Maintenance of Order and the Entropy Law –Examples in Life, Earth Environment and Fusion Device–

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Abstract: When work is done in a closed system, energy is converted to heat and physical entropy, the ratio of the system heat to the system temperature, increases. Law of increase of entropy, when broadly interpreted, leads to deterioration of order in a closed system. Thus the entropy law presents challenges to maintenance of life, the earth environment and other sytems that require sunstained internal order. In particular, creation of life and maintenance thereof presents the most interesting challenge to the implication of the entropy law. From the entropy point of view, the life is maintained by self-organization and maintenance of order based on DNA information with a help of intake of negentropy and exhaust of increased entropy outside of the body. Such is possible only in an open system where exchange of entropy with external environment is allowed. Here the negentropy is defined as a free energy that can do work a result of which leads to increase of the system internal entropy[1]. The global balance of entropy needed to sustain lives on the earth is provided by the negentropy flow from the sun and the exhaust of increased entropy from the earth in the form of the black body infrared radiation. Particular emphasis is placed in this paper on the necessity of exhaust of increased entropy to the external environment for the healthy maintenance of a life and habitable environment of the earth, or an order in a system in general. Desease and aging are caused by increase of internal entropy of a body and similarly the health of the earth environment is deteriorated by the increase of entropy in the form of heat, chemical and nuclear waste unless increased entropy is ejected out to outer space. In this regard only the solar energy, geothermal energy and/or the tidal energy can play the role that does not lead to increased entropy on the earth surface and sustain the habitable environment, thus these are the most desirable energy source. not because of the abandance of the resources as commonly considered. Maintenance of order of a system or a unit is only possible by a continuous ejection of the increased entropy out of the system which is often more important than intake of energy to do internal work.

Keywords: entropy, life, thermodynamics, the earth environment, system order.

1. Introduction

In a closed system, when work is done, the energy is converted to heat and the entropy increases. The entropy law is interpretted as temporal deterioration of quality of energy in thermodynamics or that of order in information theory in a system. The entropy law applies to a closed system. In an open system where exchange of entropy with external environment is allowed, the system can sustain low entropy state, or an ordered state, even when work is done internally, provided a proper intake of negentropy [1] and simultaneous ejection of increased entropy out of the system are performed continuously. Here negentropy is defined as a form of free energy in physical or chemical processes and/or order in information theory whereby when work is done the system entropy increases and negentropy decreases. Schrödinger [2] is the first to point out importance of intake of negentropy rather than energy for a life. However he failed to notice the importance of exhaust of increased entropy to external environment for healthy maintenance of a life or to maintain the low entropy state, that is, the order in a body. Note that intake of oxygen, food

(hydrocarbon and protein) and other nutrition is considered as import ingedient of negentropy. The work is done inside a body in the form of muscle motions, blood circulations, electrical switching of synapses and neurons as well as regeration of cells based on DNA information from aminoacid. Increased entropy produced in these works is exhausted out of the body in the form of carbon dioxides, water, heat and other wastes. The autofugy plays the important role of cleaning up the internal entropy of the cell [3]. Only due to the proper ejection of increased entropy from the body, the proper order and low entropy state of a body, consequently the life can be sustained. For example if carbon dioxide and heat remain in the body after chemical reaction of oxigen with glucose, the life is terminated almost immediately. Therefore intake of negentropy is not equivalent to exhaust of increased entropy. Aging is considered to be a consequence of gradual accumulation of entropy failed to be exhausted, while desease is caused by undesirable accumulation or internal increase of entropy. In order to maintain a life, increased entropy should be taken out of the body. An exponential increase of entropy may occur if a system is locally closed, an example of which is a cancer. Cancer cells are no different from ordinary cells, thus some people believes they do not represent the increased entropy. However the unpredicatable and uncontrollable growth of the cell represents an increase of disorder and is nothing but an increased entropy from the point of informatin theory.

In the example of the earth environment, the negentropy source that sustains the order on the earth surface including the life activities is the solar radiation. The solar radiation heats the air to a proper temperature for life activities and provides photons for various photosyntheses for vegitation and animals. When the work is done, the solar radiation becomes heat which is radiated out of the earth in the form of infrared black body radiation so that there is no net increase of entropy on the earth surface. Here again the habitable environment and the order on the earth surface are sustained only because of the continuous entropy ejection from the earth to outer space. However, during the past century human started to use energies from fossile and nuclear fuels. The problem of this is not whether these energy resouces are available in future or not, but whether the increased entropy as a consequence of the work done by these energies can be exhaused out of the earth or not. Unfortunately the answer is no. Fossil fuels increases carbon dioxide contents in the air which reduces the ability of infrared ratiation from the earth thus reduces entropy exhaust from the earth at least for a period of time until a new equilibrium is established.. Similarly use of nuclear energy accumulate nuclear wastes both from the used fuels and from the radioactivated reactor structures, thus the increased radioactive entropy raminas on the earth surface and can not be ejected out to space. Similar to the life activity, the increase of entropy on the earth surface results in unhealthy environment and eventually leads to unhabitable environment of the earth. The concept of necessity of ejection of increased entropy out of a system in order to maintain the internal low entropy state or the internal order applies broadly to any system that requires internal order. Other example includes fusion devices, corporation structure, national order and/or domestic order. It is clear from these examples, the exhaust of increased entropy is or even more important than resources of negentropy. In this manuscript, by taking examples of the earth, life sytem, and a fusion device, I present examples of how an order, or a low entropy state can be maintained in an open system that allows entropy exchange with external environment.

2. Merit of the sun as the ultimate source of negentropy

Low entropy of a system is maintained by continuous ejection of increased entropy out side of a system. In this section we take the example of the earth and demonstrate how the orde, or the habitable environment of the earth is maintained inspite of continuous increase of internal entropy by the atmospheric heating and various life activities. Note that the sun is in its thermal equilibrium and is

regarded to be at the maximum entropy state. The black body radiation from the sun, the solar radiation, is in thermal equilibrium in the solar environment and has no negentropy there. The earth is also in thermal equilibrium in that the heat that comes from the solar radiation is continuously radiated out of the earth by her own blackbody ratiation. However, entropy carried in by solar radiation is much less than that radiated from the earth because the radiation temperature of the sun is much higher than that of the earth. Or alternatively, number of photons in the solar raditaion at visible wavelengths is much less than that of the black body radiation from the earth at infra-red radiation. Note that number of photons in radiation is given by the energy of the radiation devided by the frquency of the photons. Therefore from the earth point of view solar radiation brings in negentropy to the earth, which can do work on the earth surface and its entropy increases. As seen in this example, it is important to recognize that negentropy is a relative concept, not of an absolute concept. The solar radiation can not do any work on the sun since it is in thermal equilibrium with the sun, but can do work on earth since it has negentropy seen from the earth. However, the solar radiation has absolutely zero negentropy for the sun itself.

The birth and the maintenance of life require continuous import of negentropy from the environment. The entropy that results form life activities is ejected out of the body and increases the entropy of the environment. In case of animals, this is done by intake of oxygen, photons and food and exhaust of water, heat and other waste from the body. The life is an entropy-producing machine like an automobile. In addition to thermodynamical negentropy, life needs information negentropy to cover the loss of information stored in DNA and living cells through regenerations. As will be shown protein supplies major source of information to a body. The hydrocarbon provides energy and and chemincal negentropy while protein provides some energy and information negentropy. Oxygen comes from plants, where carbon dioxide and water are taken in and oxygen is exhausted out where the solar radiation is used in the reaction. The photosynthesis helps production of oxygen from carbon dioxide and water as well as the synthesis of the plant body itself. Since the light, which carries the electromagnetic energy, has lower entropy than chemical entropy of carbon dioxide and water, it can overcome the decrease of chemical entropy by bringing in enough electromagnetic negentropy to the system. This is possible because the grade of electromagnetic energy is higher than that of chemical energy[1].

The sun is generally considered as the energy source for our lives. This is not quite correct since the total energy that comes from the sun to the earth is reemitted out of the earth to outer space in the form of infrared radiation, the black body radiation of the earth. As a result the earth has no net energy intake from the sun. If the intake of the solar energy is more (less) than the radiation loss of energy from the earth, the earth temperature will keep increasing (decreasing). Then what the sun is providing to the earth? As was shown above it is the negentropy, a huge amount of negentropy that is needed for her life activities. The sunlight originates from the black body radiation of the solar surface. The solar spectrum covers ultraviolet and visible wavelengths, which are essential for the photosynthesis on the earth. On the other hand the black body radiation from the earth is primarily in infrared wavelength. Thus the earth receives a high-grade energy from the sun and radiates out low-grade energy.

Let us briefly compute the amount of the negentropy provided by the sun to the earth. The solar power on the earth is approximately $1\mathrm{kW/m^2}$. Thus the entire energy that the earth receives from the sun is obtained by multiplying it with the cross-sectional area of the earth, and becomes 1.3×10^{17} Watt. Namely, the earth receives 1.3×10^{17} Joule of energy from the sun every second. The solar power is carried by electromagnetic wave. It should be noticed that the peak spectrum exists around at the energy of a few electron volt that is suitable for photosynthesis. The solar radiation originates from

the blackbody radiation from the solar surface whose temperature is approximately 5500^{O} Kelvin. On the other hand the energy loss from the earth is primarily carried out by infrared radiation that corresponds to the black body temperature of the earth at about 300^{O} Kelvin. Thus the negentropy intake of the earth from the sun, ΔS in every second becomes

$$\Delta S \left(= \Delta \frac{Q}{T}\right) = \frac{1.25\times10^{17}}{300} - \frac{1.25\times10^{17}}{5500} = 4 \times 10^{14} \text{ J/K .} \quad (1)$$

This huge amount of negentropy flow from the sun to the earth allows the entire life activities on the earth.

To illustrate this, let us calculate here the amount of entropy that is produced by human being every second. Let us assume that one human takes 2000 kilocalories of food daily. This amounts to 100 J/s. and the negentropy intake becomes, 0.3J/K/s assuming the body temperature of 300^{O} K. The life activity exerts this amount of entropy to the environment. In addition to the food, average Japanese consumes about 100 times more energy for industrial purposes including heating, transportation and production of goods. So the total entropy production per person every second becomes about 30J/K. If the entire population on the earth of 7 billion consumes this much of energy, the total entropy production becomes 2×10^{11} J/K in each second. Fortunately, this amount is still much smaller than the negentropy supply from the sun, of Eq. (1), although certainly not negligible.

The black body radiation is given by ;

$$I = \sigma T^4 . \quad (2)$$

Here

$$\sigma = \frac{2\pi^5 k^4}{15c^2h^3} = 5.67\times10^{-8} W/m^2K^4$$

is the Stefan-Bolzman constant. We note that the black body radiation is proportional to the 4^{th} power of the black body temperature, i. e., if the temperature goes up by 1%, the radiation goes up by 4%. This is the very reason why the earth temperature stays relatively constant in spite of the large solar raditation input. This indicates that the thermal entropy production on the earth surface does not lead to the entropy increase of the earth. However, chemical entropy, i. e., carbon dioxide and other chemical products, and nuclear entropy, i.e., radiactive waste produced in nuclear reactions remains on the earth and cotributes to the increase of the earth entropy and leads to undesirable consequences for the life activities.

This conclusion teaches us the importance of exhaust of entropy much more than the energy resources. The order, or the low entropy state of the earth environment can be maintained only through continuous exhaust of increased entropy.

3. Life Activity and Entropy

In order to maintain the life, one needs intake of oxygen, photon and food. Human consumes negentropy provided by these materials and maintain the life by exhausting increases entropy to his environment. In this section the life activity is described in terms of entropy exchange.

Fat and hydrocarbon of food are primarily used as the energy source to move the body, process information and to keep the body temperature by combing them with oxygen taken to the body and the entropy increase in the form of heat, which are radiated out of the body. The digested foods are exhausted out of the body in the form of body waste. When oxygen is inhaled, it induces a chemical reaction given by

glucose($C_6H_{12}O_6$)+oxygen($6O_2$)+adenosine diphosphate(38ADP)-->
carbon dioxide ($6CO_2$)+water($6H_2O$)+adesine triphosphate(38 ATP)+heat

Here, ATP carris electro-chemical energy to various portion of the body. This reaction is essential for life activities. CO_2, H_2O and heat are entropy products in this reaction and should be exhausted out of the body in order that this essential reaction is maintained. Here again the exhaust of entry is curucial for the maintenance of life. The electro-chemical energy carried out by ATP is considered to be used also to synthesize proteins for appropriate cells based on information provided by DNA. After the work is done ATP is reduced back to ADP and is used in the above reaction.

Let us now make an estimate of the daily amount of protein intake needed to replenishing the dead

cells exhausted out of the body by the use of the information theory. For this purpose let us first estimate the amount of negentropy that a DNA contains. A human DNA is a chain of about 3 billion nucleotide whose nucleobase consists of the four types A, G, C and T, standing for the molecules adenine, guanine, cytosine, and thymine, a unit of which has 2 bits of information. Thus the maximum entropy of one chain of DNA becomes 6×10^9 bit. A human body is considered to consist of about 60 trillion cells, each of which contains a DNA chain that carries information for the construction of the specific cell. If we assume that the each cell has an independent set of DNA chain, the total number of the maximum information entropy of the body becomes, 3.6×10^{23} bit. (Note that although each cell has the same DNA, the information content of the DNA for a specific cell is different and unique to the individual cell). This is a huge amount of information if we compare it, say, with one terabyte hard disc that contains 8×10^{12} bit.

However, this huge bits of information entropy is not much in the unit of thermodynamical entropy. To compare the amount of entropy lost in information, we use the unit of thermo-dynamical entropy, defined by Boltzmann,

$$S = k_b \ln P \tag{3}$$

Here P represents the number of complexity of the system and k_b ($=1.36\times10^{-23}$Joule/Degree) is the Boltzmann constant. On the other hand the amount of information I stored in DNA of a human body, 3.6×10^{23} bit gives the complexity P given by the Shannon formula [4],

$$\log_2 P = 3.6\times10^{23} \tag{4}$$

From Eqs. (3) and (4), the maximum information entropy of a human body simply becomes 6J/K. Since the DNA chains as well as the cells have quite ordered structure, the human body should be considered to have 6J/K amount of negentropy. It is said that about 20% of the cell is replaced every day. If this is the case one needs to replenish about 1J/K amount of negentropy per day. Note that this amount of negentropy is much less than the entropy production of a body estimated in Section 1, i. e., 0.3J/ per second from the body motion.

Let us see how much of protein can provide this amount of information negentropy. Unlike hydrocarbon and fat that are primarily burned in the body and contribute as the power source of the body motion, the primary role of protein is to construct human cells. Protein taken in to the body is resolved to amino acid of various types, which are used as building blocks to construct appropriate cells according to the information proved by DNA. Computing thermodynamical entropy provided by one protein molecule is complex, but an approximate value may be estimated as follows. We first note that the process of converting protein to individual cells does not require complete resolution to elementary molecules such as hydrogen, carbon and nitrogen that a protein consists of. Instead, it requires to resolve only to about ten amino acids, retaining much of the macromolecule structure of the protein. The process is done with the help of exygen as catalizer thus may require approximately one tenth of chemical reaction of hydrogen atom. Therefore energy involved in the process of converting a protein to human cells may be estimated to be about 2eV per protein. As the average molecular weight of food protein, let us take 10^5. Then the number of protein molecules in one gram becomes approximately 6×10^{18}. Thus the total energy to resolve one gram of protein for this purpose becomes about 2 Joule. It should be noticed here that this amount of energy does not represent the energy that can be extracted by burning one gram of protein completely, which is usually estimated to be about 20 kJ, (This may be computed by counting the total amount of hydrogen and carbon in one gram of protein and multiplying the result by 2 electron volts). Although some of protein may be burned in the body, the amount of relevant protein considered here is that used to replenish the human cells lost daily. Thus the negentropy that one gram of protein can provide becomes 2/300 J/K=0.07J/K. Thus to replenish the negentropy loss due to the daily loss of cells, i.e., ~1J/K, one needs intake of about 120 gram of protein. Interestingly

this corresponds to the daily-recommended minimum amount of protein intake for a person. Although this argument is correct only in the order of magnitude, this indicates that protein intake is related to the supply of negentropy to replenish the information lost from the human cells. The negentropy provided by oxygen intake should also be taken into account since the oxygen plays crucial role as catalyze in protein synthesis.

A few remarks follows from the intake of negentropy and life activity. From the point of view of negentropy intake via food, it is apparent that smaller the entropy of the food, more it is effective as provider of negentropy. In this regard, it is interesting to note that the empirical order of the so called healthy food, sea vegetations, vegetable, fish meat, bird meat and mammal meat matches to the order of less complexity of food and thus of amount of entropy. This order also matches to the order of evolution and complexity of life on the earth.

There are other example that relates health to negentropy intake and exhausting entropy. Exercise may be considered as a process of accelerating the exhaust of entropy out of the body. Controlled inhale of air used in meditation may be interpreted as a controlled intake of negentropy of oxygen. As a matter of fact, during meditation in Zen the brain wave reaches to its ground state in that the alpha rhythm reaches to the state of well correlated in various parts of the brain. This can be interpreted that the brain activity can reach to the zero entropy state by controlled intake of exygen. Then the brain becomes ready to be most creative.

4. A Novel Design Concept of a Fusion Reactor

As another example of the present concept, let us take the example of fusion reactor design. A classic concept of a magnetically confined fusion device is to put large enough energy to a magnetically confined fuel plasma so that the temperature reaches to the level at which nuclear fusion takes place at sufficient level and confine the plasma energy for sufficient extent of time τ_E so that the fusion energy exceeds the invested energy. This condition is called Lawson criterion and for D-T fusion, it is approximately given by

$$n\tau_E \geq 10^{20}\, s/m^3 . \qquad (5)$$

Here n is the fuel number density in m^{-3}.

In an ideal device the plasma is in MHD equilibrium and satisfies the force balance condition given by

$$\mathbf{J}\times\mathbf{B} = \nabla p . \qquad (6)$$

Here **J** is the current density, **B** is the magentic flux density and p is the pressure of the plama. In a symmetric device such as a Tokamak, the pressure profile is a function of magnetic flux function ψ. The classic concept of a fusion device is to construct a desirable pressure profile $p(\psi)$ for fusion to take place with sufficiently large energy input and maintain the profile adiabatically until the Lawson criterion is met. Magnetically confined plasma that is in the maximum entropy state should have equal energy contents distributed among all flux tubes. Only a dipole magnetic confinement [5] with the maximum entropy can provide sufficiently peaked pressure profile for fusion to take place. All other devices require certain low entropy state for fusion to take place. Tokamak is one example. However, since the plasma pressure profile that has a peak in minor radius is not in the maximum entropy state, and thus is subject to various instabilities and plasma behaves non-adiabatically. Thus the plasma entropy is expected to increase rapidly and adiabatic assumption is violated. Consequently the Lawson criterion is difficult to achieve in a closed system. On the other hand, as shown in previous two examples if the system is open to external environment, maintenance of internal order or the low entropy state is possible. If we treat the fusion device as an open system, what is required is the maintenance of the proper pressure profile but not the energy confinement time. It requires continuous injection of high quality energy, i.e., negentropy *and* continuous ejection of increased entropy out of the device.

In practice in most Tokamak devices, in addition to Ohmic heating, subsidiary energy in the form of neutral beams or RF is injected in a fusion device. These are regarded as negentropy sources; the

monochromatic energy sources have zero entropy. In this way an actual Tokamak is open to injection of negentropy. What is missing, however, is a design that allows active ejection of increased entropy without which the internal entropy increases rapidly and maintenance of desirable pressure profile is difficult to achieve.

The self-organized state and formation of zonal flow [6] [7] may help to sustain the low entropy state, such as the so-called H-mode. However, the state cannot be sustained without ejection of increased entropy. A properly designed diverter can play a role of entropy ejection. Here it is important to recognize a scheme in which ejected entropy does not transport fuel heat. Thus it is desirable that the increased entropy is carried out either by electrons or by RF. I propose to use the Alfvén wave as a medium for ejection of increased entropy. Because of low frequency nature of the wave, it can carry a large amount of entropy for the same energy and can be coupled out electromagnetically to an external receptor. Note that the number of photons for lower (higher) frequency RF is larger (lower) thus can carry larger (smaller) entropy. Theoretically the process of coupling out the increased entropy by Alfvén wave can be described by excitation of the field-aligned current induced in the plasma as a result of inverse cascade of the turbulent energy.

5. Conclusion

Since the first derivation of the second law of thermodynamics, the meaning of the entropy law has evolved and more profound interpretation of the law has been made during the 20th century with the help of nonlinear physics and mathematical theory of information. The newly interpreted law of increase of entropy is applied here to biological systems, the earth environment and to a fusion device. The life is maintained through the intake of negentropy of oxygen, food and photons and the increased entropy in the body is continuously exhausted out of the body, while the earth receives negentropy from the sun and the increased entropy is exhausted out by means of infrared black body radiation. In either case, the exhaust of internally increased entropy to external world is essential to maintain the low entropy state, i.e., the internal order. A similar consideration applies to the fusion device where the ejection of increased entropy via Alfvén wave is proposed.

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References

[1] Brillouin, L (1953) "Negentropy Principle of Information", J. Appl. Phys. 24, 1152-1163, also see “Science and Information Theory”, Acad. Press, New York 1962.

[2] Schrödinger, E:(1944) "What is Life-the Physical Aspect of the Living.", Cambridge University Press, Cambridge-the Physical aspect of the Living.", Cambridge University Press.

[3] Hamasaki M, Furuta N, Matsuda A, Nezu A, Yamamoto A, Fujita N, Oomori H, Noda T, Haraguchi T, Hiraoka Y, Amano A, Yoshimori T. (2013) Nature. 495, 389-93. (2013)

[4] Shannon, C. E. (1951) "A Mathematical Theory of Communication", Bell Syst. Tech. J. Vol. 30, January, pp.50-64

[5] Hasegawa, A., Comments Plasma Phys. Control. Fusion, **11**, 147.

[6] Hasegawa, A and Wakatani, M. (1987) Phys. Rev. Lett. **50**, 682.

[7] Diamond, P. H., Itoh,S-I, Itoh, K,and Hahm, T. S. (2005) Plasma Phys. Control. Fusion, **47**, R35.

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