Harnessing Energy from Convective Vortices

Louis Michaud
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Introduction

There is an urgent need to find a solution to global warming and to energy shortage. At present over 70% of the world's energy is derived from greenhouse gas producing fossil fuels and there is no substitute in sight. A possible solution to this problem may be the extraction of energy from atmospheric vortices. Theory and experiments suggests that controlled atmospheric vortices can be used to harness energy. The energy produced in a single hurricane can exceed the energy produced by humans in a whole year. Harnessing a small fraction of the energy produced during upward heat convection in the atmosphere could supply human energy needs without carbon emissions.

The scientific basis of atmospheric vortex engine (AVE) is consistent with the prevailing thermodynamic theory of vortical storms. The engineering approach used to analyze the process described in this article provides a range of valuable benefits. The technology has much potential and a focused development program to assess its feasibility is recommended. Power engineers could play a major role in the development of the AVE because of their practical knowledge of the thermodynamics of power cycles, convection processes and cooling towers. There will be technical challenges to overcome but they should be no more difficult than those found in the development of other industrial processes. Producing and controlling a vortex extending kilometers into the atmosphere is a major undertaking and cannot be done in the laboratory.

An atmospheric vortex engine uses a controlled vortex to capture the mechanical energy produced during upward heat convection. The vortex is created by admitting warm or humid air tangentially at the base of a cylindrical enclosure. The source of heat can be solar energy, warm sea water, warm or humid air, or waste heat from thermal power plants and other industrial processes. The AVE harnesses energy from sources similar to those that drive hurricanes, tornadoes and waterspouts. The feasibility of the concept has been demonstrated theoretically and with small scale models, but not yet in an installation large enough to power turbines.

Fig. 1. Conceptual rendering of an AVE.

(See Figure file)

An AVE will look like a natural draft cooling tower with a controlled vortex emerging from its open top. The artistic rendition in Fig. 1 illustrates how a vortex engine would appear. From the inside an AVE will look like a large circular open roof stadium with a controlled vortex firmly anchored at its center. Fig. 2 illustrates how a natural draft cooling tower might be modified to produce a vortex. An AVE could have a diameter of 100 m and a height of 50 to 80 m; the vortex could have a diameter of 30 m at the base and could extend to a height of up to 15 km. The mechanical energy would be extracted from the vortex by peripheral turbo-generators. An AVE of the above size could generate about 200 MW of electrical power. Wet or dry heat exchangers similar to those used in cooling towers are used to heat the air.

Fig. 2. Atmospheric vortex engine plan and side views.

The AVE has the same thermodynamic basis as the solar chimney, except that instead of the updraft being contained by the physical wall of a chimney it is contained by centrifugal forces in the vortex, and the solar collector is replaced by waste heat from a power plant. A solar chimney consists of a tall vertical tube surrounded by a circular greenhouse. The Manzanares solar chimney built in Spain in the 1980`s operated successfully for 7 years and had a peak electrical capacity of 50 kW. The chimney was 200 m tall, 10 m in diameter and was surrounded by a 250 m diameter solar collector. The work of buoyancy was transferred to a vertical axis turbine located in the base of the chimney. Fig. 3 compares the Manzanares solar chimney, a proposed Australian solar chimney and the AVE. The efficiency of the solar chimney is proportional to its height; the center panel in Fig. 3 shows that a vortex can extend the updraft to higher altitudes than a physical chimney and therefore can achieve much higher heat to work conversion efficiency.

Fig. 3. Solar chimney and vortex engine height and efficiency comparison.

In the AVE, warm air enters the area within a cylindrical wall referred to as the arena via tangential entry ducts thereby filling it with spinning warm air. An annular roof with a central circular opening forces the air entering the arena to converge. A vortex with a diameter somewhat smaller than the roof opening forms as the air escapes through the roof opening. The lower end of the vortex is shielded from the wind by a cylindrical tube. The entry of air in the vortex is restricted to a thin layer next to the underlying surface. Once the vortex is established, the pressure difference between the surrounding ambient air and the base of the vortex forces air into the turbines. Turbine exhaust can be directed either to the entrance of the tangential entry ducts or to the center of the vortex via an opening in the center of the arena floor. The airflow is controlled with dampers located upstream of the heat exchangers or within the tangential entry ducts. The vortex can be stopped by closing air dampers.

The AVE concept was tested with models with diameters of 1 m and 4 m. The vortex, which looked like a small dust devil, was rendered visible with saltpeter smoke emitters. The 4 m diameter model produced a vortex 30 to 50 cm in diameter extending up to 20 m above the top of the model. Four 20 kW propane heaters located upstream of the tangential entry ducts were used to warm the air. Fig. 4 shows a photo of a vortex produced by the 4 m model.

Fig. 4. Photo of vortex produced with a 4 m diameter model.

A natural draft chimney is a cylinder in radial compression that prevents ambient air from mixing with warm rising flue gas. The draft at the bottom of a natural draft chimney is proportional to the difference in temperature between the rising warm air and the surrounding cooler ambient air and to the height of the chimney. In a vortex, the centripetal force replaces the physical chimney and prevents cooler ambient air from entering the rising warm air stream. The diameter of the vortex is self-regulating and adjusts itself until centrifugal force balances radial pressure differential. The vortex acts as a chimney and transmits the draft produced by the warm buoyant air above to the turbine below. The rising air in the vortex chimney is continuously replaced by moist/warm air at its bottom. The chimney and the rising air column are essentially one.

Cooling towers are commonly used to transfer waste heat to the atmosphere. Using order of magnitude calculations for illustration, a 500 MW thermal power plant typically rejects 1,000 MW of waste heat. By rejecting 1000 MW of waste heat to the upper atmosphere instead of doing it at ground level, an AVE can generate an additional 200 MW of electrical energy, thereby increasing the net electrical output of a power plant by 40%. The AVE increases the efficiency of a thermal power plant by reducing the temperature of the heat sink from about +20 °C at the bottom of the atmosphere to about -70 °C at the tropopause.

Fig. 5 illustrates the earth's energy budget. Heat is carried upward by convection because the atmosphere is heated from the bottom by solar radiation shown in yellow and cooled from the top by infrared radiation shown in red. There is a potential for producing work equal to the heat carried upward by convection shown in green (102 W/m^2) multiplied by the Carnot efficiency based on the average temperature at which the heat is received and given up because more energy is produced by the expansion of warm air than is required to compress the same air after it is cooled.

Fig. 5. Earth energy budget.

Thermodynamics

Fig. 6 depicts the idealized AVE process consisting of: constant entropy expansion processes 1-2, constant pressure heating process 2-3, and constant entropy lifting process 3-4. The water spray whereby enthalpy is transferred from water to air in process 2-3 can represent either a wet cooling tower or sea spray at the eyewall of a hurricane. The total energy equation

$$w = q - \Delta h - \Delta gz$$

is used to calculate the energy received and produced in each of the three processes, where w is work, q is heat, g is the acceleration of gravity, z is height, and h is enthalpy. In the ideal process, kinetic energy and frictional losses are assumed to be negligible. After the ideal process is understood, the effects of adding irreversibilities can be investigated.

Fig. 6. AVE ideal process.

The work in process 1-2 drives a generator to produce electricity; the work in process 3-4 is used to lifts the air. The key to solving the problem is realizing the net work in process 3-4 is zero. Given the temperature (T_3) and relative humidity (U_3) at state 3, the pressure at the base of the vertical tube P_3 required the make the work w_{34} zero is calculated by iteration. A second iteration can be used to find the value of P_4 that maximizes w_{12}; work is maximized when state 4 corresponds to the level of neutral buoyancy which is usually near the tropopause.

Table 1 shows sample thermodynamic calculations for four cases. Properties are per unit mass of pure air. Enthalpy (h) and entropy (s) include the contribution of water in any phase. The Case 1 state 3 conditions were selected to make the work zero when there is no heat addition in process 2-3 to provide a datum. The height of the 10 kPa level 16,570 m is typical for maritime tropical conditions.

Table 1 - Vortex Engine Process Calculations.
(See Table file)

In Case 2, The temperature and relative humidity of the air in state 3 of 24.5 °C and 97% respectively correspond to hurricane eyewall air conditions. The water temperature of 26 °C corresponds to typical hurricane eyewall water temperature. The calculated pressure at the base of the vertical tube (P_3) of 97.7 kPa agrees with observed category 5 hurricane eyewall pressure measurements. The calculated specific work of 2984 J/kg corresponds to a velocity of 77 m/s which agrees with observed in category 5 hurricanes maximum wind. The heat received during process 2-3 is 8490 J/kg; the work done in process 1-2 is 2984 J/kg for an efficiency (n) of 35%. The efficiency (n) is approximately equal to the Carnot efficiency given by: $n = 1 - T_4 / T_3$, where T_3 and T_4 are the temperatures at the bottom and at the top of the vertical tube in degrees Kelvin.

Case 3 shows that work can be produced with a dry heat instead of a wet heat. Case 4 shows that the dry heat can be supplied upstream of the turbine. The conditions in cases 3 and 4 were selected to produce approximately the same work as in case 2. The bottom item of the table show that the heat source temperature is 26 °C in case 2, 36 °C in case 3, and 40 °C in case 4. The ability to use low temperature heat sources is valuable since they are more widely available. Approximately 35% of the heat received is converted to work during the convection process regardless of whether the heat is received as sensible or latent heat. The work is proportional to the heat received; doubling the specific heat would double the specific work.

The energy of hurricanes is the result of upward flow in the eyewall. There can be a weak downward flow on the axis of the vortex but the downward flow in the eye is small compared to the upward mass flux in the eyewall. The lower end of the eyewall acts like the rotor of a centrifugal pump and entrains the air in the eye downwards. Because of this forced rotation, the pressure at the eye of a hurricane is smaller than the pressure at the eyewall.

The heat content of oceanic tropical surface air is typically sufficient to produce work of between 1000 and 2000 J/kg without additional hearting. Increasing the work of convection by 1000 J/kg requires either increasing the temperature of the surface air by 3 °C or increasing the mixing ratio of the air by 1.2 g/kg corresponding to an increase the relative humidity of approximately 7%. Sea surface temperatures of 26 °C are sufficient to sustain a hurricane; tropical sea surface temperatures can be as high as 31 °C. The temperature of power plant waste heat can be as high as 45 °C.

Heating process 2-3 is a constant enthalpy mixing process wherein the enthalpy gain of the air is equal to the enthalpy loss of the water. The final temperature of the air (T_3) is slightly lower than the water temperature. Producing 24.5 °C air at 97% relative humidity with 26 °C water requires a water to air mass flow ratio of 0.5 to 2. Air temperature increases with water flow. In hurricanes the air is repeatedly sprayed with water; the quantity of water sprayed per unit mass of air is unknown but could well be around one kilogram of water per kilogram of air because water spray called spume can be very heavy.

The temperature difference between the rising air and the surrounding ambient air in the 200 m high Manzanares solar chimney illustrated in Fig. 3 was 20 °C. To produce the same power with same flow, a 1000 m high solar chimney would require a temperature difference of only 4 °C and a 10 km high chimney would require a temperature difference of only 0.4 °C. The higher is the chimney; the lower is the required temperature difference. A vortex can extend much higher than a physical chimney and therefore can make use of lower temperature heat sources thereby eliminating the need for a solar collector.

The temperature of saturated air decreases less rapidly as it rises than the temperature of dry air because the heat of condensation reduces the cooling rate of the rising air. Heat of condensation comes into play once the condensation level has been reached which is usually at elevations of between 500 and 3,000 m. The heat source in a solar chimney, which cannot extend high enough to reach the condensation level, has to be sensible heat. The heat source in a vortex engine, where the vortex can extend well past the condensation level, can be either latent heat or sensible heat. The heat source in an atmospheric vortex engine can have a lower temperature than the heat source in a solar chimney since the water temperature only has to be slightly higher than the wet bulb temperature of the air. Reduced pressure at the base of the vortex further enhances the heat transfer from water to air thereby increasing the enthalpy of the air and the power production. An AVE could improve the efficiency of the conventional part of the power plant by reducing cooled water temperature.

The rotation of the rising air inhibits mixing and reduces turbulence and friction losses. This happens because when rotating air is forced inward its tangential velocity increases to conserve angular momentum, resulting in an increase in centrifugal force which in turn pushes the air back outward as evidenced by the smooth appearance of dust devils, waterspouts, and tornadoes.

Based on a specific work of 10 kJ/kg of air, a 200 MW vortex engine could have a heat input of 1,000 MW with air and water flows of 20 Mg/s, and 40 Mg/s respectively. In a vortex engine with 20 sectors the work and heat duty per sector will be 10 MW and 50 MW respectively. Each sector will have a single 10 MW turbine with a diameter of 5 to 10 m. Based on a precipitation rate of 12 grams of water per kilogram of air the precipitation would be 240 kg/s or 20,000 Mg/day. The precipitation produced by an AVE would be small compared to that produced in natural storms. The 20,000 Mg/day of precipitation produced by a 200 MW vortex power station will produce rainfall rates of less than 2 mm/day when spread over an area of 10 km^2.

An AVE will be provided with numerous safety features. Redundant air dampers and quench systems could be provided to permit rapid shutdown. The air flow and the diameter of the vortex will ultimately be limited by the size of the tangential air entries. Natural vortices are rare in spite of the fact that natural heat sources are ubiquitous. Humid air at 40 °C is not dangerous unless given a spin. Testing of large prototypes would be restricted to remote locations and stable atmospheric conditions until the ability to control the vortex including starting and stopping at will is demonstrated. An AVE may reduce the likelihood of natural storms in its vicinity by reducing the heat content of surface air.

Fig. 7. AVE combined cycle power plant.

The most favorable sites for the production of controlled vortices are tropical maritime areas. The water production benefits could be invaluable in warm dry climates. The fact that the elevation of the 10 kPa level is lower in high latitude and the large difference in temperature between waste heat source and ambient air in cold climates could make mid latitudes favorable locations when the heat source is waste heat. Fig. 7 shows how the AVE could increase the efficiency of any thermal power plant. Waste heat from power plants is the low hanging fruit as far as heat sources are concerned; the heat is already concentrated and utilities already pay to get rid of it. Existing costly waste heat disposal systems could be replaced with power producing AVE's.

Future Outlook

The AVE has potential to produce large quantities of carbon free energy because the atmosphere is heated from the bottom by solar radiation and cooled from the top by infrared radiation. There is a potential of converting and capturing 12% of the heat carried upward by convection to work. Fig. 8 shows that converting 12% of the heat carried upward by convection in the atmosphere could produce 3000 times the present world electrical energy production. The upward heat flux of 52,000 TW in Fig. 8 is the upward heat flux of 102 W/m^2 of Fig. 5 multiplied by the earth’s surface. The energy production potential of the AVE is far greater and cost is far less than those of conventional solar power plants because the solar collector is the earth’s surface in its natural unaltered state. The cost of power could be as low as $0.03 per kWh; there is no fuel cost.

Fig. 8 AVE energy production potential.

Providing the energy need of a city with conventional solar power plants would require an area 50 to 500 times that of the city and would make the area unavailable for other uses such as farming. An AVE power plant does not require a solar heat collector and would have approximately the same footprint as a thermal power plant of equivalent capacity.

Fig. 9 Comparison of the potential of the Earth’s energy resources.

Fig. 9 shows that the heat content of an ocean layer warmed by 3°C is 20 times the heat content of the world’s remaining oil resources. The AVE process provides a means of converting 10 to 30% of this heat into useful work. There is no need for collecting the solar heat directly; it is already stored in our oceans. The work of convection is produced where warm air rises and not where the heat is received. The AVE has the potential of concentrating the work produced from heat received over a long period of time and over a large area in a small location. Mechanical energy production is concentrated in a small location as it is for hydraulic energy resulting in a high intensity energy source.

The AVE has potential for greatly reducing greenhouse gas (GHG) emission. The output of a power plant could be increased by 20 to 40% without increasing GHG emissions; alternatively the existing output could be maintained but with a 20 to 40% emission reduction. There is a potential for further GHG emission reduction when the heat content of the lower layers of the atmosphere or of warm sea water are used as the heat source. The AVE replicates a natural process and can be turned off at will and therefore would be far less hazardous than geo-engineering global warming mitigation proposals.

Tornadoes, water-spouts, and dust-devils demonstrate that low intensity solar heat can produce vortices that can concentrate mechanical energy into small volumes. The mechanical energy produced by a tornado can be as much as that produced by a large thermal power plant. The AVE produces a controlled flow of rising air and captures its energy. The AVE has the potential of capturing the energy content of low temperature heat sources such as warm sea water. In addition to producing energy, the AVE process could be used to alleviate global warming, even to produce precipitation, to enhance the performance of cooling towers, or to clean or elevate polluted surface air.

The most appropriate way of developing the AVE could be to build and test prototypes at existing thermal power plants. The initial prototype could have 20 to 30% of the capacity of the existing cooling tower. The waste heat could gradually be transferred to the vortex engine prototype; means would be provided to regulate heat input and air flow. The development process would be safe since initial testing could take place at low heat input and low air flow. A gas fired power plant in a non urban location with dry cooling tower considering adding cooling capacity would be a good candidate site for an AVE prototype. The technology could be developed without risk to existing plant operation. The prototype would be designed per normal engineering practice by a team including: a utility, an engineering design contractor and specialized equipment suppliers. Once vortex control has been demonstrated, turbines could be added or the prototype could be replaced with a large AVE capable of handling the complete plant cooling load while also producing power.

The ultimate goal would be to produce power without burning any fossil fuel. Building the prototypes at existing thermal power plants would have the advantage that the heat source can have a higher temperature and can be controlled. The use of saltwater as heat source should be delayed until the process has been demonstrated with fresh water because the design of salt water cooling towers is more demanding.

For further reading

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Background technical information including: peer reviewed articles, thermodynamics analysis, drawings and videos of models, and reference material is available on Vortex Engine web site: http://vortexengine.ca

Biographies

Louis Michaud (lmichaud@vortexengine.ca), AVEtec Energy Corporation, developed the AVE concept. He was process control engineer with Exxon-Mobil for 26 years.