International Journal of Environmental Engineering and Management.
ISSN 2231-1319, Volume 4, Number 3 (2013), pp. 239-244

http://www.ripublication.com/ ijeem.htm

Role of Water in Controlling Entropy of Living Systems

C.S. Mulherkar

P.C. Polytechnic, Akurdi, Nigdi, Pune, INDIA.

Abstract

Life is order. Living organisms with their complex organic structure, evade spontaneous degradation as stated by the Second Law of Thermodynamics by continually renewing themselves at the microscopic to macroscopic level of organization. This is achieved by a continual inflow of low entropy and outflow of the inevitably generated high entropy. Water, the ubiquitous life substance, has an important role to play in this regard. An attempt is made in this paper to identify certain life processes that demonstrate how water acts as an indispensable carrier of entropy from the inside to the outside of the organismal environment.

Keywords: Entropy; water cluster; oxidative phosphorylation; cerebrospinal fluid CSF; catabolism; perspiration.

1. Introduction

The Second Law of Thermodynamics states that every ensemble must necessarily go from a state of order to one of disorder. Systems always tend to proceed to a state of equilibrium. This tendency is manifested as a flux wherever a gradient exists. A gradient in this sense denotes a state of separation, of low entropy or high order, while equilibrium denotes high entropy or disorder. Gradients can be of many types – gravitational, heat, fluid pressure, electric charge, concentration, etc., and in each case the corresponding flux tends to be set up to restore homogeneity/equilibrium. If one is to generalize these into one term, it can be said that they all represent what we might call a conformational gradient – a difference between the number of conformations that the system can exist in. The flux then is in the direction of the state with the higher number. Greater the difference-or gradient- stronger is the tendency.

Living beings represent a highly complex system operating in specific ways under stringent physical and chemical conditions. The special permeability of cell membranes, the organized structure of large molecules, etc., are examples of highly polarized phenomenon i.e. smaller number of conformations and hence very low entropy. Such an ensemble must degrade very rapidly if the Second Law is to hold true. However, as long as an organism is alive it does not degenerate. This is achieved by continually ingesting low entropy and removing high entropy, both in the form of energy and matter. Now entropy as represented by random heat motion is continuously generated at the molecular level and hence for any higher level of organization the following must hold true if the total entropy of the system is to be kept constant.

Entropy Input + Internal entropy generation = Entropy output

This may apply to any macroscopic control volume in a living system – from cells, tissues, organs, complete organisms, to populations, ecosystems, and finally the entire planet. Keeping the total internal entropy low is tantamount to preserving the structure, function and identity of the organism/system. The ingested energy/matter must therefore necessarily have lower entropy than that of the system and the removed energy/matter must have higher entropy. Thus even if it is continuously generated within the organism, it can be kept at a constant low value by effectively displacing the generated amount. Now since entropy is generated at the microscopic level, it must be taken up at that level itself and displaced to the outside of the system. This requires a carrier substance that is ever present and in intimate contact, wherever a metabolic process is taking place.

2. Role of Water in Life Processes

Water acts as a universal solvent to provide a medium for various biological reactions. It also acts as a carrier of heat and entropy on account of its cluster structure, hydrogen bonding, suitable viscosity and high specific heat capacity. Water helps extract entropy inside living systems at the microscopic to macroscopic levels, in the following ways.

2.1 Phosphorylation

During oxidative phosphorylation, the redox reaction transporting electrons from the pair $NAD^+/NADH$ to the pair $\frac{1}{2}O_2/H_2O$ represents an energy transfer of 52 Cal/mol.

$$\frac{1}{2}O_2 + NADH + H^+ \rightarrow H_2O + NAD^+$$

The three ATP molecules thus synthesized each capture 7.3 Cal of energy i.e., 21.9 Cal in total. The energy difference of 52 – 21.9 = 30.1 Cal is said to be given away as heat (U. Satyanarayana, 1999). This heat is taken by water during the reaction. It has been previously observed that if the solvent water is partly replaced by another compound viz. dimethyl sulfoxide, much greater amounts of heat and entropy are released as compared to when a complete aqueous medium is used (de Meis et al, 1982). Clearly, in a totally aqueous medium a large amount of heat and entropy is taken up by the solvent water.

2.2 Hydrophobic Effect in Protein Folding

The number of degrees of freedom of a system defines the number of available conformational states that the system can take. The entropy is then proportional to the natural logarithm of the number of micro conformations that yield the same macro state as follows:

$$S = k \ln W$$

Where, S is the system entropy; k is the Boltzmann constant; and W is the number of accessible microstates

This equation as given by Ludwig Boltzmann directly applies only to an ideal gas where all micro states are accessible and equally probable. There the value of W is large. In real systems, few of the total number of conformational states are accessible and moreover their probabilities are different. Hence the actual value of S is lower than the one given by the above equation. This is because in a real system the degrees of freedom of the individual components and subsystems are dependent on each other and are hence limited in number. The folding of proteins for example is an endergonic process as it involves a decrease in entropy. Yet it takes place, as the entropy decrease is balanced by an increase in the entropy outside of the protein. The hydrophobic effect is the most satisfactory explanation for this phenomenon. Dr. Udgaonkar (2001) explains that the tightly structured water molecules around the amino acid residues in an unfolded protein are released as the protein folds. This results in an increase in the entropy of the water and hence balances the process in accordance to the Second Law.

2.3 Dissipative Water Clusters in Cerebrospinal Fluid

The breaking up of an ensemble into smaller ones signifies an increase in the number of degrees of freedom and consequently, entropy. When a cluster of water molecules breaks up into smaller clusters, the breaking of hydrogen bonds results in an increase of entropy. Bennum(2013) describes how this phenomenon helps to eliminate toxins and take away heat and entropy from the cerebrospinal fluid(CSF) in human beings. Water enters the CSF with clusters of larger size and leaves with smaller ones. Entropy is thus transferred to the water. After it comes out of the system (here, the CSF), it comes in contact with cooler surroundings. This causes the slow rearrangement of water molecules due to the exothermic H-bond formation between them. In this way, the cycle continues and water displaces the entropy generated inside the CSF to the surroundings.

2.3 Excretion and Perspiration

Water serves as a carrier for the removal of wastes from the body. Dissolution of waste substances into water represents a multi phase system with no concentration gradient and consequently higher entropy as compared to one where the two are separated.

The human body exchanges heat with the surroundings via conduction, evaporative cooling and radiation. Of these three ways, the rates of conduction and radiation for carrying away heat from the body decrease as the ambient temperature approaches the body's surface temperature. If the ambient temperature is higher than that of the body, the transfer is reversed and heat is carried to the body. In case of evaporative cooling via perspiration however, the transfer is always from the body to the surroundings and the rate rises with increasing ambient temperature. Therefore water plays a central role in carrying away heat and hence entropy from the body to the surroundings.

3. Global Water Cycle

Water not only carries entropy out of living organisms but also helps the entropic balance on the planet. The heat flux from the sun to the Earth and from the Earth into space, passes through the water cycle. The oceans may be considered as a high entropy reservoir into which most water ends up after it has been cycled through various living systems. Evaporation of ocean water via the high frequency (low entropy) solar radiation separates it from impurities but increases its overall entropy through the addition of heat. Condensation of this water gives out low frequency (high entropy) radiation into space. The result is precipitation having very low entropy, which again passes through systems extracting entropy each step of the way.

4. Conclusion

A quantitative analysis of the entropy gain in living systems compared with the total entropy budget of the Earth needs to be made. This may provide an idea of the impact of individual actions and changes to the energy and entropy balance of the planet. Water is our most precious material resource. The fraction of global water at each position in the global water cycle defines how much of it we can use and for how long. Human actions and the addition of entropy that they make to the water on Earth in turn determine the size of this fraction. Arresting water in the early stages after precipitation i.e., at lower entropy allows us to use it better without investing in entropy reducing activities such as purification before use. The more degraded form of water we use, the more we shall have to treat it. This means additional energy degradation and a greater burden on the entropic balance of Earth – which once again is handled by that same water. It is like drinking sea water in an effort to satiate thirst. We shall only have to ingest more water to flush out the salts i.e., reduce the internal entropy! Shifting the emphasis from fanciful activities such as desalination of ocean water to the urgent ones like recharging of groundwater reserves and rainwater harvesting is therefore obvious and essential to our ability to sustainably use water in the present and future. Analysis from the point of view of entropy increase may help identify opportunities and threats in our efforts to effectively utilize water.

References

[1] A Bennun (2013), The coupling of thermodynamics with the organizational water-protein intra-dynamics driven by the H-bonds dissipative potential of cluster water, eprint arXiv:1303.6993.

[2] J Udgaonkar (2013), Entropy in Biology, *Resonance*, **6**, *9*, pp. 61-66.

[3] L de Meis, A de Souza Otero, O B Martins, E W Alves, G Inesi and R Nakamoto (1982), Phosphorylation of sarcoplasmic reticulum ATPase by orthophosphate in the absence of Ca2+ gradient. Contribution of water activity to the enthalpy and the entropy changes, *J. Biol. Chem.*, **257**, *9*, pp. 4993-4998.

[4] U Satyanarayana, U Chakrapani (1999), *Biochemistry*, Books and Allied (P) Ltd., Kolkata.