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Energy 33 (2008) 331–339
ENERGY
www.elsevier.com/locate/energy

The solar cyclone: A solar chimney for harvesting atmospheric water

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Received 22 November 2006

Abstract

The Solar Cyclone has been introduced as a means of extracting fresh water from Earth's atmosphere. The conceptual device operates in the fashion of a Solar Chimney; it is composed of a greenhouse for collecting and storing solar energy as heat, with a central chimney that channels an updraft of surface air heated in the greenhouse. An expansion cyclone separator for condensing and removing atmospheric water is placed at the base of the chimney. The separator consists of a strongly rotating vortex in which the central temperature is well below the dew point for the greenhouse air. Power consumed in the expansion and separation is furnished by the motive potential of the chimney updraft. Turbulent flow conditions are established in the expansion cyclone separator to enhance the centrifugal separation. Excess updraft power is used to generate electricity, as is done in the Solar Chimney. The article furnishes a theoretical basis for the feasibility of the Solar Cyclone, suggesting that an experimental study of the separation device would be worthwhile.

Keywords: Fresh water; Solar power; Renewable resource; Sustainable resource; Solar chimney; Atmospheric updraft; Cyclone separator; Ranque–Hilsch; Tornado vortex

1. Introduction

This article gives a theoretical basis for the feasibility of using direct insolation to extract fresh water from Earth's atmosphere. A device called the "Solar Cyclone" has been introduced for harnessing the solar power, and for accomplishing the separation of water from surface air [1]. This device, if shown operable, could create an entirely new, and sustainable, fresh water resource. The rate at which the water could be collected is unclear, but the possibility is sufficiently compelling to provide strong motivation for more detailed theoretical and experimental studies.

There are currently about six billion humans on this planet, of which about one billion do not have adequate fresh water to drink on any given day; this is to say nothing about water for growing foodstuffs sufficient to prevent starvation, or for sanitation to help prevent disease. For the "lucky" five-sixths of earth's population, vanishing groundwater, sporadic precipitation, surface pollution, and water wars, are causes of increasing inconvenience in daily life. A growing global population places even more pressure on fresh water resources; the only known remedy for satisfying future water needs is extensive and wide-spread conservation [2].

Much of the devastation due to drought on Earth occurs in relatively undeveloped regions, which, as luck would have it, are comparatively rich in sunshine. At the surface Earth's atmosphere contains water vapor, in varying (but finite) amounts, everywhere—even in the driest desert. Hence a means of extracting water from the atmosphere would potentially be very useful, not only for making life more convenient for five-sixths of the population, but for making life possible for the other one-sixth.

There exists a device called the "Solar Chimney", introduced and promoted by Schlaich [3], which consists of a greenhouse with a central chimney that channels an atmospheric updraft. The chimney base is fitted with a turbine-driven generator that produces continuous

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doi:10.1016/j.energy.2007.06.003

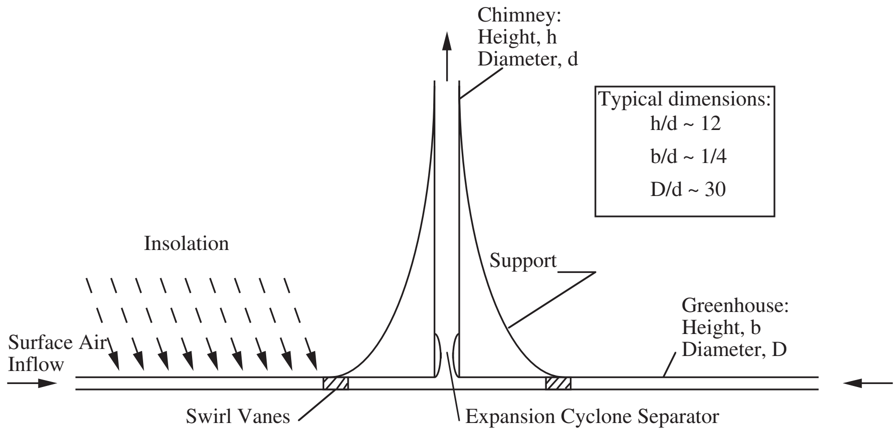

Fig. 1. Schematic of the Solar Cyclone.

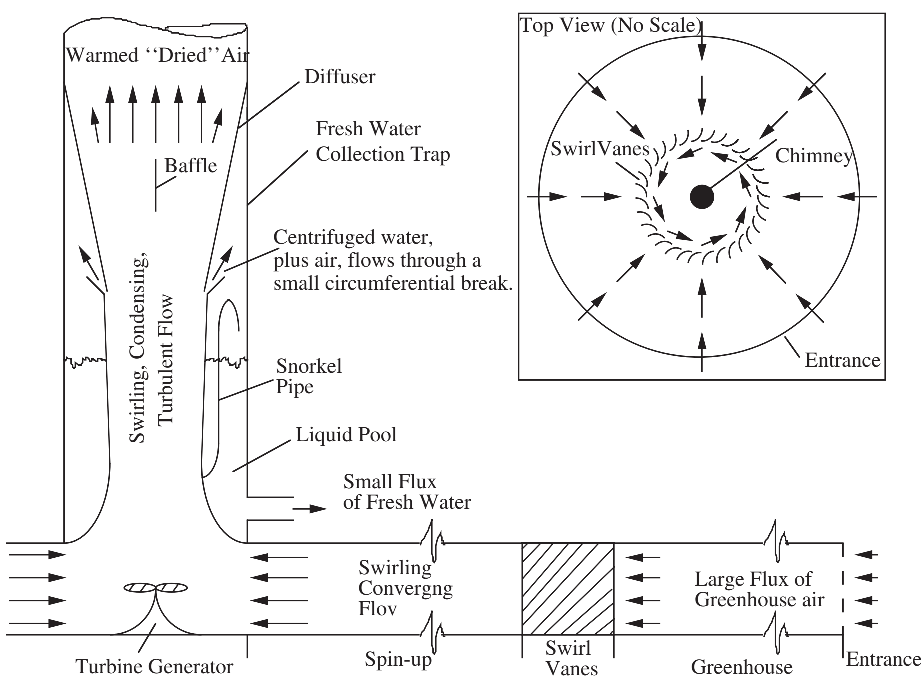

Fig. 2. Schematic of the expansion cyclone separator.

electrical power from the updraft. Operation of the Solar Chimney has been successfully demonstrated, so the motive potential of an updraft can in fact be used to perform useful work. The motive potential increases with both height of the chimney, and with the temperature rise in the greenhouse [4–10].

The Solar Cyclone is, in effect, a Solar Chimney used to extract atmospheric water, in addition to generating electricity. There are many possible configurations for the Solar Cyclone. In one configuration, an expansion cyclone separator is placed in the flowpath between the greenhouse and the chimney. This arrangement is shown schematically in Fig. 1.

With reference to Fig. 1, surface air enters the greenhouse at the outer periphery, and is heated as it flows radially toward the center. Swirl vanes in the greenhouse cause the radial inflow to spin. As the swirling flow moves toward the chimney base both the radial component and the swirl component of the velocity increase. Conservation ensures that this velocity increase is accompanied by a decrease in temperature, pressure and density; when the temperature is sufficiently far below the dew point for the surface air, condensation occurs. The velocity reaches a maximum; and temperature, pressure and density reach a minimum, as the flow turns from horizontal (and inward) to vertical (and upward).

Fig. 2 illustrates the principle of operation of the expansion cyclone separator. The separator has the appearance of a converging-diverging nozzle, whose inflow is spinning. The mean flow temperature drops well below the dew point in the converging part, where condensation of a fog immediately occurs; intense turbulence causes rapid droplet growth; centrifugal action moves droplets to the wall in the nozzle throat where a spinning film of water is guided into a collection trap. A small negative pressure, relative to the throat pressure, is maintained in the collection trap in order to promote flow of the film into the trap. The low pressure in the collection trap is maintained by a venturi effect, using a "snorkel pipe" as shown in Fig. 2. A turbine generator can be placed in the flow; in this case it is shown below the expansion cyclone separator.

Unfortunately there is no simple analysis that will quantify the "dryness" of the air exiting the expansion cyclone separator. This dryness is measured by the ratio of the water actually retained in the trap, to the water that could be removed in the absence of re-evaporation. This ratio is a separation efficiency; if the exiting air has a dew point corresponding to the throat temperature, the efficiency is 100%. (Any moisture that re-evaporates in the updraft will raise the dew point above the throat temperature.) At the present time, experimental knowledge of the separation efficiency does not exist. However, the fact that the expansion cyclone separator will work at all is established. For example, Redemann [11] developed such a separator, that can be used to drive a turbine as well as to remove condensible vapor from the motive gas stream.

In Section 2 a discussion of the power contained in the chimney updraft is presented; an expression for updraft velocity, which is validated by experiment, is developed. Correlation to experimental data for electricity generation is also shown. The updraft velocity is used in Section 3 to speculate on potential water production rates, and to obtain reasonable estimates for electricity production using excess updraft power (as in the solar chimney). A simplified analysis of the flow through the Solar Cyclone is given in Section 4, showing the feasibility of achieving a given minimum temperature in the separator. Section 5 is a discussion on achievement of the minimum temperature, and Section 6 is a summary.

2. Updraft power

Conditions of atmospheric pressure, temperature and water content vary at any location, between day and night, and from moment to moment. These variations can always be averaged over time. If the time average is sufficiently long (like many years), conditions can be considered fixed at any location, on average. Furthermore one can average over all locations to obtain what is called an averaged atmosphere. The lowest order analysis, performed here, considers a globally averaged atmosphere.

Let z signify the vertical coordinate, with an origin at the chimney entrance, and where the local averaged air density is $\rho_\circ = 1.2\,\mathrm{kg/m^3}$. The globally averaged density of Earth's lowest atmosphere $\rho(z)$ is given by

$$\rho(z) = \rho_\circ \mathrm{e}^{-z/H}, \tag{1}$$

where $H \sim 8\,\mathrm{km}$ is the averaged atmospheric scale height [12]. Also let $T_\circ$ be the ambient temperature outside the greenhouse, at the surface. As a parcel of air is moved from the surface to a greater elevation, it undergoes an expansion in volume due to the lower pressure at increasing altitude. If the parcel is isolated so that heat is neither gained nor lost to the surroundings, this expansion is accompanied by adiabatic cooling. If the changes in state of the atmosphere are approximated as both adiabatic and isentropic, then conditions at any elevation are related to surface conditions by Poisson's adiabat

$$(p/p_\circ) = (\rho/\rho_\circ)^\gamma = (T/T_\circ)^{\gamma/(\gamma-1)}, \tag{2}$$

where $\gamma = c_p/c_v = 1.4$ is the ratio of specific heats for air; p is the local pressure; and T is the local temperature.

The motive potential due to buoyancy $\Delta\phi$, for the air inside the chimney, can be expressed by the integral

$$\Delta\phi = g \int_0^h \rho \left[\frac{T_c - T}{T}\right] \mathrm{d}z, \tag{3}$$

where g is the gravity magnitude; $T_c(z)$ is the temperature inside the chimney; and $T(z)$ is the outside temperature, both functions of z. For a perfectly insulated chimney, the adiabatic temperature change inside and outside the chimney is the same so that $(T_c - T) = \Delta T$ is approximately independent of z. Using Eqs. (1) and (2) the integration can be carried out, with the result

$$\Delta\phi = \rho_\circ g H' \frac{\Delta T}{T_\circ}\left[1 - \mathrm{e}^{-h/H'}\right], \tag{4}$$

where $H' = H/(2-\gamma)$. This updraft potential, which has the units of pressure, is to be balanced against flow losses due to wall friction, boundary layer separation, and work that is extracted by the turbines. This balance constitutes a steady-state solution to the momentum conservation equation for flow in the direction of the chimney axis. It can be written

$$\Delta\phi(1-\varepsilon_t) = \left[\mathrm{e}^{h/H} + \varepsilon + \left(\frac{fh}{d}\right)\right]\frac{1}{2}\rho_\circ u_\circ^2. \tag{5}$$

On the right side the flow losses are all correlated to the flow energy at the base of the chimney, where the axial component of velocity is $u_\circ$ and the density is (approximately) $\rho_\circ$; coefficients in brackets are, respectively, the exit loss at the chimney top (with unit coefficient), other point losses, and wall friction. Typically, $f \sim 0.01$ for high-Reynolds number flow in a pipe that is not too rough [13, Chapter 3, p. 60]. The point loss coefficient ε accounts for the energy expended to (1) the swirl vanes that spin the flow; (2) turning the turbulent flow; (3) separation of the condensate; and (4) re-compression of the flow in the diffuser section of the separator. When a turbine generator is placed in the flow an arbitrary portion of the motive potential can be removed. It is common practice [4] to express this work in terms of a multiple of the motive potential, in this case given by $-\varepsilon_t\Delta\phi$ which appears on the left side of Eq. (5). Expressed in terms of the updraft velocity at the chimney base, this is

$$u_\circ(h) = \left[\frac{2(1-\varepsilon_t)(\Delta T/T_\circ)gH'(1-\mathrm{e}^{-h/H'})}{\mathrm{e}^{h/H}+\varepsilon+(fh/d)}\right]^{1/2}, \tag{6}$$

which can be checked against data for the experimental Solar Chimney that was operated in Manzanares, Spain [4,5]. For that facility $d = 10.16\,\mathrm{m}$, $\Delta T/T_\circ \sim 15/298$, $h = 194.6\,\mathrm{m}$. Under a no-load condition (no turbine power extracted) the updraft velocity was $\sim 12\,\mathrm{m/s}$; with the turbine load enabled, the updraft velocity was $\sim 7.5\,\mathrm{m/s}$; and the power generated was 30 kW. Using $h/d = 194.6/10.16 = 19.2$, with h/d held fixed, Fig. 3a is a plot of $u_\circ(h)$ for three conditions: (a) $f = 0, \varepsilon = 0, \varepsilon_t = 0$ (frictionless flow); (b) $f = 0.01, \varepsilon = 0.1, \varepsilon_t = 0$ (frictional flow, no-load); and (c) $f = 0.01, \varepsilon = 0.1, \varepsilon_t = 0.67$ (frictional flow, with generator load). The circle marks the no-load data for Manzanares, which should correspond to (b); the cross marks the Manzanares data with the turbine load on, which should correspond to (c). These comparisons are quite reasonable; thus Eq. (6) can be considered representative of the experimental data. Fig. 3a also shows that the effects of friction and other flow losses are small compared to extracting motive potential for the turbine generator work.

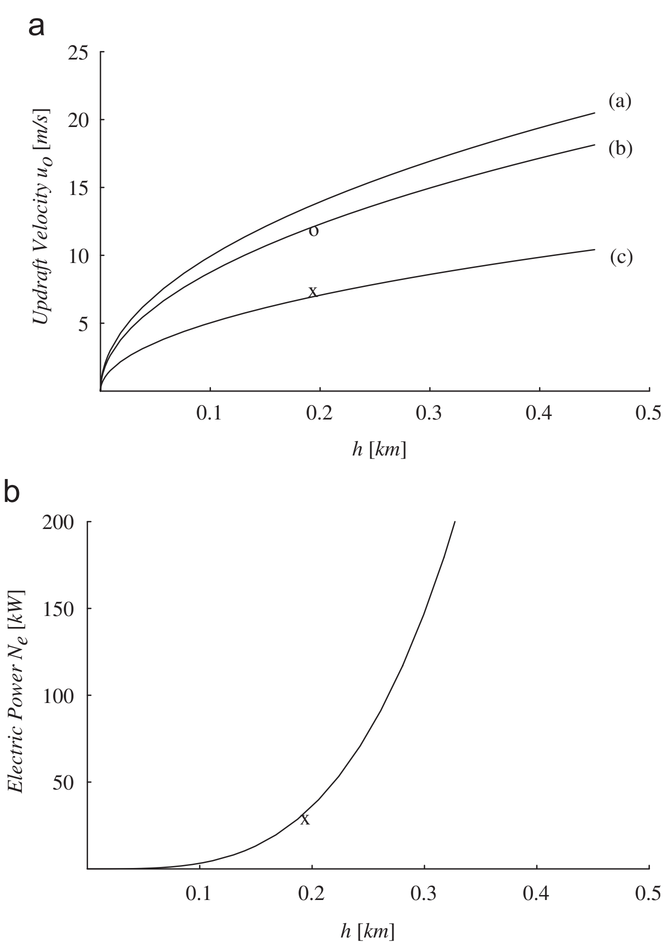

Fig. 3. Updraft velocity and electric power for the Manzanares experiment. (a) $u_\circ(h)$; (b) $N_e(h)$.

The electrical power generated N_e, is given by the experimental correlation

$$N_e = \dot{M}\eta_t\varepsilon_t\Delta\phi \tag{7}$$

where the mass flow rate is $\dot{M} = \rho_\circ u_\circ \pi d^2/4$; and η_t is a turbine efficiency. Recall that ε_t is the fraction of the motive potential that is due to pressure drop across the turbine generator. Design values for the Manzanares experiment are $\eta_t = 0.83$ and $\varepsilon_t = 0.67$ [4]. Eq. (7) for N_e is plotted in Fig. 3b, with a cross that marks the experimental data from the Manzanares experiment (again $h/d = 19.2$, so d increases with h). This demonstrates that the assumed turbine efficiency and turbine flow loss were very reasonable estimates at the time of the experimental design. Equations (6) and (7) form the basis for the studies in the next section.

Note that Eq. (6) explicitly includes the compressible nature of the atmosphere, so the expression differs in an important way from that used by Haaf [4], which was valid only for a very short chimney. Eq. (6) is, in effect, an explicit solution to the problem posed by Backström & Gannon [7] for $u_\circ(h)$, and solved numerically. To see this, one can consider a constant diameter solar chimney, with parameters from [7] as follows: $h = 1500\,\mathrm{m}$; $d = 160\,\mathrm{m}$; $(\Delta T/T_\circ) = (20/303.2)$; $f = 0.008428$; $\varepsilon = 0.5$; $\varepsilon_t = 2/3$; $\eta_t = 0.83$. Equations (6) and (7) give $u_\circ = 18.9\,\mathrm{m/s}$ and $N_e = 205\,\mathrm{MW}$ which are in agreement with values obtained in [7].

3. Available water and electric power

When the temperature of a water–vapor/air mixture drops to the dew point, the mixture is said to be at saturation. A further drop in temperature results in a supersaturated state called subcooling, and the potential for condensation exists. In order for condensation to proceed, thereby making small droplets of water (fog), nucleation of the condensed phase must occur. When the mixture is devoid of impurities, such as dust, a very large subcooling can be achieved prior to nucleation, after which condensation proceeds rapidly until a new saturation condition is achieved. Nucleation in a pure (clean) mixture is called homogeneous nucleation. Nucleation in a dusty mixture (like Earth's atmosphere) is called heterogeneous nucleation, and is characterized by immediate condensation as soon as the mixture drops to a temperature only very slightly below the dew point; if the temperature continues to fall, condensation continues apace, keeping the mixture essentially at saturation at all times.

Heterogeneous nucleation can be expected to occur in the Solar Cyclone because the surface air always contains some amount of dust. Therefore a saturation condition will be maintained in the flow at and below the ambient dew point. Accordingly, the maximum amount of water that can be extracted from the surface air depends only on the minimum temperature achieved in the cyclone, and on the local ambient water vapor content of the surface atmosphere.

For example, suppose that the local annual-averaged specific humidity of the surface air, q_A, is 6.00 g of water per kilogram of moist air. At sea level, the corresponding dew point is 279 K (6 °C). Suppose that a minimum cyclone temperature of 263 K (−10 °C) is achieved, at which point the saturation condition is $q_s = 1.60$ g/kg [13, Chapter 4, p. 84]. This means that $6.00 - 1.60 = 4.40$ g of water is available for removal, per kg of air passing through the Solar Cyclone. Of course there is a concomitant release of latent heat associated with the condensation which heats the air and actually augments the updraft. The actual temperature rise due to latent heat release is an efficiency times the potential heat rise. That is, $\eta_s(L/c_p)(q_A - q_s)$, where η_s is the efficiency of separation, $L = 2503$ kJ/kg is the latent heat of evaporation for water, $c_p = 1.05$ kJ/kg/K is the constant pressure specific heat of air, and the specific humidities are given in kg/kg. For $\eta_s = 1$, and at a rate of $(q_A - q_s) = 0.0044$ kg/kg, the heat release is about 10 K, which is comparable to (and, under some conditions, can even exceed) the greenhouse heat gain.

To compute the liquid water and electricity production rates, let us assume: (1) a greenhouse temperature gain of 15 K; (2) $h/d = 12$; (3) $f = 0.01$, $\varepsilon = 1.50$; (4) a minimum separator temperature of 263 K; (5) $\eta_t = 0.83$, $\varepsilon_t = 0.50$; and (6) $\eta_s = 0.80$. First the water and power production, given these six conditions, are displayed. Then the extent to which the conditions are reasonable to achieve will be discussed. The total temperature rise is

$$\Delta T = 15 + \eta_s(L/c_p)(q_A - q_s), \tag{8}$$

the water production rate is

$$R_w = \dot{M}\ \eta_s\ (q_A - q_s), \tag{9}$$

and the electrical power is given by Eq. (7). The results are shown in Figs. 4 and 5. For water production, three values of q_A are used (shown in units of g/kg); for electricity production, four values are used.

To put the water production results into perspective, consider a single Solar Cyclone, 500 m tall. At $h/d = 12$ the diameter is about 42 m, and yearly water production in an arid region ($q_A = 6$ g/kg) is about 2×10^9 kg/year. Typical *per capita* urban water usage is about 0.2×10^6 kg/year, so this single cyclone could serve 10,000 urban dwellers. In terms of electricity, there are presently about 0.4 kW of installed electrical capacity for every citizen in the United States, for example. The same 500 m tall cyclone could produce 3 MW of power, which would serve the electrical needs of 7500 US citizens.

It is important to notice the variation of water and power with q_A, as shown in Figs. 4 and 5. Because a small greenhouse heat gain is assumed (and held fixed), the condensation heat release has a significant effect for even the smallest specific humidity assumed. (In Fig. 5, for $q_A = 1.6$, there is no condensation heat release.) For high q_A (typical of equatorial latitudes) the heat release is the dominant part of ΔT; in such cases it could be possible to dispense with the greenhouse altogether, and replace it with a gas burner placed above the expansion cyclone separator, to be used only for getting the flow started. In this case the device might be called the "Condensation Cyclone" because the motive potential comes completely from the latent heat release. [Remark: Earth's averaged ambient surface specific humidity varies from about 4 g/kg at ±55° latitude, up to about 20 g/kg at the equator. Values of 4–6 g/kg, are characteristic of the Western part of North America, the African Sahara Desert, the Asian Gobi Desert, and the Australian outback. A value of 12 g/kg, is characteristic of the Hawaiian islands, sub-Saharan Africa, and much of the populated areas of Asia. The equatorial parts of South America and Africa have large areas where the humidity hits 18 g/kg [14, p. 281].]

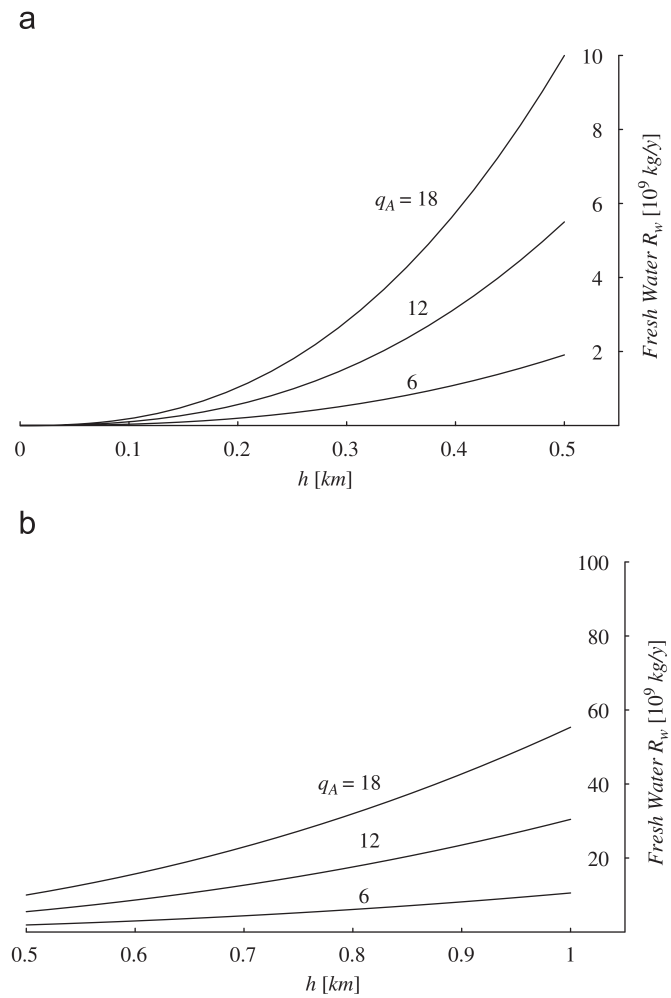

Fig. 4. Fresh water versus height. (a) $0 \leqslant h \leqslant 0.5$ km; (b) $0.5 \leqslant h \leqslant 1.0$ km.

Now consider in turn the five assumptions: (1) greenhouse temperature gain; (2) chimney h/d; (3) frictional and total point losses; (4) minimum separator temperature; (5) turbine efficiency η_t and turbine point loss ε_t; and (6) separation efficiency η_s.

First, the assumed temperature gain of 15 K was demonstrated in the experimental station at Manzanares,

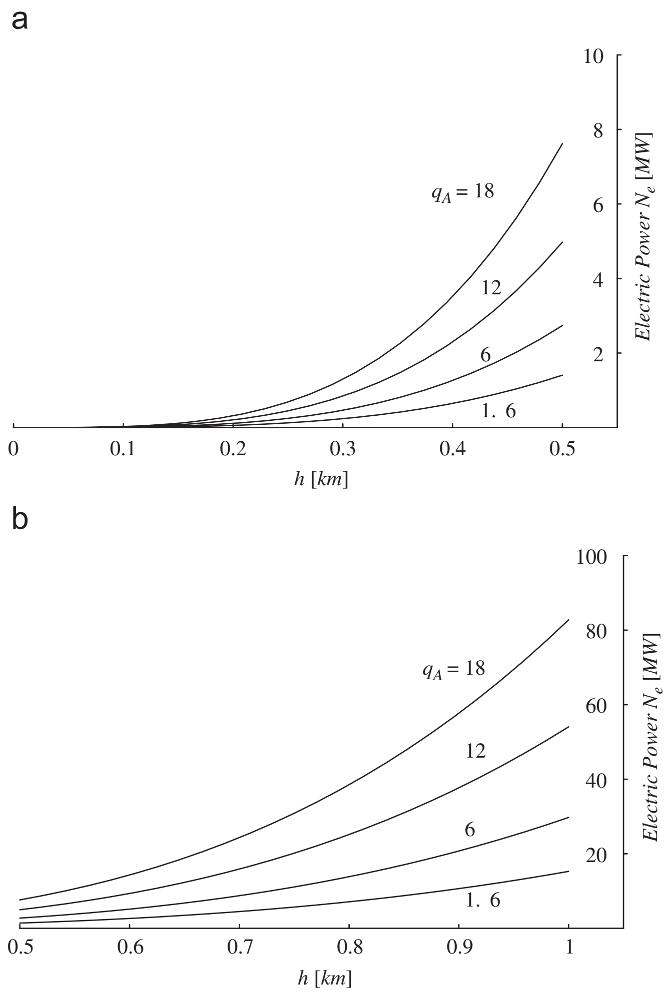

Fig. 5. Electric power versus height. (a) $0 \leqslant h \leqslant 0.5$ km; (b) $0.5 \leqslant h \leqslant 1.0$ km.

Spain (39° North latitude); so the goal is clearly achievable. In that test, the greenhouse diameter was 244 m so the ratio of greenhouse diameter D, to chimney diameter d, was $D/d = 48$. Improved heat-storage schemes suggest that an equal temperature gain can generally be achieved with a smaller greenhouse. The value of $D/d \sim 30$, displayed to correct relative scale in Fig. 1, is considered well within reason for most latitudes.

Second, the Manzanares h/d was about 19. This value was clearly sufficient to generate and maintain an updraft, given an averaged $\Delta T = 15$ K. Generally this is considered to be larger than is really necessary. Schlaich [3] correctly realized that the smallest h/d possible is desirable from an economic standpoint. The aspect ratio h/d determines how slender the chimney appears. If the chimney is not sufficiently slender, then wind variation at the chimney top can have a strong influence on the updraft. A value of $h/d = 12$ is considered sufficiently slender to avoid a strong influence on the updraft by the inevitable winds.

Third, as was shown in Section 2, the Manzanares data suggest that $f = 0.01$ for the wall friction is quite reasonable. However, the pressure loss due to the cyclone separator will be greater than for the turbines alone so one must expect $\varepsilon > 0.1$ (the Manzanares value). A conservative value can be estimated using data from the so-called direct-flow cyclone which operates according to the same principle as the expansion cyclone separator. Idelchik [15, p. 587, Diagram 12–7, second from bottom] shows a loss coefficient of 1.50; so the value used in these studies, $\varepsilon = 1.50$, can be considered experimentally verified, at least in part. The Idelchik data are for a small-scale device ($d = 0.05$ m) and the separator of interest here must be larger by up to three orders of magnitude. Hence the results here must be viewed as provisional, until full-scale test data become available.

Fourth, the assumed minimum separator temperature of 263 K, represents a nominal total cyclone temperature drop of 50 K ($= 298 + 15 - 263$). Achieving this temperature drop, without incurring a severe flow loss, is a critical aspect of the Solar Cyclone operation. It is accomplished by giving a strong spin (via the swirl vanes) to the converging flow between the greenhouse and the chimney base. An elementary analysis detailing this process is given in Section 4.

Fifth, the turbine efficiency $\eta_t = 0.83$ is exactly the value demonstrated at Manzanares [4,5]; a work factor of $\varepsilon_t = 0.50$ is used here to extract relatively less electrical power which gives emphasis to water production.

Sixth, a separation efficiency of 100% is not expected to be achievable. The direct-flow cyclone considered above [15] has a collection efficiency that depends on the free fall velocity of the dispersed material; a collection efficiency of 100% can be realized, if the free fall velocity is large enough. The free fall velocity is a measure of droplet size, which for the expansion cyclone separator is not yet known. Generally, separation efficiency increases with increasing droplet size. This is because large droplets can move relative to the air much more readily than can very small ones. A moderate value of $\eta_s = 0.80$ is used here, in order to show what the production *could* be. This efficiency represents the largest uncertainty in the actual water produced, given the available water vapor. The condensed water must grow from sub-micron droplets up to millimeter scales in order for a rapid centrifugal separation to occur. This is the reason that physical experiments, combined with much more detailed flow analysis, are so important. Because turbulent fluctuations influence the droplet growth rate, the more turbulent the better (probably up to a point), insofar as separation is concerned [16]. For a given updraft velocity the turbulence increases with the separator diameter; hence it is expected that large-scale experiments will be needed to fully explore separator efficiencies.

4. Flow analysis

This section discusses the conditions under which the minimum cyclone temperature may be achieved. The main assumption is that the flow Reynolds number in the Solar Cyclone is very large, implying that the boundary layers are

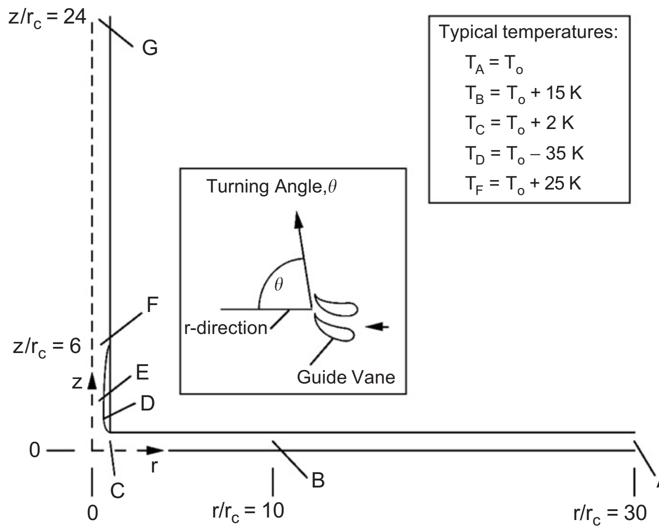

Fig. 6. Sample geometry in r–z coordinates.

very thin, so that a nonviscous, isentropic, compressible flow is a reasonable approximation.

Let $r_c = d/2$ be the radius of the chimney, and consider a cylindrical coordinate system with an origin on the greenhouse floor, as shown in Fig. 6. With reference to Fig. 6; point A is the greenhouse entrance; point B is just after the swirl vanes; point C is in the greenhouse just below the chimney; point D is at the throat; and point F is on the centerline above the expansion section.

The goal is to estimate the temperature difference in the flow between points B and D. (Using the same method, one can show that the pressure-temperature drop due to acceleration through the swirl vanes is negligible.) The isentropic temperature change is given by the equation for conservation of total energy on a streamline,

$$c_p(T_D - T_B) + (K_D - K_B) = 0, \tag{10}$$

where $K = \frac{1}{2}u^2$ is the mean kinetic energy, and where the variation of air density is neglected momentarily—this provides a low-order estimate that we use for illustrative purposes only. The kinetic energies are obtained as follows.

Assume that the radially-averaged vertical flow velocity at point F in the chimney is $u_\circ$. To simplify the arithmetic, assume a greenhouse height equal to one-half of the chimney radius, so the vertically-averaged radial velocity at point C is $-u_\circ$.

Let $R = r/r_c$ be the radial coordinate, normalized by the chimney radius, so that R_A through R_D are the nondimensional radii of points A through D. The radial velocity at point B is then $-u_\circ/R_B$, and the azimuthal velocity component is $-\alpha u_\circ/R_B$ where α is the ratio of the azimuthal (swirl) component of velocity to the radial component. (With reference to Fig. 6, if the angle of the swirl vanes measured from the radial direction is θ, then $\alpha = \tan\theta$.) Hence, the kinetic energy at B is $K_B = \frac{1}{2}u_\circ^2(1+\alpha^2)/R_B^2$. If frictional momentum loss to the greenhouse walls is ignored, both the mean radial and mean azimuthal components of velocity vary according to $1/R$ [17, p. 270–273]. Thus, assuming frictionless flow, the kinetic energy at C is $K_C = \frac{1}{2}u_\circ^2(1+\alpha^2)$, because $R_C = 1$.

At the axial level of point D the averaged axial velocity component is $u_\circ/R_D^2$, and the azimuthal component is $\alpha u_\circ/R_D$, assuming that the spin-up continues like $1/R$ as the flow converges and moves upward. Thus $K_D = \frac{1}{2}u_\circ^2(1/R_D^4 + \alpha^2/R_D^2)$, which will be larger than K_C because $R_D < 1$. With these we obtain

$$\begin{aligned} T_D - T_B &= -\frac{u_\circ^2}{2c_p}\left[\frac{1}{R_D^4} + \frac{\alpha^2}{R_D^2} - \frac{(1+\alpha^2)}{R_B^2}\right] \\ &= -\frac{u_\circ^2}{2c_p}\left[16 + 4\alpha^2 - \frac{(1+\alpha^2)}{100}\right] \\ &\sim -\frac{u_\circ^2}{2c_p}[16 + 4\alpha^2], \end{aligned} \tag{11}$$

where we have assumed $R_D = \frac{1}{2}$, and $R_B = 10$, as illustrated in Fig. 2. (So the swirl component dominates the cooling process for $\alpha > 2$.) Hence, the ratio α needed to achieve a given temperature drop between B and D is

$$\alpha = \sqrt{4 - c_p(T_D - T_B)/2u_\circ^2}. \tag{12}$$

For a temperature drop of -50 K, and an air updraft velocity of 10 m/s, we have $\alpha \sim 16$ or a swirl vane turning angle of about 86°, which is steep but not impossible to achieve. Because the flow can potentially spin even faster at radii close to the centerline of the venturi section, temperatures well below the freezing point can persist there. Also, using $\alpha = 16$, $T_C - T_B \sim -13$ K. The corresponding decrease in pressure and density are given by Eq. (2).

To summarize, consider again Fig. 6. Surface air enters at temperature $T_\circ$ and is heated by 15 K, on average, in the greenhouse. After passing through the swirl vanes, and converging to the chimney base, the temperature is reduced, approximately, to a 2 K rise because of the increase in kinetic energy of the flow. In turning the corner at the chimney base a further (and larger) velocity increase occurs, resulting in a temperature of -35 K relative to ambient. While passing through the separator throat, condensation occurs and latent heat is released adding another 10 K to the flow (for $q_A = 6$ g/kg). When the flow finally spins down and slows to fill the full chimney diameter, the temperature rise is 25 K (15 K from the greenhouse, and 10 K from condensation).

The foregoing summary may be better understood by considering the physical processes that are important in the Solar Cyclone. For this, consider Fig. 7, a pressure-volume schematic for the thermodynamic state of a parcel of air as it passes through the device, and where the specific volume is $v = 1/\rho$. Symbols in Fig. 7 correspond to physical locations in Fig. 6.

Fig. 7 shows isentropic lines representing Eq. (2), and passing through states at physical locations A, B, and F; as well as three dashed horizontal lines that correspond,

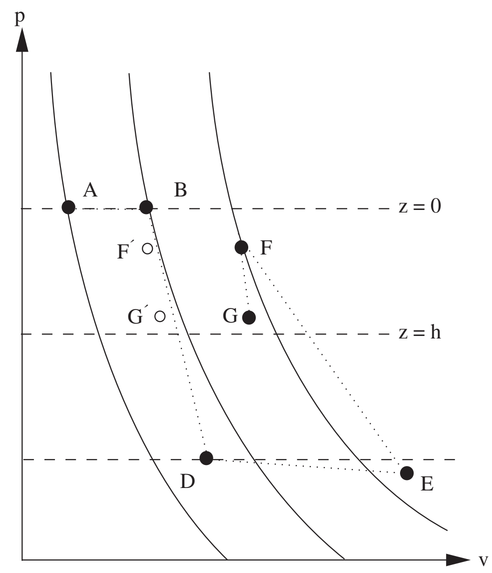

Fig. 7. Pressure-volume schematic.

respectively, to the pressure at ground level $z = 0$, atmospheric pressure at elevation $z = h$, and the pressure at point D in the expansion cyclone separator. Surface air enters at state point A and is heated in the greenhouse at constant pressure, which shifts the state to an isentrope lying to the right and passing through point B. After turning through the guide vanes, the rotating-converging flow accelerates as in a so-called bathtub vortex; by turning the corner and converging to the separator throat a very low pressure and temperature are achieved at point D, which is below the isentrope passing through B due to nonisentropic processes (separation and viscous flow losses). Point E represents a region in the separator, above the throat; this state is shown as a reminder that the condensation process results in a release of latent heat that moves the state to yet another isentrope that lies even farther to the right. This process is accompanied by another (very small) pressure loss. The physical process shown as E–F is a pressure recovery accomplished in the diffuser section of the separator, which has a baffle that removes the rotation from the flow (a flow straightener). The diffuser section and baffle are shown in Fig. 2. Process F–G is an adiabatic (but nonisentropic) expansion in the chimney flow, with nonideal behavior due to wall friction. For this reason, point G lies below the isentrope passing through point F.

The overall pressure drop in the expansion cyclone separator is the difference $p_B - p_F$. Its value is $\approx \varepsilon\rho_\circ u_\circ^2/2$; and the corresponding temperature drop is $\approx \varepsilon u_\circ^2/(2c_p)$ which, for the conditions of operation, is negligible compared to the combined greenhouse heating, and latent heat release. The pressure loss due to condensation, and trapping of the condensate is likewise negligible because of the very small mass of water that is involved (recall that the specific water content of the air is of order 10^{-3}).

Also in Fig. 7 state path A–B–F′–G′ corresponds to the Solar Chimney. Notice that the separation of isentropes through points B and F depends on the separation efficiency η_s and ambient humidity q_A; if either value tends toward zero, isentrope F will overlap B (no heat release), and the Solar Cyclone path overlays the Solar Chimney path. Hence, the Solar Cyclone becomes a Solar Chimney if either the separator fails, or if there is no moisture to be condensed from the surface air.

5. Discussion

Condensation in the expansion cyclone separator produces a substantial heat release that enhances the motive potential of the updraft. For arid regions, the heating that drives the updraft is dominated by the greenhouse heat gain; in humid regions, latent heat release can be dominant. In very humid regions, both water production and power production can be three times greater than for arid regions. Under conditions of high humidity and high separation efficiency, it is possible that the greenhouse could be omitted, saving both physical space and construction expense.

Efficiency of the expansion cyclone separator is a key unknown factor that remains to be determined. A dedicated research project involving detailed measurements of flow structure and temperature could be undertaken in order to quantify this crucial parameter. In this project, theoretical modeling of the turbulent two-phase flow can be helpful in guiding the measurements and for optimization of separator performance. Such a future research project is facilitated by a large collection of related work on the Ranque–Hilsch vortex tube [18], the separator itself [11], and most notably in connection with the tornado vortex. Morphology of the swirling flow that enters the expansion cyclone separator is reminiscent of the flow entering the base of a tornado funnel. This vortex has been studied extensively at small scales in laboratory experiments [19], which show that recirculation patterns can persist that create a radial flow toward the wall. It is this radial flow, and the very low central temperature, that lead to the strong belief that the wall of the tornado funnel is a swirling mass of water, ice, and debris [20]. If this is indeed the case, and can be replicated in the Solar Cyclone, then it may just be possible to design an expansion cyclone separator with a high separation efficiency.

If a high separation efficiency can be demonstrated, it becomes possible to consider a greenhouse that uses a pool of water for solar energy storage. If the warm water is sprayed in the greenhouse in order to saturate the incoming surface air, then a large updraft can be created with very little temperature rise in the greenhouse. In this case, the solar energy is released in the separator, and the pool water becomes a recirculating working fluid. Using the formulae developed here it can be shown that, regardless of the ambient humidity, net fresh water production can be three times greater, and electrical production can be ten times greater, in such a system.

6. Summary

A device called the Solar Cyclone is introduced for the condensation and separation of water from the atmosphere. Energy from direct sunlight is used to furnish a portion of the separation power by heating air in a greenhouse and channeling the heated air in a chimney updraft. An expansion cyclone separator is placed at the base of the chimney, along with a turbine generator. A rough analysis suggests that a single Solar Cyclone 500 m high could satisfy the household fresh water needs, and about 75% of the electrical needs, for an urban population of 10,000 residing in an arid region. This assumes a separation efficiency of 80%; the separation efficiency that can actually be achieved is unclear. The efficiency could be determined by a coordinated effort that includes large-scale experiments along with theoretical modeling and computer simulation of the turbulent two-phase flow in the separator.

Acknowledgments

Los Alamos National Laboratory is operated by Los Alamos National Security LLC, for the U. S. Department of Energy's National Nuclear Security Administration. Partial DOE support, and the encouragement of Henry M. Kashiwa, are gratefully acknowledged.

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