

Atmospheric Vortex Engine

Technical description

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1. Introduction

An atmospheric vortex engine (AVE) is a device for producing mechanical energy by means of a controlled tornado-like vortex. The vortex is produced by admitting air tangentially at the base of a circular wall. The process could become a major source of clean energy and could provide other benefits such as precipitation and cooling. Vortex engines would help alleviate global warming by reducing fuel consumption or by hastening upward heat convection. The AVE would harness the process responsible for tornadoes and hurricanes. Raising a unit mass of warm moist air from the bottom to the top of the troposphere can produce as much energy as lowering a unit mass of water 1000 m.

The operation of AVE is based on the facts that the atmosphere is heated from the bottom and cooled from the top and that more mechanical energy is produced by the expansion of a heated gas than is required to compress the same gas back to its original pressure after it has been cooled. The energy is produced as a result of reducing the temperature of the heat sink from to temperature at the bottom of the atmosphere to the temperature at the tropopause. The source of the energy is thermal convection, the process responsible for producing circulation in boilers and in many other industrial processes. The technology is akin to that of cooling towers.

The vortex is started by temporarily heating the air within the cylindrical wall with steam or fuel. The heat required to sustain the vortex once established can be the naturally occurring heat content of ambient air or can be provided in a peripheral heat exchanger located outside the circular wall; the heat source for the peripheral exchanger can be warm seawater or waste industrial heat. The peripheral heat exchanger can be a wet cooling tower or a dry finned tube heat exchanger. The mechanical energy is produced in a plurality of peripheral turbo-expanders. The circular wall could have a diameter of 200 m and the vortex could be 50 m in diameter at its base and extend up to the tropopause. The system would generate 50 to 500 MW of electrical power.

An AVE is a solar chimney where the physical chimney is replaced by the centripetal force produced by spiraling upward airflow. The AVE has the same thermodynamic basis as the natural draft cooling tower except that the material hyperbolic stack is replaced by centripetal force in the vortex. Replacing the conventional cooling towers of a thermal power plant with a vortex cooling tower could increase power output by 20%.

The description of the process is followed by presentation of its thermodynamic cycle and by engineering calculations. The process is analyzed using both the total energy equation and a chemical engineering process simulator. The relationship of the AVE to current atmospheric science is reviewed. Finally implementation options are considered and discussed.

2. Process description

An embodiment of the vortex engine is shown in Figures 1a and 1b. Admitting air tangentially at the base of a vertical axis circular cylindrical wall produces a convective vortex that acts as a dynamic chimney. The vortex is started by temporarily heating the air near the center of the station with fuel or steam. The starting steam can be injected in the tangential entries to help entrain the air in the station while heating the air. The heat required to sustain the vortex after it is established can be the naturally occurring heat content of ambient air or be provided in a peripheral heat exchanger located outside the cylindrical wall and upstream of the deflectors. The heat source for the peripheral heat exchanger can be warm seawater or waste industrial heat. The heat exchange mean can be a crossflow wet cooling tower or a dry heat exchanger; a plurality of heat exchange means would be located around the outside perimeter of the cylindrical wall. The air inlet to the cooling tower is restricted so that the cooling towers operate at sub-atmospheric pressure; the pressure difference between ambient air and the cooling tower is used to drive a plurality of peripheral turbines.

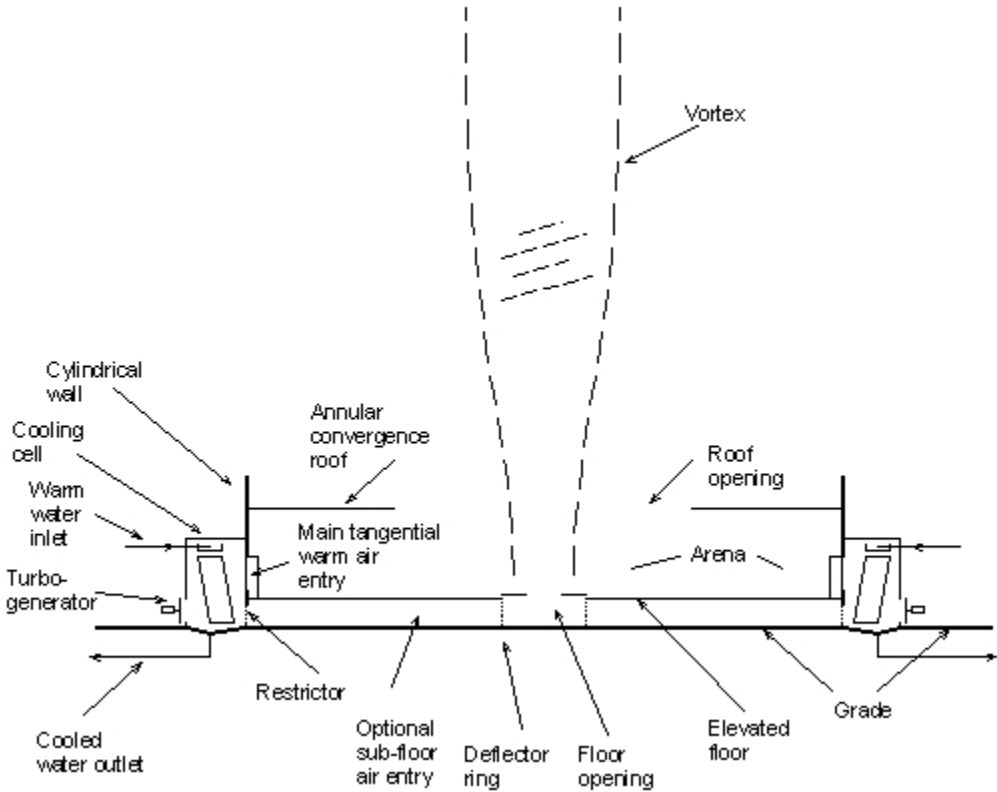


Figure 1a. Atmospheric Vortex Engine - side view.

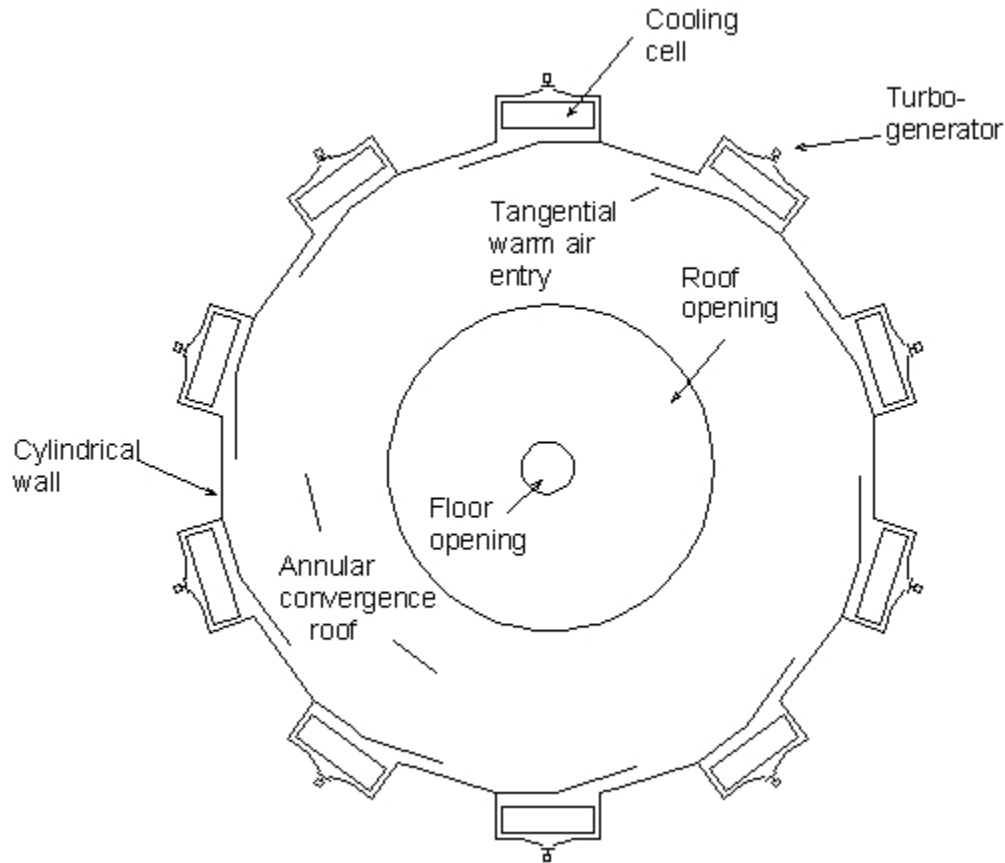


Figure 1b. Atmospheric Vortex Engine - plan view.

The cylindrical wall would be open at the top and could be 100 to 200 m in diameter by 50 m high. The eyewall diameter, the diameter of maximum tangential velocity near ground level, could be a tenth to a quarter of the diameter of the cylindrical wall. The vortex could be 50 m in diameter at its base and extend up to the tropopause. The diameter of the vortex would increase with height. The vortex could be the size of a medium tornado or of a large waterspout. The system would generate 50 to 500 MW of power. The mechanical energy is produced in a plurality of peripheral turbo-expanders. A 200 MW station could have 20 cooling tower cells each with a single 10 MW turbo-expander.

Warm air enters the area within the cylindrical wall, called the arena, via tangential air entry ducts. The airflow can be controlled via adjustable restrictors located either upstream of the cooling cells or within the tangential entry ducts. For inlets with turbines, the upstream flow restrictor can be the turbines at the cooling cell air inlets. An annular roof with a central circular opening forces the air entering the arena to converge thereby forming a vortex. The diameter of the roof opening could be 30% of the diameter of the cylindrical wall. The diameter of the vortex at the roof level could be 10 to 50% of the roof opening diameter. The height of the arena could be 30% of its diameter. The height of the tangential entry is approximately half of the height of the arena.

Convergence in the arena is restricted to the boundary layer adjacent to the floor where friction reduces tangential velocity and centripetal force. There is little convergence at the level of the upper part of the tangential entry because the air gap above the top of the tangential air entry and the roof ensures that there is little friction against the under side of the roof. Convergence in the boundary layer above the floor can be enhanced by floor surface roughness. The vortex could be stopped by restricting the flow of heated air with positive rotation, i.e. cyclonic and if necessary introducing unheated air with negative rotation, i.e. anti-cyclonic.

The purpose of the cylindrical wall is to force the air to go through the tangential entry ducts and to prevent ambient wind from disturbing the vortex until it is well established. The cylindrical wall could have a constant diameter or a diameter that varies as a function of height. Some of the air could be routed to the center of the vortex via ducts located under the arena floor to make the pressure downstream of the turbines approach that at the center of the vortex. Waste heat could be transferred to the air as sensible heat by replacing the wet cooling tower with finned tube heat exchangers.

The author tested the basic concept with a model 100 cm in diameter by 60 cm high. Ambient air heated by 20 C in a plenum entered the 30 cm high arena via 8 tangential entry deflectors. Smoke emitters were used to make the vortex visible. The vortex which looked like a small tornado was approximately 10 cm in diameter and extended up to 200 cm above the roof. The opening in the roof was 30 cm in diameter. A computerized fluid dynamic study carried out at the University of Western Ontario replicated the physical model result and confirmed that convergence is limited to a thin layer above the floor and that there is much less dilution of the rising warm air steam than in a flow that is not rotating. Model photos, videos, drawings and CFD results are available at Atmospheric Vortex Engine web site:
http://vortexengine.ca/Physical_Models_LM-3.shtml

Cooling towers are commonly used to transfer waste heat to the atmosphere; a 500 MW thermal power plant typically rejects 1000 MW of waste heat. An atmospheric vortex engine could increase the electrical output of a 500 MW plant to 700 MW by converting 20% of its 1000 MW of waste heat to work thereby increasing the output of the power plant by 40%. Wet cooling towers are particularly effective at transferring heat from water to air; falling water drops on splash bars and is repeatedly broken up into small droplets to enhance contact between the air and the water. The temperature of the water entering a cooling tower is typically 10 to 20°C higher than ambient air temperature. The air leaving a cooling tower is typically saturated at a temperature 3 to 10°C lower than inlet water temperature. Industrial cooling towers can be forced or natural draft. Natural draft cooling towers, which usually have hyperbolic stacks up to 200 m high, are two to four times more costly than forced draft cooling towers, which usually have top mounted induced draft fans. The higher cost can be justified because there is no need for energy to drive the fans; a 1000 MW forced draft cooling tower can require 20 200 kilowatt fans. The hyperbolic stack is a mechanical energy producer in the sense that it eliminates the need to produce energy to drive fans. Increasing the height of the hyperbolic stack to increase draft would make it possible to produce mechanical energy with turbines installed in the cooling tower air inlets. The number of cooling cells and their size in a vortex cooling tower would be about the same as in a conventional cooling tower of the same cooling capacity.

A natural draft chimney is a cylinder in radial compression that prevents ambient air from mixing with rising flue gas. In a vortex, centripetal force replaces the physical wall and prevents ambient air from entering the rising air stream; the vortex is self-regulating, its diameter adjusts itself until the radial pressure differential is balanced by centripetal force. The entry of air in the vortex is restricted to a thin layer next to its bottom surface where centrifugal force is low because tangential velocity is reduced by surface friction. The energy loss due to friction in the upper part of the vortex is small because friction losses are negligible in very large diameter conduits. The kinetic energy of the rising air would be recovered when the air decelerates as the vortex diameter expands at the top of the vortex. The kinetic energy recovery process is similar to the recovery of kinetic energy in a Venturi tube. Between the time the kinetic energy is produced and recovered, it provides centripetal force creating a dynamic chimney.

The air leaving a cooling tower approaches equilibrium with the water entering the cooling tower. The approach to equilibrium depends on the size of the volume of the cooling tower fill and on the ratio of the water flow to the airflow. In a vortex engine using seawater as the heat source, the outlet air could have a temperature 1 to 3°C lower than the sea surface temperature and have a relative humidity of over 95%. The pressure reduction at the base of a controlled vortex could be higher than the pressure reduction at the base of hurricanes or waterspouts because the air-water contacting could be more effective and better controlled in a cooling tower than in natural spray. Evaporatively cooled spray falling back in the sea reduces sea surface temperature and tends to reduce the intensity of the hurricane. In a vortex engine using warm sea-water, the cooled water could be discharged below the surface to avoid reducing sea surface temperature.

3. Thermodynamic basis

The ideal thermodynamic cycle for the atmospheric vortex engine is shown in Figure 2. The total energy equation

$$w = q - \Delta h - \Delta gz - \Delta \frac{v^2}{2} \quad (1)$$

is used to calculate the energy received and produced in each process, where w is the work given up, q is the heat received, h is the enthalpy of the air including the enthalpy of its water content, g is the acceleration of gravity, z is the height, and v is the velocity. Entropy (s) is conserved in reversible adiabatic processes 1-2 and 3-4. In the ideal cycle, the velocity of the air at the four numbered states is taken to be negligible. The key to solving the problem is that the work for upward flow process 3-4 is zero. The pressure at the base of the upward flow tube is calculated by assuming an approach to equilibrium, calculating the work during process 3-4 for two P_3 guesses, and then interpolating to determine the value of P_3 required to make the work w_{34} zero.

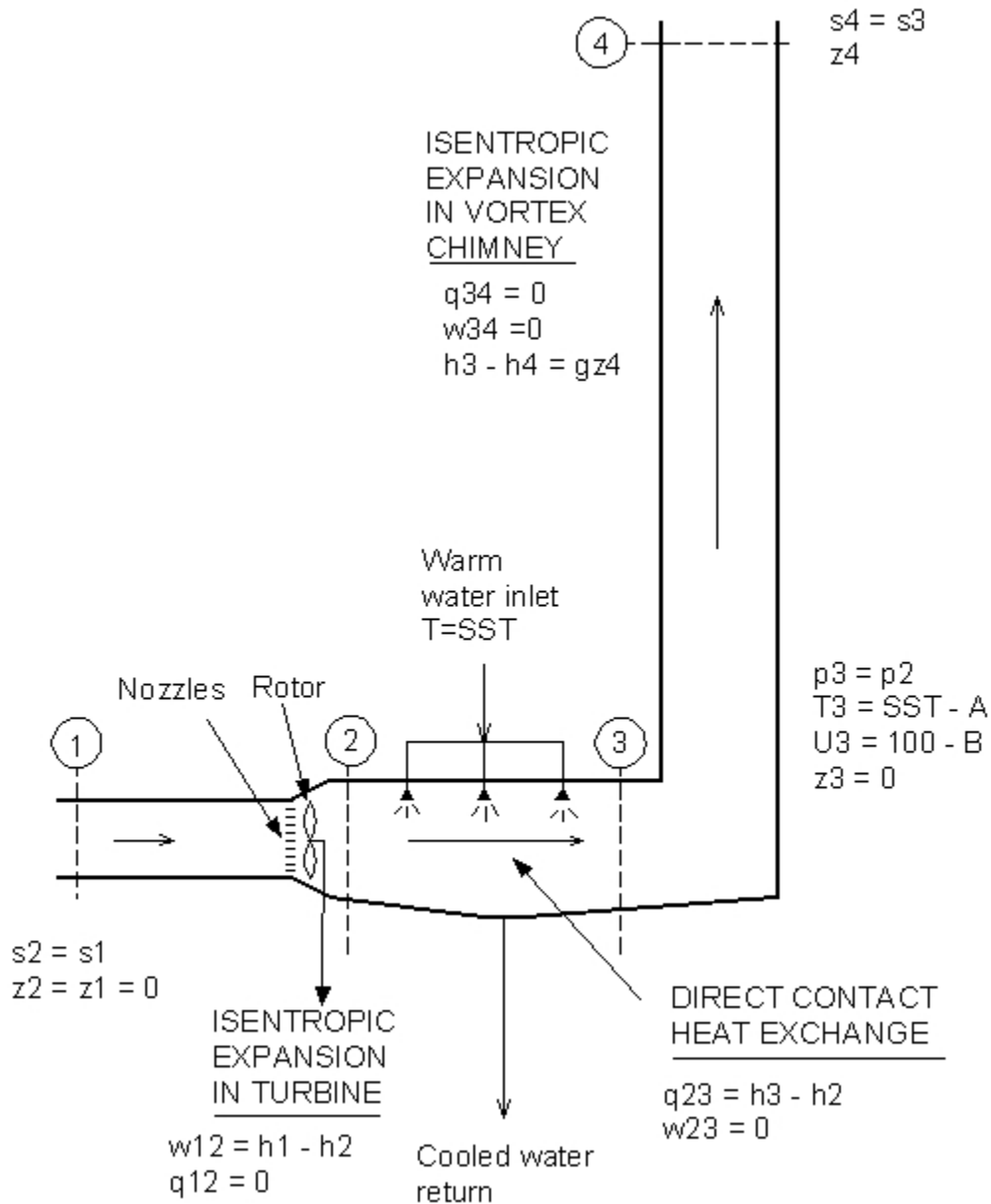


Figure 2. Thermodynamic ideal cycle of atmospheric vortex engine.

Table 1 shows calculation results for temperatures approaches (A) of 0, 1 and 3°C and for relative humidity (U) approaches (B) of 0, 5 and 10%. These sample calculations are based on the Willis Island 17 January 1999, 0000Z atmospheric sounding reproduced in Figure 3. Willis Island is located north-east of Australia. The sea surface temperature (SST) was assumed to be 1°C higher than the temperature at the base of the sounding because tropical sea surface temperatures are typically 1°C higher than surface air temperature. The work ranges from 4090 J kg⁻¹ in Case 0 where there is no heat addition in the cooling tower to 25770 J kg⁻¹ in Case 4 where the rising air at point 3 is in equilibrium with the water at reduced pressure P_3 . The corresponding air

velocities are 90 and 227 m s⁻¹ respectively. The pressure in the cooling tower ranges from 96 kPa in Case 0 to 75 kPa in Case 4. Saturating the air at 40 °C would yield a work of 48000 J kg⁻¹. The datum for entropy and enthalpy in Table 1 is liquid water at 0 °C, and air at 0 °C and 100 kPa.

The sensitivity of work to initial updraft temperature T_3 is 4050 J kg⁻¹ K⁻¹, and the sensitivity of work to initial updraft relative humidity U_3 is 512 J kg⁻¹ %⁻¹. The ratio of incremental work to incremental heat is approximately 30%. The heat to work conversion efficiency (n) is close to the Carnot efficiency given by: $n = (T_3 - T_4)/T_3$, where T_3 and T_4 are the temperatures at the bottom and at the top of the troposphere in degrees Kelvin. Approximately 30% of the heat received is converted to work during the convection process irrespective of whether the heat is received as sensible or latent heat.

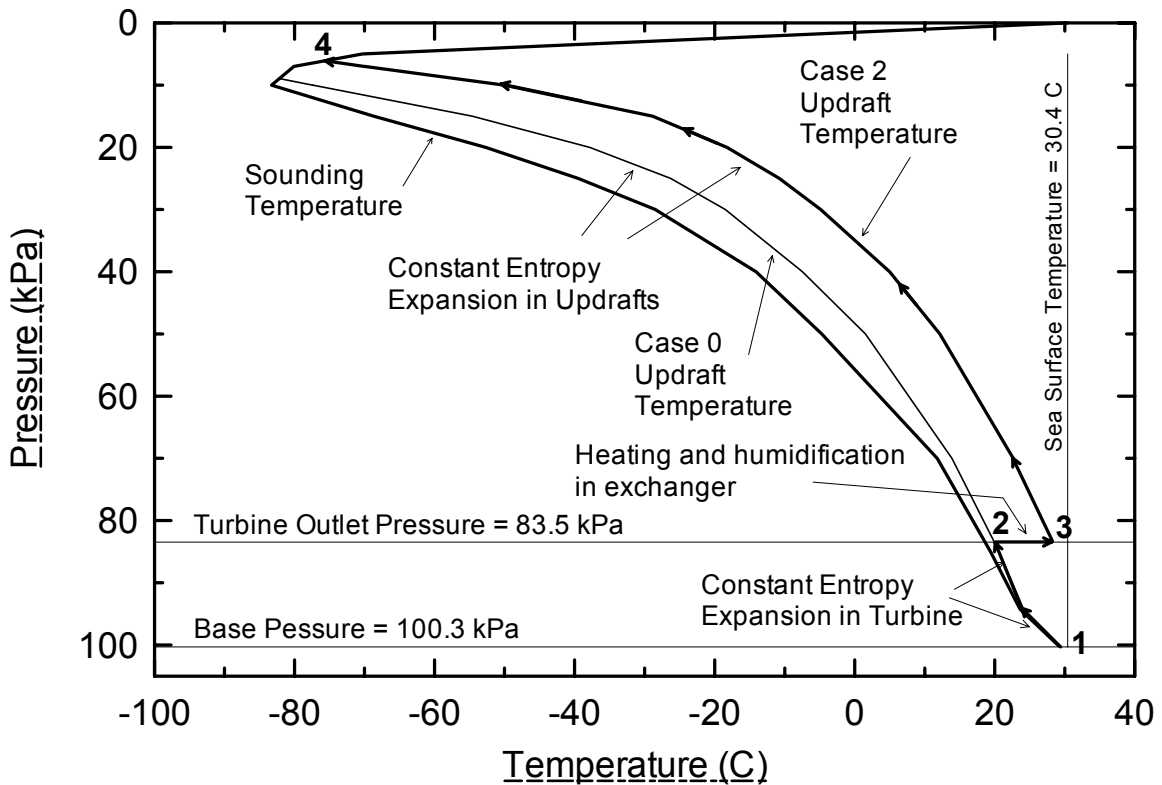


Figure 3. Willis island sounding. Case 0 updraft temperature without heat addition - true adiabatic expansion with freezing. Case 2 updraft temperature rising air approaching equilibrium with sea at reduced pressure, temperature approach $A=1^{\circ}\text{C}$, relative humidity approach $B=10\%$.

Table 1. Atmospheric Vortex Engine energy calculations for a range of temperature and humidity approaches. Ambient surface air conditions: $P_1 = 100.3$ kPa, $T_1 = 29.4$ °C, $U_1 = 77.5\%$, $r_1 = r_2 = 20.50$ g kg⁻¹, $s_1 = s_2 = 287.0$ J kg⁻¹ K⁻¹, $h_1 = 81920$ J kg⁻¹. Heights based on 17 January 1999, 0000Z Willis Island sounding, see Fig. 3. Approach based on Sea Surface Temperature (SST) = 30.4 °C.

<u>Properties</u>	Case 0 <u>$q_{23} = 0$</u>	Case 1 <u>$A=3, B=10$</u>	Case 2 <u>$A=1, B=10$</u>	Case 3 <u>$A=1, B=5$</u>	Case 4 <u>$A=0, B=0$</u>
$P_2 = P_3$ (kPa)	95.80	91.38	83.42	81.02	74.62
$P_1 - P_2$ (kPa)	4.50	8.92	16.88	19.28	25.68
T_2 (°C)	25.47	23.10	19.99	18.99	16.14
U_2 (%)	94	103	115	119	131
h_2 (J kg ⁻¹)	77820	73670	65720	63200	56150
$T_3 = \text{SST} - A$ (°C)	25.47	27.4	29.4	29.4	30.4
$U_3 = 100 - B$ (%)	94	90	90	95	100
$r_3 = r_4$ (g kg ⁻¹)	20.50	23.25	28.87	31.43	38.35
h_3 (J kg ⁻¹)	77820	86840	103320	109840	128590
$s_3 = s_4$ (J K ⁻¹ kg ⁻¹)	287.0	331.3	413.5	444.1	531.1
P_4 (kPa)	10	10.0	7.0	7.0	5.0
T_4 (°C)	-77.39	-68.01	-69.91	-63.21	-62.77
z_4 (m)	16570	16570	18580	18580	20560
h_4 (J kg ⁻¹)	-87890	-79330	-84020	-77970	-80630
$h_4 + gz_4(1+r_4)$	77820	86840	103320	109840	128590
$q_{23} = h_3 - h_2$ (J kg ⁻¹)	0	13170	37590	46650	72440
$w_{12} = h_1 - h_2$ (J kg ⁻¹)	4090	8250	16190	18720	25770
v_x (m s ⁻¹)	90	128	180	193	227
$\Delta w_{12} / \Delta T_3$	n/a	4050	base	n/a	n/a
$\Delta w_{12} / \Delta U_3$	n/a	n/a	base	512	n/a
$\Delta w_{12} / \Delta r_3$	n/a	n/a	base	1000	n/a
$\Delta w_{12} / \Delta q_{23}$	n/a	32.8%	base	28.1%	28.2%

4. Conventional solar chimney

The vortex engine operates on the same thermodynamic principle as the solar chimney. A solar chimney power plant consists of a tall chimney surrounded by transparent solar collector; the turbines are installed in the base of the chimney downstream of the solar collector, see Schlaich et al. The Manzanares solar chimney built in Spain in the 1980's, which operated for 7 years, had an electrical output of 50 kW, a 10 m diameter chimney 200 m high, and a 6000 m² solar collector. The Australian solar chimney project proposed by EnviroMission would have an electrical output of 200 MW, a 130 m diameter chimney 1 km high, and a 40 km² collector area. The 4000-fold power increase is due to increasing the collector area by a factor of 700, increasing chimney height by a factor of 5, and from smaller losses. Energy calculations for the two solar chimneys are shown in Table 2.

The heat to work conversion efficiency of a solar chimney is proportional to its height. The Manzanares plant had a theoretical efficiency of 0.7% whereas that of the proposed Australian plant is 3%. The actual efficiency of the Manzanares plant was 0.1% because the efficiency of the solar collector was only 30% and because a large fraction of the energy was lost as exit kinetic energy. A vortex engine is a solar chimney where the physical chimney wall is replaced by the centripetal force produced by spiraling upward airflow. The peripheral heat exchanger eliminates the need for the conventional solar collector. The efficiency of a vortex engine could be as high as 30% because a vortex can extend to a much greater height than a physical chimney. The chimney height required to produce a significant amount of power using a conventional solar chimney is prohibitive, but replacing the physical chimney with a vortex could make the atmospheric convection process an economically attractive energy source.

The heat received per unit mass of air was around 20 kJ kg⁻¹ in the Manzanares solar chimney, would be around 30 kJ kg⁻¹ in the Australian solar tower, and could be 20 to 100 kJ kg⁻¹ in an atmospheric vortex engine. The work produced per unit mass of air raised was 130 J kg⁻¹ in the Manzanares plant, would be 600 to 1000 J kg⁻¹ in the proposed Australian plant, and would be 10 to 30 kJ kg⁻¹ in the vortex engine. The upward air flow in a 200 MW AVE could be 10 times less than in the 200 MW Australian solar chimney because the work per unit mass of air is 10 times higher. The diameter of the vortex at its base in a 200 MW vortex engine could be 50 m, three times less than the diameter of the proposed Australian solar tower, because only one tenth as much flow would be required to produce the power.

Table 2. Energy calculations for two solar chimney plants. Ambient surface air conditions: $P = 100$ kPa, $T = 25$ °C, $U = 0\%$, $s = 87.98$ J kg⁻¹ K⁻¹, $h = 25117$ J kg⁻¹. Pressure at the top of the chimney based on 25 °C surface temperature and dry-adiabatic lapse rate.

<u>Properties</u>	<u>Manzanares</u>	<u>EnviroMission</u>
P_1 (kPa)	100	100
T_1 (°C)	45	55
h_1 (J kg ⁻¹)	45210	55257
$s_1=s_2=s_4$ (J K ⁻¹ kg ⁻¹)	153.2	184.3
P_2 (kPa)	99.856	98.957
T_2 (°C)	44.869	54.02
h_2 (J kg ⁻¹)	45079	54271
P_4 (kPa)	97.729	89.010
T_4 (°C)	42.92	44.26
z_4 (m)	200	1000
h_4 (J kg ⁻¹)	43119	44471
h_4+gz_4	45079	54271
$q = \Delta h$ (J kg ⁻¹)	20093	30141
$w_{12} = \Delta h_{12}$ (J kg ⁻¹)	131.5	986.1
v_x (m s ⁻¹)	16.2	44.4
$n=100w_{12}/q_{01}$ (%)	0.65	3.25
Exit loss, $v^2/2$ (J kg ⁻¹)	50	200
Misc. loss, (J kg ⁻¹)	23	26
Collector Area (km ²)	0.06	40
Chimney diameter, d (m)	10	130
Chimney area, A (m ²)	78	13300
Velocity, v (m s ⁻¹)	10	20
Mass Flow $M = \rho v A$ (kg s ⁻¹)	860	282000
Power Ideal $P_i = M w_{12}$ (kw)	113	278000
Power Actual P_a Ideal - Loss (kw)	50	214000

5. Process Simulation

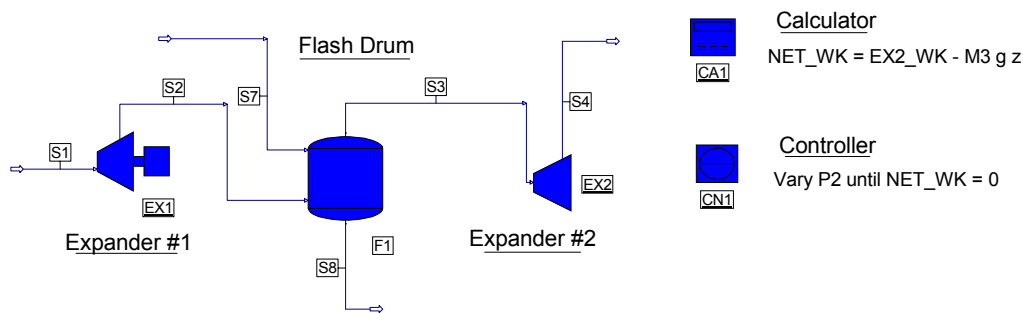
AVE process calculations can readily be carried out with standard chemical engineering process simulators. Figure 4 shows a simulation done on Simulation Science PROII. Expansion takes place in isentropic expanders EX1 and EX2. EX1 work can be used to drive a generator. Expander EX2 represents the upward flow process. EX2 work is used to lift the air and is not available to do other work. Air and water are brought to equilibrium at reduced pressure in flash drum F1. Calculator CA calculates the net work during the upward flow process as expander EX2 work minus the lifting work (Mgz). Controller CN finds the pressure P_2 required to make the net work during the upward flow process zero.

The table shows stream properties; the items below the table show work and heat transfer duty both of which are calculated from the change in total enthalpy. Figure 4 is based on a nominal flow of 1000 kg/s (1 t s^{-1}) of air with a mixing ratio of 20.5 g/kg . In flash drum F1, 1 t s^{-1} of air at $30 \text{ }^\circ\text{C}$ is mixed isenthalpically with 2 t s^{-1} of water at $33 \text{ }^\circ\text{C}$. Expander #1 work is 15.3 MW . Work and duty are proportional to airflow; increasing the airflow to 10 t s^{-1} would increase the power output to 153 MW .

With the chemical engineering process simulator, the effect of process parameters can readily be investigated. The effect of process parameters such as: water temperature, water flow, air temperature, air mixing ratio, expander #2 outlet pressure and expander efficiency can readily be investigated by changing the parameter and recalculating. The height at which a given pressure occurs in the atmosphere can be taken from atmospheric soundings. The heights taken from the sounding were entered in a look up table in PROII so that specifying EX2 outlet pressure would select the appropriate height. EX2 outlet pressure was then varied to find the pressure required to maximize expander EX1 work. For Case 0 where no heat is added in the cooling tower the equilibrium level is 10 kPa ; for Case 4 where heat is added the equilibrium level is 5 kPa . A well-established vortex the air is likely to rise up to its level of neutral buoyancy, which is usually close to the tropopause.

Water flow and water temperature have more effect on expander #1 work than ambient air temperature or humidity. Reducing the water temperature to $25 \text{ }^\circ\text{C}$ reduces expander #1 work to close to zero. Increasing the water temperature to $40 \text{ }^\circ\text{C}$ increases expander #1 work to 24 MW . The lowest cooling water temperature achievable in conventional cooling towers is typically $5 \text{ }^\circ\text{C}$ higher than the wet bulb of the air. Vortex cooling towers could produce cooled water temperature 10 to $15 \text{ }^\circ\text{C}$ colder than conventional cooling towers. Cooled water temperature in conventional cooling towers can only approach the wet bulb of ambient air; cooled water temperature in a vortex engine could approach the temperature at state 2.

The conditions for Figure 3 were selected to correspond roughly to Case 2 of Table 1. In case 2 the temperature and humidity of the air at state 3 are specified. In Figure 3 the flow and temperature of water stream 7 are specified. The thermodynamic system used in the PROII simulation is SIMSCI SRK; the datum for entropy and enthalpy is not the same as the one used in Table 1.



Stream Name Stream Description		S1	S2	S3	S4	S7	S8
Phase		Vapor	Mixed	Vapor	Mixed	Liquid	Liquid
Pressure	KPA	100.30	84.33	84.33	7.00	105.00	84.33
Temperature	C	30.00	20.45	28.66	-69.07	33.00	28.66
Total Sp. Enthalpy	KJ/KG	47.528	32.568	70.571	-111.522	122.783	103.557
Total Sp. Entropy	KJ/KG-C	6.507	6.507	6.618	6.618	5.106	5.043
Total Mass Rate	KG/SEC	1020.500	1020.500	1030.568	1030.568	2000.000	1989.933
Total Enthalpy	M*WATT	48.502	33.235	72.729	-114.931	245.565	206.072

EXPANDER #1 WORK = 15.3 MW
 EXPANDER #2 WORK = 187.66 MW
 FLASH DRUM DUTY = 39.49 MW
 S4 HEIGHT = 18580 m

Figure 4. Simulation of the vortex engine on a chemical engineering process simulator.

Capturing the work produced when heat is transported upward by convection requires that the expansion be carried out at mechanical equilibrium. The vertical conduit channels the differential pressure produced by buoyancy difference downward; the differential pressure produces kinetic energy in the turbine nozzles; and the turbine blades capture the kinetic energy. All three elements are required in order to produce the work. A constant entropy process requires that there be an expander to extract work from the flowing stream. In the PROII simulation, reducing the efficiency of the turbine EX1 to zero or replacing EX1 with a restriction changes process 1-2 from constant entropy to constant enthalpy and reduces the net work to zero.

6. Meteorological considerations

The source of the energy in the AVE is the same as that of hurricanes, water-spouts, tornadoes, and dust-devils. In each case, the observed base pressure reduction and velocity can be explained by the lifting of air approaching equilibrium with the underlying surface at reduced pressure. Michaud (2000) describes the thermodynamic cycle of the atmospheric upward heat convection process and shows that the work produced when air is raised is proportional to the heat received by the air and roughly independent of whether the heat is received as sensible or latent heat. Renno et al (2001) "Simple Theory for Waterspouts" is in accord with the thermodynamic cycle described in Michaud (2000). Holland (1997) calculated the effect of equilibrium at reduced pressure on tropical cyclone intensity using an average January Willis Island

sounding. Michaud (2001) showed that using the total energy equation and solving to find the base pressure at which the work produced during the upward flow process is zero give results in accord with Holland (1997).

Atmospheric soundings routinely show the path followed by a parcel of surface air rising isentropically, the light line labeled Case 0 in Figure 3. The vertical line at the right of Figure 3 represents the sea surface temperature of 30.4 °C. In Case 0, the air approaches equilibrium with the sea surface temperature at a surface pressure of 100.3 kPa; in Case 2, the air approaches equilibrium with the sea surface temperature at the reduced pressure of 83.4 kPa. For the same temperature air at low pressure can hold more moisture than air at higher pressure. The saturation mixing ratio for air at 30 °C is 27.5 g kg⁻¹ at 100 kPa and 34.7 g kg⁻¹ at 80 kPa. Figure. 3 illustrates the fact that the entropy of air in equilibrium with water at a given temperature is much higher at reduced pressure than at normal surface pressure. Increasing the mixing ratio increases the entropy of the mixture. Heat transfer between water spray and air plays a major role in the existence of hurricanes and waterspouts. Reduced pressure enhances the heat transfer from water to air. The minimum SST required for a hurricane to develop is approximately 26°C; tropical sea surface temperatures can reach 31°C.

The lifting work in Case 0 where there is no heat transfer in the cooling tower will be called Convective Energy (CE). CE is roughly equivalent to Convective Available Potential Energy (CAPE) which is widely used in meteorology. By convention, CAPE is calculated assuming that the water does not freeze, that the water separates from the air immediately after it condenses, and that the rising air has the average properties of the lowest 500 m of the atmosphere. CAPE is routinely provided with atmospheric soundings; the CAPE of tropical oceanic soundings is typically between 500 and 2500 J kg⁻¹. The Willis Island sounding had a CAPE of 2124 J kg⁻¹. CE and CAPE move in step. The CE of 4090 J kg⁻¹ in Case 0 is higher than the CAPE of the sounding because the lifted air is taken from the bottom layer of the atmosphere, because the condensed water freezes, and because the condensate is not immediately separated the air. Heat transfer from sea to air increases CAPE while convection reduces CAPE. Natural convection prevents CAPE from getting much above 4000 J kg⁻¹ and keeps the atmosphere in quasi-equilibrium.

The height of the 10 kPa surface can be 1000 m lower in winter middle latitudes than in the tropics. Therefore for a given water temperature, the work could be 10000 J kg⁻¹ greater in middle latitudes winter than in tropical latitudes. For a given water temperature, the work calculated using height based on a tropical sounding is therefore a minimum. The pressure at the base of the upward flow tube, P_3 , is equal to that at the top of the tube, P_4 , plus the weight per unit area of the air inside the tube. Ambient pressure, P_1 , is equal to that at the top of the tube, P_4 , plus the weight per unit area of a column of ambient air. The density of the air inside the tube is lower than the density of ambient air at the same level partly due to the temperature of the rising air being higher than that of the ambient air, and partly due to the pressure in the tube being lower than the ambient pressure.

The temperature of saturated air decreases less rapidly with decreasing pressure than the temperature of unsaturated air because heat of condensation warms the rising air. Heat of condensation only comes into play once the condensation level has been

reached which is usually at elevations of between 500 and 3000 m. In Figure 3, the temperature of the rising air in Case 0 does not become significantly higher than the ambient temperature until after the condensation level is reached. Latent heat is ineffective in getting the rising air less dense than the ambient air until the condensation level is reached. The heat source in a conventional solar chimney, which cannot be high enough to reach the level of condensation, must be the sensible heat of the air. The heat source in a vortex solar chimney, which can extend well past the condensation level, can be the latent heat of the vapor in the air. The heat source in the vortex solar chimney can have a lower temperature than the heat source in a conventional solar chimney because evaporation occurs at lower temperature at reduced pressure.

There has been a recent surge of interest on the effect of sea spray on sea to air enthalpy transfer. Tropical cyclones depend exclusively on self-induced heat transfer from the oceans, Emanuel (1986). The heat transfer at the eyewall of hurricanes Opal was estimated at 20 kW m^{-2} , Shay et al (2000). The heat transfer in the cooling tower of a vortex engine could be 100 kW per square meter of horizontal area of tower fill. Re-entrant sea spray is a major factor in enhancing heat transfer. When a spray droplet is ejected from the ocean, it cools to a temperature below the local air temperature in a time that is short compared to typical droplet residence times but long compared to the time required for it to evaporate an appreciable fraction of its mass. The spray droplet is not initially in equilibrium with the air because the vapor pressure of the liquid is higher than the partial pressure of vapor in the air. A small fraction of the drop, less than 1%, evaporates cooling the drop to the wet bulb temperature, Andreas et al (2001). The passage of a hurricane can reduce sea surface temperature by 3°C .

The temperature and humidity of ambient air has little effect on the work because the air at the base of the updraft approaches equilibrium with the water irrespective of the initial enthalpy of the air. If the enthalpy of the ambient air is low, the enthalpy transfer from the water increases and makes up for the low enthalpy content of ambient air. High CAPE is not necessary for the existence of hurricanes; enthalpy transfer from the sea can make up for low CAPE, Emanuel (1986).

7. Other design considerations

Enthalpy transfer between liquid water and air is proportional to the affinity of the air for water and to the surface to mass ratio of the liquid droplets. Affinity increases exponentially with the difference in vapor pressure between the liquid and the vapor phase. The rate of enthalpy transfer from the liquid phase to the gas phase decreases as equilibrium is approached. Increasing the contact time and decreasing the drop size reduce the approach to equilibrium.

The temperature of the water decreases as it falls through the cooling tower therefore the air going through the lower part of the tower comes in contact with water which has been cooled by the air in the upper part of the tower. The radial length of tower fill and the water flow could be increased to reduce the effect of the water getting cooler. Industrial cooling towers, where the goal is to produce cold water, typically have mass flow ratio of water to air of 1:1. A vortex engine using warm seawater as the heat source where the goal is to produce high enthalpy air could have a water to air ratio of 2:1.

The air inlet to the cooling cells would be sized to keep the air velocity in the cooling tower below 3 m/s to prevent high air velocity from damaging the fill, and to increase residence time and thereby reduce the approach to equilibrium. Sub-atmospheric pressure in the cooling tower would enhance heat transfer because affinity is higher at lower pressure and because for a given temperature air can hold more water at lower pressure.

The shape of the upward flow conduit does not affect an ideal process; replacing the circular upward flow tube with an annular tube can help explain how a vortex can act as a dynamic chimney. Giving the rising air rotation about the vertical axis before it enters the annular tube makes the air spin as it rises. The resulting centrifugal force opposes the radial differential pressure. If the annular walls were suddenly to disappear, the diameter would adjust itself until the radial pressure differential is balanced by centripetal force. Turbulence in the radial direction is inhibited because if a particle of air moves inward its tangential velocity increases to conserve angular momentum resulting in an increase in centripetal force which in turn pushes the particle back outward. As a result the flow in the vortex is laminar instead of turbulent as evidenced by the smooth thread shape of some tornadoes and waterspouts. Centrifugal force stabilizes the flow reducing turbulence and friction losses. The rising air behaves like a spinning top being raised; there is little decrease in the angular momentum of the large mass of rising air in the 30 minutes or so required for the air to rise to the top of the troposphere.

8. Turbine and total flow

The turbo-expanders could be axial flow turbines similar in construction to the low-pressure stages of steam turbines or to the expander stages of gas turbines. Axial flow turbines consist of stationary nozzles located immediately upstream of a bladed rotor; the kinetic energy of the gas leaving the nozzles is captured by the rotating blades. The differential pressure across the nozzle produces the kinetic energy; a differential pressure of 5 kPa produces a velocity of approximately 100 m/s, while a differential pressure of 20 kPa produces a velocity of approximately 200 m/s, see Table 1. The turbines could have one or two stages. Gas turbines can have efficiencies of 90%.

Based on a unit work of 10 kJ kg^{-1} of air, a 200 MW vortex engine would have a heat input of 1000 MW; air and water flows of 20 t/s, and 40 t/s respectively. In a vortex engine with 20 cooling cells, the work and heat duty per cooling cell could be 10 MW and 50 MW respectively. Each cell could have a single 10 MW axial flow turbine, which could have a diameter of 5 m. Based on a precipitation rate of 10 g of water per kilogram of air, the precipitation would be 0.2 t/s or 17000 t/d.

A pilot plant 50 m in diameter should be sufficient to demonstrate the feasibility of producing a self-sustaining and controllable vortex. Pilot plant cost could be reduced by injecting steam to heat the air instead of using cooling towers and by using restrictors instead of turbines. Starting with replacing a cooling tower in an existing power plant would reduce financial risk. The replacement cooling tower would not need to have turbines; the elimination of induced fan power requirements and the reduction in cooled water temperature could be sufficient to justify a cooling tower replacement project.

Tornadoes are dangerous, but the vortex engine could be provided with safety features to reduce hazards. Natural vortices are rare in spite of the fact that an adequate heat source is commonly available. Testing could be restricted to remote locations and stable atmospheric conditions and until the ability to control the vortex, including starting and stopping at will, is demonstrated. In order for a convective vortex to exist many conditions have to be right, removing one or more of them should be sufficient to quench the vortex. In addition to restricting the air supply and introducing air with reverse rotation, the warm water flow could be stopped, and the vortex could be doused with chilled water.

The energy production potential of the atmospheric vortex engine is huge. The energy produced in a single hurricane can exceed all the electrical energy produced in a year. Converting 20% of the solar energy received at the earth's surface to work would produce 10000 times more mechanical energy than presently produced by humans.

9. Summary

In addition to producing energy, the AVE process could be used to produce precipitation, to enhance the performance of cooling towers by reducing cooled water temperature, to cool the environment, to clean or elevate polluted surface air, to produce fresh water, to alleviate global warming, or to otherwise affect weather. There are times and locations where the heat content of ambient air would be sufficient to sustain a vortex without the peripheral heat exchanger.

The quantity of precipitation produced by an AVE would be small compared to the precipitation produced in natural storms. The 20000 t/d of precipitation produced by a 200 MW vortex power station would produce a rainfall of 2 mm/d when spread over an area of 10 km². The horizontal extent of the cloud cover in the downwind direction could be 20 kilometers or more. The area of active convection would be under one square kilometers. Airplanes could easily avoid a convective vortex in a fixed location. During the daytime, clouds would indicate the location of the vortex.

The atmospheric vortex engine is a solar engine capable of using the natural heat content of water and air and therefore does not require the usual solar heat collector. Large industrial plants commonly reject heat at temperatures of up to 50°C in quantities sufficient to sustain a convective vortex. Raising air saturated at reduced pressure with water at 40°C to the top of the troposphere could produce 40 kJ of mechanical energy per kilogram of air raised under most atmospheric conditions.

The most favorable sites for the production of controlled vortices are likely to be maritime tropical locations. The water production benefits would be most valuable in warm and dry climates. The large difference in temperature between waste heat source and ambient air in cold climates could also provide favorable locations when the heat source is waste heat.

Developing the atmospheric vortex engine will require determination, engineering resources, and cooperation between engineering and atmospheric sciences disciplines. There will be difficulties to overcome and there will be many improvements as the

process is developed. The existence of tornadoes provides virtual experimental proof that low intensity solar heat can produce high intensity mechanical energy..

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