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Development of a Simple Model to Estimate Entropy Generation of Earth

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Abstract

Entropy generation can be caused by the energy transfer from a high-temperature recourse to a low-temperature resource; this is defined by the second law of thermodynamics. This phenomenon can occur for the Earth by transferring the solar energy from the sun to the earth. The process of entropy generation of the Earth is an important concept for the life of the earth. This process also has significant effects on the global hydrological cycle, carbon cycle of the Earth's atmosphere, and global warming. This paper presents an approximate method to estimate the entropy generation of the earth caused by the sun. Application of the heat engine to calculate the entropy generation of the planets has been carried out so far. In this research work, the concept of heat engine is applied to calculate the entropy generation of the earth and the atmosphere surrounding it in a relatively simple model. Based upon this calculation, the rate of entropy generation of the earth and its surrounding atmosphere is $6.5149 \times 10^{14}\, {}^{W}/_{K}$. Moreover, by considering this imaginative heat engine, the first and second law efficiencies are equal to 0.11036 % and 0.11546 %, respectively. The results of this research work have also been justified by similar works on this topic.

Keywords: *Entropy, Earth, Atmosphere, Thermodynamic, First Law Efficiency, Second Law Efficiency.*

1. Introduction

The constructal law can be applied to justify the generation of a flow regime that is used to predict the main features of the atmospheric circulation and the earth's environment change. This feature has been modeled as the convection loops, and it can be proposed to the earth model as a heat engine. In this model, the earth is heated by the Sun and cooled by its environment, and then the maximum power generated by this heat engine can be dissipated in the form of friction acting like brakes. The mentioned model is known as a heat engine and brakes [1-4].

Dissipation of the power generated by the earth engine can be exploited by selecting the proper balance between the hot and cold reservoirs of the Earth. Then it can optimize the characteristics of the atmospheric circulation and the environment. The robustness of these predictions and the use of the constructal law are supported by the thermodynamic laws [1, 2, 5, 6].

Liu *et al*. [7-9], have surveyed the second law of thermodynamic for entropy generation on the earth. In this investigation, some concepts such as the maximum entropy production (MEP) and the negative entropy flow (NEF) on the atmosphere and atmospheric systems have been examined.

In another research work, the earth's atmosphere has been assumed as a heat engine that converts the solar energy to useful work. Thus the temperature difference across this heat engine causes a wind energy. It can be caused by the circulation of the atmosphere due to the temperature difference between the polar and equatorial regions. The heat produced by temperature difference is a major source of the drive of the cloud, rain falling down, and other metrological phenomena. Application of the thermodynamic laws to the metrological phenomena such as Hurricane Katrina caused by wind speed and entropy flow for this phenomena has been presented in details [7, 10].

The main difference of the earth system from the other planetary neighbors is the global matter cycling. The earth's global cycles are more related to the fact that the thermodynamic behavior of the earth is far away from the thermodynamic equilibrium (TE). One of the aspects of the earth system is that this system can be considered as an isolated system with strong interactions. In this isolated system, the mass exchange with space is negligible, and the energy exchange with space is crucial [11, 12].

The earth and space act as a heat engine. This engine runs between a hot reservoir of the sun with an average temperature of $T_{sun \approx} 5760$ K and a cold reservoir of the earth with a mean temperature of $T_{earth} \approx 255$ K. The matter cycling in the earth and the presence of robust atmospheric circulation and the global water and carbon circulation in this system are the main sources of running cycles. Radiative gradient fluxes can cause a heat gradient that can be powered by the heat engines such as the metrological circulation or the photochemical process. The main cause of these circulations is the low entropy solar radiation [11, 13].

The atmospheric circulation of the Earth and the water circulation of the ocean have been reviewed for a long time as a universal heat engine. This heat engine runs by receiving the solar energy from the sun and emitting it to space as the terrestrial radiation [14-17]. The efficiency of this heat engine is an essential cause of climate change [3, 18]. The concept of a heat engine applied to climate change is also ruled by the thermodynamic laws [15, 19].

The atmospheric heat engine at a steady state condition is assumed as an open system that exchanges the material and radiation of two sub-systems including the top and below of the atmosphere. As no external work is done in the atmosphere, the net energy transferred between the system and its surroundings can be converted in the form of entropy. Then this generated entropy at the fixed heat input involves a reduction in the output temperature or an increase in the input temperature or a combination of both phenomena. This model can be applied to evaluate the net radiation energy absorbed by the earth and entropy generation or entropy budget of the earth [15, 20].

Bannon *et al*. [9] have also proposed the earth system and its surroundings similar to a heat engine that absorbs the high temperature of solar radiation and emits low temperature as the terrestrial radiation to space. As energy is preserved and no work is transferred between the earth system and its surrounding, entropy generation is the net result of this phenomenon. As a result, this generated entropy can be transferred to space. The created entropy contains two components, the entropy generation sensitivity of the earth to a variant of the emission and the absorption temperatures. As the albedo of the earth has no variation, the substantial entropy generation increases to 5% for a 1 K increase in the absorption temperature. Otherwise, as the temperature absorption has not changed, the entropy generation decreases to about 4% for a 1% decrease in the earth's albedo.

The heat engine concept has been achieved to determine different parameters of the atmosphere. Based on this investigation, by considering the ocean component of the earth, the Carnot efficiency was 0.86% and the work was obtained by 110 TW, which exceeded the mechanical energy input by other sources of energy. In addition, the net ocean's entropy was found to be 0.617 TW/K [21, 22].

The model of heat engine for the atmosphere of the earth as a heat engine has been applied in another research work. In the recent model, energy dissipation due to the friction of the rainfall was considered equivalent to the turbulent dissipation. Using this approach, the entropy generation in the atmospheres of Venus, Earth, Mars, and Titan was estimated to be 23, 29, 2, and 0.1 $^{mW}/_{m^2K^{-1}}$, respectively. If frictional dissipation in the Earth's atmosphere occurred between 250 K and 288 K, the rate must be less than 7.3-8.4 $^{W}/_{m^2}$. This upper bound was much larger than the observationally based estimate of the rate of frictional dissipation. As the other sources of entropy generation were difficult to evaluate, the Carnot efficiencies of the atmospheres of Venus, Earth, Mars, and Titan were less than about 27.5%, 13.2%, 4.4%, and 4.1%, respectively [23, 24].

In other simulations [23, 24], the main irreversibility due to entropy generation is related to the water phase changes, diffusion, and latent heat process of water.

The entropy generation of the earth's atmosphere based on the short wave of 0.30 and the long wave emissivity between 0.50 to 1.00 for albedo and Planck's spectral expression ranges from 1.272 to 1.284 $\mathrm{W\ m^{-2}\ K^{-1}}$ were calculated. Based on these assumptions, the overall entropy generation of the earth was obtained to be from 6.481×10^{14} to $6.547 \times 10^{14}\mathrm{W\ K^{-1}}$ [22, 25].

The application of the Carnot cycle and the heat pump system to the earth system was also examined. The concept of "Integrated Local Carnot Efficiency" was defined as the maximum reversible thermal efficiency of the power cycle. Meanwhile, the entropy generation of the earth was evaluated to to be $0.68 \times \mathrm{I}0^{15}$ $\mathrm{W\ K^{-1}}$ [26, 27].

The rate of entropy generation the atmosphere is the main source of global circulation, and this hypothesis has led to the maximum entropy generation. Using the thermodynamic of a zonally-averaged concept, the entropy balance of a dry atmosphere was examined [28, 29].

Regarding the simulation of the earth as a heat engine, it was concluded that the value of entropy generation was sensitive to the resolution of the model and the assumption of boundary layer friction. The comparison of some important models for computing the earth's entropy generation was also carried out [30].

In this work, a simple and applicable model was developed to calculate the first and second law efficiencies and entropy generation of the earth and the surrounding atmosphere as an imaginative engine. Sun and space over the atmosphere were assumed as a heat source and sink. The entropy generation rate in the earth and the surrounding atmosphere was validated by a previous research work [25], which had a good agreement. In the next stage, another control volume was considered. In the second control volume, the earth was assumed as a heat engine. Sun and atmosphere were considered as a heat source and sink, respectively.

2. Mathematical Modeling

The configuration of the proposed model is shown in figures 1 and 2. Figure 1 shows the control volume, which contains the earth and the surrounding atmosphere as a heat engine. In this control volume, the sun is assumed as a heat source of the engine and the surrounding atmosphere is assumed as the sink of that engine. Figure 2 shows the control volume including the earth and the atmosphere. In this control volume, the atmosphere is assumed as the heat source and earth is a sink of the heat engine.

In figure 1, the work rate produced by this imaginative engine is W and the heat rate dissipation to space is shown by Q_L. The amount of sunlight that spins over the atmosphere is shown by S_1 (Q_H). Dimensions of all the parameters are J/day or W.

In figure 2, the work rate produced by this imaginative engine is W and the heat rate dissipation to the atmosphere is shown by Q_L. The amount of solar radiation over the atmosphere is shown by S_1 (Q_H). The dimensions of all the parameters are J/day or W.

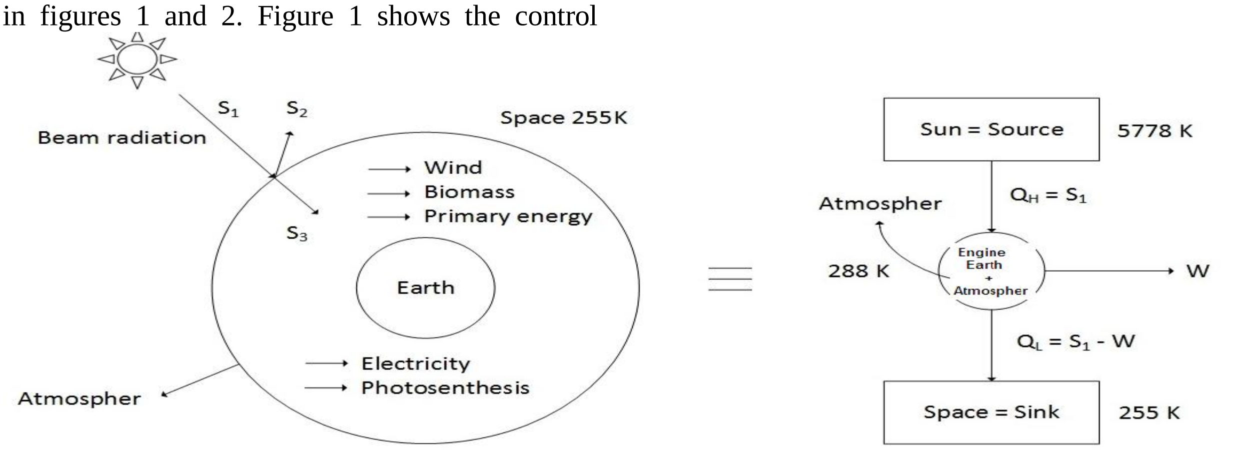

Figure 1. Control volume I (Sun (heat source), Earth and atmosphere (engine), space (heat sink)).

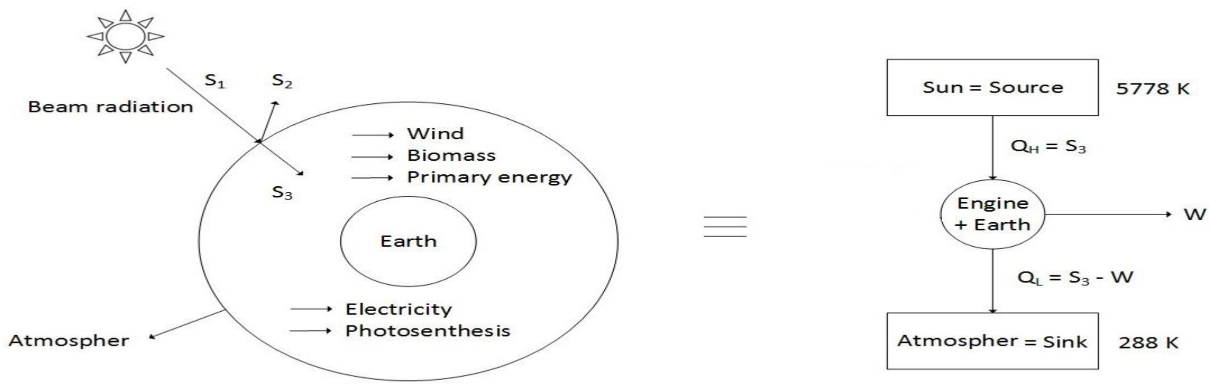

Figure 2. Control volume II (Sun (heat source), Earth (engine), atmosphere (heat sink)).

For the control volume I, T_L and T_H are the sink and heat source temperatures. Dimensions of T_L and T_H are the temperatures in terms of Kelvin. Based on the conservation of energy, we can write:

$$Q_L = S_1 - W \tag{1}$$

$$W = W_{wind} + W_{biomss\ potential} + W_{primary\ energy\ use} + W_{electricity} + W_{photosenthesis} \tag{2}$$

The subscripts wind, biomass potential, primary energy use, electricity, and photosynthesis denote the kind of main energy resource in the earth. The main part of the energy is related to photosynthesis. The second one is the wind energy resource.
For this imaginative engine, the first law efficiency of thermodynamics is calculated by the following equation:

$$\eta_{Carnot} = \frac{W}{S_1} \tag{3}$$

Regarding the Carnot efficiency, if we assume that this engine follows the Carnot engine, it can be written [31]:

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H} \tag{4}$$

If we assume that this engine is ideal, based on the Carnot efficiency, the efficiency of the imaginative engine can be calculated by the second law of the thermodynamic.

$$\eta_{II} = \frac{\frac{W}{S_1}}{1 - \frac{T_L}{T_H}} \tag{5}$$

The entropy generation of the imaginative engine can be calculated by:

$$S_{gen} = \frac{Q_L}{T_L} - \frac{Q_H}{T_H} \tag{6}$$

For the control volume II, the first and second law efficiencies of thermodynamics can be calculated by:

$$\eta_I = \frac{W}{S_3} \tag{7}$$

$$\eta_{II} = \frac{\frac{W}{S_3}}{1 - \frac{T_L}{T_H}} \tag{8}$$

It is clear that the amount of T_L in the control volume II is different from that in the control volume I.

3. Results and Discussion

For the first control volume, we know that the earth receives 174×10^{15} W or 1.50336×10^{22} $J/_{day}$ energy from the sun at the upper atmosphere [32, 33]. The temperatures of the sun and space are equal to 5778 K and 255 K, respectively [25]. The energy resources and consumptions in the earth and atmosphere are shown in table 1 [32-36].

Table 1. The energy resources and consumption in the earth and atmosphere.

No.	Kind of energy	Values ($J/_{day}$)
1	Photosynthesis	8.21918×10^{18}
2	Wind energy	6.16438×10^{18}
3	Biomass potential resource	5.47945×10^{17}
4	Primary energy	1.4767×10^{18}
5	Electricity	1.83562×10^{17}

According to the data in table 1, the summation of energy resources and primary consumption in the earth is equal to 1.65918×10^{19} $J/_{day}$. From equation 1, Q_L is equal to 1.5017×10^{22} $J/_{day}$. The first law efficiency of thermodynamics is equal to 0.11036% by Equations 1 to 3 and the data in table 1. The Carnot efficiency for this imaginative engine is equal to 95.59% from Equation 4. Entropy generation of this imaginative engine is equal to 5.69893×10^{19} $J/_{day}$ or 6.51496×10^{14} W from Equation 6. The value of entropy generation has a good agreement with a previous research work (Ref. [25]. In this control volume, the entropy generation rate of the earth and atmosphere is equal to 6.481×10^{14} to 6.547×10^{14} W/K. The second law efficiency of thermodynamics for the control volume I is equal to 0.11546%.
For the second control volume, T_L is equal to 288 K and the solar energy received by the earth is equal to 1.05479×10^{22} $J/_{day}$ [32] (S3 in figures 1 and 2). In this regard, the first and second law efficiencies of thermodynamics and entropy generation for control volume II are equal to 0.15729%, 0.1655%, and 3.35146×10^{19} $J/_{day.K}$ or 3.879×10^{14} $W/_K$, respectively.

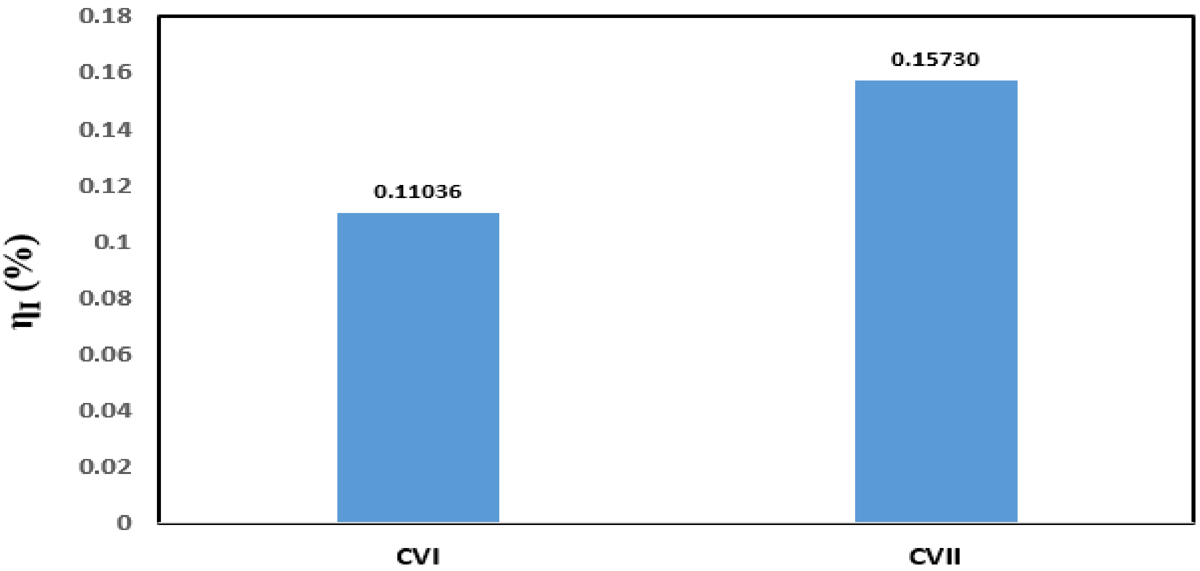

Figure 3. Comparison between the first law of thermodynamic efficiency between the two control volumes.

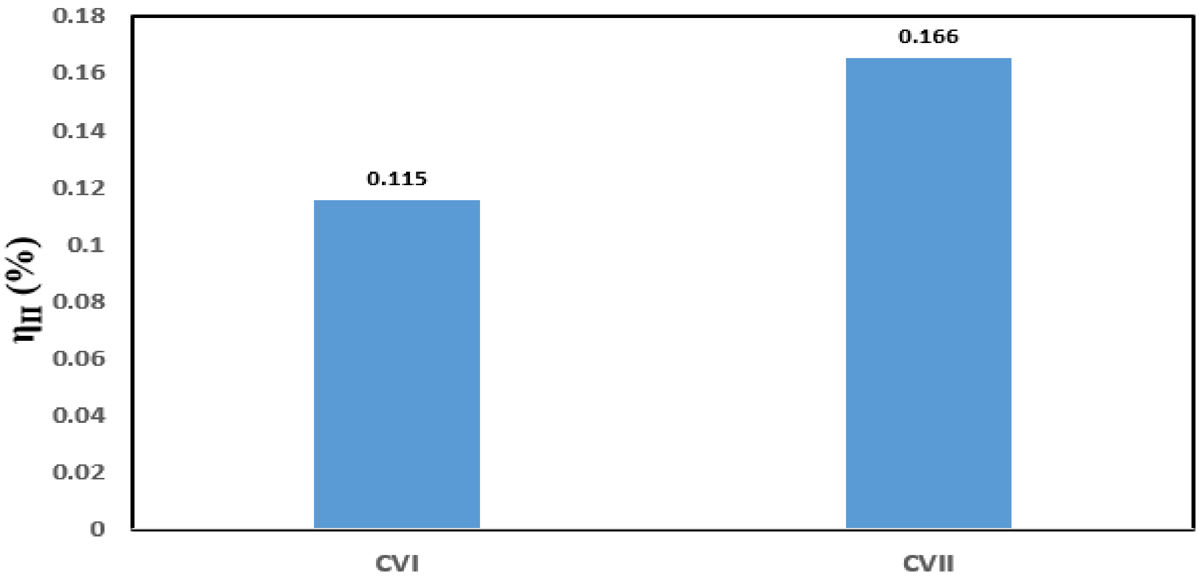

Figure 4. Comparison between the second law of thermodynamic efficiency between the two control volumes.

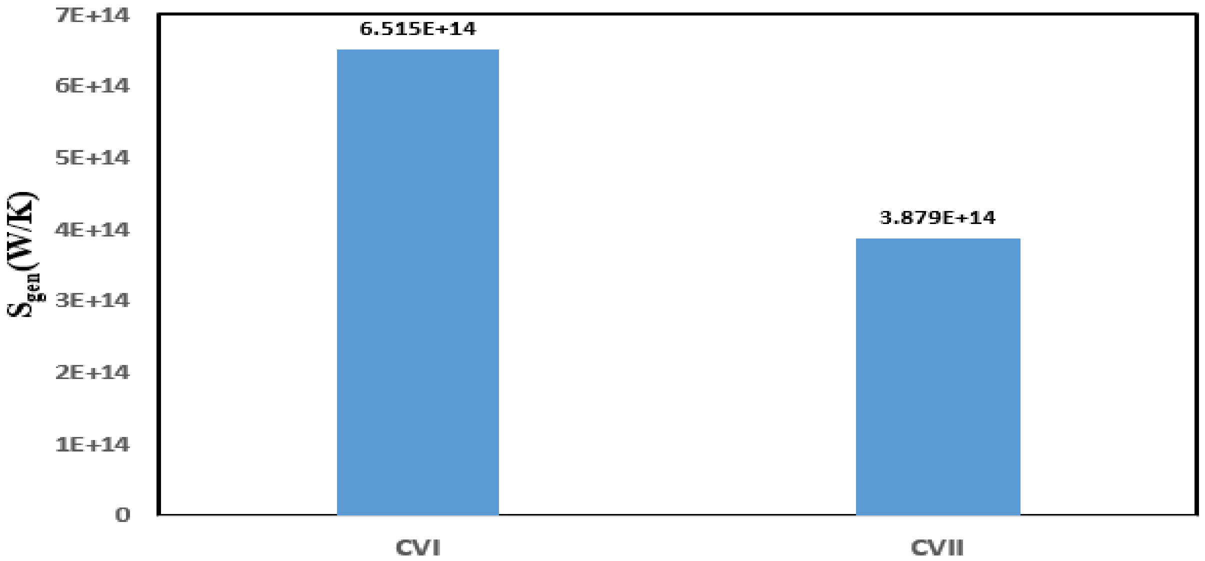

Figure 5. Comparison between the entropy generation between the two control volumes.

4. Conclusion

In this work, a simple and applicable model was developed to calculate the first and second law efficiencies and entropy generation of the earth by resembling the earth as a heat engine. The first and second law efficiencies and entropy generation for the control volume including the earth and atmosphere were equal to 0.11036%, 0.11546% and $6.5149 \times 10^{14}\ \mathrm{W}/_{\mathrm{K}}$, respectively. For the second control volume II, the variables were equal to 0.1573%, 0.1655% , and $3.879 \times 10^{14}\ \mathrm{W}/_{\mathrm{K}}$, respectively. Moreover, the entropy generation of the earth due to solar radiation was calculated to be $6.5149 \times 10^{14}\ W/_{K}$. This entropy generation is a main source of hydrological and weather changes and global warming.

Nomenclature

Q	Heat transfer rate (W or J/day)
S1	Solar radiation over the atmosphere (W or J/day)
S2	Solar radiation reflected by the atmosphere (W or J/day)
S3	Solar radiation absorbed by the atmosphere and the earth (W or J/day)
S_{gen}	Entropy generation (W/K or J/dayK)
T	Temperature (K)
W	Work produced by the imagine engine (W or J/day)

Greek symbols

ɳ	Efficiency (-)

Subscripts

L	Sink
H	Source
I	First
II	Second
Q	Heat transfer rate (W or J/day)
S1	Solar radiation over the atmosphere (W or J/day)

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