ENERGY EFFICIENCY OF HEAT TECHNOLOGICAL SYSTEMS

***Sergii Samiilenko*[a], *Roman Hryshchenko*[b], *Maksym Kryvosheiev*[c]**

[a] *National University of Food Technologies, Kyiv, Ukraine, samiilenko@nuft.edu.ua,*
[b] *National University of Food Technologies, Kyiv, Ukraine, rgryshchenko@nuft.edu.ua,*
[c] *National University of Food Technologies, Kyiv, Ukraine, maksymko@nuft.edu.ua, CA*

Abstract:

This paper addresses the limitations of traditional energy efficiency definitions in heat technological systems (HTS), which often fail to identify the specific causes of inefficiency or the potential for optimization. We propose a methodology based on the "principle of energy compensation for irreversibility," which treats any internal or external irreversibility as a driver for additional fuel consumption. By combining energy and entropic characteristics with the application of Constructal Law, the study establishes a direct quantitative relationship between entropy generation and primary energy resource expenditures. A key result is the derivation of the specific fuel consumption for irreversibility compensation, which is shown to depend solely on the thermodynamic temperature of the environment and the fuel's heat of combustion. This approach resolves the "exergy contradiction" inherent in thermal systems where mechanical work is absent, offering a more direct tool for thermodynamic optimization. The proposed strategy shifts the focus from simple energy ratios to the minimization of entropy increase through architectural evolution of the system, providing a robust framework for increasing the thermodynamic perfection of industrial energy-technological complexes.

Keywords:

Constructal Law; ECOS Conference; Energy Efficiency; Entropy Generation; Exergy; Thermodynamics.

1. Introduction

One of the main efficiency criteria of modern heat technological systems is their energy efficiency. However, as the study [1] considers that the traditional definition of energy efficiency, as the ratio of energy costs to the produced product, in many cases does not provide an objective answer to two fundamental questions: what is the cause of inefficiency and what is the energy efficiency potential of the system. Energy analysis involves improving energy efficiency by reducing fuel consumption while maintaining or increasing existing productivity, which, in turn, requires reducing energy consumption for technological needs and improving generation efficiency. Such analysis allows establishing quantitative relationships between primary energy resources and sources of their losses, but does not provide an understanding of the nature of these losses. We find the answer to this question in the qualitative analysis of irreversible changes occurring in systems, along with quantitative ones, at all stages of energy transformations.

Many contemporary works are devoted to the problematics of this issue. For instance, Bejan [2] provides a comprehensive analysis of modern thermodynamic concepts. The vast majority of these approaches are based on the concepts of exergy and exergy destruction, which are fundamentally linked to the useful work potential of a system. Furthermore, Morosuk and Tsatsaronis [3] present state-of-the-art advancements in advanced exergy-based methods.

However, thermal technology systems, such as heat exchangers, evaporators, condensers, etc., have characteristics that differ from heat engines, since the primary form of energy interaction is thermal, and not mechanical.

Also, unlike heat engines in heat technological systems, the results of irreversible processes in the energy equivalent manifest themselves only at the final stage of energy transformations, which significantly complicates the analysis procedure.

One study [4] examined one of the approaches is "the principle of energy compensation for irreversibility", that is, any irreversibility leads to additional heat losses and, therefore, requires energy compensation. The solution to this problem is to combine the system's energy characteristics with its entropic ones and apply the Constructal Law.

2. Theoretical Framework and Energy Balances

Generally, the energy transformations. can be illustrated as shown in Figure. 1.

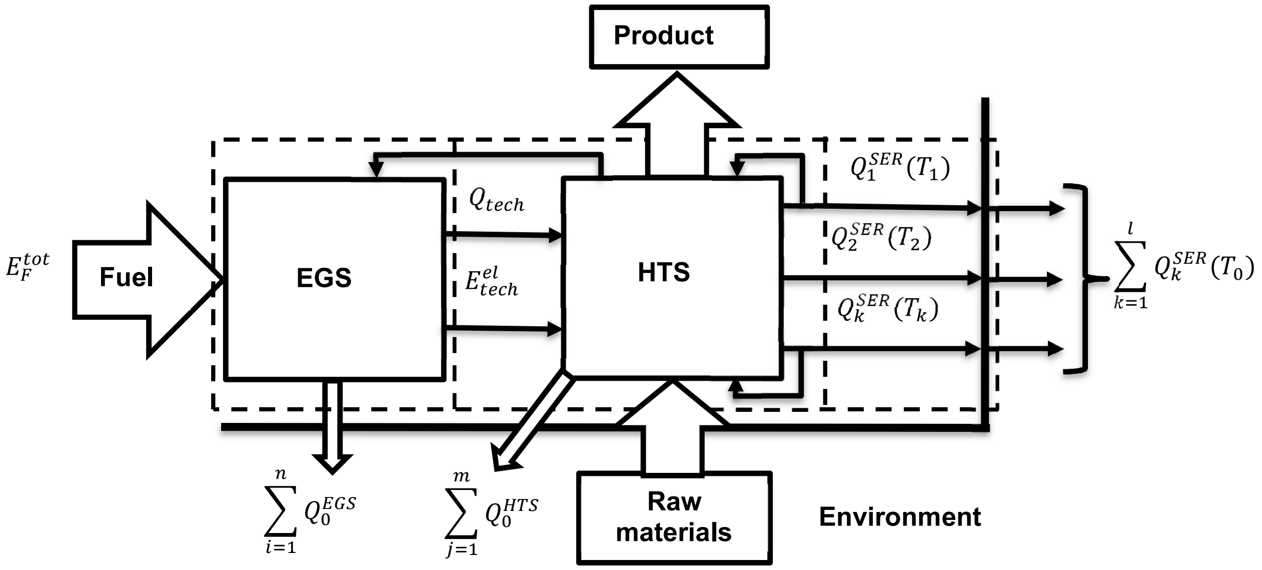

Figure 1. *Generalized schematic of energy transformations within an enterprise.*

As can be seen, the fuel energy E_F^{tot} in the form of heat Q_{tech} and electrical energy E_{tec}^{el} , which are the result of the functioning of the energy-generating system (EGS), ensures the realization of energy-technological processes in the heat-technological system (HTS) with the aim of producing products in the required quantity and of specified quality.

According to classical considerations, the energy efficiency of an enterprise is determined by the expenditures of fuel and energy resources or consumed energy for the production of a unit of product, which in our case can be expressed through the specific fuel consumption:

$$f_{tec}^{tot} = \frac{Fuel}{Product}. \tag{1}$$

An analysis of the general synthetic energy balances of the systems depicted in Figure. 1 allows establishing the correspondence between the fuel energy $\boldsymbol{E_F^{tot}}$ and other energy characteristics in three main variations:

$$E_F^{tot} = Q_{tech} + E_{tech}^{el} + \sum_{i=1}^{n} Q_0^{EGS}, \tag{2}$$

$$Q_{tech} + E_{tec}^{el} = \sum_{k=1}^{l} Q_k^{SER}(T_k) + \sum_{j=1}^{m} Q_0^{HTS}, \tag{3}$$

$$E_F^{tot} = \sum_{i=1}^{n} Q_0^{EGS} + \sum_{j=1}^{m} Q_0^{HTS} + \sum_{k=1}^{l} Q_k^{SER}(T_0), \tag{4}$$

where Q_{tech}, E_{tech}^{el} – are the total thermal and electrical loads of the HTS, respectively; $\sum_{i=1}^{n} Q_0^{EGS}$– represents the total heat losses in the EGS; $\sum_{j=1}^{m} Q_0^{HTS}$– represents the total heat losses in the HTS; $\sum_{k=1}^{l} Q_k^{SER}(T_k)$ – is the total heat of the secondary energy resources (SER) exiting the HTS; $\sum_{k=1}^{l} Q_k^{SER}(T_0)$ – represents the total heat losses from the SER.

According to equation (2), the energy need, which is provided by the combustion of fuel F_{tech}^{tot} in EGS, is mainly determined by the thermal and electrical load of HTS. This allows dividing the total fuel consumption F_{tech}^{tot} into thermal and electrical components and establishing a connection with the corresponding energy characteristics:

$$F_{tech}^{tot} = F_{tech}^{Q} + F_{tech}^{el}, \tag{5}$$

$$F_{tech}^{Q} = \frac{Q_{tech}}{Q_c \eta_{EGS}^{Q}}, \tag{6}$$

$$F_{tech}^{el} = \frac{E_{tech}^{el}}{Q_c \eta_{EGS}^{el}}, \qquad (7)$$

where η_{EGS}^{Q} and η_{EGS}^{el} – are the efficiency of EGS for generated heat and electrical energy respectively; Q_c – heat of combustion of fuel.

Analysis of Eq. (5)-(7) shows that a decrease in total fuel consumption implies a decrease in energy consumption for technological needs and an increase in generation efficiency. However, at this stage it is not yet clear how to achieve this.

Partially, the answer to this question is given by Eq. (3), which shows that the technological thermal and electrical load mainly depends on the efficiency of using SER, that is, on the total heat of unused low-potential flows $\sum_{k=1}^{l} Q_k^{SER}(T_k)$, which leave the HTS.

An important conclusion also allows us to make Eq. (4), which demonstrates that all fuel energy through a sequence of energy transformations at the final stage is transferred to the environment (ENV) and is lost for technological use. Obviously, the reason for this negative phenomenon is both direct thermal interaction of high-potential flows of heat with the ENV due to insufficiently effective insulation or technological process and dumping of heat of low-potential SER into the ENV, which under given heat-technological conditions is impossible or impractical to use.

Summarizing the results of the analysis based on general production energy balances, it can be emphasized that such an approach allows quickly establishing quantitative interrelations between the main energy characteristics of the enterprise and formulating at the first stage the basic directions of energy efficient strategy.

3. Methodology: The Principle of Energy Compensation

However, during the generation of thermal and electrical energies in the EGS system, irreversible changes occur, which are connected not only with quantitative transformations, but also with qualitative ones: there is a generation of *low-potential entropy-containing heat*, which relative to the highly organized chemical energy of fuel has worse qualitative characteristics. At the stage of energy analysis of EGS, this problem almost does not manifest itself, but negatively affects the energy efficiency of HTS, leading to additional heat losses at the final stage of energy transformations. To fundamentally sort out this problem, let's look at energy transformations from the point of view of the second law of thermodynamics.

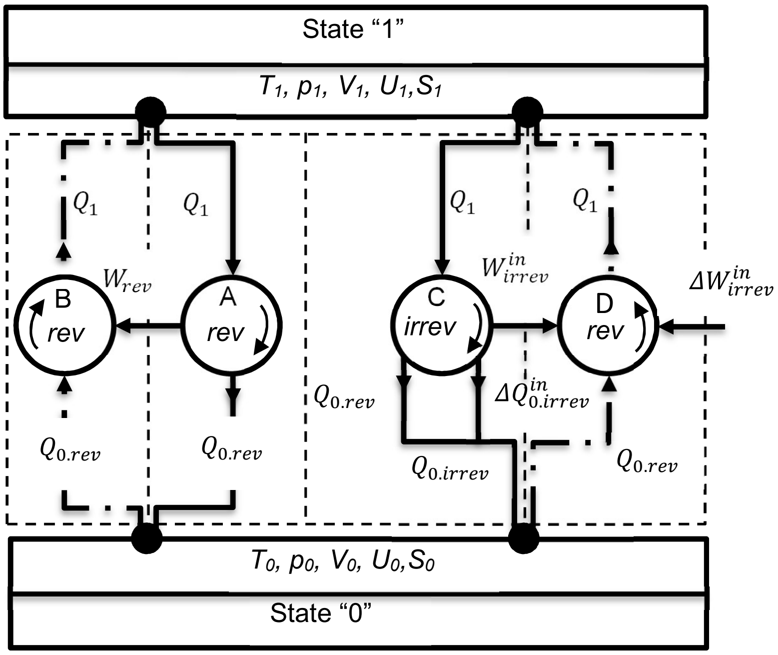

Figure 2. *Reversible and irreversible thermal interactions between a system and the environment via heat engines.*

For simplification and clarity of the analysis, let's consider the thermal interaction of a hypothetical system (Figure 2) with the environment (state "0") with the help of heat engines (subsystems "A" and "C"). Figure 2 shows two variants of such interaction: reversible (*rev*) with the help of an ideal heat engine (HE) "A" and irreversible (*irrev*) with the help of a real HE "C". It is important that thermal interaction in both cases occurs within the same states, which corresponds to absolutely identical change of thermodynamic parameters and state functions. Exactly this similarity most often hides the irreversibility of processes during classical energy analysis. However, the energy characteristics of these processes will differ.

To begin with, let us consider reversible energy transformations in subsystem "A", the result of the functioning of which is the generation of a useful "energy product" in the form of reversible (maximum) work W_{rev} and minimum (reversible) heat $Q_{0.rev}$, which is transferred to the ENV. The reversibility of such interaction is confirmed by the functioning of an ideal refrigeration machine (RM), with the help of which, using W_{rev}, the system can independently return to the initial state so that according to the results of both processes in the ENV no changes will occur, that is, the reverse process completely compensates the direct one. In this sense, $Q_{0.rev}$ plays the role of functional expenditures, and not heat losses, as it might seem at first glance.

If internally irreversible processes occur in the system, as, for example, in "C", then such a system is capable of generating a smaller "energy product" W_{irrev}^{in}, but at the same time additionally gives the ENV heat $\Delta Q_{0.irrev}^{in}$. Obviously, $\Delta Q_{0.irrev}^{in}$ is a consequence of the realization of irreversible processes and under given conditions can justifiably be considered a heat loss.

For the return to the initial state with the help of subsystem "D" (Figure 2), in which, as in "B", internally reversible processes occur, W_{irrev}^{in} is already not enough. And therefore, compensation occurs at the expense of external energy in the amount

$$\Delta W_{irrev}^{in} = W_{rev} - W_{irrev}^{in}, \tag{8}$$

or

$$\Delta W_{irrev}^{in} = \Delta Q_{0.irrev}^{in} = Q_{0.irrev} - Q_{0.rev}. \tag{9}$$

Equations (8) and (9) already at this stage allow evaluating the influence of process irreversibility on the energy characteristics of the system and making an important conclusion: *any irreversibility leads to heat losses in the ENV and requires energy compensation*. We call this conclusion the "principle of energy compensation of irreversibility".

Until now, irreversibility in our reasoning appeared as an abstract characteristic, however the second law of thermodynamics with the help of entropy allows giving it perfectly concrete values and linking it with the energy characteristics of the system. For this, let's write down the entropy balances for subsystems "A" and "C" (Figure 2), considering that $U = f(T, p, V)$, $S = f(T, p, V)$, and therefore:

$$(U_0 - U_1)_{rev} = (U_0 - U_1)_{irrev}, \tag{10}$$

$$(S_0 - S_1)_{rev} = (S_0 - S_1)_{irrev}. \tag{11}$$

Taking into account that in subsystem "A" reversible processes occur, the change of entropy is determined only by thermal interaction with the ENV:

$$(S_0 - S_1)_{rev} = -\frac{Q_{0.rev}}{T_0}. \tag{12}$$

In subsystem "C" irreversibility according to the second law of thermodynamics leads to the generation of additional entropy ΔS_{irrev}^{in}, therefore the change of entropy in this case we can write like this:

$$(S_0 - S_1)_{irrev} = -\frac{Q_{0.irrev}}{T_0} + \Delta S_{irrev}^{in}. \tag{13}$$

By solving Eq. (12) and Eq. (13) for $Q_{0.rev}$ and $Q_{0.irrev}$ respectively, and substituting these expressions into Eq. (9), while accounting for the equality in Eq. (11), we yield:

$$\Delta W_{irrev}^{in} = \Delta Q_{0.irrev}^{in} = T_0((S_0 - S_1)_{rev} - (S_0 - S_1)_{irrev} + \Delta S_{irrev}^{in}) = T_0 \Delta S_{irrev}^{in}. \tag{14}$$

Eq. (14) in classical thermodynamics is called the Gouy-Stodola formula and is used to determine the losses of work capacity (exergy losses) of the system from the irreversibility of processes.

However, in the case of HTS, where the main form of energy interaction is thermal, and mechanical interaction may be completely absent, the concept of "exergy loss" generates a methodological contradiction. Therefore, we propose the product of the thermodynamic temperature of the ENV T_0 and the increase in entropy of the system from the irreversibility of processes ΔS_{irrev}^{in} to be considered, as was shown above, *the energy compensation of irreversibility*.

A similar result we will obtain in the case of external irreversibility of processes. Figure 3 shows the irreversible thermal interaction of system "B" with the ENV as a result of the temperature difference $\Delta T = T'_0 - T_0$.

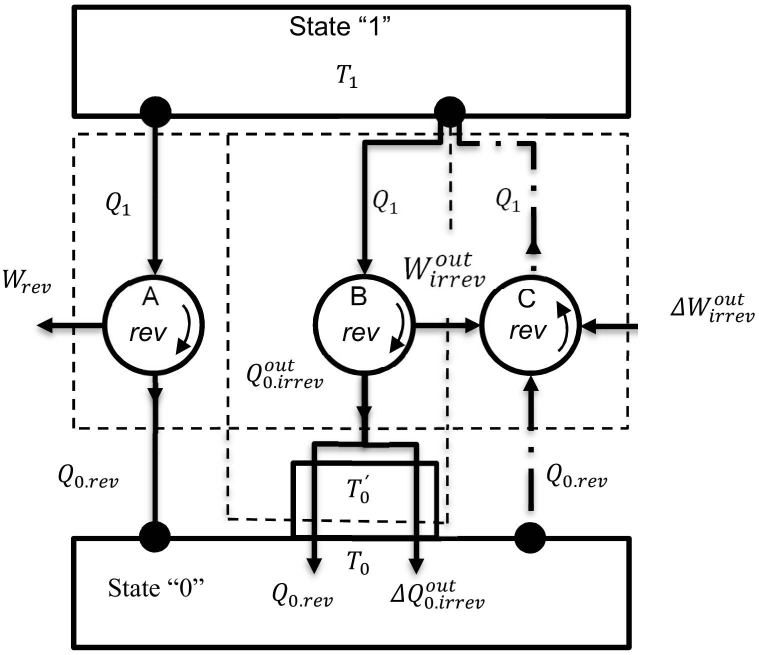

Figure 3. *Scheme of analysis of externally irreversible thermal interaction*

Considering that in systems "A" and "B" internally reversible processes of the Carnot cycle occur, we can determine the corresponding "energy products" of these systems in the form of the following equations:

$$W_{rev} = Q_1\left(1 - \frac{T_0}{T_1}\right), \tag{15}$$

$$W^{out}_{irrev} = Q_1\left(1 - \frac{T'_0}{T_1}\right). \tag{16}$$

Due to the irreversibility of thermal interaction with the ENV, system "B" generates less work, and therefore the return to the initial state with the help of system "C" requires additional energy compensation in the amount:

$$\Delta W^{out}_{irrev} = W_{rev} - W^{out}_{irrev}. \tag{17}$$

Let's substitute Eq. (15) and Eq. (16) into Eq. (17) and we will obtain the dependence of compensation work on ΔT, which is the cause of this compensation

$$\Delta W^{out}_{irrev} = Q_1\left(\frac{T'_0}{T_1} - \frac{T_0}{T_1}\right) = Q_1\frac{\Delta T}{T_1}. \tag{18}$$

Next, we will show that, as in the case of internal irreversibility, the energy compensation of external irreversibility is proportional to the increase in entropy. For this we will prove the following equality:

$$\Delta Q^{out}_{0.irrev} = \Delta W^{out}_{irrev} = Q_1\frac{\Delta T}{T_1} = T_0 \Delta S^{out}_{irrev}. \tag{19}$$

Irreversible thermal interaction between two systems with different temperatures causes additional generation of entropy in the amount:

$$\Delta S^{out}_{irrev} = \frac{Q^{out}_{0.irrev}}{T_0} - \frac{Q^{out}_{0.irrev}}{T'_0} = Q^{out}_{0.irrev}\left(\frac{T'_0 - T_0}{T'_0 \cdot T_0}\right) = Q^{out}_{0.irrev}\frac{\Delta T}{T'_0 \cdot T_0}. \tag{20}$$

Let's substitute Eq. (20) into Eq. (19) and after simplifications we will obtain a result that coincides with Eq. (18)

$$\Delta Q^{out}_{0.irrev} = \Delta W^{out}_{irrev} = T_0 Q^{out}_{0.irrev}\frac{\Delta T}{T'_0 \cdot T_0} = \left(Q_1 - W^{out}_{irrev}\right)\frac{\Delta T}{T'_0} = Q_1\frac{T'_0}{T_1}\frac{\Delta T}{T'_0} = Q_1\frac{\Delta T}{T_1}. \tag{21}$$

Eq. (21) once again confirms that any irreversibility leads to additional useless thermal interaction with the ENV and requires energy compensation measures.

Having established the interrelation between irreversibility, entropy, heat losses and accordingly compensation energy expenditures, at the next stage we can tie them with fuel and energy resources.

According to Figure 1 the total fuel consumption for the realization of energy-technological processes we can write in the form of the relationship:

$$F_{tech}^{tot} = \frac{\sum Q_0^{tot}}{Q_c}, \tag{22}$$

where $\sum Q_0^{tot} = \sum_{i=1}^{n} Q_0^{EGS} + \sum_{j=1}^{m} Q_0^{HTS} + \sum_{k=1}^{l} Q_k^{SER}(T_0)$ – total heat losses in EGS and HTS systems.

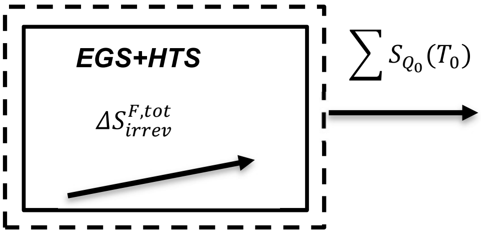

Figure 4. *Scheme of the entropy balance of the EGS+HTS complex*

The general entropy balance of the EGS+HTS complex will have the form (see Figure 4):

$$\Delta S_{irrev}^{F,tot} = \sum S_{Q_0}(T_0) = \frac{\sum Q_0^{tot}}{T_0}. \tag{23}$$

4. Results: Fuel Consumption for Irreversibility Compensation

Taking into account Eq. (22) and Eq. (23), let's determine the ***specific fuel consumption for the compensation of irreversibility***:

$$f_{irrev}^{tot} = \frac{F_{tech}^{tot}}{\Delta S_{irrev}^{F,tot}} = \frac{T_0}{Q_c}. \tag{24}$$

As we can see, the specific fuel consumption for the compensation of irreversibility depends only on the type of fuel and the temperature of the ENV.

Taking into account the previous results and the additivity of entropy, the "principle of energy compensation of irreversibility" we can write in the form of fuel consumption for the compensation of the *i-th* irreversible process:

$$F_i = f_{irrev}^{tot} \Delta S_{irrev,i}, \tag{25}$$

where $\Delta S_{irrev,i}$ – is the increase in entropy from the irreversibility of the *i-th* process.

Then the total fuel consumption for technological needs can be calculated as the sum of fuel consumption for the compensation of all irreversible processes that are realized in the system:

$$F_{tech}^{tot} = \sum F_i = f_{irrev}^{tot} \sum \Delta S_{irrev,i}. \tag{26}$$

Let's rewrite equation (1) taking into account equation (26):

$$f_{tech}^{tot} = \frac{\text{Fuel}}{\text{Product}} = f_{irrev}^{tot} \frac{\sum \Delta S_{irrev,i}}{\text{Product}}. \tag{27}$$

Thus, in the form of Eq. (27) we obtained the dependence of the energy efficiency of the EGS+HTS complex on the irreversibility of the processes that are realized in it. As a result, the maximization of energy efficiency (decrease of f_{tech}^{tot}) implies the minimization of entropy generation at all stages of energy transformations, which gives an understanding of the character and algorithm of technical measures. Besides this, taking into account the additivity of entropy, any decrease of ΔS_{irrev} without complex comprehensive calculations shows an energy efficient effect and allows to realize the next stage – thermoeconomic optimization, the task of which is the determination of optimal thermodynamic perfection of the system.

5. Conclusions

In our opinion, the "entropy approach" has great both methodological and applied significance. From a methodological point of view, it does not contradict the fundamental principles of functioning of neither heat-technological systems, nor heat engines, and the analysis of fuel or energy consumption for the compensation of irreversibility allows us to approach differently the idea of energy efficiency, bringing to the foreground the qualitative characteristics of processes.

In fact, ***the strategy of energy efficiency can be reduced to the strategy of increasing the thermodynamic perfection of the system by means of minimization (optimization) of entropy increase***.

In the practical plane, the direct connection between the primary energy resource and the irreversibility of processes allows faster realization of the energy optimization of the project, since any measures on reducing entropy will lead to a proportional decrease in the consumption of the primary energy resource.

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