Atmospheric Efficiency

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Abstract

The determination of efficiency is the fundamental problem of atmospheric energetics. Estimates of atmospheric efficiency range from up to 12 %, calculated from the Carnot efficiency based on the average temperatures at which heat is received (290 K) and given up (255 K) to less than 0.7 % based on models and on estimates of dissipation. Estimates of average per unit area atmospheric power production range from 25 to 2 W/m^2. Estimates of total atmospheric power production potential range from 6000 TW to under 600 TW. Human primary and electrical power productions are 30 and 2 TW, respectively 0.5 and 0.03 % of the upper estimate of the atmospheric potential.

The wide range in efficiency is due the fact that actual efficiency can be much lower than ideal efficiency. The efficiency of early steam engines was much lower than their Carnot efficiency because, without appropriate mechanisms, ideal work degrades to heat without producing significant useful work. The efficiency of an idling engine is zero.

This article uses steady-state open thermodynamic processes and close thermodynamic cycles to show unambiguously that the atmosphere has the potential to produce the higher 12% efficiency estimate. The technique is more effective than the Lorenz (1978) close system and reference state approach and is explained using the Jordan mean hurricane-season Caribbean sounding.

The divisor for efficiency is the upward convective heat flux at the bottom of the atmosphere of ≈50,000 TW (≈100 W/m^2) and not the incoming solar radiation of 178,000 TW; 6000 TW is 12 % of 50,000 TW and 3.4 % of 178,000 TW. Solar radiation reflected to space and infrared radiation to space from the lower atmosphere do not contribute to work production.

Atmospheric work of convection can be concentrated in a small area. An atmospheric vortex engine (AVE) could have an area of less one square kilometer and produce 1000 MWe. AVE's could convert 25 % of low temperature heat to work. A large hurricane can produce more mechanical energy than produced by humans in a whole year. A large tornado can produce ≈10 GW of mechanical energy. The article expands on earlier tweets.

1. Introduction

The atmosphere can be viewed as an array of air reservoirs. Moving air from one reservoir to another can produce work. The source reservoir can be at the bottom of the atmosphere. The receiving reservoir, the environment to which the air is moved, can be the upper troposphere. The work is free in the sense that there is no need to provide costly high temperature heat. The work is produced from the pre-existing natural heat content of the moved air.

Fig. 1 shows a thermodynamics system applicable to any open steady-state, continuous flow, single input and single output process. Conservation of energy requires that external energy inputs equal external energy output because the system is in a steady state. The first law of thermodynamics, for an open, steady-state, continuous flow system is:

$$W = -\left(\Delta H + g\,\Delta z + \Delta v^2/2 \right) + Q \qquad (1)$$

where: *W* is work produced, *Q* is heat received, *H* is enthalpy, z is height, *v* is velocity and *g* is acceleration of gravity. All terms are in Joules per kilogram. See Smith and Van Ness "Introduction to Chemical Engineering Thermodynamics" chapter 2, Eq. 2.32.

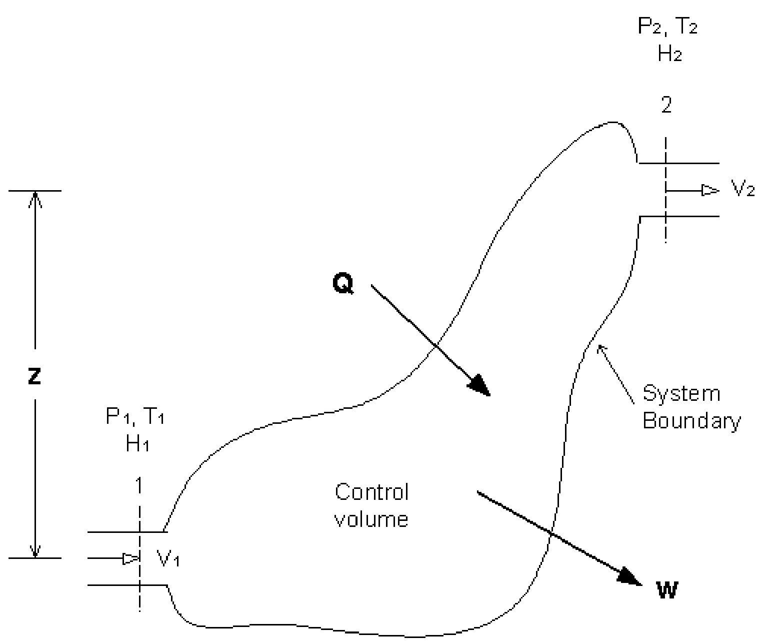


Figure.1 Energy balance for open continuous steady-state thermodynamic system,with one inlet and one exit.
Based on Smith and Van Ness Figure 2.6

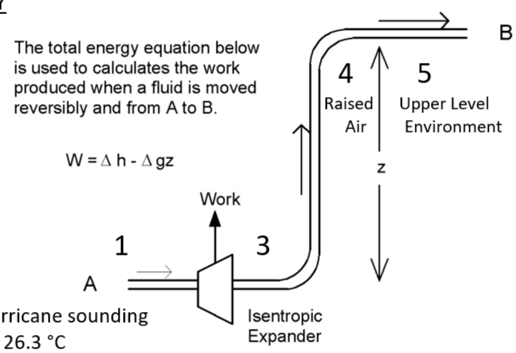
The ideal work (W_i) for a reversible process with no heat transfer, with negligible velocities and with no degradation of work to heat by friction is:

$$W_i = E_z = -\Delta H - g\,\Delta z = -\Delta\mu \qquad (2)$$

Q and Δv^2 are zero for adiabatic ideal processes. μ is the moist static energy of the flowing air. Ideal work (W_i), which will be called **ezergy** (E_z), is equal to the decrease in enthalpy minus increase in potential energy or more concisely to decrease in moist static energy of the raised air.

Figure 2 shows an example of an ideal open reversible adiabatic process moving air from the bottom to the top of the troposphere. Work degradation through friction and kinetic energy change are negligible because velocity is low. There is no heat transfer because the conduit is perfectly insulated. The three cases show the effect of final pressure on ideal work.

EXERGY vs EZERGY



Basis:
Jordan Caribbean hurricane sounding
P_1 = 101.51 kPa, T_1 = 26.3 °C
U_1 = 84.03 %, M_1 =18.20 g/kg
True adiabatic with ice. s1 = s3 = s4 = 253.0 J/(K.kg). h1 = 72822 J/kg.
s_{15} = 226.1 J/(K.kg), h_{15} = - 76517 J/kg
$W_b = W_{13}$ = Turbine Work. W_p = PE of condensed water. $W_t = W_b + W_p$.

EZERGY / Total Energy Equation Method: $W_b = (h_1 - h_4) - (1 + M_1)\Delta gz$

P_4 (kPa)	P_3 (kPa)	z_4 (m)	Δh (J/kg)	Δgz (J/kg)	W_b (J/kg)	v (m/s)	W_p (J/kg)	W_t (J/kg)	ΔT_4 (K)
20	99.36	12400	125621	123736	1885	60.3	2186	4071	9.8
15	98.99	14182	143731	141516	**2215**	65.4	2525	4740	5.3
12.64	99.05	15292	153855	151692	**2163**	64.6	2710	**4873**	0.0

EXERGY / Gibbs Method: $A = (h_1 - h_5) - T_0 (s_4 - s_5) - (1+ M_1)\, gz$

P_4(kPa)	z_4(m)	Δh(J/kg)	$T_0\Delta s$(J/kg)	Δgz(J/kg)	A(J/kg)	W_p(J/kg)	W_t(J/kg)
20	12400	136272	10417	125117	2119	2204	4324
15	14182	149338	5535	141516	**2286**	2527	4813
12.64	15292	153862	6	149002	**2163**	2710	**4873**

@ 15 kpa: $A - W_b$ = 2286 – 2215 = 71 J/kg is the extra work produced by cooling the raised air from T_4 to T_0 with a reversible Carnot engine.
@ 12.64 kPa: at temperature equilibrium, $A - W_b$ = 2163 - 2163 = 0

Fig. 2 Ideal work for surface air raised to a range of levels.

An adiabatic reversible process is a constant entropy process, $S = C$. From known initial air conditions and final pressure, the final temperature for a constant entropy process can be calculated using a solver. Ideal work can then be calculated from the known initial and final enthalpy and the change in elevation.

Ideal work peaks when the air is raised to the level where the pressure is approximately 15 kPa. The 15 kPa elevation is ≈14.2 km in the tropics and ≈13.2 km in high latitudes. Figure 2 is based on the Jordan mean Caribbean hurricane-season sounding. Ideal work for surface air peaks at ≈2215 J/kg for surface air raised to the 15 kPa (14182 m) level. The troposphere is cooled by radiating heat to space at approximately 1.5°C/d; there is little radiative cooling above the top of the troposphere which is near the 15 kPa level.

Willard Gibbs showed that ideal work, E_x, which he called free-energy, and which is now called "**exergy**", for a fluid is brought reversibly to equilibrium with different environment is:

$$E_x = -\Delta H - T_o\,\Delta s - g\Delta z \qquad (3)$$

See Smith and Van Ness (eq. 5.24 and 5.27). T_o is the temperature of the final environment; ΔH is the difference between the enthalpy of the raised air in its initial state and of the enthalpy of the environment at the final state. For a process without change in elevation, the $g\Delta z$ term is zero. In Figure 2, for surface air raised to the 15 kPa level, ideal work is 2286 J/kg. The exergy is slightly larger than the ideal work of 2215 J/kg because a Carnot engine producing a small amount of work could be used to bring the temperature of the raised air to the temperature of the final environment. The 12.64 kPa case of Figure 2 shows that ideal work and exergy are identical for air raised to the level of temperature equilibrium because there is no need to transfer heat via a Carnot engine to reach temperature equilibrium.

Exergy is a defined thermodynamic name: "the maximum work that can be produced when a fluid is brought reversibly to full equilibrium with an environment". There is no currently defined name for the ideal work of eq. (2) "where a fluid brought reversibly to a different pressure, without heat transfer and without bringing the fluid to temperature equilibrium with the final environment.". Eq. (2) is widely used in engineering. There is a need for a name for this type of free energy; it is proposed that it be called **"ezergy"**, (E_z) to reflect change in elevation (Δz). The potential energy of condensed water is not included in exergy or in ezergy because lifting the waters is essential to the production of the work. Kelvin used the term **"motivity"** for **"ezergy"**.

Ezergy (E_z) is a good approximation of exergy (E_x) when the final temperature of the raised air is close to that of the final environment. The ezergy of air raised to the 15 kPa level is a good approximation of the peak exergy for deep convection. Warm and humid surface air has both exergy and ezergy. The appendix proposes some other variations of the "exergy" names for specific types of free energy.

For given inlet and outlet conditions, ezergy is identical for all reversible adiabatic processes. There are many possible lifting processes; the process could be a batch discontinuous process rather than a continuous one; the conduit could have a snaky or spiral shape. The conduit need not be vertical and can have a gradual slope; horizontal spacing is not a factor for an ideal process because there is no friction loss. The turbine can be at any elevation in the conduit. The ezergy is produced by the expanding/rising air and is captured by the turbine where the flow is restricted wherefrom it leaves the system as shaft work. There is no need for the diagram of figure 2. All that is required to calculate ezergy is to know the initial and final conditions. Ezergy can be calculated from pure thermodynamics; there is no need for the Navier-Stokes equations of motion or for dynamic model. Ezergy is simply the maximum quantity of mechanical that can be produced when air is moved from one location to another without heat transfer.

Actual work, W_a, for an irreversible process is less than ezergy, E_z, because ezergy easily degrades to heat. For the same initial and final conditions, the enthalpy reduction, (ΔH) in eq. (2), is smaller for an irreversible than for a reversible process. For a fully irreversible process $W = 0$ and $\Delta H = \Delta gz$. The process of Figure 2 can be made irreversible by replacing the turbine with one or more restrictions. Actual work (W_a) is less than ezergy (E_z) in irreversible processes or for processes with significant exit kinetic energy.

Ezergy is akin to Convective Available Potential Energy (CAPE) which is widely used in atmospheric science, and which is the kinetic energy acquired by a buoyant air mass rising without heat exchange, friction or mixing. CAPE is based on the equation of motion, not on energy conservation. With CAPE the air accelerates as it rises. The acceleration depends on the difference in density between the rising air and the surrounding air which both change with elevation.

Exergy and CAPE both assume that there is no dilution of the rising air by surrounding ambient air. Evaporative cooling associated with entrainment reduce buoyancy. Deep convection (>10 km) is rare; shallow convection (<3 km) is ubiquitous. Deep convection requires that evaporative cooling be reduced by centrifugal force or by high humidity aloft. Shallow updrafts increase humidity aloft making the environment more favorable for deep convection. See: Michaud (1998) "Entrainment and detrainment required to explain updraft properties and work dissipation".

The exergy is produced when air is raised. In steady-state conduit flow, the shaft work is produced wherever in the conduit the isentropic turbine is located. In a conduit, work is transferred from where it is produced to where the flow is restricted. Figure 2 shows that the work can be transferred to a horizontal turbine located at grade. The horizontal conduit at the bottom of Figure 2 could be several thousand kilometers long because there is no friction loss in an ideal process. The turbine could be located at the upstream end of this conduit. The point where the shaft work is produced could be several thousand kilometers away from where the upflow occurs.

Ezergy when there is no change in elevation will be called **emergy** (E_m), where the "*m*" stands for same (même) elevation. In figure 2, the ezergy of the overall process E_z is equal to the emergy at the turbine E_m. The emergy of a gas turbine is simply its ideal work.

In a continuous process, the exergy of the raised air is determined by the pressure and elevation of the final reservoir. The density of the environment does not matter except for its effect on the final elevation. In continuous processes, work is transferred to wherever the flow is restricted. In Fig. 2 the turbine can anywhere in the vertical tube or in the horizontal conduit as shown. Expansion is at constant entropy throughout the conduit including across the turbine. Ezergy is real work, it can produce shaft work or kinetic energy; it can produce vertical or horizontal velocity.

Computational fluid dynamics models (CFD) have difficulty arriving at the conclusion that work of convection can be concentrated and captured at one location. Thermodynamics analysis require that there be an expander via which shaft work leaves the system. Thermodynamics specifies the flow and calculates the maximum work. CFD calculates the flow, which is very difficult since there are many possible paths. Atmospheric efficiency is an oxymoron because there is no shaft through which work can leave the system. Since there is no way for work to leave the system, all the work eventually reverts to heat. Atmospheric energy calculations do not show the expander because there is none in the atmosphere. The expansion cannot be isentropic without there being a way of getting the work out of the system. Ideal cycle analysis is impossible without an expander.

Mechanical energy can be converted reversibly from one form to another. It can degrade to heat due to viscous friction, mixing or because there is nothing to push against like for expansion in an unrestrained piston. Kinetic energy is difficult to calculate because most of the ezergy degrades back to heat without producing significant kinetic energy. Zipser and LeMone (1980) showed that the kinetic energy of strong GATE updraft is typically approximately 4% of CAPE.

Ezergy is more appropriate than exergy for atmospheric problems because there is no practical way of producing work from small temperature differences, especially if the Carnot engine has to be located near the tropopause.

Enthalpies and entropies values are based on Dufour and Van Mieghem: "Thermodynamique de l'Atmosphère". The zero for enthalpy (*H*) and entropy (*S*) is 0 °C and 100 kPa for air and liquid water at 0 °C. There is a link in the references to the HP48 calculator atmospheric thermodynamics program AT1 used for ezergy calculations. The program is available on the vortexengine.ca web site and is an invaluable tool. HP48 calculator emulators for computers and smart phones are widely available and free.

In this article, ezergy calculations are based on expansion with freezing and without separation of the condensed water. Molinari's Figure 3 shows that CAPE for expansion with fusion (freezing) and no fallout (separation) is close to CAPE for expansion with no fusion and fallout.

No fallout (also called true adiabatic expansion) calculations can be done in a single step while fallout (also called pseudo adiabatic expansion) requires multiple expansion steps. Ezergy is roughly the same for the above two expansion processes. The potential energy of the condensed water is less in the fallout case.

In this article, the enthalpy (*H*) of moist air is the sum of the enthalpy of one kilogram of pure air plus the enthalpy of its water content in any phase. Energy values in the figures are per kilogram of dry air plus its water content in any phase. In Figure 2, 1 kg of dry air contains 1.0182 kg of substance because the mixing ratio is 18.2 g-water/kg-air. The potential energy term must be multiplied $(1 + m) = 1.0182$ where m is the mixing ratio in kg-water/kg-air. The ezergy of 2215 J is per 1.0182 kg of substance or per kilogram of pure air plus its water content. The ezergy per kilogram of substance is 2215/1.0182 = 2175 J/kg of substance. Both values correspond to a velocity of 66.0 m/s.

The enthalpy of the 85 % relative humidity air at the base of the Jordan sounding is 72,820 J/kg; the enthalpy of dry air at the same pressure is 26,420 J/kg. The contribution of moisture to enthalpy is 46,400 J/kg. Water vapor contributes 1.82 % of the mass content and 63.7 % of the heat content.

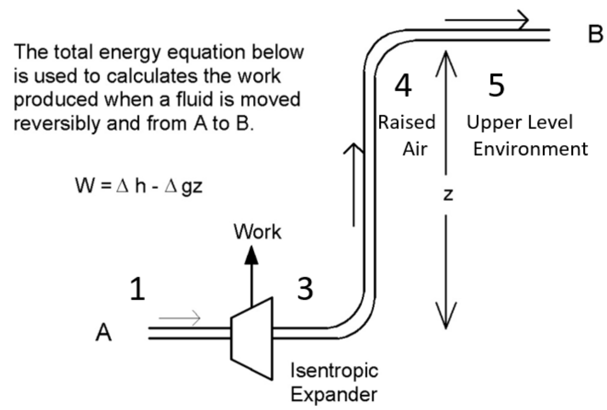
Ezergy equation (2) is applicable to any mass of fluid including all components in any phase. In figure 3, the mass of dry air is 1 kg in all three cases, the mass of water is 16.95 g in case 1 and 18.01 g in case 4. Keeping the air mass constant simplifies analysis and is common practice in psychometry. The ezergy equation is valid for rising or descending air. For the Jordan sounding, lowering a kilogram of ambient air from the 15 kPa level adiabatically to the surface has an ezergy of -11100 J/kg; lowering upper troposphere air requires rather than produces energy.

Ideal power is ezergy multiplied by flow in kilogram per second. A standard flow of 10000 kg-air/s will be used to provide an appreciation of the power production potential. A small tornado with a 30 m base diameter could have an upward flow of 10000 kg/s (10 t/s). At this standard flow, an ezergy of 2215 J/kg correspond to a power output of ≈22 MW. Megawatt equals Joules per kilogram divided by 100. For a given upward velocity, flow increases with the square of diameter. Power potential is proportional to ezergy and to the square of vortex base diameter. Specific ezergy is independent of velocity; time and velocity do not matter. Per unit mass calculations facilitates comparisons of different cases.

Friction losses are much higher for cumulus batch flow than for continuous flow. For the same continuous flow friction losses are inversely proportional to the fourth power of conduit diameter for turbulent flow and to the fifth power of conduit diameter for laminar flow. Friction losses for the above standard flow could be approximately 2 MW for turbulent chimney flow and 0.1 MW for vortex laminar flow. Friction losses are a small fraction of ideal power for large diameter vortices. To the flow of heat is due all motion including every form of atmospheric motion.

2. Effect of surface air temperature and humidity

Fig. 3 and 4 show the effect of surface air temperature and humidity on ezergy. Increasing surface air temperature by 1°C, at constant mixing ratio, increases ezergy by 316 J/kg. Increasing surface air mixing ratio by 1 g/kg, at constant temperature, increases ezergy by 695 J/kg. Increasing surface air temperature by 1°C, at constant relative humidity, increases ezergy by 1044 J/kg. The incremental efficiency (RZ), the ratio of ezergy increment to heat increment range from 27.2 to 30.5 %. RZ is higher for sensible heat addition than for latent heat addition because there is no need to raise additional water.



Basis:
Jordan Caribbean hurricane sounding
P_1 = 101.51 kPa,
P_4 = 15 kPa, Z_4 = 14,182 m
True adiabatic with ice.
$W_b = W_{13}$ = Turbine Work (Ezergy).

Total Energy Equation Method: $W_b = (h_1 - h_4) - (1 + M_1)\Delta gz$

Reversible								Irreversible	
T_1 (K)	U_1(%)	M_1(g/kg)	W_b(J/kg)	$\Delta W_b/\Delta x$	H_1 (J/kg)	ΔH_1 (J/kg)	RZ (%)	W_i(J/kg)	RI(%)
27	75	16.95	1564	Base	70361	Base	Base	2232	Base
28	70.6	16.95	1880	316 J/K	71397	1026	30.5	2679	43.6
27	79.4	17.95	2259	695 J/g	72912	2551	27.2	3183	37.3
28	75	18.01	2608	1044 J/K	74100	3739	27.9	3667	38.4

Carnot Efficiency = $1 - (T_4/T_1) = 1 - (209/301)$ = 30.5 %.

Figure 3. Effect of increasing surface air temperature and humidity on ezergy and on efficiency.

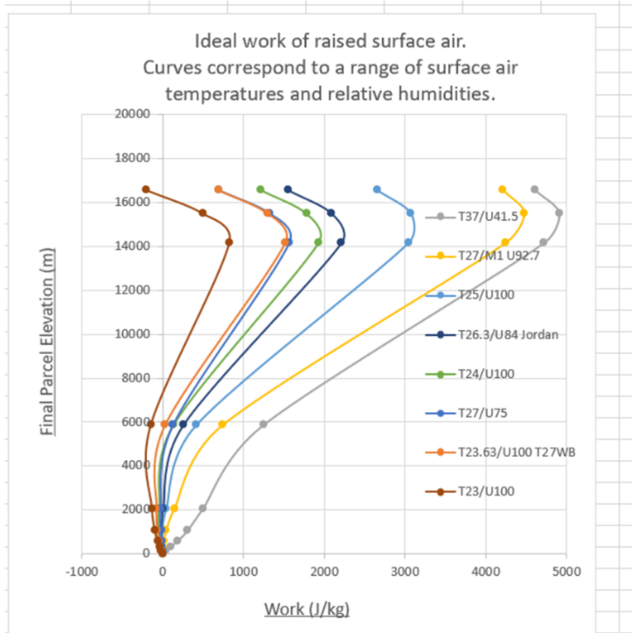


Fig.4 Effect of surface air temperature and humidity on ezergy.
Based on Jordan hurricane-season sounding.

Converting 30% of heat received at a temperature as low as 30°C would be an amazing feat for any engine. Conventional thermal engines typically require heat source temperatures of at least 300°C. The reason for the high incremental efficiency is that the air previously received heat through natural processes as will be shown in the continuous cycle analysis in the next section. The reason for the ability to produce work from small temperature differences is that small temperature differences are enough to cause warm air to rise.

The previous calculations are for a reversible process where the work leaves the system. In an irreversible process, dissipated work (Wi) is more than the corresponding exergy because the dissipated energy becomes heat which produces additional work. In the second case of Figure 3, the reversible exergy and irreversible dissipated work are 1880 and 2679 J/kg respectively, corresponding to pressures at the base of the updraft of 99.38 and 98.48 kPa respectively. The work dissipated (W_d) in an irreversible process will be called **"inergy"** (E_i) where "i" stands for irreversible.

Fig. 4 shows the effect of surface air temperature and humidity on ezergy and on peak ezergy level. Peak ezergy occurs close to the 15 kPa (14.2 km) level in all cases. The negative ezergy at low elevation is akin to convective inhibition (CIN). Surface air can be in a metastable state and may have to be raised several kilometers to produce significant positive ezergy. Ezergy is transferred downward to the turbine where the flow is restricted and to overcome resistance to flow wherever it occurs in the conduit, including raising surface air up to the level where it becomes buoyant. Any excess of work of expansion beyond what is required to raise the air is transferred to the turbine which produces work which can leave the system via a shaft.

A temporary heat source or other disturbance may be required to overcome the metastable state and to start the flow. Starting the upward flow is akin to stating a syphon or a thermosyphon. In figure 2, the maximum ezergy level (15 kPa) is slightly lower than the temperature equilibrium exergy level (12.64 kPa) because less work is required to raise water. Decreasing the relative humidity of 27°C surface air to 64%, or of 26.3°C air to 69%, reduces exergy to close to zero.

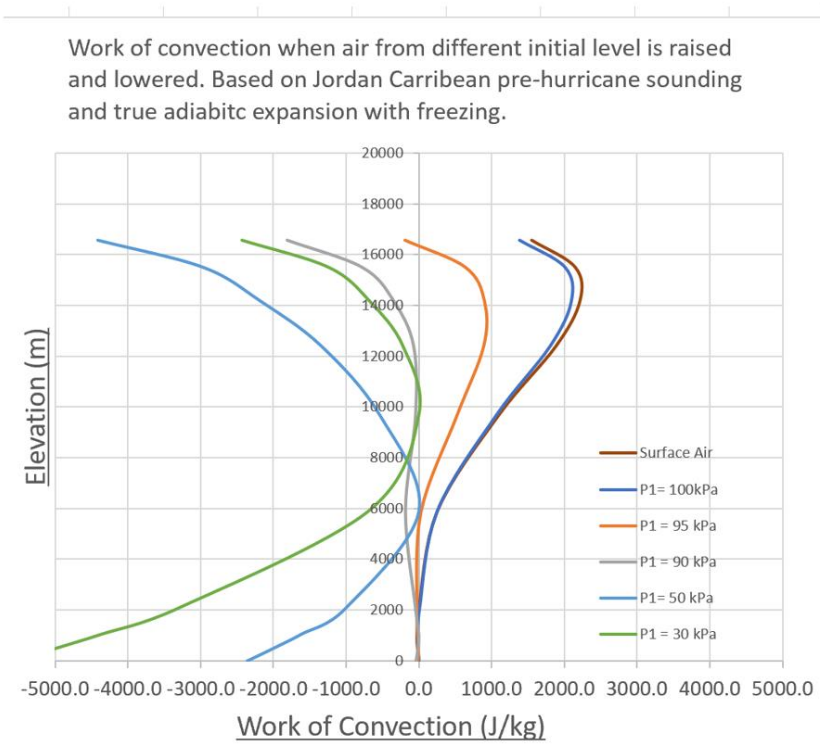


Fig. 5 Effect initial air level of on ezergy.

Fig. 5 shows the effect of the source initial pressure (or elevation) on ezergy. Ezergy decreases rapidly with increasing source air level. The ezergy of air initially at the 95 kPa level is half of that of surface air. The ezergy of air initially at 90 kPa is close to zero. Ezergy decreases rapidly with initial elevation because mixing ratio decreases with elevation. The relative humidity of maritime tropical air can be 85 % and 60 % at the sea surface and at the 3 km level respectively. The mixing ratio of maritime tropical air can be 17 and 6 g-water/kg-air at the surface and at the 3 km level respectively. Mixing ratio decreases rapidly with elevation. Ezergy decreases rapidly with initial elevation.

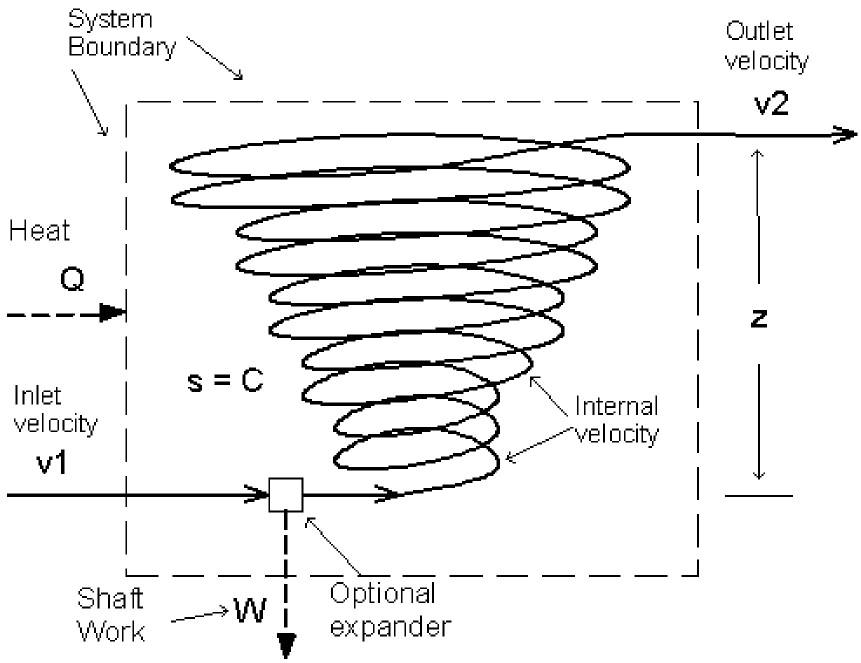


Figure 6. Continuous flow system with a spiral path.
High internal velocities do not affect the energy balance which only depends on external energy flows.

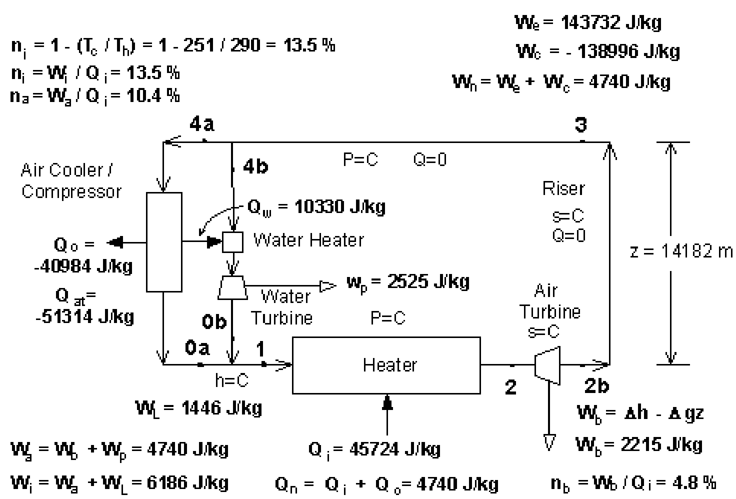
Raising high enthalpy air from near the earth's surface is essentially the only process capable of producing work. Providing a short stack should help prevent the base of a vortex from drifting away from a vortex engine because of the low heat content and mixing ratio of air at higher elevation. The energy of tornadoes is often attributed to descent from above. Figure 5 shows that such an attribution must be incorrect; lowering upper troposphere air does not produce energy, it requires energy.

The ezergy of air initially at a pressure of 80 kPa or less is negative whether the air is raised or lowered. Moving mid or upper troposphere air either up or down requires rather than produces energy. As a result, the upper troposphere is stable. There is little turbulence outside the updraft areas which are much smaller than the surrounding downdraft area. In the upper troposphere, friction losses associated with horizontal flow are small because stability suppresses turbulence.

Fig. 6 shows a continuous process wherein surface air is raised in a vortex, an expanding spiral. Internal kinetic energy can be large without violating conservation of energy provided this kinetic energy is recovered before the air leaves the system to make exit velocity is low. The high internal velocity provides centrifugal force and prevents the high external pressure from driving the surrounding air into the lower pressure air rising in the vortex, thereby suppressing mixing, turbulence and exergy degradation to heat.

3. Close cycle

Close cycles will be used to calculate efficiency. Efficiency cannot be calculated from the open process of Fig. 2 and 3 because the heat input is zero. Process 2-3 of Fig. 7 corresponds to the 15 kPa case of Figure 2. The air and condensed water separate at point 4. During their separate descent, the air is cooled, and the water is heated so that they both arrive at the surface at 25 °C. The descending air is cooled in a reversible polytropic process by radiation to space and by heat transfer to the descending water. There is no evaporation during the descent; the air and water follow separate paths to make the process analysable.



State	P (kPa)	T (°C)	r (g/kg)	s (J/ K kg)	h (J/kg)	gz (J/kg)	h+gz (J/kg)
1	101.51	8.89	18.20	95.56	27098	0	27098
2	101.51	26.30	18.20	253.01	72822	0	72822
2b	98.99	24.17	18.20	253.01	70607	0	70607
3	15.00	-62.27	18.20	253.01	-70910	141516	70607
4a	15.00	-62.27	0.03	254.99	-62489	138991	76502
0a	101.51	25.00	0.03	84.04	25193	0	25193
4b	15.00	-62.27	18.17	-32.02	-8427	2525	-5902
0b	101.51	25.00	18.17	6.67	1903	0	1903

Figure 7. Close, reversible, atmospheric cycle
Adiabatic expansion with freezing.
No separation during ascent
Lapse rate of 6.153 °C/km

In an ideal process, friction losses can be zero because velocities can be very low. The cycle is per kilogram of pure air; time is irrelevant. The only unavoidable loss is mixing process 0-1. The temperature decreases from 25 °C to 8.89 °C in the isenthalpic mixing process, during which a small part of the water evaporates. There is an increase in entropy and an unavoidable work loss in mixing process 0-1; the work loss (W_L) equal to $T\Delta s$ is 1446 J/kg. In a real process, where the moisture is provided by shallow updrafts, work loss (W_L) could be slightly lower. Heating process 1-2 is reversible; the air and the water are in equilibrium; and the heat source is at a temperature slightly higher than the temperature of the saturated air water mixture.

“Overall Work” is the sum of: air-turbine work (W_b = 2215 J/kg), water-turbine work (W_p = 2525 J/kg) and loss work (W_L = 1446 J/kg). “Overall Efficiency” is overall work divided by heat received 13.5 % (=6186/45724). Overall Efficiency is the same as the Carnot efficiency, n_i = (1 - T_c/T_h), where T_c (251 K) and T_h (290 k) are the average temperatures of the cold and hot source respectively. Ezergy is equal to the work of the air turbine (W_b = E_z). The potential energy of the condensed water is assumed to leave the system but does not produce useable work.

The heat received (Q = 45724 J/kg) is large compared to the ezergy of 2215 J/kg because the air has been dehumidified and must be re-humidified. The re-humidification water need not be the water that was separated. The re-humidification water can come from the sea via shallow updrafts. Dry air has a high affinity for warm sea water. As a result, oceanic surface air typically has relative humidity of 60 to 80%.

Efficiency based on the work of the air turbine alone is 4.8 % (2215/45724). Fig.3 shows that adding heat to surface increases ezergy by 27.2 t 30.5 % of the added heat. The reason for this high incremental efficiency lies in the metastable nature of moist air. The 15 kPa ezergies of 26.3 °C surface air with 85, 69.7 and 0 % relative humidity respectively are 2215, 0, and -12353 J/kg respectively. The corresponding surface air enthalpies are 72822, 64907 and 26423 J/kg. Surface air enthalpy of ≈64900 J/kg can be viewed as the ezergy zero. The 38384 J/kg difference in enthalpy between 0 % and 69.7 % relative humidity is insufficient to make ezergy positive. Heat supplied at enthalpy of less than ≈64900 J/kg is incapable of producing ezergy. Ezergy production is 25 to 30 % of the heat supplied at enthalpy above the enthalpy zero (≈64900 J/kg).

Tropical ocean surface air ezergy is usually between -2000 and +2000 J/kg. Surface air is often close to the point where a small amount of heat is sufficient to release the energy production potential of heat provided by natural processes at lower temperature or relative humidity. Adding a small amount of heat releases the ezergy potential of heat received earlier. Adding heat to surface air increases ezergy (W_b) and has little effect on potential energy of condensed water (W_p) or loss work (W_L); the increase in overall work goes mainly to ezergy (W_b).

The close cycle of Fig. 7 can explain many features of the atmosphere better than atmospheric models. The total turbine work equals heat input minus heat output (45724 – 40984 = 4740 J), and to work of expansion minus work of compression (143732 – 138986 = 4740 J). The enormous works of expansion and compression are not obvious in atmospheric models. The work of expansion is 314 % (143,732 / 45724) of the heat received. The second law puts a limit on net work but does not limit work of expansion.

The potential energy of condensed water of 2440 J/kg is larger than the ezergy of 2215 J/kg. The total turbine work is 10.4 % (4740/45724) of the heat received, the ezergy efficiency is 4.8% (2215/45724). Exergy efficiency and total turbine efficiency could be ≈6 % and ≈12 % due to higher surface air temperature and humidity, cooling at higher latitudes and to water spray.

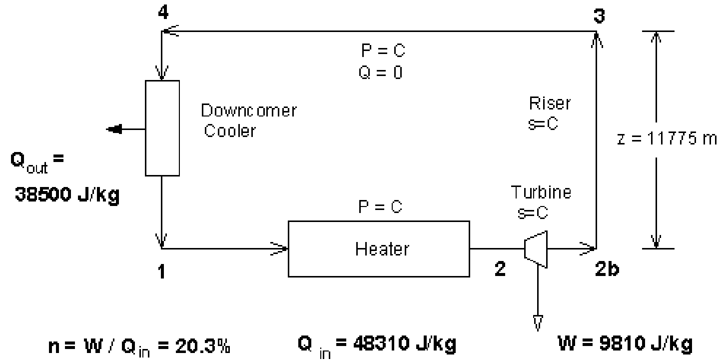
Subsidence occurs preferentially where the air is cold. Local subsidence compresses and warms underlying air thereby favoring remote subsidence. The subsidence occurs where the fluid is densest like in a manometer. Local subsidence would increase the 15 kPa elevation which would push the subsidence area away from the upflow area. Strong hurricanes produce no significant increase in the 15 kPa elevation in the neighboring region.

Energy is transported poleward mainly by work of compression rather than by sensible or latent heat. The descending air received 138986 J as work of compression which provides its increase in enthalpy of 87662 J plus its heat loss of 51314 J. The descent must be much slower than the ascent to give the air the time to cool by radiation to space. Radiating 41000 J/kg at 1.5 °C/d takes ≈27 days, corresponding to a subsidence velocity of ≈500 m/d (≈6 mm/s). An upward velocity of 3 m/s is ≈500 times the downward velocity corresponding to an ascent time of ≈1.3 h or ≈0.055 d. At a cooling rate of 1.5 °C/d, the descending air looses ≈41000 J/kg during its 27 days descent. The rising air only looses ≈80 J/kg during its ≈100 minutes ascent justifying the ascent process being considered adiabatic.

The role of work of compression in transporting heat poleward is seldom considered in atmospheric science. It is occasionally recognised that the energy of a column of air is increased by adding air at the top of the column while removing the same quantity from the bottom because moist static energy increases with elevation. In the irreversible case, shaft work (W_a) is zero and heat out (Q_o) equals heat in (Q_i).

Conservation of mass requires that downflow equals upflow which requires that the downflow area be ≈500 times the area of the upflow area. Hadley and Ferrel circulation cells with updraft and downdrafts of roughly equal area are inconsistent with the requirement that the downdraft area be much larger than the updraft area. The upflow and downflow processes are very different. Upflow produces work, downflow requires work. Upflow is essentially an adiabatic process, downflow is a polytropic cooling process. Upflow is fast ≈3 m/s, downflow is slow ≈500 m/d. Upward velocity is approximately 500 times the downward velocity. Energy is transferred to the subsidence areas by work of compression. The location of upflow areas is not fixed. Hurricanes wander and form in random locations. Additional information can be found at Michaud (1998, 2000 and 2012).

Single component systems are easier to understand than binary system ones. Figure 8 shows a pure air single component system with a lapse rate is 6.5°C/km. The surface air receives sensible heat instead of latent heat. In both cases the raised air is at the temperature of the environment in state 3. The surface air is heated by 38°C and is very unstable. The tropospheric lapse rate is ≈6.5°C/km because the whole troposphere is cooled by radiation to space; without this cooling the lapse rate would be the dry adiabatic lapse rate of 9.8°C/km. The pure air system shows that the work is transferred to wherever in the circuit the flow is restricted. The turbine can be anywhere in the circuit. In an ideal process, ezergy is independent of turbine location.



State	P (kPa)	T (K)	s (J/ K kg)	h (J/kg)	gz (J/kg)	h+gz (J/kg)
1	100	290	60.14	16929	0	16929
2	100	338.1	214.14	65239	0	65239
2b	90.25	328.3	214.14	55429	0	55429
3	20	213.5	214.14	-59567	115395	55429
4	20	213.5	214.14	-59567	115395	55429

Carnot Efficiency based on average source temperatures

$$n^c = 1 - T_c / T_h = 1 - 251.7 / 314.0 = 19.8\%$$

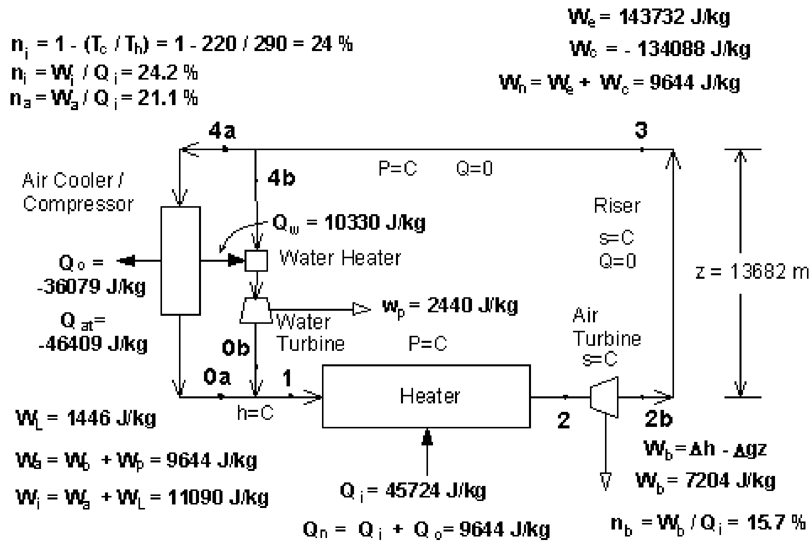
Carnot Efficiency based on **log** average source temperatures

$$n_c = 1 - T_c / T_h = 1 - 248.8 / 313.1 = 20.5\%$$

Figure 8. Reversible close cycle - Pure air - no water,
Doncomer cooling. Height based on lapse rate of 6.5 K /km

Figure 9 shows a case where the 15 kPa surface is 500 m lower than in Figure 7. Lowering the 15 kPa surface by 500 m increases ezergy by ≈5000 J/kg. The elevation of the 15 kPa pressure is approximately 1000 m lower at the poles than in the tropics. A 500 m reduction corresponds to mid-latitude elevation. At 85 % relative humidity, the air temperature required to achieve an ezergy of 2215 J/kg is 26.2 °C in the tropics and only 21.5 °C in mid latitude because the 15 kPa air is 500 m lower. The appendix suggests the name **“epergy”** for exergy based on the use of lower than local elevation. The “p” stands for poleward.

Raising tropical air in high latitudes where geo-potential heights are lower can produce more mechanical energy than doing so locally thereby increasing atmospheric efficiency. Satellite videos of tropical cyclones occasionally show hurricane exhaust air streaming towards colder regions. High latitude descent can contribute to increasing hurricane intensity. Horizontal distance is not a impediment because friction losses can be small.



State	P (kPa)	T (°C)	r (g/kg)	s (J/ K kg)	h (J/kg)	gz (J/kg)	h+gz (J/kg)
1	101.51	8.89	18.20	95.56	27098	0	27098
2	101.51	26.30	18.20	253.01	72822	0	72822
2b	88.36	19.36	18.20	253.01	65618	0	65618
3	15.00	-62.27	18.20	253.01	-70910	136527	65617
4a	15.00	-62.27	0.03	254.99	-62489	134087	71598
0a	101.51	25.00	0.03	84.04	25193	0	25193
4b	15.00	-62.27	18.17	-32.02	-8427	2440	-5987
0b	101.51	25.00	18.17	6.67	1903	0	1903

Figure 9. Close, reversible, atmosheric cycle
Adiabatic expansion with freezing, No separation,
Effect of reducing z4 by 500 m. Lapse rate 6.378°C//km..

4. Sea water spray.

Figures 10 and 11 show how spraying the air with warm sea water can increase available work. Holland (1997) recommended using hurricane eyewall air temperature of 1 °C lower than the eyewall sea surface temperature and a relative humidity of 90 %. Eyewall sea surface temperature can be 1 °C lower than pre-hurricane sea surface temperature. The 26 °C 90 % relative humidity case is based on air 2 °C colder than the pre-hurricane sea surface temperature of 28 °C. The water spray increases mixing ratio from 16.95 to 20.25 g/kg and available work by a factor of 3 from 1564 to 4791 J/kg,.

The available work with sea spray will be called **evergy**, where “v” stands for evermore energy. The heat content of tropical seas is much greater than that of surface air and is essentially inexhaustible. The ratio of the increment in evergy to the heat supplied by the water spray of ≈25 % is slightly less than the previous RX of 27.2 to 30.5 % because there is a need to raise additional water and because the heat is supplied at slightly lower temperature.

Air can hold more water vapor at reduced pressure. For a given temperature and relative humidity, mixing ratio increases with decreasing pressure. The mixing ratio for 26 °C air with 90% relative humidity is 19.14 g/kg at 101.51 kPa and 20.25 g/kg at the reduced pressure of 96.12 kPa, corresponding to exergy and evergy are 2762 and 4791 J/kg respectively. For the same temperature and relative humidity, reduced pressure increases available work by 73 %. Ezergy production is enhanced by spraying the air with warm sea water downstream rather than upstream of the turbine.

Spraying air with fine water drops tends to produce air with high relative humidity air. The temperature of the air increases with the water to air mass flow ratio. A very large water to flow ratio would produce saturated air at the temperature of the water. Figure 10 shows that the air temperature increases with water flow. The effect of the initial temperature and humidity of the air on evergy is minor and can be compensated for by increasing the water spray. A small fraction of the spray evaporates, typically 0.3 %; the remaining 99.7 % falls back into the sea at the wet bulb temperature of the air. The heat of evaporation is provided by the reduction in the sensible heat of the part of the spray which does not evaporate. Producing 26 °C air with 90 % relative humidity at the reduced pressure requires more spray at low initial air relative humidity. Reduced pressure reduces the water temperature needed to produce a given evergy.

WORK TO SPRAY SENSITIVITY

Basis:

Jordan Caribbean hurricane sounding

P_1 = 101.51 kPa, T_1 = 27 °C

U_1 = 75%, M_1 =16.95 g/kg

SST = T_7 = 28 °C

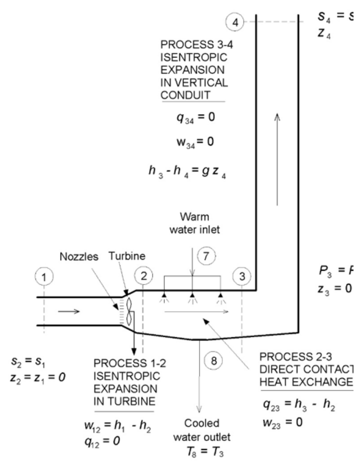
True adiabatic with ice.

$W_b = W_{12}$ = Turbine Work (Ezergy)

P_3 = Updraft base (eyewall) pressure

Observations

1. Ezergy and P_3 reduction increase with state 3 temperature and %RH.
2. Ezergy increases with water flow.
3. Sensitivities are 25% higher when the air is raised to its level of neutral buoyancy.
4. Sensitivities to water flow would be 30 to 50% higher when flow is irreversible .



P_4(kPa)	z_4(m)	T_3(°C)	U_3(%)	P_3(kPa)	M_3(g/kg)	W_b(J/kg)	F_7/F_3(kg/kg) REV.	IRR.
Without water spray								
15	14180	25.49	80.75	99.73	16.95	**1564**		
With water spray								
15	14180	25	90	98.13	18.64	**2983**	0.28	0.12
15	14180	25	100	95.61	21.28	**5258**	1.09	0.68
15	14180	26	90	96,12	20.25	**4791**	0.86	0.51
15	14180	26	100	93.73	23.10	**6981**	2.50	1.67
10	16577	26	100	91.78	23.60	**8797**	2.86	1.81

Sensitivites

$\Delta W_b/\Delta U_3$ = 281 (J/kg)/% (at T_3 = 25)

$\Delta W_b/\Delta U_3$ = 219 (J/kg)/% (at T_3 = 26)

$\Delta W_b/\Delta T_3$ = 1760 (J/kg)/K (at constant U_3)

$\Delta W_b/\Delta T_3$ = 2200 (J/kg)/K (at U_3 = 100%, P_4 = 10 kPa)

$\Delta W_b/\Delta(F_7/F_3)$ = 2810 J/kg (at T_3 = 25°C, reversible)

$\Delta W_b/\Delta(F_7/F_3)$ = 1340 J/kg (at T_3 = 26°C, reversible)

$\Delta W_b/\Delta(F_7/F_3)$ = 3120 J/kg (at U_3 = 90%, reversible)

$\Delta W_b/\Delta(F_7/F_3)$ = 1220 J/kg (at U_3 = 100%, reversible)

Figure 10. Effect of sea water spray on ideal work (Evergy)

The mass transfer from spray to air is much higher than from the sea surface because drops have more surface area per unit mass than the surface of the sea. The affinity of air is zero for water at the dew point temperature of the air and increases rapidly with water temperature. Enthalpy transfer between water and air increase with affinity and with contact area. The ProII process simulation in the references show that increasing water flow increases temperature and evergy. Holland (1997) calculated hurricane base pressure reduction rather than ideal work. He obtained results consistent with this article by using a dynamic rather than thermodynamic approach,

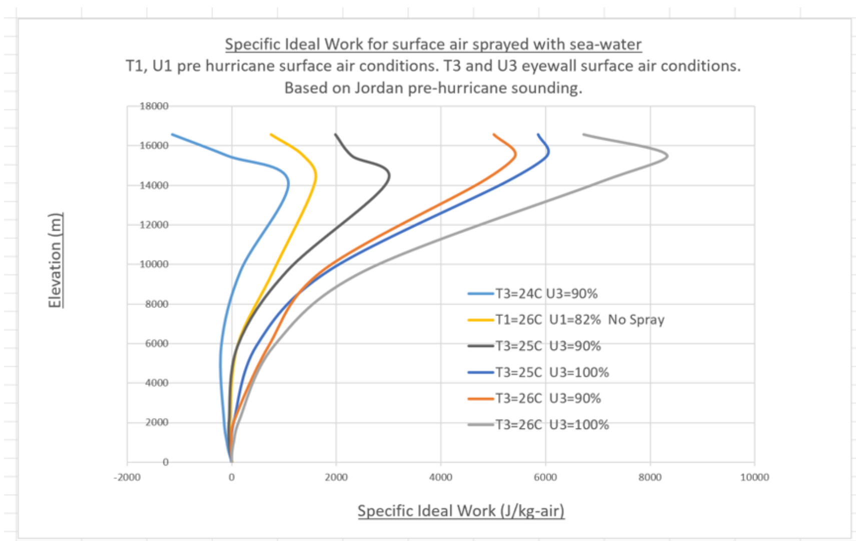


Figure 11. Effect of water spray on ideal work (Evergy). Curves show effect of eyewall temperature and relative humidity.

5. Atmospheric Science

Ukrainian/Austrian thermodynamicist Max Margules used close thermodynamic systems to study the energy of storms. His 1903 paper showed that available energy is equal to reduction in total system enthalpy. His last 1906 paper calculated the energy produced by raising a small air mass and his method gives results consistent with those of this article. The name enthalpy was coined by Dutch thermodynamicist Heike Onnes in 1909. The open system of Figure 1 and energy balance equation (1) greatly simplified process energy calculations. Open thermodynamic systems were not widely used before that time. Open thermodynamic systems are widely used in engineering and have rarely been used in atmospheric science, presumably because there is no conduit in the atmosphere. Contained steady-state continuous processes can be used to understand non-contained non-steady state processes because, for the same process conditions, ezergy is the same for all reversible processes

Lorenz (1977) expanded the on the Margules system; he defined available energy as the difference between the actual enthalpy of the atmosphere and the enthalpy of a reference state. The reference state is minimum total enthalpy that could be achieved by rearranging the mass under reversible adiabatic processes. At the reference state, the atmosphere must be uniform in the horizontal direction and the entropy must increase in the upward direction; the atmosphere is everywhere stable.

The reference state method is valid for dry air but impractical for moist air. Heating the atmosphere from below or cooling the atmosphere from above increase available energy. The atmosphere never comes close to the reference sate. The reference state is not reached so long as the exergy of moving any air mass from any place to another is positive. The total enthalpy of the atmosphere goes up and down but is always far away from a reference state. There have been numerous peer reviewed articles based on the reference state concept. For example, Randall and Wang (1992) showed that the available energy of a uniform atmosphere is small because of local subsidence warming.

Margules abandoned meteorology in 1905 because his ground-breaking work was not appreciated. In his last paper, he used small air masses. He calculated the achievable velocity of both dry and moist air masses. He obtained results consistent with those of this article without explicitly using an open thermodynamic system.

Margules understood the atmospheric engine, in his last paper, he wrote:

- I hold vertical movement under the influence of gravity to be the essential cause of storms.
- The energy potential of horizontal pressure difference is very small.
- The energy source is not to be found in gradients but in the sinking of colder air and the rising of warmer and moister air.

- One could gain a closer understanding, when better method than presently known, for the handling of aerodynamic problems are found (like the HP48 AT1 program).
- For reasons I will not go into I am leaving meteorology.

The efficiency of engines is calculated by following a fluid through close cycles wherein the properties are related via properties such as pressure, temperature, entropy, enthalpy and composition. Thermodynamics specify the flow and the type of process from which heat, work and efficiency are calculated.

Atmospheric models attempt to calculate future trajectories based on initial and current conditions. Trajectories are not specified; there are many trajectories that satisfy the equation of motion including every weather pattern that has ever occurred. Hurricane models produce a spaghetti of trajectories. There is mixing of fluid with unrelated properties in unspecified proportions.

Atmospheric model performance is judged by how well they predict future weather or the effect of conditions such as carbon dioxide on climate. An average atmospheric velocity of 20 m/s could be the result of an actual work production of 25 W/m^2 with a ≈0.7-day degradation time or of 0.25 W/m^2 with a ≈70-day degradation time. Getting the velocity right is of little value in calculating actual efficiency and of even less value in determining maximum possible efficiency. Friction factors are adjusted to make results agree with observations. Calculating efficiency from model is virtually impossible.

Emanuel (1997) showed that the energy of hurricanes is primarily due to heat transfer from the underlying warm sea. Kleidon (2012) estimated the total atmospheric energy potential is ≈6000 TW most of which is dissipated during atmospheric convection. He did not see the possibility of making atmospheric energy available. He states that wind energy is mainly due to poleward gradients and not by vertical gradients.

Available work can be calculated from ezergy equation (eq. 2). The reference state approach adds nothing of value. There is no need to consider the effect of subsidence on upper-level elevation because the subsidence occurs over a wide area and mostly well away from the updraft. The reference state approach provides no information about where the work is produced. The ezergy approach shows that the available work can increase the kinetic energy of the rising air itself and that it can be captured by restricting the flow with an expander. Closed cycles produce available work in accord with Carnot efficiency.

Here is a link to a tweet explaining how I came to the ezergy approach:
https://twitter.com/VortexEngine/status/1049055433514803202

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Appendix
PROPOSED FREE ENERGY NAMES

Free energy is the maximum work that can be made available by bringing a fluid to equilibrium with an environment. The energy is **free** because there is no need to provide costly heat. Free Energy is real work and can become shaft work. There are several kinds of free energy; distinctive names for them would be useful.

Existing free energy name

Exergy (E_x) is the maximum work that can be made available when a fluid is brought reversibly to pressure and temperature equilibrium with an environment.

$$E_x = A = -\,\Delta H + T_0\ \Delta S - g\Delta z \qquad (A1)$$

where ΔH and ΔS are the difference in enthalpy and entropy of the fluid between its initial and final state, where T_0 is the temperature of the final environment, and where Δz is the change in elevation. There is no need for a solver since the temperature, enthalpy and entropy of the fluid in the initial and final state are known. Discovered by Willard Gibbs in 1873 and given the name "Free Energy"; renamed **Exergy** by Zoran Rant, in 1951. The usual symbol for ezergy is ***"A"***. The $g\Delta z$ term is zero in processes where there is no change in elevation. Ezergy may or may not include the potential energy of condensed water which is zero in processes where there is change in elevation is negligible.

Proposed new free energy names

Ezergy (E_z) is the maximum work that can be made available at a fluid initial location when it is brought to pressure equilibrium with an environment via a reversible adiabatic (*S=C*) process. The "***z"*** stands for change in elevation (Δz).

$$E_z = -\Delta H - g\Delta z \qquad (A2)$$

where ΔH is the reduction in the enthalpy of fluid moved at constant entropy from the initial to the final pressure. Final temperature and enthalpy are calculated from known final pressure using a solver. **Ezergy** is always less than **exergy** because a Carnot engine producing work could be used to bring the moved fluid to temperature equilibrium with the final environment, irrespective of whether the temperature of the raised air is initially higher or lower than the temperature of the final environment. Ezergy (E_z) is independent of the temperature of final environment. Exergy (E_x) is dependent of the temperature of final environment. Ezergy does not include the potential energy of condensed water because it is not available at the initial location. Ezergy is the maximum available work and not the maximum work because it does not include the potential energy of condensed water.

Emergy (E_m) is the maximum work that can be produced when there is no change in elevation such as in an ideal gas turbine. The "***m***" stands for same (même), no change in elevation ($\Delta z = 0$), and also for Emmie, the carer, in Geinor Styles' musical "The Eye of the Storm".

$$E_m = -\Delta H \qquad (A3)$$

In Figures 2 and 3, turbine emergy is equal to system ezergy, therefore ezergy can produce shaft work at grade. Ezergy is much less than work of expansion because most of the work of expansion is needed to raise the air and its water content.

Evergy (E_v) is the maximum work that can be produced, based on specified temperature and relative humidity at turbine outlet pressure and temperature, via a reversible adiabatic ($S=C$) process. The "***v***" stands for e**v**er more energy. For the same temperature and relative humidity, evergy is larger than ezergy because air hold more vapor at reduced pressure.

Epergy (E_p) is the maximum work that can be produced when fluid is brought reversibly to an environment where pressure surfaces are lower than directly overhead, which is generally a more poleward location. The "*p*" stands for poleward.

Imergy (E_i) is the work produced and dissipated in a fully irreversible moving process.

Subscripts and Defaults.

Free energy type can be further specified with subscripted numbers in parentheses. Default shown may be omitted.

$E_{z(s\text{-}15)} = E_z$ Ezergy of surface air raised to 15 kPa level.

$E_{z(s\text{-}e)} = E_x$ Ezergy of surface air raised to its level of neutral buoyancy (LNB) - Exergy equivalent.

$E_{v(26\text{-}90\text{-}15)} = E_v$ Evergy of 26°C, 90% relative humidity air at the reduced pressure at the base of the updraft

$E_{p(500)} = E_p$ Epergy of air surface sir raised to an environment where the 15 kPa surface is 500 m than directly overhead.