Thermodynamics of the evolution of the biosphere

A B Ptitsyn
Institute of Natural Resources, Ecology and Cryology Siberian Branch of RAS, 16a Nedorezova Street, Chita, 672014, Russian Federation
E-mail: aleksei_ptitsyn@mail.ru

Abstract. The thermodynamic foundations of the evolution of the biosphere are considered: the variability of natural systems with different dispersion of their components, the alternative ways of development of such systems, the alternative of intermediate stable states of ecosystems depending on fluctuations of external factors, primarily climate. The necessity of developing a system of mutually agreed complex indicators of this process is postulated. The necessity of including the water content of ecosystems in the number of parameters of nonequilibrium thermodynamics is justified. A new section of land hydrology is formulated - the study of thermodynamic aspects of the dynamics of natural waters.

Concerning the evolution of the biosphere, especially its early stages, different opinions are expressed, although the main scheme is recognized by most researchers.

Climate (from Ancient Greek klima, meaning inclination) is to a certain extent a geochemical factor as well, since it affects the mobility of chemical elements in the biosphere. In the past, changes in global climate were caused by cosmic phenomena and led to sharp, sometimes even catastrophic, changes in the biosphere. Currently, the human impact on global climate (mediated by the greenhouse effect) is being widely discussed. In this matter science is faced with conjecture and politics.

The cryptobiosphere comprises "outskirts" of the major biosphere that are inhabited solely by microorganisms. These include: non-freezing solutions of the permafrost zone; cold groundwater isolated from the major biosphere; millimeter-size pore water. Specific properties of water in these kind of extreme systems are determined by a specific composition and particular functions of the microbial community living there.

The provisions of thermodynamics, both classical, equilibrium (according to Gibbs) and non-equilibrium (according to I Prigogine, P Glansdorff) are based on the laws of statistical physics that describe the intimate essence of an object, and therefore are fundamental. They can be applied to almost any natural system in which random, non-deterministic processes play an important role. Even the behavior of socio-economic systems obeys the laws of thermodynamics [1]. The dispersion of the system plays an important role in the variability of the system (the number of degrees of freedom), and therefore in the number of its alternative stable states.

As an example, we can cite the thermodynamic description of the “water – rock” system given by A I Rusanov [2]. The number of degrees of freedom of the dispersed system depends on the curvature of the water films adsorbed on mineral surfaces. In his monograph, A I Rusanov convincingly proves that if the radius of curvature of the film is equal to or less than the thickness of the film, then each phase will have its own pressure value and, accordingly, the number of degrees of freedom will not
depend on the number of phases and the expression for the number of degrees of freedom will take the form

\[ f = K + 1, \]

instead of \( f = K - F + 1 \).

In this case, the variability of the system increases dramatically. Accordingly, the number of possible alternative stable states of the system also increases. Highly dispersed systems are not uncommon in geology, so the laws of nonequilibrium thermodynamics play an essential role here.

The position of the adsorbed films during physico-chemical analysis required special consideration [3]. The question was whether the adsorbed films can be considered a phase or not, since they cannot exist without a mineral substrate. As a result, the term “non-autonomous phase” appeared [4].

The position of this phase on the state diagram constructed by the author (figure 1) is limited by a complex A-B-C-G-I-D-S-R surface and the left coordinate plane. These concepts open a new thermodynamic page in the multifactorial problem of ”water-rock interaction”. This includes a whole bunch of processes, namely, solid-liquid reactions (kinetics of reactions in heterogeneous systems), complexation, adsorption, the formation of non-autonomous phases on mineral surfaces, the effect of some elements on mobility of others, electrochemical processes and even the vibrational modes of reactions and processes.

![Figure 1. Phase diagram with the non-autonomous phase, describing the distribution of water phases in the coordinates of the concentration in the CaCl₂ solution - mineral surface - temperature.](image)

The theory of nonequilibrium thermodynamics according to I Prigogine and P. Glansdorff [5] provides for the possibility of the existence of several stable states during the evolution of a particular system. We can also call them metastable states characterized by an intermediate (temporary) minimum of internal free energy.

As recent studies have shown (for example, [6]), an important parameter of nonequilibrium processes is water, its amount in the system (excess or lack) can fundamentally change the sequence of stable states. The role of water in the evolution of the Earth as a planet is huge. There is an extensive literature on this topic, but its analysis is not the task of the author of this publication.
In the works of I. Prigogine and P. Glensdorf, the question of the possibility of alternative stable states was not considered. In recent publications by various authors, this possibility is proved by the example of some natural systems. For artificial systems “guided” by a person, this possibility is practically absent. Consequently, Nature is variable and therefore its dynamics are difficult to predict. The course of evolution of natural ecosystems depends on a random (rather only seemingly random) combination of external factors. This fundamentally important conclusion makes it necessary to develop the theory of non-equilibrium processes, i.e. increases the importance of a new section of thermodynamics – "thermodynamics of evolving systems".

The inclusion of water as a parameter in the apparatus of nonequilibrium thermodynamics develops the theoretical ideas of Prigogine-Glensdorf, allows us to explain the possibility of alternative stable states in natural hydrobiological systems and to link them with the influence of external factors, primarily climate, whose fluctuations have recently become more and more concerned about humanity.

To ensure the reliability of environmental and economic forecasts, it is necessary to systematically study the causes and mechanisms of changes in external conditions for the studied system, which is possible only with complex interdisciplinary research. However, this requires special interdisciplinary institutes that will be able to solve common natural science problems.

In connection with the above, there is a need to revise the concept of modern natural science [7], taking into account new thermodynamic concepts.

For a reliable reconstruction of the evolution of the biosphere, a system of mutually agreed indicators is necessary. As such indicators, it is necessary to choose such components of natural ecosystems that are able to deposit changes in the biosphere over a certain period of time and have a fairly wide distribution in the biosphere. These requirements are met by some species of organisms that live, for example, in Central Asia and in particular in Transbaikalia (molakofauna, straight-winged insects, benthic fauna, and others).

A good indicator of the climate dynamics, and therefore the evolution of the biosphere, is the dynamics of the hydrological regime of the territory in combination with geomorphological data. Studies of Pleistocene glaciations on the territory of Transbaikalia and the Baikal region [8] have revealed the great role of underground lakes in changing the hydrological picture of this territory, as well as the adjacent regions of China and Mongolia. According to R. F. Yenikeyev [8], the regime of modern lakes is characterized by significant fluctuations in the parameters of the reservoir, mineralization, and the ratios of the components of the salt composition of the waters. This is due to the physical, geographical, climatic features and the interaction of the lake with surface and underground waters.

The stages of the stable states of ecosystems are also complex indicators of the evolution of the biosphere.

As the most important geochemical factor and the major component of the biosphere, water deserves special attention. It is involved in the majority of events occurring in the Earth’s crust. Water properties support the biosphere’s evolution in all respects. Its boiling and thawing points set the temperature boundaries of life for the majority of organisms; its heat capacity, fusion heat and heat of vaporization regulate the climate; ice that floats in its own melt protects reservoirs from freezing; oceans play an essential role in maintaining the global gas regime; due to its high dielectric constant, water is an inert solvent fit for supplying nutrients and removing wastes from organisms without entering into a reaction with their tissues. The lack of any of these water functions is detrimental to life.
Rusanov A I 1967 Phase equilibriums and surface phenomena (Leningrad: Khimiya) p.388

Lopatkin A A 1987 New trends in thermodynamics of adsorption on solid surfaces Physical Chemistry: Modern Problems (Moscow: Khimiya) pp 89–127

Urusov V S, Tyson V L and Akimov V V 1997 Geochemistry of Solid (Moscow: GEOS) p 500

Glensdorf P and Prigozhin I 2003. Thermodynamic theory of structure, stability and fluctuations (Trans. from English) (Moscow: URSS) p 280

Patel B H, Percivalle C, Ritson D J, Duffy C D and Sutherland J D 2015 Nat. Chem. 7 301–07

Dubnishcheva T Ya 1997 Concepts of modern natural science (Novosibirsk: UCEA) p 830

Enikeev F I 1998 Pleistocene glaciations of the north of the Trans-Baikal Territory Coll. of abstr. of reports of the All-Union meeting "The main results in the study of the Quaternary period and the main directions of research in the XXI century" (St. Petersburg:VSEGEI) pp 107.