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**MODERN KNOWLEDGE:
RESEARCH AND DISCOVERIES**

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19-20.07.2024

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EDITOR

Anna Svoboda

Doctoral student
University of Economics;
Czech Republic
annasvobodaprague@yahoo.com

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Mariia Granko

Coordination Director
LLC Scientific Publishing Center
«InterConf»; Ukraine
info@interconf.center

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The model of the installation for hot galvanizing

**Biliuk Ivan¹, Buhrim Leonid², Savchenko Oleh³, Havrylov Serhii⁴,
Trushkin Oleksandr Oleksandrovych⁵**

¹ PhD, Associate Professor;
Admiral Makarov National University of Shipbuilding; Ukraine

² PhD, Associate Professor;
Admiral Makarov National University of Shipbuilding; Ukraine

³ Head of Laboratory of Automation Department;
Admiral Makarov National University of Shipbuilding; Ukraine

⁴ PhD, Associate Professor;
Admiral Makarov National University of Shipbuilding; Ukraine

⁵ student of the automation department;
National University of Shipbuilding named after Adm. Makarova; Ukraine

Abstract.

The mathematical model of the installation is offered for the hot zinc-plating, as an object of adjusting of temperature of external wall of corps of bath. An algorithm for computation of parameters on the set mode is developed. Computation of coefficients of mathematical model is executed. Possibility of research of influence on dynamic descriptions of the control object and a few revolting influences and structural parameters is got. Transitional descriptions are got.

Keywords:

*mathematical model
zinc-plating
object of adjusting
dynamic descriptions*

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Introduction. One of the first and important stages in the construction of automatic control systems (ACS) is obtaining a mathematical model that describes the behavior of the control object (CO).

The use of mathematical dependencies allows you to conduct design work on the development of the ACS at the stage of development of the CO. Knowledge of the dependence of the properties of the CO on the structural characteristics can be used for some changes in the design of the object in order to improve its properties as an CO. This approach allows you to select the law of operation of the automatic regulator and calculate the parameters of the adjustment of the regulator. It is especially important that there is an opportunity to conduct research on the operation of CO and ACS when simulating emergency situations, which are dangerous to conduct at a real facility.

Nowadays, microprocessor control systems are becoming more and more widespread, and the use of adaptive systems, which use mathematical models of CO, is becoming a real problem. The use of mathematical models of CO in the development of ACS is beneficial from an economic point of view. The relevance of using mathematical models is confirmed by the fact that more and more works are devoted to their development and use [1,2,3].

The purpose of the work. The development of such mathematical dependencies that allow obtaining curves of transient processes of parameters characterizing the course of the technological process of hot-dip galvanizing, performing comparative studies of the influence of disturbing and regulating actions and design parameters on the dynamic properties of the bath as an OR, investigating the nature of transient processes when changing the energy supply from the heater, when galvanizing products are immersed in a bath, the influence of the mass and surface area of products and other disturbing actions.

Presentation of the main material. When performing the mathematical description, it is assumed that the coefficients of heat transfer and heat output do not change when the temperature changes and are assumed to be equal to their value at the average value of the temperature in the steady state.

To compile a mathematical description, we used the heat

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balance equation for individual areas participating in the thermal process in the stationary mode:

$$Q_1 = Q_2; Q_3 = Q_1; \quad (1)$$

$$Q_4 = Q_5 + Q_3; Q_5 = Q_6,$$

where $Q_1, Q_2, Q_3, Q_4, Q_5, Q_6$ – the amount of heat (or its consumption) supplied (removed) according to the zinc melt; spent from the bath; which is diverted from the heating elements; which is supplied from the heating elements to the lining and the outer wall of the bath; which is lost to the environment in the stationary mode.

The equations of system components (1) have the following form:

$$Q_2 = Q_7 + Q_8 + Q_9 + Q_{10} + Q_{11} + Q_{12}, \quad (2)$$

where $Q_7, Q_8, Q_9, Q_{10}, Q_{11}, Q_{12}$ – the amount of heat at steady state, which is spent, respectively, on heating products and equipment when immersed in molten zinc; which is lost by radiation from the surface of the zinc melt; which is consumed by convection from the surface of the zinc melt; due to short circuits; through the foundation surface; on losses with the air mixture above the bath surface.

Heat transferred from the inner surface of the bath wall to the zinc melt:

$$Q_1 = (t_{co} - t_{zo})F_c / (\delta_c / \lambda_c + S_z / \lambda_z), \quad (3)$$

where t_{co}, t_{zo} – the temperature of the outer surface of the wall and the zinc melt in the stationary mode, respectively; F_c – area of the wall covered with zinc; δ_c, S_z – the thickness of the bath wall and the layer of molten zinc; λ_z, λ_c – thermal conductivity of zinc melt and steel wall.

It should be noted that the heater elements are installed on all four walls of the bath stove, and in the places that

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are located closer to the corners of the bath, the heating is more intense, which complicates the calculations and is planned to be investigated at further stages. In the work, when calculating the heating of zinc, it is conventionally accepted that the heaters are installed only on two opposite walls, which have a total length equal to the perimeter of the bath. Under these assumptions, the plane F_{dz} of the mirror of the molten zinc and the amount of heat transferred are conserved.

The form of equation (3) for determining the heat supplied from the wall of the bath to molten zinc within the framework of metallurgical engineering is formulated in the form of heat conduction equations. Molten metals have high thermal conductivity and provide high convective thermal conductivity at low speeds due to the value of the thermal conductivity coefficient, which minimizes the resistance of the boundary layer.

The heat transfer from the heater to the outer wall Q_1 and to the lining Q_2 is calculated as that which passes through radiation. The amount of heat transferred from the heater to the outer wall of the bath is equal to:

$$Q_3 = kc_0\varepsilon_p[(T_{ho}/100)^4 - (T_{co}/100)^4]F_c, \quad (4)$$

where $k=1,16$ – coefficient that takes into account heat loss [6]; $c_0=5,67 \text{ W/(m}^2 \text{ K}^4)$ – absolute black body transmittance coefficient; $\varepsilon_p = \varepsilon_1^{-1} + \varepsilon_2^{-1} - 1$ – the transmittance coefficient from the heater to the outer wall is given; $\varepsilon_1, \varepsilon_2$ – the degree of blackness of the heater and the outer wall, respectively; T_{ho}, T_{co} – heater and wall temperature, respectively.

The heat supplied to the lining from the heater is equal to:

$$Q_5 = kc_0\varepsilon_{p1}[(T_{ho}/100)^4 - (T_{fo}/100)^4]F_f, \quad (5)$$

where $\varepsilon_{p1} = \varepsilon_1^{-1} + \varepsilon_3^{-1} - 1$ – the transmittance coefficient from the heater to the liner is given; ε_3 – the degree of blackness of the inner wall of the lining; F_f – the plane of the inner surface of the lining that is heated.

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Heat emitted from the lining to the environment:

$$Q_6 = \frac{(t_{fo} - t_{no}) F_{fn}}{\frac{\delta_{sh}}{\lambda_{sh}} + \frac{\delta_d}{\lambda_d} + \frac{\delta_{ob}}{\lambda_{ob}} + \frac{1}{\alpha_{kob}}}, \quad (6)$$

where δ_{sh} , δ_d , δ_{ob} , λ_{sh} , λ_d , λ_{ob} – thickness and thermal conductivity of fireclay and diatomite linings and cladding, respectively; α_{kob} – coefficient of heat transfer from the cladding to the environment; F_{fn} – the plane of the outer surface of the lining.

To determine the effect on the temperature of the zinc melt of the heat consumption Q_7 supplied to the product, the formula was used:

$$Q_7^1 = C_B \cdot m_B \cdot (t_{zo}^p - t_{bo}^1), \quad (7)$$

where t_{zo}^p , t_{bo}^1 – the temperature of the zinc melt and the product before galvanizing; C_B, m_B – heat capacity and mass of the product.

In all other cases, the calculations were carried out according to the heat transfer equation from molten zinc to the product immersed in zinc:

$$Q_7^2 = \frac{F_b(t_{zo} - t_{bo}^n)}{S_b/\lambda_b}, \quad (8)$$

where F_b – surface area of the product, which depends on the shape and size of the product; t_{bo}^n – temperature of the surface of the product on the thickness 0,001...0,005 m; S_b, λ_b – area and thermal conductivity of the material of the product.

The use of the surface temperature of the product is explained by the fact that the quality of the galvanizing process depends on the value of this temperature.

Heat supply from the outer wall of the bath to zinc:

$$Q_{ch.o} = \frac{(t_{co} - t_{ho}) F_c}{\delta_c/\lambda_c + S_{\Pi}/\lambda_{\Pi}}, \quad (9)$$

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where δ_c, λ_c – thickness and thermal conductivity of the wall;
 $S_{\text{ц}}, \lambda_{\text{ц}}$ – thickness and thermal conductivity of the zinc layer
between the wall and the product.

In the non-stationary regime, dependencies (1) are violated, which leads to a change in time of the corresponding temperatures in each section. The dynamics equations in the absolute deviations of the variables have the following form:

$$\begin{aligned} (C_B m_B + C_{\text{ц}}(m_{\text{ц}}^{\text{л}} + m_{\text{ц}}) + C_{\text{св}} m_{\text{св}} + C_{\text{ст}}^1 m_{\text{ван}}) (d\Delta t_{\text{ц}}/d\tau) = \\ = \Delta Q_{\text{цц}} - \Delta Q_{\text{цв1}} - \Delta Q_{\text{витр}} - \Delta Q_{\text{конв}} - \Delta Q_{\text{кз}} - \Delta Q_{\text{пов. сум}}; \\ C_{\text{ст}} m_{\text{ван}} (d\Delta t_{\text{с}}/d\tau) = \Delta Q_{\text{нс}} - \Delta Q_{\text{цц}}; \\ C_{\text{н}} m_{\text{н}} (d\Delta t_{\text{н}}/d\tau) = \Delta Q_{\text{н}} - \Delta Q_{\text{нц}} - \Delta Q_{\text{нф}}; \\ (C_{\text{ф}} m_{\text{ф}} + C_{\text{с}} m_{\text{обш}}) (d\Delta t_{\text{ф}}/d\tau) = \Delta Q_{\text{нф}} - \Delta Q_{\text{ф. навк}}; \\ C_B m_B (d\Delta t_B/d\tau) = \Delta Q_{\text{цв2}} \end{aligned} \quad (10)$$

where $\Delta t_{\text{ц}}, \Delta t_{\text{с}}, \Delta t_{\text{н}}, \Delta t_{\text{ф}}, \Delta t_B$ – absolute deviations of temperatures from their values at steady state; C – heat capacity of the corresponding areas; ΔQ_i – absolute deviations of heat.

Components of the right part of system (9) are functional nonlinear dependencies of variables:

$$\begin{aligned} \Delta Q_{\text{цв1}} = f_1(\Delta t_{\text{ц}}, \Delta t_B, \Delta m_B); \quad \Delta Q_{\text{цв2}} = f_2(\Delta t_{\text{ц}}, \Delta t_B); \\ \Delta Q_{\text{витр}} = f_3(\Delta t_{\text{ц}}, \Delta t_{\text{навк}}); \quad \Delta Q_{\text{конв}} = f_4(\Delta t_{\text{ц}}, \Delta t_{\text{навк}}); \\ \Delta Q_{\text{навк}} = f_5(\Delta t_{\text{ф}}, \Delta t_{\text{навк}}); \quad \Delta Q_{\text{кз}} = f_6(\Delta t_{\text{навк}}); \\ \Delta Q_{\text{пов. сум}} = f_7(\Delta t_{\text{пов. сум}}, \Delta t_{\text{навк}}, \Delta m_{\text{пов. сум}}); \\ \Delta Q_{\text{нс}} = f_8(\Delta t_{\text{н}}, \Delta t_{\text{с}}); \quad \Delta Q_{\text{цц}} = f_9(\Delta t_{\text{ц}}, \Delta t_{\text{с}}); \\ \Delta Q_{\text{н}} = f_{10}(\Delta P_{\text{н}}); \quad \Delta Q_{\text{нф}} = f_{11}(\Delta t_{\text{н}}, \Delta t_{\text{ф}}). \end{aligned} \quad (11)$$

System (10) after linearization of dependencies (11) and taking into account only the effects of regulating $\Delta P_{\text{н}}$ (changes in heater power) and disturbing Δm_B (immersion in molten zinc of the product) actions, in the operational view for absolute deviations of variables, looks like this:

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$$\begin{aligned}
 T_H(d\Delta t_H/d\tau) + \Delta t_H &= K_{H1}\Delta P_H - K_{H2}\Delta t_c - K_{H3}\Delta t_\phi; \\
 T_c(d\Delta t_c/d\tau) + \Delta t_c &= K_{c1}\Delta t_H - K_{c2}\Delta t_\Pi; \\
 T_\phi(d\Delta t_\phi/d\tau) + \Delta t_\phi &= K_{\phi1}\Delta t_H; \\
 T_\Pi(d\Delta t_\Pi/d\tau) + \Delta t_\Pi &= K_{\Pi1}\Delta t_c - K_{\Pi2}\Delta t_B - K_{\Pi3}\Delta m_B; \\
 T_B(d\Delta t_B/d\tau) + \Delta t_B &= K_B\Delta t_\Pi,
 \end{aligned} \tag{12}$$

where $T_H = A_H/B_H$; $T_c = A_c/B_c$; $T_\phi = A_\phi/B_\phi$; $T_\Pi = A_\Pi/B_\Pi$; $T_B = A_B/B_B$ - time constants, respectively, of the heater, bath walls, lining, bath with zinc and products; K_{H1} ; K_{H2} ; K_{H3} ; K_{c1} ; K_{c2} ; $K_{\phi1}$; $K_{\Pi1}$; $K_{\Pi2}$; $K_{\Pi3}$; K_B - transmission coefficients on the corresponding input.

The calculation of time constants and coefficients of system (11) is performed according to the following dependencies:

$$\begin{aligned}
 A_\Pi &= C_B m_B + C_\Pi(m_\Pi^\Pi + m_\Pi) + C_B m_B + C_{CB} m_{CB}; \quad A_H = C_H m_H; \\
 A_\phi &= C_\phi m_\phi + C m_{\text{обш}}; \quad A_B = C_B m_B; \\
 B_\Pi &= \left(-\frac{\partial Q_{c\Pi}}{\partial t_\Pi} + \frac{\partial Q_{B2}}{\partial t_\Pi} + \frac{\partial Q_{\text{БИТР}}}{\partial t_\Pi} + \frac{\partial Q_{\text{КОНБ}}}{\partial t_\Pi} \right); \\
 B_c &= \frac{\partial Q_{c\Pi}}{\partial t_c} - \frac{\partial Q_{HC}}{\partial t_c}; \quad B_H = \frac{\partial Q_{HC}}{\partial t_H} + \frac{\partial Q_{H\phi}}{\partial t_H}; \\
 B_\phi &= \frac{\partial Q_{\text{НАБВК}}}{\partial t_\phi} - \frac{\partial Q_{H\phi}}{\partial t_\phi}; \quad B_B = -\frac{\partial Q_{B2}}{\partial t_B}; \\
 K_{\Pi1} &= \frac{(\partial Q_\Pi/\partial t_\Pi)}{B_\Pi}; \quad K_{\Pi2} = \frac{(\partial Q_{B2}/\partial t_B)}{B_\Pi}; \quad K_{\Pi3} = \frac{(\partial Q_{B1}/\partial m_B)}{B_\Pi}; \\
 K_{c1} &= \frac{(\partial Q_{HC}/\partial t_H)}{B_c}; \quad K_{c2} = \frac{(\partial Q_\Pi/\partial t_\Pi)}{B_c}; \\
 K_{H1} &= \frac{(\partial Q_H/\partial P_H)}{B_H}; \\
 K_{H2} &= \frac{(\partial Q_{HC}/\partial t_c)}{B_H}; \quad K_{H3} = \frac{(\partial Q_{H\phi}/\partial t_\phi)}{B_H}; \quad K_{\phi1} = \frac{(\partial Q_\phi/\partial t_H)}{B_\phi}; \quad K_B = \frac{(\partial Q_{B2}/\partial t_\Pi)}{B_\Pi}.
 \end{aligned}$$

According to the system of equations (12), a structural diagram of the bath was developed as a function of the temperature t_c of the outer wall of the bath. The structural diagram showing only two (main) input actions - the controlling ΔP_n and one of the disturbing ones - Δm_B is shown in Fig. 1.

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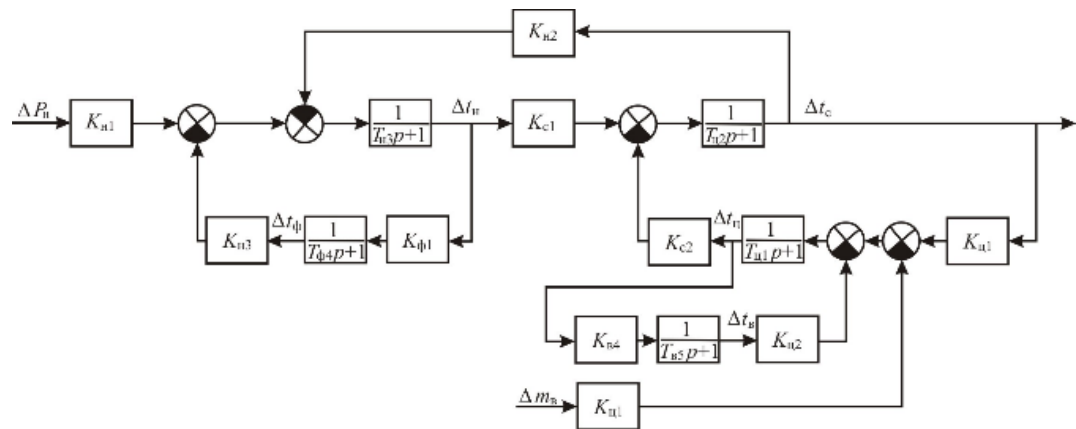


Figure 1

Analysis of the obtained results. In the paper, it is customary to compare the deviation of all temperatures relative to the temperature $t_{\text{uo}} = 460^{\circ}\text{C}$, which is maintained during galvanizing.

Basic values of heater power $\Delta P_n = 105 \text{ kW}$, mass of products $\Delta m_B = 2000 \text{ kg}$. Data for calculations were selected from [4–8]. Numerical data and consumption of bath heat from paper [8].

Temperatures: zinc melt during galvanizing 4600 C^0 , products entering galvanizing $(50\text{--}80) \text{ C}^0$, environment in the room 200C^0 , zinc melting 4200C^0 .

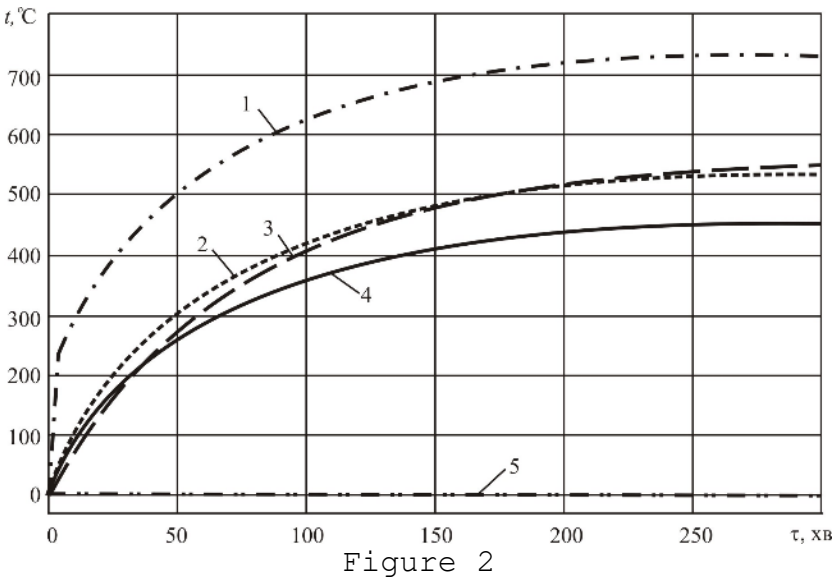
To calculate the coefficients of the system (12), it is necessary to first determine the values of the variables at the set mode.

In fig. 2 shows the curves of transient processes of heating the bath from a cold state.

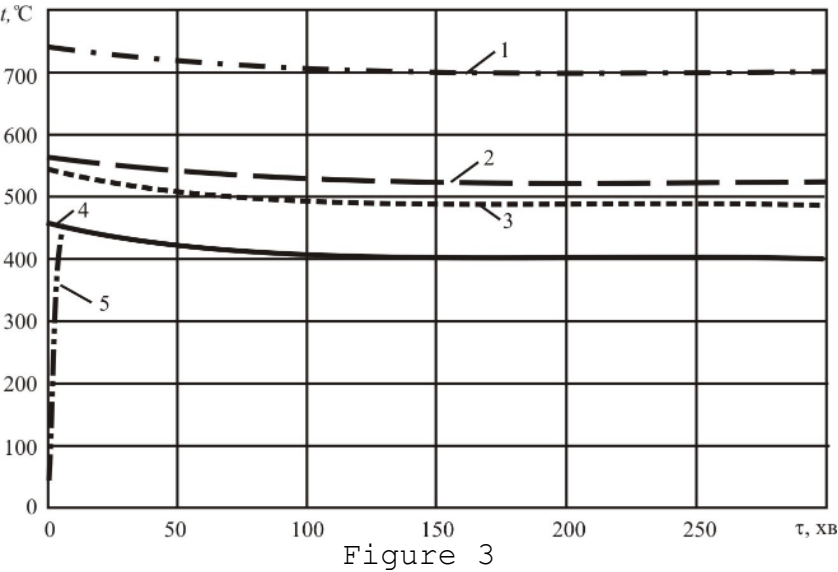
In fig. 3 shows the curves of transient temperature processes when products are immersed in a bath.

It can be seen from the figures that the time of transient processes in all variables is close. This is explained by the mutual dependence of all areas presented in the model. When the value of the time constant of the area decreases, the parameter corresponding to it changes at a higher speed and by a larger amount, and then a slower transition process occurs, where the temperatures change at a low speed due to mutual influence through the feedback of more inertial areas to less inertial areas.

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1 – T_H ; 2 – T_c ; 3 – T_ϕ ; 4 – T_u ; 5 – T_B



1 – T_H ; 2 – T_ϕ ; 3 – T_c ; 4 – T_u ; 5 – T_B

The introduction of non-zero initial conditions correspond to preheating. If the products are immersed in the

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bath, the change in temperature depends on the preliminary heating and on the power given by the heaters. The largest decrease in temperatures is when the heaters are turned off, the smallest is when the power of the heaters more closely matches the loading of the bath with products. In fig. 3 shows transient processes when the bath is fully loaded, and the power of the heaters is less than the maximum and that required to maintain 4600 C°. The temperature of the products rises to the value of the temperature of the zinc melt and then changes according to the same law as the temperature of the melt. Quantitative changes can be seen from fig. 2, 3.

Conclusions:

1. The proposed mathematical model allows obtaining the dynamic characteristics of the bath as an object of temperature regulation of the outer wall, zinc melt, lining and product.

2. It was possible to develop systems for automatic regulation of bath technological processes both at the early stages of design work and in parallel with work on a full-scale object, especially when studying work in emergency situations.

3. The influence of controlling and disturbing actions on the nature of transient processes has been established.

4. It is possible to refine the model based on natural experiments. The refined mathematical model can be used to improve the properties of the bath as an object of regulation by introducing the necessary structural changes.

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