where conditions are so dry that no amount of additional water crossing the coast can ever bring any benefit.

2. Places where the conditions are close to, but not at present quite enough to produce rain. Here a small nudge in humidity might tip the balance and trigger the precipitation of a greater quantity of water than that evaporated from the turbine array.

3. Places where rain already occurs but not in sufficient quantities. Here the increase due to spray turbines might start the rainy season earlier, make it last longer and increase the quantity that falls, perhaps in rough proportion to the gain in total water content of the air column.

4. Places where there is already enough rain and an increase would be undesirable.

Only if meteorologists can say how the boundaries of these sub-regions would move from their present positions as a result of various levels of spray turbine numbers, can they come to a scientifically respectable conclusion and give politicians the data they need in a form they can easily follow.

6. CONCLUSIONS

The maximum amount of water that the marine boundary layer can ever get from spray turbines is set by the combination of the falling temperature and the rising relative humidity.

Values can be estimated using psychrometric charts if the temperature and humidity of the input air stream are known through the thickness of the boundary layer but sea observations are rare.

With low humidity and high input temperatures a few grams of water per cubic metre of air can be added. The consequential temperature drop could be as much as 10C. Unfortunately this will increase atmospheric stability and reduce the upward transfer rate.

7. REFERENCES

1. Csanady, G. T. *Air-Sea Interaction Laws and Mechanisms.* Cambridge University Press. Cambridge 2001. (Section 1.6.2 Page 32)
2. Salter, S. H. "Spray Turbines to Increase Rain by Enhanced Evaporation from the Sea". *Tenth Congress of International Maritime Association of the Mediterranean, Crete, May 2002.* (also from http://www.mech.ed.ac.uk/research/wavepower/rain%20making/shs%).
3. Sverdrup, H. U. "The humidity gradient over the sea surface". J. Meteor. Vol. 3 pp. 1-8 1946.
4. Brooks, I. M., Goroch, A. K. Rogers D. P., "Observations of strong surface radar ducts over the Persian Gulf". Journal of Applied Meteorology, 38, 9. pp 1293-1310. 1999.
5. Emmons, G. Vertical distributions of temperature and humidity over the ocean between Nantucket and New Jersey.". *Papers in Physical Oceanography and Meteorology.* Vol. X, No3. Woods Hole Contribution 413. December 1947.
6. http://ag.arizona.edu/~lmilich/clim.html
7. http://orbit36i.nesdis.noaa.gov/atovs/movies
8. http://pm-esip.msfc.nasa.gov
9. http://birger.maskin.ntnu.no/kkt/grzifk/java/PsychProJava.html
10. http://www.cgd.ucar.edu/csm/models/atm-ccm3/b003.02.html#TMQG
11. http://weather.uwyo.edu/upperair/sounding.html.
12. Pierce, E. A. and Smith, C.G. *World Weather Guide.* Hutchinson, London 1990.

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