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Atmospheric Chemistry and Physics Discussions

Interactive comment on "On the validity of representing hurricanes as Carnot heat engine" *by* A. M. Makarieva et al.

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While our revised manuscript is being evaluated, here we return to the issue of the dissipative heat engine with a few more arguments, as we have good grounds to believe that among the readers of this discussion there are (and will be) many people interested in the physical essence of the problem. We also re-consider the arguments presented by Referee 1 and, in particular, the interpretation of entropy budget for the dissipative heat engine given by Eq. (2) on p. S7916 in the first comment of Referee 1. We excluded consideration of this equation from the revised manuscript, because the arguments we provided did not appear to us as having a sufficient explanatory power with the discussion participants. We hope that the arguments that we provide now are clearer and will be of interest to the readers.

1 Efficiency of energy transformation

The essence of all processes, natural as well as technological, consists in the transformation of one type of energy to another. Energy transformation can be characterized by certain efficiency $\varepsilon \leq 1$ that is specific for the considered process. Usable work obtained during transformation of one type of energy to the other can either be equal to ($\varepsilon \leq 1$) or smaller than ($\varepsilon < 1$) the amount of external energy added to the system. In the latter case a relative part ($\varepsilon - 1$) of the added energy is lost to waste.

Let us consider an energy transformer that converts the initial type of incoming energy Q^{in} into the final type of energy $A = \varepsilon Q^{in}$ at $\varepsilon \leq 1$, so that useless energy $Q^{out} = Q^{in} - A = (1 - \varepsilon)Q^{in}$ is lost to the outer environment. We will also assume that there exists an ideal energy transformer that converts the final type of energy A back into the initial type of energy Q at $\varepsilon = 1$. Such a transformer can be exemplified by an elastically jumping ball, pendulum or man on the trampoline. In these "engines" loss of energy only occurs at the moment when the kinetic energy is converted to the potential energy in the gravitational field $(\varepsilon \leq 1)$. The reverse conversion of potential energy into kinetic energy occurs without energy losses $(\varepsilon = 1)$. Another example is the rotation of comets around the Sun over elongated elliptical orbits. The kinetic energy of comets practically does not dissipate. Potential energy accumulated on the orbit far from the Sun is converted to kinetic energy and back with efficiency equal to unity. This makes comet rotation practically infinite in time.

Another example is given by the dissipative heat engine (e.g., Rennó and Ingersoll (1996), Emanuel and Bister (1996), Pauluis and Held (2002)). In this engine external heat Q^{in} is transformed into work A with Carnot efficiency $\varepsilon = (T_s - T_0)/T_s < 1$. Then the obtained work is converted back into heat $Q_A = A$ with an efficiency equal to unity.

In all cases the value of efficiency is determined by the peculiarities of the considered energy transformer. In particular, Carnot efficiency is determined by the second law of thermodynamics. Efficiency cannot change if the energy transformer does not change

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itself.

From the definition of efficiency we have

$$A_1 = \varepsilon Q_1^{in}, \quad Q_1^{out} = Q_1^{in} - A_1 = (1-\varepsilon) Q_1^{in}. \tag{1}$$

Now we convert work A_1 back into the initial type of energy $A_1 = Q_2^{in}$ with an efficiency equal to unity. We can now convert the resulting additional amount of the initial type of heat energy Q_2^{in} to an additional amount of work $A_2 = \varepsilon Q_2^{in} = \varepsilon A_1$ with efficiency ε and sum the results of these two processes:

$$A \equiv A_1 + A_2, \quad Q^{in} \equiv Q_1^{in} + Q_2^{in}, \quad Q^{out} \equiv Q_1^{out} + Q_2^{out}, \quad A = \varepsilon Q^{in}. \tag{2}$$

Thus, expressing A, Q^{in} and Q^{out} via A_1 and Q_1^{in}, we have

$$A = A_1(1+\varepsilon), \quad Q^{in} = Q_1^{in}(1+\varepsilon), \quad Q^{out} = (1-\varepsilon) Q^{in}. \tag{3}$$

Divided by common multiplier $(1+\varepsilon)$, relationships (3) coincide with (1). From Eqs. (3) we have

$$A = \varepsilon(Q_1^{in} + A_1) = A_1(1+\varepsilon) \neq A_1! \tag{4}$$

Let us now consider whether the following relationship is possible that is proposed to characterize the dissipative heat engine:

$$A_1 = \varepsilon_1 (Q_1^{in} + A_1). \tag{5}$$

Such an engine is apparently not equivalent to Carnot engine. Its efficiency ε_1 has a different physical nature compared to efficiency of Carnot cycle (1), (4). One can analyze how efficiency ε_1 depends on the properties of the engine on the example of other (not thermal) engines, e.g., a hydropower station for which the value of ε_1 can approach unity, $\varepsilon_1 \to 1$. As is clear from Eq. (5), in such a case the external energy

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input Q_1^{in}, which, in the case of hydropower, represents potential energy of the falling water, tends to zero, while the value of final work A_1 takes an arbitrary value unrelated to the amount of the incoming energy Q_1^{in}. Thus, we have a typical example of a perpetual motion machine of the first (not second) kind. Equation (5) in fact represents **the definition** of ε_1 which otherwise cannot be deduced from anywhere:

$$\varepsilon_1 \equiv \frac{A_1}{Q_1^{in} + A_1}, \quad \text{or} \quad A_1 = \frac{\varepsilon}{1-\varepsilon} Q_1^{in} \to \infty \ \text{at} \ \varepsilon \to 1 \ \text{and} \ Q_1^{in} = \text{const}. \qquad (6)$$

Now imposing the condition of energy conservation, $Q_1^{in} + A_1 = A_1 + Q_1^{out}$, gives $Q_1^{in} = Q_1^{out}$. It follows from this and Eq. (6) that A_1 ceases to be determined by $Q_1^{in} = Q_1^{out}$ at any value of ε. That is, work A_1 of an arbitrary magnitude is produced from nothing. This corresponds to the perpetual motion machine of the first kind.

2 Derivation of Equation 5

We will now discuss how the physically meaningless equation (5) could be derived. Let us continue the procedure started in Eq. (2) to infinity. That is, we take initial external energy Q_1^{in} and convert it to work A_1 with efficiency ε, $A_1 = \varepsilon Q_1^{in}$. Then we take the obtained work A_1 and convert it back to the external type of energy Q_2^{in} with efficiency equal to unity: $A1 = \varepsilon Q_2^{in}$. We then convert energy Q_2^{in} convert to work A_2 with efficiency ε, $A_2 = \varepsilon Q_2^{in} = \varepsilon A_1$, and add it to work A_1: $A \equiv A_1 + A_2$. Further on, we convert work A_2 back to the external type of energy $Q_3^{in} = A_2$, and then Q_3^{in} into A_3: $A3 = \varepsilon Q_3^{in} = \varepsilon A_2$, then add work A_3 to the sum: $A \equiv A_1 + A_2 + A_3$. And so on. Then, for the total sum of all consequential amount of work we obtain:

$$A \equiv A_1 + A_2 + A_3 + ... = A_1(1 + \varepsilon + \varepsilon^2 + ...) = \frac{1}{1-\varepsilon} A_1 = \frac{\varepsilon}{1-\varepsilon} Q_1^{in}. \qquad (7)$$

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The obtained relationship between A and Q_1^{in} has the form of Eq. (6). But we should take into account that when amounts of work are formally summed, one should similarly sum the amounts of external type of energy, i.e. to perform the summation $Q^{in} \equiv Q_1^{in} + Q_2^{in} + Q_3^{in} + ...$:

$$Q^{in} \equiv Q_1^{in} + Q_2^{in} + Q_3^{in} + ... = Q_1^{in}(1 + \varepsilon + \varepsilon^2 + ...) = \frac{1}{1-\varepsilon} Q_1^{in}. \qquad (8)$$

Therefore, the "cumulative" work A and the "cumulative" external energy Q^{in} in any energy transformer are related as

$$A = \varepsilon Q^{in},$$

which corresponds to Eq. (1) for each individual process:

$$A_n = \varepsilon Q_n^{in} : \quad A = \sum_{n=1}^{\infty} A_n = \varepsilon \sum_{n=1}^{\infty} Q_n^{in} = \varepsilon Q^{in}. \qquad (9)$$

It should be noted that the performed summation of n sequential processes of energy conversion is mathematically faultless, but physically meaningless at $\varepsilon < 1$. Indeed, we sum a sequence of processes where each next nth process is the result of the preceding $(n-1)$th one and is accompanied by continuous growth of energy losses with growing n. At $\varepsilon = 1$ this sequence of processes corresponds to an oscillatory conversion of one type of energy to another and back without energy loss. In such a case the sum of oscillations tends to infinity with growing number n of oscillations, which is reflected in Eqs. (7) and (8).

3 Entropy budget of the dissipative heat engine

Finally, we provide here one more explanation of the physical untenability of the equation on entropy change in the dissipative heat engine, see Eq. (2) in the first comment

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of Referee 1 (ACPD 8, S7915-S7918, 2008):

$$\frac{\Delta Q_s}{T_s} - \frac{\Delta Q_0}{T_0} + \frac{A}{T_A} = 0. \tag{10}$$

Here $\Delta Q_s \equiv Q^{in}$ is the external heat input to the dissipative heat engine, $\Delta Q_0 \equiv Q^{out} = \Delta Q_s \equiv Q^{in}$ is the amount of heat lost to space, $T_s > T_0$, work A dissipates to heat at $T = T_A = T_s$. At $\varepsilon = (T_s - T_0)/T_s$ Eq. (10) is equivalent to Eq. (5), see also Eq. (3) on p. S7916 in the first comment of Referee 1.

The interpretation given to Eq. (10) in the works where dissipative heat engine is considered is as follows. The first two terms represent the conventional terms of Carnot cycle, while the third term represents entropy rise due to the irreversible process of the dissipation of work A to heat at the temperature of the warmer isotherm of Carnot cycle with $T_A = T_s$.

However, one should remember that heat input in Carnot cycle occurs at the isotherms. Since entropy of ideal gas depends on volume and temperature and the temperature does not change along the isotherm, it means that the entropy budget term $\Delta Q_s/T_s$ has a strictly unambigous physical meaning: This entropy increase is exclusively due to gas expansion at constant temperature. And when the gas isothermally expands, it performs work equal in amount to the received heat. Therefore, when the entropy of the engine increases by $\Delta Q_s/T_s$ this unequivocally means that the gas has expanded and performed work.

Now then, the third term of Eq. (10) should have the same meaning! That is, heat $\Delta Q_A = A$ that is formed after dissipation of work A does not warm the gas (because this dissipation occurs isothermally). So, in order that entropy increases as the third term of Eq. (10) prescribes, the gas must expand (there is no other way of increasing entropy at constant temperature). And when the gas expands isothermally, it performs work equal to the amount of received heat. Thus, we have come to the conclusion that the third term in Eq. (10) describes dissipation and re-generation of work at one and

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the same temperature T_s, which is prohibited by the second law of thermodynamics. This shows once again why the dissipative heat engine is equivalent to a perpetual motion machine of the second kind.

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