Unrestrained Expansion - A Source of Entropy
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Abstract

The paper examines the role of unrestrained expansion in atmospheric entropy production. Lack of mechanical equilibrium is shown to be a far larger producer of internally generated entropy than other internally generated entropy production processes. Isentropic expanders are used to explain atmospheric entropy production. Unrestrained expansion can account for the discrepancy between the energy that would be produced if the heat were carried by Carnot engines and the energy actually produced. Having an expander in more important to mechanical energy production than reducing friction losses. The method of analysis is applicable to the solar chimney and to the atmospheric vortex engine.

1. Introduction

Entropy is produced when the Earth intercepts solar radiation emitted at high temperature and re-emits infrared radiation at lower temperature. Fig. 1 shows the Earth's entropy budget based on a recent paper by Kleidon and Lorenz (2004). The entropy received by the Earth is 41 mW K^{-1} m^{-2} (S_{ei}), the entropy given up by the Earth is 933 mW K^{-1} m^{-2} (S_{eo}), the difference 892 mW K^{-1} m^{-2} (S_i) must be produced internally within the Earth system. 255 mW K^{-1} m^{-2} (S_{ia}) is produced when solar radiation is absorbed by the upper atmosphere, 560 mW K^{-1} m^{-2} (S_{ib}) is produced when solar is absorbed by the Earth's surface, and 77 mW K^{-1} m^{-2} (S_{ic}) is produced when heat is transported upward through the troposphere.

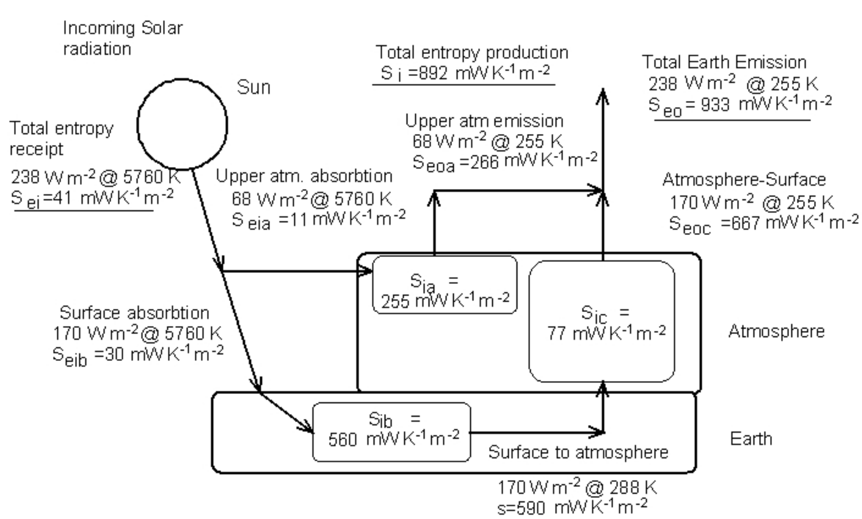


Fig.1 Earth overall entropy budget

When entropy is produced there is a potential for producing work and life. The second law of thermodynamic only requires that there be a net increase in entropy, but low entropy organized structures can be formed provided there is a net entropy production. Sadi Carnot wrote: “to the flow of heat is due all movement we see on the Earth”. Ilya Prigogine wrote: “to the flow of heat are due all organized flow structures including life itself”. Absorption in the upper atmosphere produces ozone, a low entropy organized structure. Under the right circumstances, absorption near the Earth’s surface can produce living organisms which can eventually become fossil fuels. Upward heat transport by convection can produce mechanical energy in the form of wind and hydraulic energy.

Balancing the Earth’s entropy budget requires that entropy be produced within in the Earth system. Internal entropy production must make up for the net external entropy export irrespective of process details. If the 238 W m^{-2} of solar radiation were received on the moon and re-transmitted at 255 K, the total internally generated entropy would be the same 892 mW K^{-1} m^{-2}.

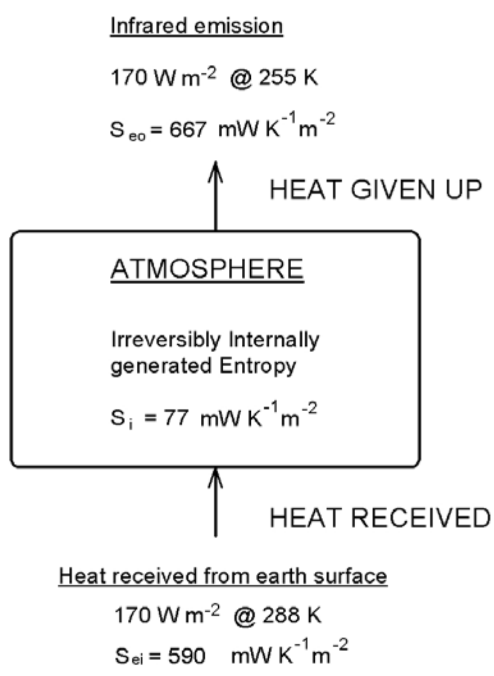


Fig. 2 Entropy budget of atmospheric upward heat convection.

2. Atmospheric entropy production

This paper will focus on entropy production when heat is carried upward in the atmosphere, the process shown in Fig. 2. Osawa et al. (2003) showed that entropy is produced whether the heat is carried through a system by conduction, radiation, or convection. The entropy production for heat transported by conduction is well understood and results from thermal non-equilibrium. The entropy production for heat transferred by radiation is the same as that for the solar radiation absorbed in the upper atmosphere and is also results from thermal non-equilibrium. The entropy production for heat transported by convection is more subtle and results from mechanical non-equilibrium.

Of the three upward heat transport processes convection is by far the most important. In this paper, it will be assumed that convection is the only heat transport process. What regulates the entropy production process? Why is total entropy production independent of the heat transport processes?

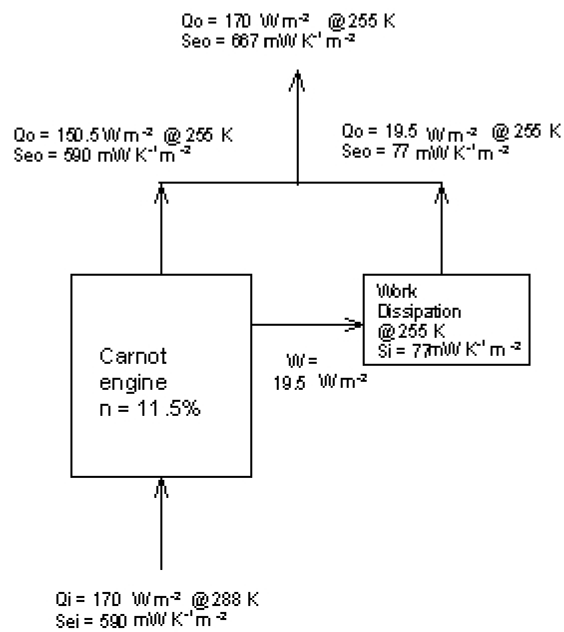


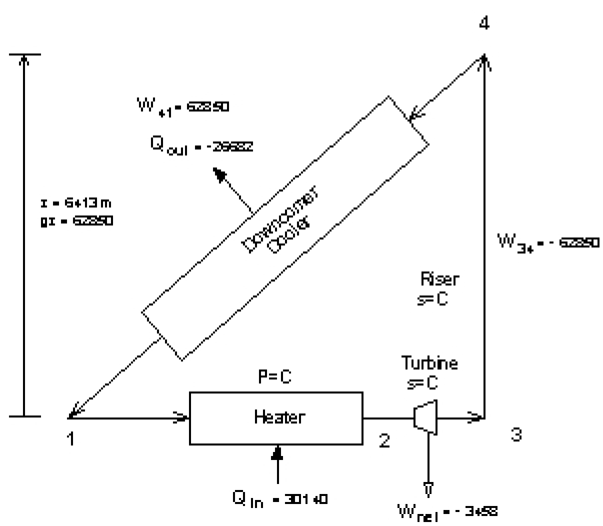
Fig. 3. Entropy budget when the heat is carried by a Carnot engine followed by dissipation of the work at cold source temperature.

There is a way of avoiding the production of entropy when heat is carried upward by convection and that is to use a Carnot engine as shown on the left side of Fig. 3.
A reversible Carnot engine maximizes work production while reducing entropy production to zero. An irreversible engine would reduce but not eliminate entropy production while producing less work than a Carnot engine.

I apologize for mentioning reversible cycles at non-equilibrium thermodynamic session. Van Ness wrote: “The reversible cycle is the only one for which we can do calculations. The alternative is likely to be no calculations at all”. Sadi Carnot discovered the second law by playing with ideal expanders. Rudolf Clausius took 40 years to rediscover the second law and he had the advantage of being aware of Carnot’s work. How long would it have taken for someone to discover the second law without the use of ideal engines?

Two common types of expanders are: the cylinder and piston, and the turbine. A thermodynamic engine requires an expander with a shaft to transfer mechanical out of the system. The expander in a Carnot engine is a two-stage expander: an isentropic stage and a constant temperature stage.

The right side of Fig. 3 shows that, when the work produced by the Carnot engine is dissipated at cold source temperature; the entropy produced when the work is dissipated is the same as without the Carnot engine. Since there is no way of exporting work from the Earth system and since it is very difficult to store work, 77 mW K^{-1} m^{-2} of entropy must eventually be produced.



State	P (kPa)	T(K)	s (J/K-kg)	h (J/kg)	Duty (J/kg)
1	100	273	-0.55	-150	
					30140
2	100	303	104.20	29989	
					-3458
3	96.08	299.6	104.20	26531	
					-62850
4	42.32	237	104.20	-36319	
					36168

T_h = 288 K T_c = 255 K Efficiency = 11.47%

Fig. 4 Gravity power cycle - Pure Air

3. Gravity power cycle

The Gravity cycle in Fig. 4, described by Michaud (2000), illustrates how work can be produced when heat is carried upward. The conditions in Fig. 4 were chosen to make the average temperatures at which heat is received and given up are the same as in Fig. 3. The working fluid is pure air. The cycle of Fig. 4 requires a vertical conduit 6414 m high. The descending air is compressed as it subsides; there is no need for a physical compressor. The air is heated at constant pressure in process 1-2, expanded isentropically in an expander represented by a turbine in process 2-3, expanded further isentropically as it rises in process 3-4, and cooled at it subsides in process 4-1. Expanding air as it rises in a tall conduit is another type of expander. The work produced during process 3-4 is used to lift air and the potential energy of the raised air is used to compress the descending air in process 4-1. The work of expansion during adiabatic process 3-4 is equal to the work required to compress the air descending in process 4-1, and to the potential energy of the air at point 4.

Isentropic expansion requires that there be an opportunity to do work whether the expansion occurs in one of the two traditional types of expander or in an upflow conduit. The air in the upflow conduit expands isentropically; its temperature decreases at the adiabatic lapse rate of 9.8 K km^{-1}. The air in the down flow conduit is cooled polytropically as it descends; the lapse rate is 5.6 K km^{-1}. The heat received (Q_{12}) is 30140 J kg^{-1}, the heat given up (Q_{41}) is -26689 J kg^{-1}, and the turbine work (W_{23}) is -3453 J kg^{-1}, for an efficiency of 11.5%. The work of expansion in process 3-4 and the work of compression in process 4-1 are both 62855 J kg^{-1}.

Michaud (2000) showed that the gravity cycle is equivalent to the gas turbine cycle. Both cycles are reversible cycles in the sense that no entropy is produced when heat is transported upward. In a Carnot cycle the heat is received at a single temperature; in an ideal gas-turbine cycle the heat is received from a range of temperature. No entropy is produced during the heat transfer provided the temperature of the sources is close to the air temperature. Therefore, for the same average effective source temperature, the efficiency of the gravity cycle is the same as in the Carnot cycle. There is no entropy production when heat is transferred in a Carnot cycle, in an ideal gas-turbine cycle, or in an ideal Gravity cycle.

Entropy production can be immediate or delayed. When solar radiation is absorbed entropy production is immediate. Entropy production as a result of convection is not immediate; the atmosphere can delay the production of entropy. The entropy is produced when the heat is transported upward by convection not when heat is received by conduction.

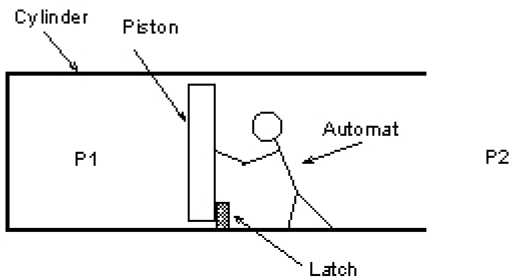
4. Unrestrained Expansion

There are two entropy production processes involved in the upward heat convection process: “mechanical” and “non-mechanical”. Goody (2003) explained that mechanical entropy production can be eliminated by using low velocities. Non-mechanical entropy production cannot be eliminated. Mixing is the only non-mechanical entropy production process. The irreversible mixing process can be either: mixing of air at different temperatures, or mixing of water and air not in equilibrium. Fortunately the non-mechanical entropy production is readily calculated. Michaud (2000) showed that non-mechanical entropy production is at most 10 mW K^{-1} m^{-2}.

The gravity cycle of Fig. 4 can be extended to apply to systems containing water and air, see Michaud (2000). When there is water present its potential energy can be captured. Entropy is produced when the water is mixed back into the air. It is possible to devise an ideal cycle where the water is postulated not to separate from the air, where the water remains in equilibrium with the air throughout the cycle, and where no non-mechanical internally generated entropy is produced.

The atmospheric entropy production process has been the object of much speculation. Kleidon and Lorenz (2004), Fig. 1.2 shows a total atmospheric entropy production of 56 mW K^{-1} m^{-2}, distributed as follows: absorbtion of terrestrial radiation 24 mW K^{-1} m^{-2}, latent heating 23 mW K^{-1} m^{-2}, frictional heating 7 mW K^{-1} m^{-2}, sensible heating 2.1 mW K^{-1} m^{-2}. These numbers were taken from Peixoto and Oort (1992). Kleidon and Lorenz (2004) correctly moved latent heating from the internally generated category to the external entropy input category, but accepted Peixoto and Oort (1992) other internally generated entropy numbers. The calculation of how much entropy is produced by various thermodynamic processes appears to have been influenced by the desire to balance the entropy budget. The entropy produced in above four processes approaches zero as velocities and temperature approaches are reduced - at mechanical and thermal equilibrium. Pauluis (2005) showed that the energy lost in these above four processes is small compared to the Carnot energy.

The Van Ness expander shown in Fig. 5 can be used to explain why entropy is produced when heat is carried upward by convection. Consider a cylinder containing 1 kg of air at 100 kPa and 30 ^oC, with a piston held in place with a latch, and with a surrounding pressure is 95 kPa. The work produced if the air is expanded isentropically is 4430 J kg^{-1}. The work produced when the same air is expanded by releasing the latch is 3384 J kg^{-1} because pushing away the surrounding air only requires 3384 J kg^{-1}. The difference 1046 J kg^{-1} gets dissipated in the air within the cylinder and increases the temperature of the air in the cylinder. Early thermodynamists used *automats* is to illustrate the fact that capturing the work requires that the expansion be restrained. The temperature of the air in the cylinder after the expansion is 25.60 ^oC in the isentropic expansion case and 26.63 ^oC in the unrestricted expansion case. The sudden release of the restraint or latch allows the individual molecules to accelerate and heat is produced when this kinetic energy dissipates. Unrestrained expansion results in sudden work dissipation and entropy production.



Cylinder initially contains pure air at 100 kPa and 30 C.
Ambient pressure is 95 kPa.

Case 1
Isentropic expansion
Piston restrained by automat when the latch is released
T1 decreases to 25.6 C, work is 4431 J/kg

Case 2
Unrestrained expansion against 95 kPa
Piston not restrained by the automat when the latch is released
T1 decreases to 26.63 C, work is 3384 J/kg.
Loss work 1047 J/kg

Loss work is 23% and approaches 22% as pressure ratio approaches 1.

Fig. 5 Use of Van Ness expander to explain the difference between restrained and unrestrained expansion

In Fig. 5, where the pressure ratio is 0.95, unrestrained expansion reduces work by 23.6%. The reduction in work approaches 22% as the pressure ratio approaches 1. For an initial cylinder pressure of 100 kPa and an ambient pressure of 99.999 kPa, unlatching the piston without restraining produces 22% less work than restrained expansion. If the cylinder were gradually raised sticktion between the cylinder and piston would be sufficient to bring about work loss and entropy production. The piston is not necessary; entropy would be produced even if the two air masses were separated by a flexible membrane. Raising a bubble of warm air in a loose bag suffices to produce entropy.

Unrestrained expansion in an ascending air parcel is capable of reducing work to zero and of producing the entropy required to balance the atmosphere's entropy budget. 22% of the total work of expansion of 66300 J kg^{-1} of Fig. 4 would be more than the net cycle work of 3450 J kg^{-1}. Entropy production is self-regulating; once mechanical equilibrium is reestablished entropy production ceases.

5. Conclusion

Entropy production as a result of unrestrained expansion is well recognized in engineering, but not in meteorology. Engineers invariably assume expansion process without an expander to be isenthalpic process – no expander means no isentropic expansion. The reversible Gravity cycle of Fig. 4 can be converted to an irreversible cycle by simply replacing the turbine with a restriction.

The realization that atmospheric entropy production is mainly the result of unrestrained expansion is important because it means that work could be captured by simply providing expanders which should be easier than eliminating friction losses. Two processes have been proposed for capturing the work by restraining expansion: the solar chimney, a working prototype of which was built in Spain, and the atmospheric vortex engine proposed by the author. For information on these processes visit web site: vortexengine.ca

Atmospheric scientists have not investigated the use expanders because there is no expander in the atmosphere. Understanding dissipation without the use of imaginary expanders is difficult.

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