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1269 Andrew Court, Sarnia, Ontario, N7V 4H4 Canada

Thermodynamic Cycle of the Atmospheric Upward Heat Convection Process

L. M. Michaud

With 13 Figures

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Summary

Closed ideal thermodynamic cycles are used to analyze the atmospheric upward heat convection process which is compared to the Brayton gas-turbine cycle. The heat to work conversion efficiency of the atmosphere is shown to be close to the Carnot efficiency calculated using the average temperatures at which heat is received and given up for hot and cold source temperatures, respectively. The efficiency is independent of whether the lifting process is discontinuous or continuous, and nearly independent of whether the heat is transported as sensible or as latent heat.

The total energy given up by an air mass going through any process is shown to be equal to the reduction in its static-energy. For a given sounding, there is a definite quantity of work which can be produced per unit mass of air raised. The paper investigates how updraft and sounding properties affect the work produced when air is raised and shows that the work can be transferred downward.

1. Introduction

The article uses ideal thermodynamic cycles to investigate how heat is converted to work during upward heat convection in the atmosphere. Three closed thermodynamic cycles are analyzed for both discontinuous and continuous processes. The three cases were selected to permit introducing new entities one at a time to examine their individual contributions. Case 1 uses a system with a uniform adiabatic lapse rate; cases 2 and 3 use systems with a uniform sub-adiabatic lapse rate. The working fluid is dry-air in cases 1 and 2 and moist-air in case 3.

The heat to work conversion efficiency of the atmosphere is shown to be close to the Carnot efficiency calculated using the average temperatures at which heat is received and given up for hot and cold source temperatures, respectively. The efficiency is independent of whether the lifting process is discontinuous or continuous, and nearly independent of whether the heat is transported as sensible or as latent heat. For a given sounding, there is a definite quantity of work which can be produced per unit mass of air raised. The article investigates how updraft and sounding properties affect the work produced when air is raised and shows that the work can be transferred downward.

To the question: "Real processes are never reversible, why spend so much time discussing reversible processes?" Van Ness (1969, see pages 22 and 27) gave the following answer: "The reversible process is the only one for which we can readily do calculations, the alternative is likely to be no calculations at all". The three cases were selected more because they are analyzable than because they are an exact representation of the atmospheric process. The primary purpose for using turbines and compressors in analyzing the atmospheric process is that, without machines to capture the work, there can be no reversible process. While irreversible cycles are difficult to analyze directly, they can easily be explained by adding the effect of irreversibility to reversible cycles.

The atmosphere is an open system, but closed systems are used because they help understand open system. Dry-air is used for the first two cases to postpone the introduction of water until the essential features of the energy conversion process have been explained. The resistance to flow is initially concentrated at a single location to make thermodynamic analysis possible. Constant lapse rates are used because a variable lapse rate does not change the basic process. It is usually possible to conceive different implementations of a reversible cycle in which the working fluid can go through the same states.

The thermodynamic analysis is presented in Sects. 2 and 3. Sect. 2 examines three discontinuous lifting processes, Sect. 3 examines three continuous processes with the same process conditions. Case 1 is shown to be equivalent to the Brayton gas-turbine cycle, cases 2 and 3 correspond to gas-turbine cycles where the gas is cooled while it is compressed. Sects. 2 and 3 use closed cycles to show that energy is conserved and that the total work is in accord with the Carnot efficiency. Sect. 4 shows that a continuous cycle can be implemented with a single vertical tube, and that the work of buoyancy can be transmitted downward. The theory is verified with experimental results from the Manzanares solar chimney. The effect of updraft and sounding properties on work production are examined. Sect. 5 shows that the circular tube can be replaced with an annular tube which can be either a physical tube or a vortex, and that it might be possible to capture the work using a controlled vortex. Appendix A describes a mechanism for calculating the work produced when an air mass is raised reversibly.

The paper provides a self-contained explanation of how heat is converted to mechanical energy in the atmosphere. Michaud (1995) showed that the work produced when heat is carried upward by convection is equal to the upward heat flux multiplied by the Carnot efficiency calculated using the average temperature at which the heat is received and given up. Renno and Ingersoll (1996) independently reached the same conclusion, and used the average temperature at the earth's surface for the hot source temperature and the average temperature of the troposphere for the cold source temperature. Michaud (1996) showed that the work dissipated when heat is carried upward by convection is equal to the entropy produced when work dissipates multiplied by the temperature at which the work dissipates, a result which was arrived at independently by Emanuel and Bister (1996). The heat to work conversion is $\approx 17\%$ of the convective heat flux in the lower troposphere. The convective heat flux in the lower troposphere is $\approx 150\,\mathrm{W\,m^{-2}}$, the sum of the surface sensible and latent heat flux and of the solar and infrared radiation absorbed in the lower troposphere (see Peixoto and Oort (1992), Fig. 6.3). Therefore the mechanical energy produced and dissipated in the atmosphere is $\approx 25\,\mathrm{W\,m^{-2}}$.

2. Discontinuous Lifting Process

2.1 System Description

The thermodynamic systems shown in Fig. 1 consists of a closed insulated air column covered with a piston. The bottom kilogram is heated in process 1–2, raised to the top of the system in process 2–3, and the system is cooled to return it to the initial state in process 3–1. The ideal system permits heating, cooling, and moving air masses at will. Table 1a gives the process data for the four cases. The column extends from the 100 to the 20 kPa level in each case to facilitate comparison. The piston exerts a constant pressure of 20 kPa and represents the weight of the overlying air which does not take part in the rearrangement process. This piston covered closed system was first used by Margules (1905).

The work produced when a unit mass of air is expanded adiabatically and reversibly without change in elevation is equal to the reduction in its enthalpy (h). The work of buoyancy (w_b) produced when a unit mass of air is expanded and raised isentropically is equal to the reduction in its enthalpy minus the increase in its potential energy.

$$w_b = -\Delta h - \Delta gz = -\Delta\mu, \tag{1}$$

where g is the acceleration of gravity, and z is the elevation. Equation (1) is widely used for

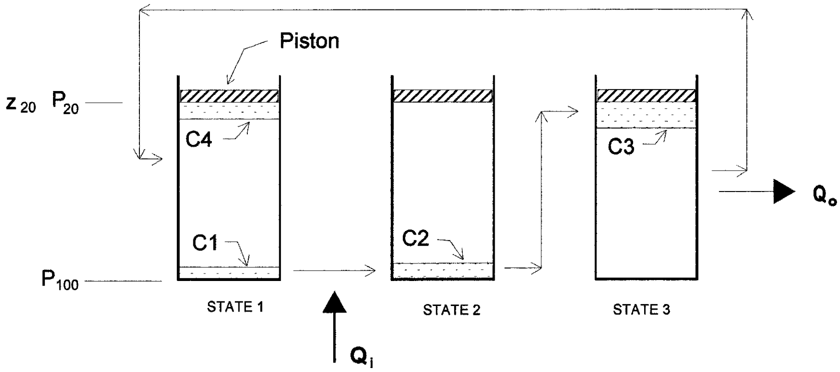


Fig. 1. Discontinuous thermodynamic cycle. The thermodynamic system consists of a column of air covered by a piston exerting a constant pressure. The bottom unit mass of air is heated in process 1–2, raised to the top of the column in process 2–3, and the system is returned to its original state by cooling in process 3–1

calculating the work required or produced in moving fluid from one place to another, it is valid for both gas-turbines and hydraulic-turbines. The validity of Eq. (1) is demonstrated in Appendix A by raising the air in a cylinder. The right-hand side of the equation can be reduced to one term by joining enthalpy and potential energy in a single term called *static-energy.* Static-energy (μ) is the sum of enthalpy and potential energy, $\mu = h + gz$. The maximum work that can be produced when a unit mass of air is moved adiabatically is therefore equal to the reduction in its static-energy during a constant entropy relocation process.

The term work of buoyancy w_b is used because when there is condensation some of the work w_p is used to lift condensed water. The total work w_t is equal to the sum of the two, $w_t = w_b + w_p$. In cases 1 and 2 where there is no potential energy of condensed water, $w_p = 0$, $w_b = w_t$, and the subscript can be omitted. The equations used for calculating entropy and enthalpy are in appendix A of Michaud (1995). The work of buoyancy is assumed to be removed from the system by an appropriate mechanism, such as the one described in Appendix A of this paper.

2.2 Case 1 – Air Column with an Adiabatic Lapse Rate

In case 1, the column has an adiabatic lapse rate (a) of g/c_{pa}, which is equal to $9.75\,\mathrm{K\,km^{-1}}$, where c_{pa} is the specific heat at constant pressure for dry-air. The potential temperature (θ) of the column in the initial state is uniform at 290 K. The bottom kilogram of the column is heated from 290 K to 300 K at 100 kPa in process 1–2. The heated parcel is raised isentropically to the top of the column in process 2–3. The raised parcel is cooled in process 3–1 to return the column to its initial state. The heat received is $10047\,\mathrm{J\,kg^{-1}}$, the heat given up to restore the initial condition is $-6343\,\mathrm{J\,kg^{-1}}$, and the work produced is $3703\,\mathrm{J\,kg^{-1}}$. 36.9% of the heat received is converted to work. The efficiency is independent of whether the unit mass is heated by 10 or by 1 K. If the parcel were only heated by 1 K, the work would be $370\,\mathrm{J\,kg^{-1}}$, but the heat received would be 10 times smaller and the efficiency would remain 36.9%. The work is produced during the re-arrangement process and not during the heating or cooling process. Alternatively heating and cooling the bottom kilogram would not produce work.

2.3 Case 2 – Air Column with a Uniform Sub-Adiabatic Lapse Rate, Dry Parcel

In case 2, the column has a uniform lapse rate of $6.5\,\mathrm{K\,km^{-1}}$. The bottom kilogram is heated from 290 K to 338.1 K in process 1–2, raised isentropically to the top of the column in process 2–3, and heat is removed from the whole column to return to the initial state in process 3–1. The initial temperature of the parcel was selected so that the parcel would have the same temperature as the environment after isentropic expansion to the 20 kPa level.

In case 1, raising the parcel increases the temperature at the 20 kPa level only, there is no temperature change at intermediate levels. In case 2 raising the parcel increases the temperature of the whole column. The temperature of the subsiding air increases in both cases, but in case 1 the subsidence warming matches the lapse rate and there is no temperature increase at inter-

Table 1a. *Process Data for the Discontinuous and the Continuous Cases*

CASE Number	1	2	3a	3b
Sounding properties				
T_{100} (K)	290.0	290.0	290.0	290.0
T_{20} (K)	183.1	213.5	213.5	213.5
a (K km^{-1})	9.75	6.50	6.50	6.50
z_{20} (m)	10959	11775	11775	11775
Parcel properties				
r (g kg^{-1})	0	0	12.55	12.55
T_1 (K)	290.0	290.0	274.12	277.65
s_1 (J K^{-1} kg^{-1})	60.14	60.14	43.04	67.04
h_1 (J kg^{-1})	16929	16929	11278	17900
μ_1 (J kg^{-1})	16929	16929	11278	17900
T_2 (K)	300.0	338.1	295.0	295.0
s_2 (J K^{-1} kg^{-1})	94.20	214.27	192.95	192.95
h_2 (J kg^{-1})	26976	65239	53851	53851
μ_2 (J kg^{-1})	26976	65239	53851	53851
T_3 (K)	189.4	213.5	213.5	213.5
s_3 (J K^{-1} kg^{-1})	94.20	214.27	192.95	192.95
h_3 (J kg^{-1})	– 84126	– 59967	– 65622	– 65622
μ_3 (J/kg)	23272	55428	51222	51222
T_4 (K)	183.1	213.5	213.5	213.5
s_4 (J K^{-1} kg^{-1})	60.14	214.27	192.95	192.95
h_4 (J kg^{-1})	– 90469	– 59967	– 65622	– 65622
μ_4 (J/kg)	16929	55428	51222	51222
Heat (J/kg)				
q_i $(= h_2 - h_1)$	*10047*	*48310*	*42573*	*35951*
q_o $(= w_t - q_i)$	– 6343	– 38500	– 38500	– 31878
Work (J/kg)				
Δh_{32} $(= h_2 - h_3)$	111101	125206	119473	119473
Δgz_{23} $(= gz(1 + r))$	107398	115396	116844	116844
w_b $(= \mu_2 - \mu_3)$	*3703*	*9810*	*2629*	*2629*
w_p $(= r_l gz)$	0	0	1444	1444
w_t $(= w_b + w_p)$	*3703*	*9810*	*4073*	*4073*
Source Temperature (K)				
T_h	295.0	313.4	284.0	285.5
T_c	186.2	249.8	249.8	246.6
Efficiency (%)				
$n_a = w_t/q_i$	36.8	20.3	9.6	11.3
$n_c = 1 - T_c/T_h$	36.8	20.3	12.0	13.6

mediate levels. In case 1, restoring the initial condition only requires removing heat from the raised air mass. In case 2, restoring the initial condition requires that heat be removed from the whole column. In case 2, the heat received is 48310 J kg^{-1}, the heat given up to restore the initial condition is – 38500 J kg^{-1}, the work is 9810 J kg^{-1}, and the cycle efficiency is 20.3%.

2.4 Case 3 – Air Column with a Uniform Sub-Adiabatic Lapse Rate, Moist Parcel

In case 3 two cycles, 3a and 3b will be considered; the work is the same for the two cycles, but the efficiency depends on the complete cycle. The column has the same 6.5 K km^{-1} uniform lapse rate as in case 2, but

Table 1b. *Conditions Before and After Mixing for Cases 3a and 3b*

CASE	Case 3a	Case 3b
Gas Phase		
r (g kg^{-1})	0.03	0.03
T_0 (K)	290.0	290.0
h_0 (J kg^{-1})	17017	17017
s_0 (J K^{-1} kg^{-1})	60.55	60.55
Liquid Phase		
r (g kg^{-1})	12.52	12.52
T_0 (K)	213.46	290.0
h_0 (J kg^{-1})	−5739	884
s_0 (J K^{-1} kg^{-1})	−21.74	3.14
Total before Mixing		
h_0 (J kg^{-1})	11278	17900
s_0 (J K^{-1} kg^{-1})	*38.81*	*63.69*
Total after Mixing		
h_1 (J kg^{-1})	11278	17900
s_1 (J K^{-1} kg^{-1})	*43.04*	*67.04*
Entropy produced and work lost during mixing		
Δs_{01} (J K^{-1} kg^{-1})	*4.23*	*3.35*
W_{lost} (J kg^{-1})	≈ 1180	≈ 940

the parcel contains water vapor. The temperature of the parcel and the mixing ratio (r) of the parcel were again selected so that the parcel has the same temperature as the environment after isentropic expansion to the 20 kPa level. The initial temperature of the parcel was arbitrarily set at 295 K and the mixing ratio determined with a solver. The initial mixing ratio corresponds to a relative humidity of 75.1%. The expansion is isentropic and the condensed water freezes. The condensed water is separated from the air at the upper level, but does not separate during the ascent.

The work of buoyancy (w_b) is 2629 J kg^{-1}. The potential energy of the condensed water (w_p) is 1444 J kg^{-1}. The total work ($w_t = w_b + w_p$) produced during the lifting process is 4073 J kg^{-1}. In order to make possible the restoration of the initial condition, the bulk of the column can be air with a mixing ratio equal to the saturation mixing ratio of the parcel at the upper level (0.03 g kg^{-1}), which is almost dry-air.

2.5 Efficiency

It is unnecessary to consider closed cycles to calculate work from (1), but closed cyclic processes are used to show that energy is conserved and that the total work is the product of heat flux and efficiency. The efficiency (n_c) of a reversible cycle can be calculated from the Carnot efficiency equation ($n_c = 1 - T_c/T_h$), where T_c and T_h are the *entropy weighted* cold and hot source temperatures. Entropy weighted temperature is equal to $q/\Delta s$, where q is the heat received and Δs is the change in entropy (s). The Carnot efficiency concept brings out the fact that the work is proportional to heat flow and a function of the temperature range through which the heat flows, $w_t = n_c q$.

Table 1a shows that in each case the work is the product of the heat received and the efficiency. In dry-adiabatic case 1, the cold source temperature is the temperature at the top of the column. In sub-adiabatic cases 2 and 3, the cold source temperature is the average temperature of the column and not the temperature of the parcel in its final condition or the temperature at the top of the column. Entropy weighted source temperature is approximately equal to the average source temperature. In case 2, the entropy weighted source temperatures are 313.4 K and 249.8 K giving a Carnot efficiency of 20.3%, using the average source temperatures of 314.0 K and 251.7 K would give an efficiency of 19.8%.

2.6 Discussion

Cases 1 and 2 can be perfectly reversible provided that the temperature of the heat sources approach the temperature of the air and provided that the air velocity is low enough to prevent friction losses. Case 3 cannot be perfectly reversible because closing the cycle requires mixing streams which are not in equilibrium. In case 3 the actual efficiency (n_a) is slightly less than the Carnot efficiency (n_c) because some work is lost in the irreversible mixing process.

In case 3a, the condensate is lowered in an insulated weightless envelope, and the condensate at 213.5 K is mixed with dry-air at 100 kPa and 290 K. In case 3b, the condensate is lowered in a perfectly conducting weightless envelope, the condensate is warmed as it descends, and the condensate at 290 K is mixed with dry-air at 100 kPa and 290 K. In both cases, the condensed water is not allowed to evaporate during its descent and is mixed isenthalpically with the air before adding the heat. In case 3a, the heat received is 42573 J kg^{-1}, the heat given up is – 38500 J kg^{-1}; the actual efficiency is 9.6%, and the Carnot efficiency is 12%. In case 3b, the heat received is 35951 J kg^{-1}, the heat given up is – 31878 J kg^{-1}; the actual efficiency is 11.3%, and the Carnot efficiency of 13.6%. The heat removed from the system is higher in case 3a than in case 3b because in case 3b some of the heat removed from the air is used to heat the descending condensate. In both cases 3a and 3b, the total work is 4073 J kg^{-1}. Except for the small loss due to chemical irreversibility the conversion efficiency is the same whether the heat is transported as sensible or latent heat. The actual efficiency (n_a) is the Carnot efficiency when there is no water and approximately 20% less than the Carnot efficiency when there is water.

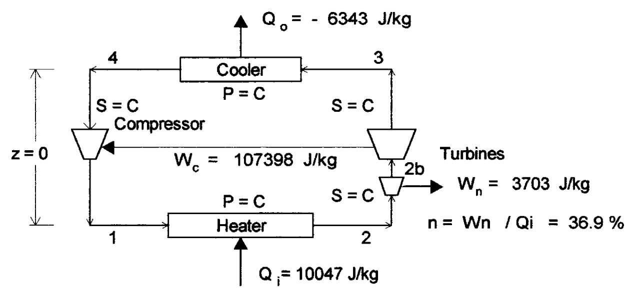
The same top and bottom pressures were used for the three cases to facilitate comparison. The adiabatic lapse rate extending through the depth of the troposphere in case 1 is unrealistic, but with smaller depth case 1 is representative of the heat transport process in the adiabatic mixed boundary layer. Case 2 is also unrealistic but was presented to show that the contributions of sensible and latent heat are similar. Case 3 is fairly representative of deep atmospheric convection.

3. Continuous Cyclic Lifting Processes

3.1 Case 1

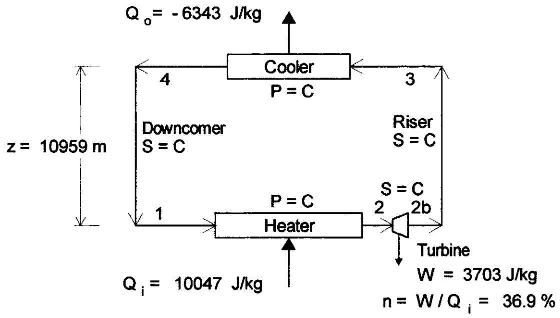
The well known Brayton gas-turbine cycle shown in Fig. 2 is thermodynamically equivalent to case 1 because the air goes through the same thermodynamic states in both cycles. The Brayton ideal gas-turbine cycle has been described in many thermodynamic text books, see for example Leonard (1958). It is customary in the analysis of ideal cycles to assume that the velocity in the conduits is sufficiently low that friction losses and kinetic energy are negligible. Reversibility also requires that the heat be received and given up from sources at temperatures approaching the temperature of the working fluid.

The turbine in the Brayton cycle of Fig. 2 is divided in two parts, a turbine driving the compressor and a turbine producing the net cycle work. Isentropic expansion and compression can take place in a vertical tube instead of in a mechanical turbine, therefore the compressor and the turbine driving it can be replaced by vertical tubes as shown in Fig. 3. The vertical tubes, called *riser* and *downcomer*, must be very high because the pressure depends on the weight of the air. The new ideal cycle of Fig. 3 will be called the *gravity* cycle because its operation requires gravity which is not required in the



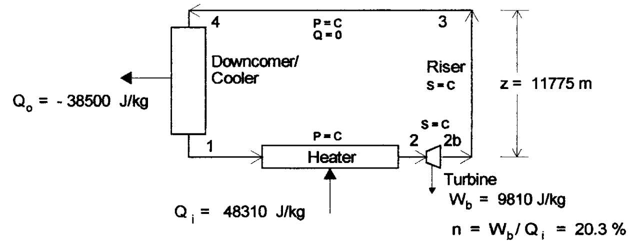
State	P (kPa)	T (K)	s (J/K.kg)	h (J/kg)
1	100	290	60.14	16929
2	100	300	94.20	26975
2b	95.77	296.31	94.20	23272
3	20	189.42	94.20	-84126
4	20	183.10	60.14	-90467

Fig. 2. Brayton gas-turbine cycle – Case 1 conditions



State	P (kPa)	T (K)	s (J/K.kg)	h (J/kg)	gz (J/kg)	μ (J/kg)
1	100	290	60.14	16929	0	16929
2	100	300	94.20	26975	0	26975
2b	95.77	296.31	94.20	23272	0	23272
3	20	189.42	94.20	-84126	107398	23272
4	20	183.10	60.14	-90467	107398	16929

Fig. 3. Gravity cycle – Case 1 conditions



State	P (kPa)	T (K)	s (J/K.kg)	h (J/kg)	gz (J/kg)	μ (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	-59967	115395	55429
4	20	213.5	214.14	-59967	115395	55429

Fig. 4. Gravity cycle – Case 2 reversible conditions

Brayton cycle. There is also no need for the shaft transferring work between the turbine and the compressor as is the case in the Brayton cycle; the combination of gravity and flow work takes care of transferring work from the expanding air to the air being compressed. Except for the addition of the change in elevation, the technique used for analyzing the *gravity* cycle is the same as the technique used for analyzing steady-state ideal thermodynamic cycles.

The Brayton cycle is impractical for the conditions shown in Fig. 2 because the mechanical efficiency of real turbines and compressor is around 80%. The work lost in the turbine and compressor (20% of $2 \times 110000 = 44000\,\mathrm{J/kg}$) would be more than the net cycle work. In real gas-turbine, the work of expansion must be significantly higher than the work of compression. Turbine efficiency is not a limitation in the gravity cycle because the work loss due to turbine inefficiency is 20% of the net turbine work (20% of $3703 = 740\,\mathrm{J/kg}$). Expansion and compression in vertical conduit can be very efficient; the compression efficiency in a slowly subsiding layer can approach 100%.

3.2 Case 2

Figure 4 shows the gravity cycle corresponding to case 2. In Fig. 3 the air is cooled at constant pressure; in Fig. 4 the air is cooled as is descends in a polytropic process. Cooling the air as it descends and is compressed is what happens in the atmosphere. Cooling a gas while it is compressed in a mechanical compressor would be difficult, but cooling the air subsiding in the atmosphere while it is giving up heat by infrared radiation to space is a natural process.

The total energy equation,

$$w_b = q - \Delta h - \Delta gz - \frac{\Delta v^2}{2} \tag{2}$$

which reduces to (1) when the process is adiabatic ($q = 0$), and when the inlet and outlet velocities (v) are negligible, is applicable to any continuous process. For processes with negligible kinetic energy, the *external-energy* ($w - q$) transfer is equal to the reduction in *static-energy* of the flowing fluid, ($w - q = -\Delta\mu$). The external-energy transfer can be fully determined from the change in the static-energy of the fluid, there is no need to consider external forces. The external-energy is work in a turbine and heat in heat exchange processes. The heat received during process 1–2 equals the increase in the enthalpy of the air because there is no external work and no change in elevation. The work given up during process 2–3 is the decrease in static-energy because there is no heat transfer during the lifting process. The heat given up during cooling process 4–1 of Fig. 4 is equal to the decrease in the static-energy of the air because there is a change in elevation and no external work. The work during process 2–2b is equal to the decrease in enthalpy because there is no heat transfer and no change in elevation. The static-energy is constant during process 2b–3 because there is no external-energy transfer.

In engineering, enthalpy change is used to calculate external-energy transfer because enthalpy avoid having to consider flow work. Change in static-energy could play a similar role for processes where potential energy cannot be neglected. Reduction in static-energy takes care of flow work and gravity work, there is no need to specifically consider the work supplied by pressure force or by gravity.

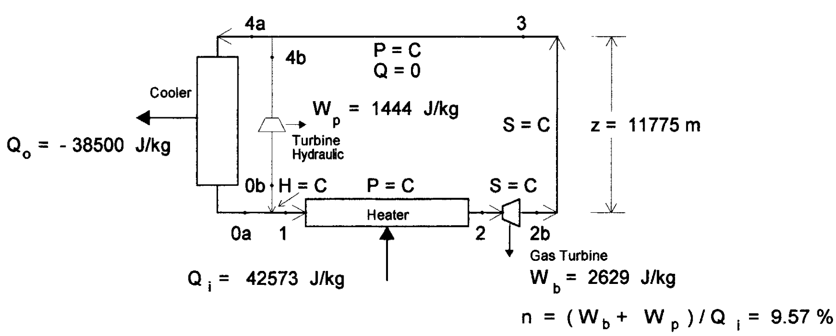
3.3 Case 3

Figure 5 shows the continuous cycle equivalent for case 3a. The potential energy of the condensed water is captured in a hydraulic-turbine to close the cycle. There are two kinds of irreversibility, *mechanical* and *chemical* irreversibility. Mechanical irreversibility can be eliminated by using ideal cycles, but chemical irreversibility is unavoidable because it is impossible to un-mix reversibly. Case 3 demonstrates a method of calculating chemical irreversibility of the cycle. Internally generated entropy is a measure of the irreversibility, and all the internally generated entropy increase occurs in the mixing process. The irreversibility of the whole cycle is therefore equal to the irreversibility of the mixing process. The work loss due to irreversibility is roughly equal to the entropy increase multiplied by the average temperature during the mixing process. Table 1b shows that the entropy produced in mixing process 0–1 is $4.23\,\mathrm{J\,K^{-1}\,kg^{-1}}$ in case 3a and $3.35\,\mathrm{J\,K^{-1}\,kg^{-1}}$ in case 3b. The entropy produced is higher in case 3a because the two streams are further from equilibrium. The work lost (w_l) in the mixing process is approximately 20% of the total reversible process work (w_t).

Cases 3a and 3b are based on the condensed water freezing and not separating from the air, true-adiabatic expansion with freezing. Michaud (1995), table 5 showed how the work is affected by freezing and separation. The work of buoyancy is slightly lower when the condensed water does not freeze. Separating the condensed water results in less potential energy of condensed water, and more work of buoyancy. Expansion without and with separation are usually called true-reversible and pseudo-reversible expansion, respectively. In fact, both processes are be reversible, although the pseudo-adiabatic expansion process is more difficult to reverse.

3.4 Discussion

Van Ness (1969, see page 78) showed that the efficiency of reversible cycles can be calculated from the first and second law of thermodynamic alone, there is no need to consider a specific cycle. All reversible cycles operating between the same source temperatures have the same efficiency. The work per unit mass of air raised is the same whether the air is raised in a continuous process such as shown in Figs. 3–5 or in the



State	P (kPa)	T (K)	r (g/kg)	s (J/K.kg)	h (J/kg)	gz (J/kg)	μ (J/kg)
1	100	274.12	12.55	43.04	11278	0	11278
2	100	295	12.55	192.95	53851	0	53851
2b	96.99	292.44	12.55	192.95	51222	0	51222
3	20	213.46	12.55	192.95	-65622	116844	51222
4a	20	213.46	0.03	214.69	-59884	115399	55515
0a	100	290	0.03	60.55	17017	0	17017
4b	20	213.46	12.52	-21.74	-5738	1444	-4294
0b	100	213.46	12.52	-21.74	-5738	0	-5738

Fig. 5. Gravity cycle – Case 3a conditions

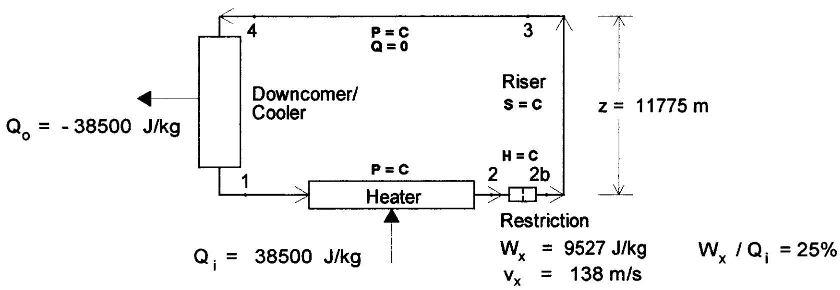
discontinuous process shown in Fig. 1. The fact that the drastically different discontinuous and continuous processes have identical efficiencies shows that the work produced when heat is transported upward by convection is the same for all reversible processes. Work of buoyancy w_b is equivalent to Convective Available Potential Energy (CAPE) which is the integral of the force of buoyancy times distance in a reversible lifting process; Michaud (1995) showed that $w_b = \text{CAPE}$. Small differences between the atmospheric process and the ideal cycles do not invalidate the analysis. The size of the components, the position of the components including the horizontal distance between them, and the velocities are unimportant. The atmospheric heat transport process is not strictly continuous or discontinuous, but the conversion efficiency is valid for processes with variable heating rate and variable convective heat transport rate.

The Carnot cycle is an ideal cycle where the heat is received at a single hot source temperature and given up at single cold source temperatures. The Brayton cycle is an ideal cycle where the heat is received and given up over a ranges of temperature. Both the Carnot cycle and the Brayton cycle are reversible ideal cycles, and both operate at Carnot efficiency provided the Carnot efficiency is calculated using entropy weighted source temperatures.

Making the cycle irreversible is simply a matter of replacing the turbine of Fig. 4 with the restriction of Fig. 6. In the irreversible cycle, the heat received and the heat given up are equal since there is no external work. Reversibility requires a turbine to capture the kinetic energy before it is dissipated by friction. The turbine is basically a restriction where differential pressure produces velocity followed by a blade to capture the kinetic energy. Without the blade the process become irreversible and isenthalpic.

It is difficult to calculate the work produced in a cyclic process without initially making some assumption about where the work is produced or dissipated; a reversible cycle with the work production concentrated at one location is a good starting point. Subsequent analysis can consider work distribution and dissipation. The resistance to flow can be later be moved or distributed around the cycle to investigate the effect of making changes to the process. Some the work can be captured with a turbine and the remainder used to overcome resistance to flow.

The conditions of the air in the subsiding process are identical in Figs. 4, 5, and 6; the heat given up is the same in the three cases. Energy is transferred to the subsiding air by work of compression. In all three cases, the heat received during process 1–2 provides the heat given up in process 3–4 plus the net cycle work if any. The majority of the energy received at the surface gets transferred to the subsiding air irrespective of whether the heat is received as sensible or latent heat, and irrespective of whether the process is reversible or irreversible. The warming occurs where the air is compressed and not where the latent heat is released. The latent heat is released where the condensation occurs, but the



State	P (kPa)	T (K)	s (J/K.kg)	h (J/kg)	gz (J/kg)	μ (J/kg)
1	100	290	60.14	16929	0	16929
2	100	328.3	184.83	55429	0	55429
2b	90.25	328.3	214.14	55429	0	55429
3	20	213.5	214.14	-59967	115395	55429
4	20	213.5	214.14	-59967	115395	55429

Fig. 6. Gravity cycle – Case 2 irreversible conditions

expansion-compression process transfers the energy to where the compression or subsidence occurs.

The static-energy of a column of dry-air with an adiabatic lapse rate is uniform; the static-energy of a column of dry-air with sub-adiabatic lapse rate increases with height. In Fig. 3, the static-energy of the air entering the column of descending air, process 4–1, is equal to the static-energy of the air leaving the column because no heat is removed from the subsiding air. In Figs. 4, 5, and 6; the static-energy of the air leaving the column of descending air, process 4–1, is smaller than the static-energy of the air entering the column because the system loses heat by radiation.

A planned future article: "Subsidence required to compensate for radiative heat loss" will examine the role of work of compression in atmospheric circulation. Raising a parcel of air to the top of a column of air with a sub-adiabatic lapse rate transfers heat upward by warming the subsiding air. The pre-requisite to the lifting process is that the parcel be positively buoyant up to its final level. The pre-requisite can be met by providing either sensible heat or latent heat to the parcel before it is lifted.

The work produced in any thermodynamic cycle is equal to the area of its pressure–volume (PV) diagram. The PV diagram for the three cycles are shown in Figs. 7a and 8a. The work

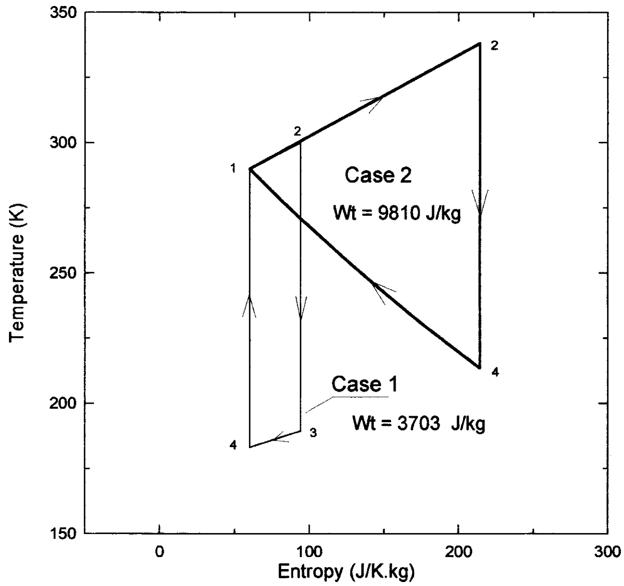


Fig. 7b. Temperature–Entropy diagram for cases 1 and 2

produced in a reversible cycle is also equal to the area of its temperature–entropy (TS) diagram. The TS diagram of the three cycles are shown in Figs. 7b and 8b. The case 1 diagrams are the same as for the Brayton gas-turbine cycle. The efficiency of a reversible cycle is equal to the area of the cycle on the TS diagram divided by the area under the heat received line; a statement which corresponds to Eq. (11) of Renno et al. (1998). The TS diagram in cases 2 and 3a have a distinct triangular shape because cooling the

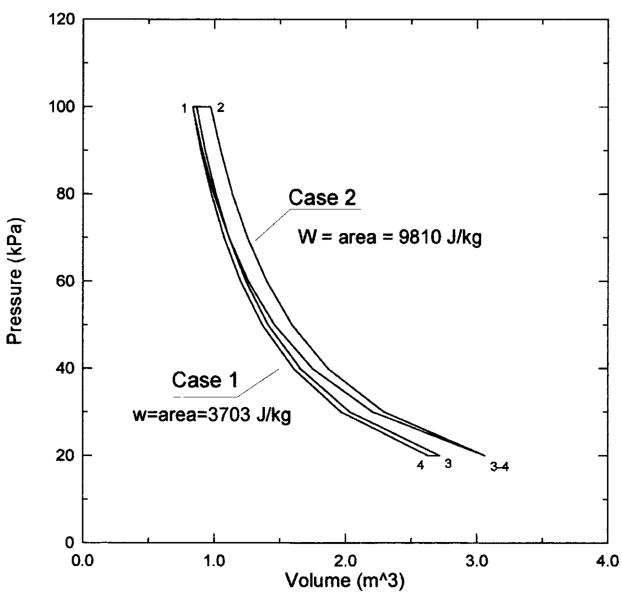


Fig. 7a. Pressure–Volume diagram for cases 1 and 2

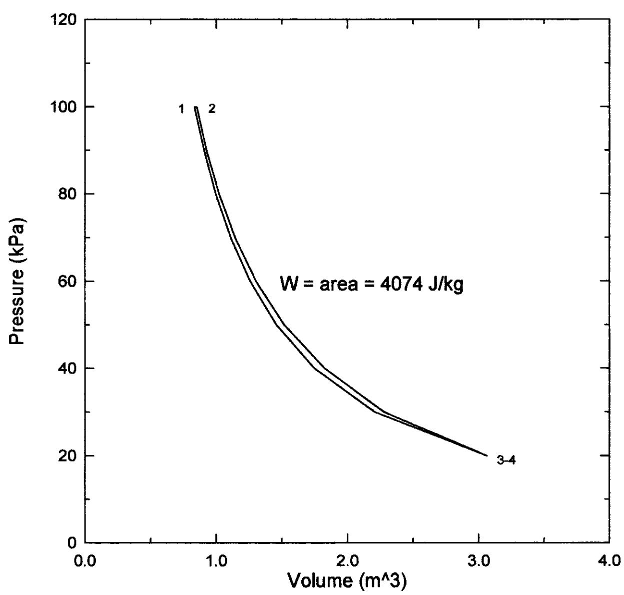


Fig. 8a. Pressure–Volume diagram for case 3

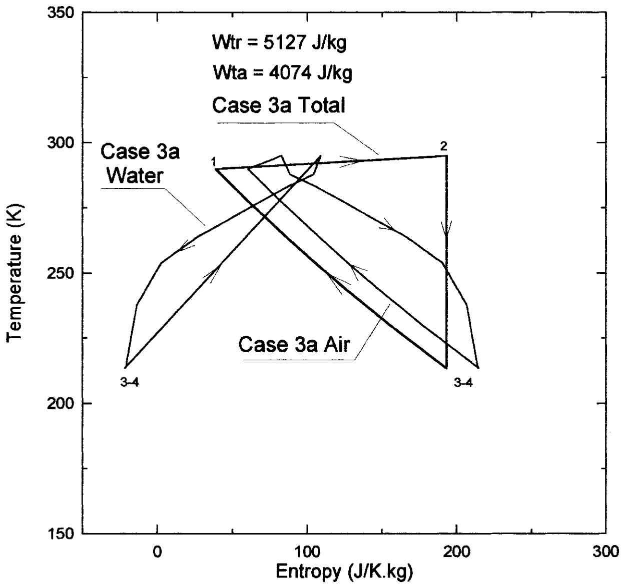


Fig. 8b. Temperature–Entropy diagram for case 3

working fluid as it subsides cuts off the lower left hand corner of the cycle. The TS diagrams show why the efficiency decreases form case 1 to case 2 to case 3a. The area of the cycle divided by the area under the heat received line is highest in case 1, and lowest in case 3a.

4. Single Tube Processes

4.1 Circular Tube

The gravity cycles can be implemented with the single circular tube as shown in Fig. 9, which is

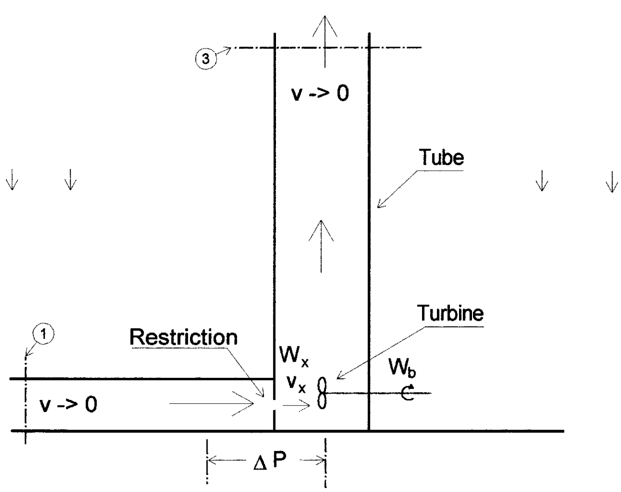


Fig. 9. Single circular tube upflow process. The kinetic energy of the air at the restriction outlet is captured by the turbine, $w_b = w_x$

simply a cyclic process where the area of the *downcomer* is much larger area than the area of the *riser*. The pressure at the base of the tube is equal to the pressure at the top of the tube plus the weight per unit area of the air in the tube. The radial pressure differential between the outside and the inside of the tube is a maximum at the bottom of the tube and zero at the top of the tube. The work produced in a turbine installed at the base of the tube, such that the turbine inlet pressure is the surface ambient pressure and the turbine outlet pressure is the surface pressure inside the tube, can readily be calculated by applying the total energy equation to the turbine, and is equal to the work of buoyancy because the turbine the only place in the cycle where work can be produced. The fact that work calculated by applying the total energy equation to the turbine is equal to the work of buoyancy proves that work of buoyancy can be transferred downward to the point where the flow is restricted.

Making the process of Fig. 9 irreversible is simply a matter of removing the turbine blade and letting the kinetic energy of the jet produce turbulence and dissipate. In the reversible case, the blade captures all the kinetic energy of the jet, $w_b = w_x$; in the irreversible case, none of the kinetic energy is captured, $w_b = 0$. The kinetic energy of a small jet entering a large volume dissipates rapidly. When there is no concentrated restriction and the tube has a uniform diameter, the tube itself becomes the restriction and the velocity persists for the length of the tube.

This paper considers the work produced when the air is raised to a single level, but the work can have negative values corresponding to the negative area on the tephigram. Work of buoyancy corresponds to the integrated area of the tephigram. CAPE depends on the difference in density between the rising air and the environment, but with the total energy equation there is no need to consider the subsiding fluid, the buoyancy force, or intermediate states. For an adiabatic process, the work is a maximum when the flow is isentropic, when there is no friction loss. For given inlet and outlet pressures, the enthalpy change is a function of the initial properties of the fluid, and the potential energy change is a function of the height between the two pressure levels.

4.2 Experimental Verification

The Manzanares solar chimney, Schiel and Schlaich (1988), provides physical verification of the concept. The pilot plant built in Spain in the 1980's, shown in Fig. 10, consisted of a vertical chimney 10 m in diameter by 200 m high with a turbine installed in its base. The chimney was surrounded by a 240 m diameter solar collector which consisted of a clear plastic sheet supported 2 m above the ground. The collector increased the air temperature by about 20 C. The air flowed through the open rim of the collector and up the chimney. The upward velocity in the chimney was approximately 9 m/s. The operating conditions shown in Fig. 10 are from Mullett (1987). The Manzanares *upward wind solar power plant* operated reliably for seven years, it had an overall efficiency of 0.1% and an electrical output of 48 KW.

The work of buoyancy (w_b), which would have been 130 J kg^{-1} in an ideal process, was distributed as follows: electrical output 61 J kg^{-1}; exit losses 40 J kg^{-1}, friction losses 7 J kg^{-1}, and turbine and generator losses 22 J kg^{-1}. The Manzanares solar chimney confirms that work of buoyancy can be transferred downward to the place where the flow is restricted. Reducing the work to zero, by orienting the turbine blades vertically, increased the upward velocity to 13.5 m/s. Under this zero work condition, the work of buoyancy decreased to approximately 107 J kg^{-1} because of the temperature increase of the air is smaller at higher flow; the work was distributed as follows: exit losses 91 J kg^{-1}, and friction 16 J kg^{-1}. In the no work condition, the work was almost entirely used to produce exit velocity, and most of the irreversibility occurred as the jet left the chimney rather than in the chimney.

4.3 Sensitivity Analysis

The work of buoyancy for a given sounding is readily calculated as the reduction in static-energy of the surface air between its initial and its final state. The four cases shown in Table 2 show the effect of the temperature and humidity on the work when surface air is raised reversibly to the 20 kPa level in typical tropical oceanic

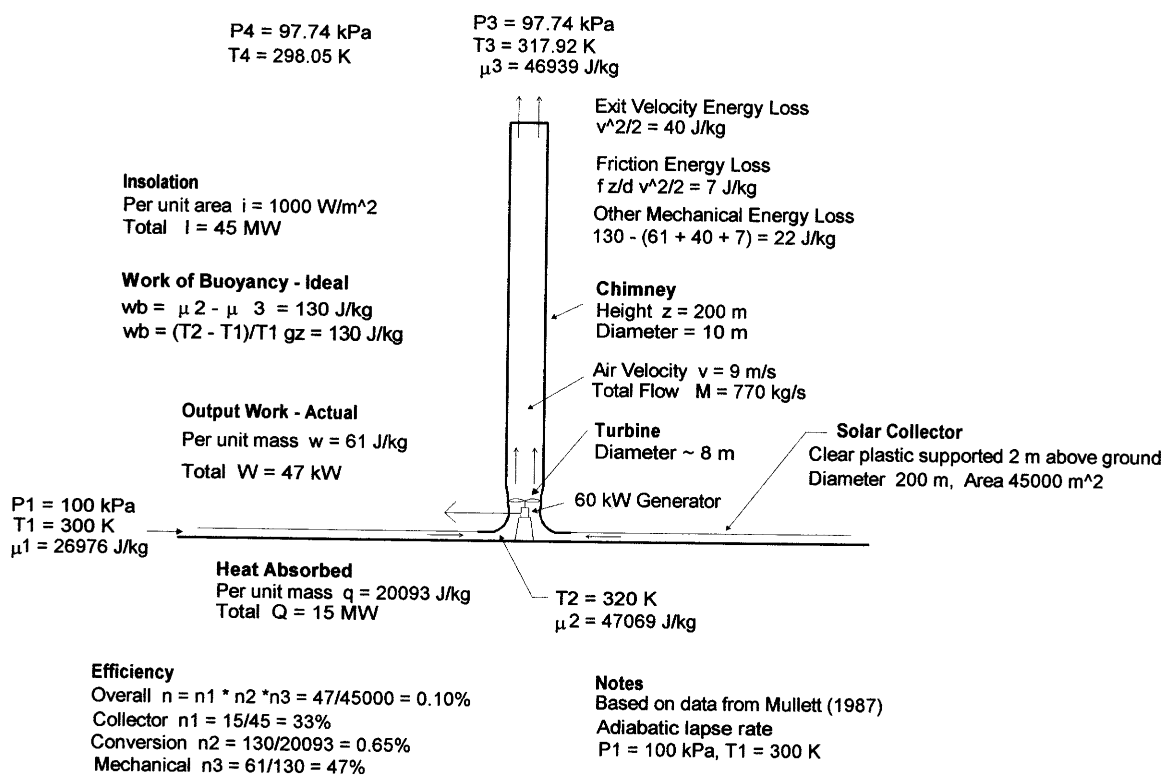


Fig. 10. The Manzanares solar chimney consisted of 200 m high vertical tube surrounded by a solar collector with a turbine in the base of the tube

Table 2. *Work Produced when Air is Raised Reversibly from Sea Level to the 20 kPa Level, Based on 20 kPa Geopotential Height of 12400 m*

Parameter	Base	$T_1 + 2$ $m = C$	$U_1 + 5$ $T = C$	$T_1 + 1$ $U = C$
Properties				
P_1 (kPa)	101.0	101.0	101.0	101.0
T_1 (C)	*27.0*	*29.0*	*27.0*	*28.0*
T_1 (K)	300.15	302.15	300.15	301.15
U_1 (%)	*80*	70.89	*85*	*80*
r_1 (g/kg)	*18.18*	*18.18*	19.31	19.31
h_1 (J kg^{-1})	73485	75562	76382	77422
s_1 (J K^{-1} kg^{-1})	256.7	263.6	266.5	269.9
P_2 (kPa)	99.06	98.53	98.41	98.16
T_2 (K)	298.50	300.02	297.94	298.71
U_2 (%)	86.71	78.57	94.70	90.09
h_2 (J kg^{-1})	71775	73355	74088	74887
P_3 (kPa)	20.0	20.0	20.0	20.0
T_3 (K)	228.50	229.91	230.85	231.54
z_3 (m)	12400	12400	12400	12400
h_3 (J kg^{-1})	−51954	−50373	−49778	−48979
μ_3 (J kg^{-1})	71775	73355	74088	74887
Work (J kg^{-1})				
$\Delta h_{31} = h_1 - h_3$	125440	125935	126160	126401
$\Delta gz_{13} = gz(1 + r)$	123730	123729	123867	123867
$w_b = h_1 - \mu_3$	*1710*	*2207*	*2295*	*2535*
$w_p = gz\ r_1$	2180	2175	2309	2306
$w_t = w_b + w_p$	3891	4382	4604	4841
Increments (J kg^{-1})				
$q = \Delta h_1$	base	2077	2897	3937
Δw_b	base	497	585	825
Δw_t	base	491	713	950
$\Delta w_b/q$ (%)	base	23.9	20.1	20.9
$\Delta w_t/q$ (%)	base	23.6	24.6	24.1
$n = 100(1 - T_3/T_1) = 23.9\%$				

conditions. The 20 kPa height in tropical area is typically 12400 m. The work of buoyancy would be higher if the air were lifted to its level of neutral buoyancy. The level of neutral buoyancy in tropical oceanic areas is usually closer to 10 kPa than 20 kPa. A uniform upper level of 20 kPa is used to facilitate comparison.

In the base case where the air temperature and relative humidity are 27 C and 80%, respectively, the work of buoyancy is 1710 J kg^{-1}. Increasing T_1 by 1 K while keeping the mixing ratio constant increases w_b by 248 J kg^{-1}. Increasing the relative humidity by 5% at constant temperature increases w_b by 585 J kg^{-1}. Increasing mixing ratio r_1 by 1 g kg^{-1} while keeping the temperature constant increases w_b by 517 J kg^{-1}. Increasing T_1 by 1 K at constant relative humidity increases the work of buoyancy by 825 J kg^{-1} because the temperature and the mixing ratio both increase. Small changes in surface air temperature have a large effect on w_b. Decreasing T_1 by 2 K at constant relative humidity is sufficient to decrease w_b to close to zero. w_b is slightly higher for pseudo-adiabatic expansion and slightly lower for true-adiabatic expansion without freezing, but the effect of separation and freezing are small compared to the effect of surface temperature or surface humidity.

Decreasing the 20 kPa height by 100 m by decreasing the average temperature of the sounding by approximately 2 K, increases w_b by 1000 J kg^{-1}, which explains why convection occurs at lower surface temperature and humidity in higher latitude where geo-potential heights are lower. CAPE in active convection areas is typically between 1200 to 2200 J kg^{-1}, Lucas et al. (1994). CAPE over the tropical gulf of Carpentaria averaged 1920 J kg^{-1} over a one month period and was only occasionally under 1000 J kg^{-1}, McBride and Frank (1999). Heating from below and cooling from above both increase CAPE. Convection reduces CAPE and tends to maintain CAPE in the 1200–3000 J kg^{-1} range. Positive CAPE without a tube is not sufficient to produce deep convection because entrainment reduces buoyancy, Michaud (1998).

Calculating the efficiency in the base case is difficult because the temperature at which the heat is received is not known, but it is easy to calculate the effect of incremental heating on the work. Table 3 shows that the incremental efficiency for the total work ($n_t = \Delta w_t/q$) is close to the Carnot efficiency of 23.9% based on bottom temperature (T_1) and top temperature (T_3). Note that the cold source temperature used in calculating this incremental Carnot efficiency is the temperature at the top of the troposphere and not the average temperature of the troposphere because adding heat to the air before it is raised increases the temperature at the 20 kPa level, but does increase subsidence heating at intermediate levels.

The incremental efficiency for work of buoyancy ($n_b = \Delta w_b/q$) is 24% for sensible heat addition and 20% for latent heat addition. The reduction in n_b for latent heat addition is almost entirely due to the fact that more work is required to lift water. The effect of chemical irreversibility on incremental efficiency is negligible because the water and the air are close to equilibrium. Mixing 1 g of water with 1 kg dry-air at 300 K generates 1.85 J K^{-1}kg^{-1} of entropy. Mixing 1 g of water with 1 kg air at 80% relative humidity at 300 K generates 0.06 J K^{-1} kg^{-1} of entropy. The lost work is 550 J in the dry air case and only 17 J in the 80% humidity case.

5. Annular Tube Process

5.1 Physical Tube

The shape of the riser does not change the thermodynamic process, therefore the upflow can take place in the annular tube shown in Fig. 11 rather than in a circular tube shown in Fig. 9. The annular tube will initially be considered to be have solid insulated frictionless walls. The upward flow takes place in the annulus; there is no flow in the central tube which is closed at the bottom. The left side of Fig. 11 represents a physical tube, while the right side represents a dynamic tube where the role of the physical wall is replaced by centrifugal force. The restriction shown at the bottom left keeps the velocity in the annular tube low so that friction losses and exit losses are negligible. The losses are therefore concentrated at the restriction. The upflow process is isentropic except for the isenthalpic dissipation of the jet at the restriction outlet corresponding to the irreversible case of Fig. 6.

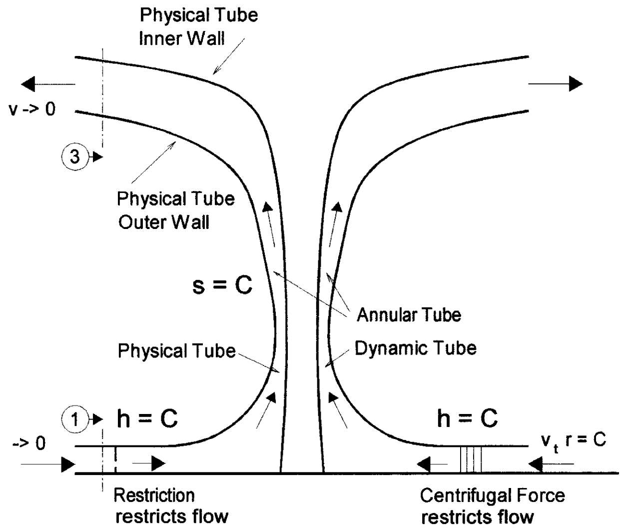


Fig. 11. Annular tube upflow process. The left side represents a real physical tube, and on the right side the physical tube is replaced by centrifugal force

A good way to understand how a convective vortex works is to start with a real physical annular tube, and consider what happens when the air converging towards the base of the tube has tangential velocity (v_t). As the air converges towards the tube, its tangential velocity increases to conserve angular momentum ($v_t r = C$), where r is the radial distance from the vortex axis. The pressure differential due to centrifugal force in the converging air is $\rho v_{tm}^2/2$, where v_{tm} is the maximum tangential velocity. The air converges up to the point where the radial pressure differential is balanced by centrifugal force. In a frictionless flow, the radial flow would stop once the centrifugal force is equal to the pressure reduction at the base of the tube. Further convergence can only occur after friction has reduced tangential velocity sufficiently for centrifugal force to become less than the base pressure differential. Convergence is limited to the thin layer against the earth's surface because friction is negligible above the surface layer.

The tangential velocity does not have to be reduced to zero for the air to converge up to the annulus. Therefore the air rising in the annulus retains some tangential velocity and the centrifugal force produced by the rising and spiralling air opposes the radial pressure differential. If the physical tube were to vanish or lose its radial strength after the vortex is established its diameter would adjust itself until the radial pressure differential is balanced by centrifugal force. Once the radial pressure balance is established there would be no further convergence at intermediate levels. The vortex would diverge at high elevation where the radial pressure differential decreases.

Trapp and Davies-Jones (1997) suggested that a dynamic pipe effect could explain the descent of tornado vortex signature from aloft. They wrote: "a vortex in cyclostropic balance permits little or no radial flow into its core because the radial pressure gradient force is in stable equilibrium with centrifugal force", and "the cyclostropic balance is upset in the surface layer because friction reduces the tangential wind and centrifugal force". Concentrating the resistance to flow near the earth's surface to make the process analyzable was a fortunate choice which appears to correspond to what take place in convective vortices. Renno et al. (1998) pointed out that the intensity of a convective vortex increases with the fraction of the total dissipation of mechanical occurring near the surface. Bister and Emanuel (1998) showed that the work dissipation in their hurricanes model is concentrated at the surface.

The work loss due to friction in a circular tube is $w_d = fz/dv^2/2$, where w_d is the work dissipated and d is the tube diameter. The work loss due to friction for turbulent flow at a velocity of 20 m/s, in a horizontal circular tube 10 km long, by 100 m in diameter, is in the order of $100\,\mathrm{J\,kg^{-1}}$. The friction factor (f) for turbulent flow in the circular tube is approximately 0.006. The friction loss in an annular vortex would probably be lower than in a circular tube of equal area because the friction factor would be lower for organized vortex flow than for turbulent flow. For a given flow, the friction loss is roughly inversely proportional to the fifth power of the tube diameter. The frictional losses in the processes 3–4, 4–1, and 1–2 which have much larger cross-sectional areas than process 2b–3 are negligible. The total frictional losses for the complete continuous cycles would depend on flow and diameter and could be around $100\,\mathrm{J\,kg^{-1}}$, which can be a small fraction of the work of buoyancy. A further advantage of vortex flow is that the tube flares out at the top the kinetic energy decreases and that the exit losses become negligible.

The high wind observed near the base of convective vortices demonstrate that frictional losses in the rising tube only consume a small part of the work of buoyancy. Friction losses are much higher in discontinuous updrafts than in continuous upflow. Michaud (1998) considered how work is dissipated in nonrotating updrafts by entrainment and drag.

5.2 Vortex Power Station

It is proposed that a tornado-like vortex could be initiated by heating the air in a circular station with fuel while giving the air converging towards the center of the station angular velocity by having it pass through tangential entry slots or a rotating screen. The proposed vortex power station is shown in Fig. 12. A vertical axis turbine located at the center of the station could capture some of the mechanical energy produced during the upward heat convection process.

The physical tube of the solar chimney is replaced by centrifugal force in the vortex. There is no need for a covered collector; the layer of humid air at the bottom of the atmosphere acts as the solar collector. Once the vortex is established it could persist without heating with fuel and would remain in the center of the station. A vortex power station with a diameter of 500 m might have an electrical output of 100 MW and produce 1000 Joules of mechanical energy per kilogram of raised air at an upward air flow of $10^5\,\mathrm{kg\,s^{-1}}$. The proposed vortex power station is described in Michaud (1999).

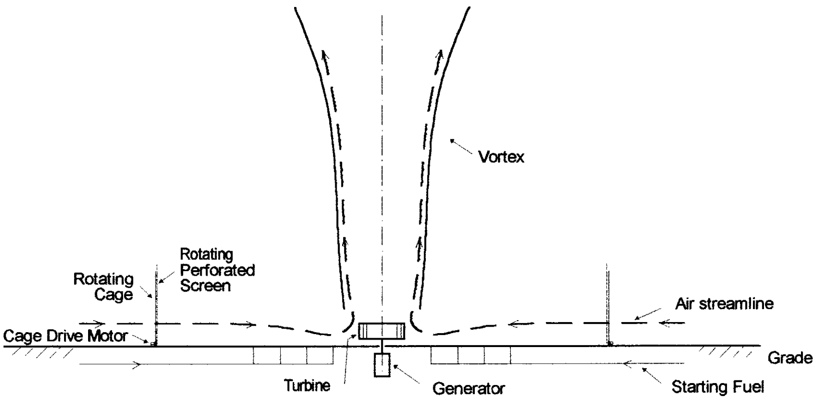


Fig. 12. Proposed vortex power station. The vortex would be initiated by heating the air in the station with fuel while giving the converging air angular momentum by having it pass through a rotating perforated screen

The work produced when a unit mass of air with a CAPE of 2000 J kg^{-1} is raised is roughly equal to the work produced when a unit mass of water is lowered 200 m. The total mechanical work produced by humans is around 2 TW while the work produced in the atmosphere is around 12000 TW ($510 \times 10^{12}\,m^2 \times 25\,W/m^2$). The work produced and dissipated in the atmosphere is 6000 times more than the work produced by humans. Finding a way of controlling and capturing the mechanical energy produced during upward heat convection could provide a large source of energy.

6. Conclusion

The atmospheric process is often considered to be too complex to be understood with thermodynamics alone. In fact, the atmospheric process is too complex to be analyzed without idealization and simplifications. Reversible cycles, which at first appear to be unrealistic, can help understand real processes. Idealized cycles, whether reversible such as Fig. 4 or irreversible such as Fig. 6, have the advantage of being readily analyzed. Results can be validated from energy conservation or from the agreement with Carnot efficiency. The results were obtained using techniques whose validity has been demonstrated on well understood processes.

Attempts to model the atmospheric process without simplification are unlikely to achieve the results possible with ideal cycles. Adiabatic processes are almost invariably modelled as isentropic. Bister and Emanuel (1998) pointed out that dissipative heating has not been accounted for in most numerical simulation. Figure 6 shows that, in an irreversible process, the expansion is partly isenthalpic and partly isentropic. Once the reversible adiabatic expansion process is understood the effect of heat exchange during the process can easily be added.

This article has used closed thermodynamics cycles to show that the work produced during upward heat convection depends on the convective upward heat flux and on the temperature difference through which the heat flows. The work was shown to be in accordance with the Carnot efficiency for the closed cycle and the incremental work was shown to be in accordance with the Carnot efficiency for the open cycles. The external-energy transfer in any process was shown to be equal to the reduction in the static-energy of the flowing fluid. The article showed that the work of buoyancy can be transferred downward and concentrated at the point where the flow is restricted.

Appendix

Mechanism for Extracting Work in a Discontinuous Lifting Process

Thermodynamic cycles must be designed with care to be reversible. As stated in Michaud (1995), the convection process could be made reversible by enclosing a sphere of buoyant air in a weightless insulated envelope and by attaching and removing weights to the sphere as it rises so that its upward velocity remains low enough for friction losses to be negligible, the work of buoyancy would increase the potential energy of the weights. Without weights, the work of buoyancy would increase the kinetic energy of

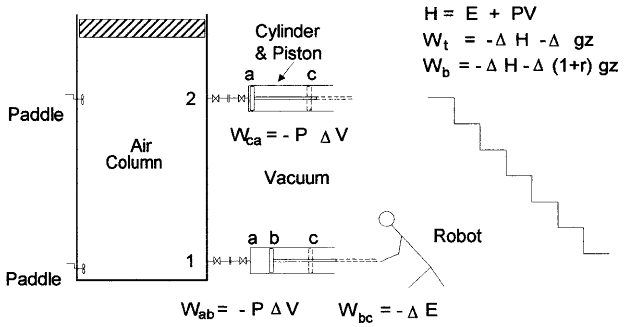


Fig. A1. Process for raising air reversibly

the rising sphere and eventually be dissipated by friction. Michaud (1998) showed that friction limits the kinetic energy to a value far below the work of buoyancy.

Figure A1 shows a reversible lifting process, in which air is moved upward in an insulated weightless cylinder by a weightless robot. The robot, which is in a perfect vacuum, has an internal mechanism for storing and giving up mechanical energy without loss. The lifting process consists of the following steps:

1. The cylinder is attached to the lower connection on the column with the piston against the cylinder head, in position *a*.
2. The two valves on the bottom connection and on the cylinder are opened.
3. The robot slowly allows the piston to move from position *a* to *b* while storing the work done by the piston in its mechanism.
4. The two valves on the bottom connection and on the cylinder are closed.
5. The robot slowly allows the piston to move from position *b* to *c* the point at which the pressure is equal to the pressure at the upper column connection. The robot stores this additional work in its mechanism.
6. The robot locks the piston in place, disconnects the cylinder at the flange and carries it up to the upper connection by using some of its energy to increase the potential energy of the air. The robot attaches the cylinder to the upper flange.
7. The robot fully opens the valves on the upper connection and on the cylinder.
8. The robot unlocks the piston, and uses some of its stored energy to slowly push the piston from position *c* to *a*.
9. The energy remaining in the robot is the work of buoyancy, w_b.
10. Before carrying the cylinder up, the robot could tip the cylinder valve downward and carefully drain the condensed water without letting any air out. Not having to provide potential energy to the condensed water increases the work left in the robot at the end of the lifting process from w_b to w_t.

The work produced when the air is moved from one place to another without change in level is equal to the reduction in its enthalpy ($w = -\Delta h$). The work used in raising the air with the piston locked in place is equal to the increase in potential energy ($w = -\Delta gz$). The process shows that, in an adiabatic reversible lifting process, the work is equal to the reduction in the static-energy of the fluid, ($w = -\Delta h - \Delta gz$). For the base case in Table 2, the reduction in the enthalpy is $125440\,\mathrm{J\,kg^{-1}}$, the increase in the potential energy is $123730\,\mathrm{J\,kg^{-1}}$, and the net work is $1710\,\mathrm{J\,kg^{-1}}$.

Moving the air in a cylinder is akin to the process used so effectively by Carnot (1824). The introduction of Carnot's book written before the discovery of the law of conservation of energy states: "To the flow of heat are due all movements including: wind, precipitation, volcanoes, and steam engines so common now a day".

The process could be made irreversible by having the robot use the energy it has left at the end of the reversible cycle to turn one of the paddle shown on the column until the work is dissipated by friction. The work could also be dissipated by only partly opening the upper valve and having the robot push hard so that whatever energy it has left is used to push the air through the valve. Friction in the pipe or in the piston are other ways the work could be dissipated.

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Author's address: Louis M. Michaud, 1269 Andrew Court, Sarnia, Ontaino, N7V 4H4 Canada (E-mail: louis.michaud@sympatico.ca)