



## **Thermodynamic substantiation of the direction of nonequilibrium processes in triadconjugations of machine parts based on the principles of maximum and minimum entropy**

**V.V. Aulin\*, S.V. Lysenko, A.V. Hrynkiv , D.V. Holub**

*Central Ukrainian National Technical University , Ukraine*

*\* E-mail: AulinVV @ gmail.com*

*Received: 05 April 2022: Revised: 05 May 2022: Accept: 27 May 2022*

### **Abstract**

The article gives a thermodynamic substantiation of the direction of nonequilibrium processes in tribocouples of machine parts, in tribosystems, based on the principles of maximum and minimum entropy. It is clarified how nonequilibrium processes can be substantiated on the basis of the minimum and maximum function of entropy production: linear and nonlinear nonequilibrium processes and their different thermodynamics. The entropy production function is considered as a function of thermodynamic force flows and thermodynamic flows.

The theory of nonequilibrium processes is based on the Liouville equation for classical tribosystems, taking into account external influences or perturbations. It is shown that in thermodynamic processes in tribosystems the principle of entropy maximization is realized as the second principle of synergetics.

**Key words:** triadconjugation of details, nonequilibrium processes, thermodynamics, synergetics, entropy, thermodynamic flow

### **Introduction**

The essence of the principle of maximum entropy production G. Ziegler is that the evolution of the nonequilibrium tribosystem develops in the direction of maximizing the production of entropy in it under given external constraints. The second law of thermodynamics in the language of entropy production is formulated as follows: entropy production  $\sigma_s \geq 0$  not only has a positive value, but also goes to the maximum.

Given the statistical interpretation of entropy and the work of Boltzmann and Gibbs, entropy, and consequently its production, tends to increase to the maximum level assumed by the constraints imposed on tribosystems. The final equilibrium state of the tribosystem is the most probable and is described by the maximum number of microstates. Such a statistical interpretation allows us to consider the principle of maximum entropy production as a natural generalization of its Clausius-Boltzmann-Gibbs formulation, and in some cases as a consequence.

### **Literature review**

The peculiarity of nonequilibrium thermodynamics in tribosystems is initially based on the equations of balance of entropy, momentum energy and matter and on the first two laws of thermodynamics [1,2] .

Compared with the principle of I. Prigogine [ 4 ] , the principle of G. Ziegler [5] describes a wider range in the evolution of nonequilibrium tribosystems and is a more generalized approach in their study and study of the relationship of characteristics and properties with entropy (entropy production) [3] . G. Ziegler's principle makes it possible to constructively construct both linear and nonlinear thermodynamics. It follows that Onsager's variational principle is valid only for linear nonequilibrium thermodynamics of tribosystems [4,6] . At that time, the principle of Onsager-Diarmati, as a partial statement, is valid for stationary processes, in the presence of free forces. From it follows the principle of I. Prigogine [7-9]. If given thermodynamic forces (flows), then, based on



the principle of G. Ziegler, the tribo system will adjust its thermodynamic flows (forces) to  $\sigma_s \Rightarrow \max$  [10-12]. If  $\sigma_s$  it is a quadratic function, then the relationship between flows and forces in the tribosystem is adjusted as a result. If the system is in a stationary weakly nonequilibrium state, but part of the thermodynamic forces remains free, then the currents generated by Ziegler will begin to reduce the thermodynamic forces, and those in turn - thermodynamic flows. As a result, the production of entropy is minimized:  $\sigma_s \Rightarrow \min$  [4].

It is possible to substantiate nonequilibrium processes in tribosystems by the methods of general statistical theory [13-15]. Classical kinetic theory is not suitable for relatively dense tribosystems with a strong interaction between their elements and particles. The problem is to create a nonequilibrium microscopic theory that can describe such systems. This is primarily to obtain the equations of energy transfer, momentum, mass and calculation of kinetic coefficients directly from the equations of classical and quantum mechanics. Such a statistical theory began to develop intensively from the middle of the twentieth century [16,17]. L. Onsager stated: the temporal evolution of the function of a given physical quantity in the equilibrium system occurs on average by the same laws as the change of the corresponding macroscopic variable in the nonequilibrium system [1,2,10,18].

Being in an unbalanced state, the tribosystem does not feel how it got into it - due to fluctuations or due to external influences, and therefore its next reaction must be the same. As a result of relaxation of the nonequilibrium tribosystem near the state of equilibrium and resorption of fluctuations will occur according to the same laws [19,20].

### Purpose

The aim of this work is a thermodynamic substantiation based on the maximum entropy of the direction of nonequilibrium processes occurring in the triad conjugations of machine parts.

### Results

If the tribosystem, the conjugation of machine parts, is in some nonequilibrium state, then after some time (relaxation time) it will come to an equilibrium state from the set of possible states for which the entropy will be maximum. The change in entropy during this period of time will be the maximum among the possible, and therefore the maximum becomes the production of entropy. The variational principle gives possible relations of linear nonequilibrium thermodynamics:

$$J_i = \sum_k L_{ik} X_k ; \quad L_{ik} = L_{ki}, \quad (1)$$

where  $L_{ik}$  – the matrix of kinetic coefficients independent of  $J_i$  and  $X_k$ .

The system of equations (1) makes it possible to describe the transfer of entropy, momentum, mass. The above equations (1) are valid for relatively small thermodynamic forces, when the relationship between forces and flows is almost linear. This is L. Onsager's first deductive formulation of linear nonequilibrium thermodynamics. If the values of irreversible forces are given  $X_i$ , then the true flows  $J_i$  maximize the expression  $[\sigma_s(X_i, J_k) - \Phi(J_i, J_k)]$ . The variation in flow  $J$  at constant  $X$  is equal to:

$$\delta_J [\sigma_s(X_i, J_k) - \Phi(J_i, J_k)]_X = 0; \quad (2)$$

$$\Phi(J_i, J_k) = \frac{1}{2} \sum_{i,k} R_{ik} J_i J_k, \quad (3)$$

where  $\Phi$  – the scattering potential ( $\Phi > 0$ );  $R_{ik}$  – coefficient matrix, inverse matrix  $L_{ik}$ , matrix  $R_{ik}$  – can be considered a system tensor, which should be considered as the sum of symmetric  $S_{ik}$  and antisymmetric  $A_{ik}$  tensors:

$$\Phi = \frac{1}{2} \sum_{i,k} (S_{ik} J_i J_k + A_{ik} J_i J_k). \quad (4)$$

Because for the antisymmetric tensor  $A_{ii} = 0$  and  $A_{ik} = -A_{ki}$ , the antisymmetric part of the tensor  $R_{ik}$  in equation (3) does not contribute to the scattering potential  $\Phi$  and the tensor  $R_{ik}$  becomes symmetric

$R_{ik} = R_{ki}$ . Substituting the expression  $\sigma_S = \sum_i X_i J_i$  into equation (2), as well as transforming (3) by replacing the variation derivative over the corresponding flows, we obtain:

$$\frac{\partial}{\partial J_i} \left[ \sum_i X_i J_i - \frac{1}{2} \sum_{i,k} R_{ik} J_i J_k \right]_{x=const} = 0. \quad (5)$$

The equation for thermodynamic force after differentiation will look like:

$$X_i = \frac{1}{2} \sum_k (R_{jk} + R_{kj}) J_k = \sum_k R_{kj} J_k. \quad (6)$$

Since the flow function is nonnegative  $\Phi \geq 0$ , the solution of equation (6) with respect to unknown flows is equal to:

$$J_j = \sum_k R_{jk}^{-1} X_k = \sum_k L_{jk} X_k, \quad (7)$$

where  $R_{jk}^{-1} = L_{jk}$ . In this case  $R_{jk}$  – a symmetric matrix, it is  $R_{jk}^{-1}$  also symmetric.

This suggests that the expression  $[\sigma_S(X_i, J_k) - \Phi(J_i, J_k)]$  in equation (2) has one extreme point  $X_i, J_k$ , which is described by expressions (6) and (7). Because the flow function  $\Phi$  is a homogeneous quadratic positive function, this point is the point of maximum.

Note that the Onsager variation principle is formulated for thermodynamic flows in the tribosystem. For the space of forces in the tribosystem, according to I. Diarmati, if the values of thermodynamic flows are given  $J_i$ , then the irreversible existing forces  $X_i$  maximize the expressions  $\sigma_S(X_i, J_i) - Y(X_i, X_k)$ , ie we have:

$$\delta_X [\sigma_S(X_i, J_i) - Y(X_i, X_k)]_J = 0; \quad (8)$$

$$Y(X_i, X_k) = \frac{1}{2} \sum_{i,k} L_{ik} X_i X_k, \quad (9)$$

where  $Y(X_i, X_k) > 0$  is the scattering potential in the force space of the tribosystem.

Analysis of entropy production shows that its function is a symmetric bilinear form. Then according to the principle of Diarmati equation (2); (3) and (8), (9) are equivalent.

The principle of minimum entropy production, formulated by I. Prigogine, against the background of the apparatus of nonequilibrium thermodynamics also describes various nonequilibrium processes supported by constant applications of irreversible forces  $X_i, i = 1, j$  where  $j \leq n$ ,  $n$  is the number of forces in the system and entropy production is minimal  $i = j + 1, \dots, n$ , disappear.

Prigogine's principle is a simple consequence of the Onsager-Diarmati principle. The theory of linear nonequilibrium thermodynamics is widely used in tribosystems:

– it becomes possible to solve the system of equations of mass transfer, momentum and energy, because the number of equations is equal to the number of unknowns;

– using non-diagonal coefficients  $L_{ik}$ , it becomes possible to describe cross-flows in chemical, electrical and other kinetic processes;

– it is possible to obtain additional information about the values of kinetic coefficients;

– the presence of entropy production values  $\sigma_s$  that have extreme values in the nonequilibrium state allows to obtain additional information about the characteristics and properties of the tribosystem.

Note that linear nonequilibrium thermodynamics in tribosystems describes thermodynamic forces of small magnitude. Linear nonequilibrium thermodynamics cannot explain and describe the fundamental problems of self-organization, oscillatory processes, etc. Onsager's linear thermodynamics in thermodynamic theory is generalized to the nonlinear case on the basis of the maximum entropy production (G. Ziegler's principle). In the flow space  $\{J_k\}$  we have:

$$\sigma_S(J_i) = \sum_k X_k(J_i) J_k. \quad (10)$$

To find the functional dependence  $X_k(J_k)$ , G. Ziegler proposed the principle of maximum entropy production  $\sigma_s$ : if an irreversible thermodynamic force  $X_i$  is given, then the true flow  $J_i$  that satisfies the equation  $\sigma_s(J_i) = \sum_i X_i J_i$  contributes to the maximum entropy production.  $\sigma_s$  [5].

This principle can be widely used in the theory of plasticity in the form of the principle of maximum rate of dissipation of mechanical energy (Mises principle): the rate of dissipation of mechanical energy per unit volume during plastic deformation has maximum value for the actual stress state among all stress states. plasticity. The strain rate is considered fixed. This principle of the theory of plasticity is in fact generalized to all nonequilibrium thermodynamics.

For nonequilibrium processes described by linear nonequilibrium thermodynamics, in the tribosystem at a given complex of forces there is always a maximization of the  $\sigma_s(J_i) \Rightarrow \max$  entropy production function, ie from the Ziegler principle we can obtain the Onsager principle. G. Ziegler's principle is realized in the system of equations:

$$\left\{ \begin{array}{l} \frac{\partial}{\partial J_i} \left[ \sum_{i,k} R_{ik} J_i J_k - \mu \left( \sum_{i,k} R_{ik} J_i J_k - \sum_i X_i J_i \right) \right]_{X, \mu = \text{const}} = 0 \\ \sum_{i,k} R_{ik} J_i J_k = \sum_i X_i J_i \end{array} \right. \quad (11)$$

Where the space of thermodynamic forces is determined by the expression:

$$X_i = \frac{2 \cdot (\mu - 1)}{\mu} \sum_k R_{ik} J_k \quad (12)$$

Substituting the last expression for the thermodynamic force in the second equation of system (11), we obtain:  $2 \cdot \left( \frac{\mu - 1}{\mu} \right) = 1$  ie  $\mu = 2$ .

Given this, we have:

$$\delta_J \cdot \left[ \sum_{i,k} R_{ik} J_i J_k - 2 \cdot \left( \sum_{i,k} R_{ik} J_i J_k - \sum_i X_i J_i \right) \right]_{X = \text{const}} = 0 \quad (13)$$

Taking into account equation (10) and making some transformations, we obtain:

$$\delta_J \left[ \sigma_s - \frac{1}{2} \sum_{i,k} R_{ik} J_i J_k \right]_{X = \text{const}} = 0, \text{ or } \partial_J [\sigma_s(X_i, J_k) - \Phi(J_i, J_k)]_{X = \text{const}} = 0 \quad (14)$$

The latter indicates that the principle of G. Ziegler follows the variational principle of Onsager.

The research shows that the function of entropy production, as a function of flows, is convex, and G. Ziegler's principle proves a mutually unambiguous correspondence between flows and forces and triadconjugations of details. This is confirmed by the geometric interpretation of the function  $\sigma_s(J_i)$ : it  $\sigma_s(J_i)$  tries to go to zero when  $J_i \rightarrow 0$ , and the whole surface  $\sigma_s(J_i)$  is sign-defined. When  $\sigma_s(J_i) \leq 0$ , for arbitrary values of forces, the line of intersection of the surface  $\sigma_s(J_i)$  and the plane  $\sum_i X_i J_i$  will lie in the negative region and  $\sigma_s \Rightarrow \max$  corresponds to this line.

Based on the principle of G. Ziegler, it can be argued that there can never be physically realized states of tribosystems with negative entropy production, ie always  $\sigma_s \geq 0$ . In the variational construction of nonequilibrium thermodynamics, a particular species  $\sigma_s$  is postulated,  $J_i$  and  $X_i$  there is some freedom in expression.

If in the tribosystem there are two thermodynamic forces  $X_1$  and  $X_2$ , which are known functions of flows  $J_1$  and  $J_2$ . The entropy production in this case is equal to:

$$\sigma_s(J_1, J_2) = X_1(J_1, J_2)J_1 + X_2(J_1, J_2)J_2. \quad (15)$$

The orthogonality condition is:

$$X_k^* = \frac{\partial \sigma_s}{\partial J_k}; k = \overline{1, n}; \quad (16)$$

$$\lambda = \sigma_s \left( \sum_{k=1}^2 \frac{\partial \sigma_s}{\partial J_k} J_k \right)^{-1}. \quad (17)$$

Converting (16) and (17), taking into account (15), we obtain:

$$X_1^* = X_1 + \frac{\Delta}{J_1}, \quad X_2^* = X_2 - \frac{\Delta}{J_2} -$$

where  $\Delta$  is the deviation from the orthogonality condition, which is finally in these conditions equal to:

$$\Delta = -\frac{\lambda J_1 J_2}{\sigma_s} \left( X_1 J_1 \frac{\partial X_1}{\partial J_1} - X_2 J_2 \frac{\partial X_2}{\partial J_2} + X_1 J_2 \frac{\partial X_2}{\partial J_2} - X_2 J_1 \frac{\partial X_1}{\partial J_1} \right). \quad (18)$$

Assuming that  $\Delta \rightarrow 0$ , we have:

$$X_2(J_1, J_2) \frac{\partial \sigma_s(J_1, J_2)}{\partial J_1} = X_1(J_1, J_2) \frac{\partial \sigma_s(J_1, J_2)}{\partial J_2}. \quad (19)$$

Equation (19) defines a class of functions  $\sigma_s$  for which thermodynamic forces are determined. It is valid for the quadratic function  $\sigma_s$  (15) if the Onsager reciprocity relations are valid.

If we assume that the fluctuation of quantities  $a_i$  near the equilibrium state occurs according to a linear law (proportional to  $X_i$ ) and that they are ergodic, we can obtain reciprocity and give kinetic coefficients  $L_{ij}$  through time correlation functions to quickly change  $\dot{a}_i$  the corresponding values:

$$L_{ij} \cong \int_0^{\infty} \overline{\dot{a}_i(t) \dot{a}_j(o)} dt, \quad (20)$$

where  $\overline{\dot{a}_i(t) \dot{a}_j(o)}$  is the averaging over the equilibrium ensemble of functions  $\dot{a}_i(t)$  with the distribution function  $P(a)$ :

$$P(\vec{a}) \cong \exp\left(-\frac{\Delta S(a)}{k_B}\right), \quad (21)$$

where  $k_B$  – the Boltzmann constant;  $\Delta S(a)$  – change of entropy at fluctuation  $\Delta S(a) = S_{eq} - S$ ;  $S_{eq}$  – entropy system in equilibrium;  $\vec{a}(a_e \dots a_i \dots a_j)$  – a set of values that characterize the system.

The physical meaning of expression (20) is as follows: the longer the fluctuation, ie, the slower the attenuation of the correlation function, the greater the canonical coefficient.

Let the tribosystem at the moment  $t_0$  be in an unbalanced state with entropy  $S_0$ . Until the next time  $t$ , when the difference  $t - t_0$  is significantly longer than the duration of one interaction, but less than the relaxation time, the system can go to one of the states with entropy  $S_1 \dots S_N$  ( $S_1 < \dots < S_N$ ). Due to the fact that the ongoing process in the tribosystem is spontaneous, the entropy  $S_i$ , will be greater than  $S_0$ . According to Onsager's approach, the transition to the state with entropy  $S_N$  will be the most probable. Each of the states  $S_1 \dots S_N$  can be considered as a fluctuation, the probability of which is greater the greater the entropy of the equilibrium state

$S_{eq} - S_N \Rightarrow \min$ . As a result, the value  $\frac{S_N - S_0}{t - t_0}$  will be maximum possible and the system evolves

according to the principle of maximum entropy production  $\sigma_s \Rightarrow \max$ .

Modern theory of nonequilibrium processes is characterized by a great variety of approaches, but the main ideas are quite close to each other [ 21,22 ]. The Liouville equations [ 23,24 ] for classical tribosystems are taken as a basis:

$$\frac{\partial \rho_q}{\partial t} + i_y L_l \rho_q = 0, \quad (22)$$

where  $\rho_q(q, p, t)$  is the phase function of the particle distribution of the triboelement material;  $q, p$  – coordinates and momentum in  $6N$  – dimensional space;  $t$  – time;  $i_y$  – imaginary unit;  $L_l$  is a linear Liouville operator.

$$iL_l \varphi = \{\varphi, H\} = \sum_k \left( \frac{\partial \varphi}{\partial q_k} \frac{\partial H_r}{\partial P_k} - \frac{\partial \varphi}{\partial P_k} \frac{\partial H_r}{\partial q_k} \right), \quad (23)$$

where  $\varphi$  is a function;  $H_r$  is the Hamiltonian of the system,  $H_r = H_r(q, p, t)$ .

We believe that the nonequilibrium macroscopic state is described by a set of observed quantities  $\overline{P_m}^t$ , which is the average value of the corresponding basic dynamic variables  $P_m$  (energy, momentum, number of particles). Since  $\overline{P_m}^t$  it does not unambiguously define the distribution  $\rho(t)$ , we choose the one that corresponds to the principle of max information entropy. Finally get the quasi-equilibrium distribution  $\rho_q$ :

$$\rho_q(t) = \exp(-\Phi(t) - \sum_m F_m(t) P_m), \quad (24)$$

where

$$\Phi(t) = \ln \left( \int \exp \left\{ - \sum_m F_m(t) P_m \right\} d\Gamma \right) - \quad (25)$$

the Masier-Planck function, which is determined from the rationing condition, and the Lagrangian factors  $F_m(t)$  are selected from the self-matching condition:

$$\overline{P_m}^t = \overline{P_m}_q^t = \int \rho_q P_m d\Gamma, \quad (26)$$

where  $d\Gamma = dq dp / (N! h_p^{3N})$ ,  $N$  – the number of particles of the material of the tribosystem element,  $h_p$  – the Planck constant.

Based on equality (26), the average values on the quasi-equilibrium ensemble (24) coincide with the true value of the macroscopic quantities.

Let at some point in time  $t'$  we have:

$$\rho(t') = \rho_q(t'), \quad (27)$$

Then the solution of Liouville's equation (22) is a function [44,45]:

$$\rho(t) = \exp(-i(t-t')L) \rho_q(t'). \quad (28)$$

It is determined that due to the significant infinity of classical phase trajectories, the behavior of the macrosystem at considerable time intervals should not depend on the microscopic characteristics of the initial conditions. Evolution with equal probability can begin with any state  $\rho_q(t')$  in the time interval from  $t_0$  to  $t$  and the distribution takes the form:

$$\rho(t) = \frac{1}{t-t_0} \int_{t_0}^t \exp(-i(t-t')L) \rho_q(t') dt'. \quad (29)$$

After some transformations of equation (16) we have:

$$\rho(t) = \lim_{\varepsilon \rightarrow +0} \varepsilon \int_{-\infty}^t \exp(-\varepsilon(t-t')) \exp(-i(t-t')L) \rho_q(t') dt'. \quad (30)$$

Note that the preboundary statistical distribution satisfies the Liouville equation with an infinitesimal source on the right:

$$\frac{\partial \rho}{\partial t} + iL\rho = -\varepsilon \{ \rho(t) - \rho_q(t) \}. \quad (31)$$

When  $\varepsilon \rightarrow 0$ , the source selects the "delayed solution" of this equation and describes the irreversible evolution of the system.

Correlations (30, 31) form the basis of the method of nonequilibrium statistical operator, which can be used to obtain kinetic, hydrodynamic or relaxation equations that describe the evolution of the nonequilibrium system at different time scales [1-3,9]. Note that the idea of the method is similar to the ideas and results of other existing approaches to building a general theory of nonequilibrium processes from the first principles.

If the effect or perturbations that disturb the equilibrium of the tribosystem are weak enough, then the given equations can be simplified by leaving linear perturbation corrections to the equilibrium values according to the theory of linear reactions.

Let the perturbation be represented as an expression  $\sum_j H_j B_j$ , where  $H_j$  are some stationary external fields;  $B_j$  – conjugate dynamic variables. The stationary equations of the reaction parameters of the system  $F_m$  for this perturbation has the form:

$$\psi_m = \sum_n D_{mn} F_n, \quad (32)$$

where  $D_{mn} = \overline{(P_m; \dot{P}_n)}_{i\varepsilon}$  – generalized transition probability;  $\psi_m = \sum_j \overline{(P_m; \dot{B}_j)}_{i\varepsilon} H_j$  – drift member.

Variational principle can be used to solve equations (32). The test set of reaction parameters of the system satisfies the condition:

$$\sum_m F'_m \psi_m = \sum_{mn} F'_m D_{mn} F_n. \quad (33)$$

Based on this, we can formulate and prove the following principle: the response parameters of the tribosystem, which is the solution (32), maximize among all functions  $\{F'_m\}$ , subject to condition (33), the entropy production of the system is equal  $\sum_j H_j \overline{B}_j^t$  to the positive constant factor. According to this principle,

there is a selection of flows (response parameters) that maximize the production of entropy at given forces. A similar generalization was made by H. Nakano, who pointed not only to the maximum entropy production  $\sigma_s$ , but also to the maximization of the transfer coefficients determined by the linear reaction theory. Given the universality of the principle of maximizing information entropy G. Hacken, considers the second beginning of synergetics [13,25].

If the external production of entropy is equal  $\sigma_{se} = \sum_i X_i I_i$ , then the internal production of entropy  $\sigma_i(\Theta)$ , where  $\Theta$  the microscopic parameters describing the internal state of the elements of the tribosystem of the system. If the thermodynamic forces  $X_i$  are fixed and maintain the state of the tribosystem, which evolves from some initial state to stationary with parameters  $\Theta^*$  with the relaxation time of the system  $\tau$ , then to produce the entropy of any stationary nonequilibrium state internal and external  $\sigma_s$  must be equal  $\sigma_i(\Theta^*) = \sum_i X_i J_i(\Theta)$ .

## Conclusions

1. There is some hierarchy of processes developing in tribosystems: at short intervals the system maximizes the production of entropy  $\sigma_s \Rightarrow \max$  at given fixed forces at the observed time, and as a result linear relations will be valid (1); on a large scale, the system varies with free thermodynamic forces to reduce entropy production  $\sigma_s \Rightarrow \min$ . This indicates that the speed of the tribosystem's attempt to reach the state with maximum entropy is the highest.

2. The system at each time so selects its thermodynamic flows at fixed thermodynamic forces, so that the change in entropy was maximum and, accordingly, the movement of the tribosystem to the final state is the fastest. This occurs continuously or abruptly (at bifurcation points), depending on the specifics of the system. In the latter case, several forces can correspond to one force at the same time, from which the one that satisfies the Ziegler principle is selected, because the relationship between flows and forces is ambiguous.

3. To construct nonequilibrium statistical mechanics of tribosystems based on the Liouville equation, it is necessary to obtain time-irreversible transfer equations. The transition to the irreversibility of processes in tribosystems is due to the rejection of a complete description of the distribution function to a brief description of their nonequilibrium states and states of elements.

## References

1. Aulin VV (2014). Fizychni osnovy protsesiv i staniv samoorhanizatsii v trybotekhnichnykh systemakh: monohrafiia [ Kirovohrad: TOV "KOD" ] 369 c.
2. Aulin VV (2015). Trybofizychni osnovy pidvyshchennia zosostiikosti detalei ta robochykh orhaniv silskohospodarskoi tekhniki [dys. ... Dr. Tech. Science: 05.02.04 ] 360 p.
3. Aulin V.V. (2016). Rol pryntsyviv maksimumu ta minimumu vyrobnytstva entropii v evoliutsiinomu rozvytku staniv trybosystem [Problems of tribology. №2] S.6-14.
4. Prigozhin I. (1960). Vvedenie v termodinamiku neravnesnykh protsesov [M.: Izdatelstvo inostrannoy literatury] 127s.
5. Tsigler G. (1966) Ekstremalnyie printsipy termodinamiki neobratimyykh protsessov i mehanika sploshnoy sredy [M.: Mir] 134s.
6. Bershadskiy L.I. (1990). Strukturnaya termodinamika tribosistem [K:Znanie] 30s.
7. Martyushev L.M. (2010). Proizvodstvo entropii i morfologicheskyy perehody pri neravnesnykh protsessah [avtoref. Dr. fiz.-mat. nauk spets: 01.04.14] 32s.
8. Martyushev L.M., Seleznev V.D. Printsip maksimalnosti proizvodstva entropii v fizike i smezhnykh oblastiakh [Ekaterinburg: GOU VPO UGTU-UII] 83 s.
9. Martyushev L., Seleznev V. (2006). Maximum entropy production principle in physics, chemistry and biology [Physics Reports. Vol. 426, Issue 1] P. 1-45.
10. Delas N.I. (2014). Printsip maksimalnosti proizvodstva entropii v evolyutsii makrosistem: nekotoryie novyye rezultaty [Vostochno-Evropeyskiy zhurnal peredovykh tekhnologiy. T.6, №4 (72)] S.16-23.
11. Dewar R.C. (2005) Maximum entropy production and the fluctuation theorem [Journal of Physics A: Mathematical and General. Vol. 38, Issue 21] P.L371-L.381.
12. Niven R.K. (2009) Steady state of a dissipative flow-controlled system and the maximum entropy production principle [Physical Review E. Vol. 80, Issue 2] P.021113.
13. Groot S., Mazur P. (1964). Neravnesnaya termodinamika [M.: Mir] 456 s.
14. Niven R. K. (2009). Steady state of a dissipative flow-controlled system and the maximum entropy production principle [Physical Review E. Vol. 80, Issue 2] P. 021113.
15. Dewar, R. C. (2005). Maximum entropy production and the fluctuation theorem [Journal of Physics A: Mathematical and General. Vol. 38, Issue 21] P. L371-L381.
16. Simak V., Sumbera M., Zborovsky I. (1988). Entropy in Multiparticle Production and Ultimate Multiplicity Scaling [Phys. Lett. B. V.206] P. 159-162.
17. Huber P.J. Robast Statistics (1981). [N.Y.: Wiley]
18. Barrodale I., Erikson R. E. (1980). Algorithms for Least Square Linear Prediction and Maximum Entropy Spectral Analysis [Geophysics. V.5, No.3] P. 420.
19. Ozawa H., Ohmura A., Lorenz R. D., Pujol T. (2003). The second law of thermodynamics and the global climate system: A review of the maximum entropy production principle [Reviews of Geophysics. Vol. 41, Issue 4] P. 1-24.
20. Kleidon A., Lorenz R.D. (2005). Non-equilibrium Thermodynamics and the Production of Entropy: Life, Earth and Beyond, Springer Verlag, Heidelberg principle [Reviews of Geophysics. Vol. 41] P. 1018-1041.
21. Cejnar P., Jolie J. (1998). Wave-Function Entropy and Dynamical Symmetry Breaking in Interacting Boson Model [Phys. Rev. E. V.58, No. 1] P. 387-399.
22. Cejnar P., Jolie J. (1998). Dynamical-Symmetry Content of Transitional IBM-I Hamiltonian [Phys. Lett. B. V.420] P. 241-247.
23. Jaynes E. T., Levine R. D., Tribus M. (1979). Where do we Stand on Maximum Entropy?' in The Maximum Entropy Formalism [M.I.T. Press, Cambridge] 105 p.
24. Vilson A.Dzh. (1978). Entropiynyye metody modelirovaniya slozhnykh sistem [M.: Nauka].
25. Budanov V.G. (2006). O metodologii sinergetiki [Voprosy filosofii. №5] S.79-94.

**Аулін В.В., Лисенко С.В., Гриньків А.В., Голуб Д.В.** Термодинамічне обґрунтування спрямованості нерівноважних процесів в трибоспряженнях деталей машин на основі принципів максимуму і мінімуму ентропії

В статті дано термодинамічне обґрунтування спрямованості нерівноважних процесів в трибоспряженнях деталей машин, в трибосистемах, на основі принципів максимуму і мінімуму ентропії. З'ясовано, як нерівноважні процеси можливо обґрунтувати на основі мінімуму та максимуму функції виробництва ентропії: лінійні та нелінійні нерівноважні процеси й різні їх термодинаміки. Функцію виробництва ентропії розглянуто як функцію потоків термодинамічних сил і термодинамічних потоків.

В основу розгляду теорії нерівноважних процесів покладено рівняння Ліувілля для класичних трибосистем з урахуванням зовнішнього впливу або збурення. Показано, що в термодинамічних процесах в трибосистемах принцип максимізації ентропії реалізується, як другий початок синергетики.

**Ключові слова:** трибоспряження деталей, нерівноважні процеси, термодинаміка, синергетика, ентропія, термодинамічний потік