

New Approaches for Optimizing Quenching Process of Steel Parts Based on Achievements of Modern Physics

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Abstract – The paper discusses new approaches for eliminating sporadic, non-uniform film boiling processes during batch quenching of steel parts and causing part excessive distortion and cracking. The film boiling process is common for batch quenching when parts are usually placed close to each other. Narrow spacing between the parts results in a high hydraulic resistance preventing an adequate flow of quenchant even when powerful propellers are used. Two alternative ways to improve quenchant agitation are considered in the paper: hydrodynamic emitters and electrolytes as a quenchant while negatively charging the steel parts being quenched. The paper also considers new quenching technologies based on a) the proper control of the nucleate boiling process parameters using a universal correlation obtained by the author, and b) the use of low concentration solutions of polymers of inverse solubility in water.

I. INTRODUCTION

Quenching of steel is one of the most important steps in the steel part manufacturing process. Quality of the quenching process affects parts' mechanical properties and performance characteristics. When quenching steel parts in batches in liquid media, one of the major problems is the film boiling process initiation at the quench's beginning. The film boiling mode of quenching is a sporadic, non-controllable process that often results in non-uniform cooling of parts, causing part distortion and cracking. The film boiling process is common for batch quenching when parts are usually placed close to each other. Narrow spacing between the parts results in a high hydraulic resistance for the quenchant flow. In this case, providing an adequate and uniform quenchant circulation required to eliminate the film boiling process is quite challenging even when using powerful propellers in intensive quenching (IQ) tanks [1]. Besides a vigorous quenchant agitation, the film boiling process can be eliminated using reverse solubility using water polymer solutions [2]. This paper discusses novel approaches for eliminating the film boiling stage of cooling during batch quenching of steel parts. The paper also considers new quenching technologies based on the proper control of the nucleate boiling process parameters using a universal correlation obtained by the author [3].

II. ELIMINATION OF FILM BOILING PROCESS BY USING OF HYDRODYNAMIC EMITTERS.

Authors [4, 5, and 6] suggested a different way of providing a more effective quenchant circulation during batch quenching, namely, the use of hydrodynamic emitters. A resonance phenomenon produced by hydrodynamic emitters has an essential effect on destroying the film boiling process. The resonance effect occurs when the local vapor films' oscillation frequency coincides with the frequency of waves generated by the hydrodynamic emitter (Fig. 1) [4].

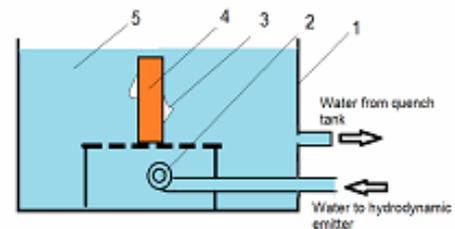


Fig. 1: Film boiling destroying by exploring hydrodynamic emitter that provides resonance effect: 1 is quench tank; 2 is hydrodynamic emitter; 3 is vapor bubble; 4 is steel part; 5 is quenchant.

Authors [7] developed a method and an apparatus for evaluating a vapor bubble oscillation frequency. Different types of hydrodynamic emitters used to eliminate the film boiling process are described in reference [4]. The described method of improving the quenchant circulation during batch quenching of steel parts can be effectively used for both the conventional quench tanks and the IQ tanks.

III. ELIMINATION OF FILM BOILING PROCESS BY USING EXTERNAL ELECTRIC FORCES

As it is well known, according to statistical physics, free electrons in the heated metal area are under pressure P , which is calculated as:

$$P = nkT \quad (1)$$

Here n is a number of electrons in one sm^3 of metal; k is the Boltzmann constant, which is equal to



$$k = 1.3806488 (13) \times 10^{-23} \text{ [K}^{-1}\text{]}.$$

During immersion of hot steel parts into an electrolyte, a double electrical layer is formed on the boundary between the liquid and the metal surface [8, 9]. It occurs due to the movement of electrons from the heated area to the cold area. Maximum electrical forces take place when the electrolyte is at an optimal concentration [1, 9]. When the density of free electrons on the metallic surface layer reaches a certain value, a forced heat exchange establishes between the quenched parts and the electrolytes. Its essence consists of the following. When

film boiling appears, electrical forces move the charged liquid layer to the metal surface. A shock boiling process starts immediately, creating a new film boiling layer, which is a reason for a periodical process. A sequence of such periodical cooling process is the following: film boiling → shock boiling → film boiling → shock boiling, and so on. Oscillating with a high frequency, the shock boiling process is characterized by high heat transfer coefficients (HTC). The shock boiling process prevails with time, increasing the average value of HTC (Table 1) [10].

TABLE 1: Heat transfer coefficients (HTCs) versus the type of material during quenching of silver and steel probes in water-salt solutions [21].

Material	Probe, concentration, and temperature	HTC at 600°C	HTC at 500°C	HTC at 400°C	HTC at 300°C
Silver	Spherical probe 20 mm in diameter cooled in 5% water solution of NaCl at 20°C	23380	41170	59800	78500
Silver	Spherical probe 20 mm in diameter cooled in 15% water solution of NaCl at 20°C	39380	66000	90650	100300
Silver	Spherical probe 20 mm in diameter cooled in 20% water solution of NaCl at 20°C	18460	23000	27400	89400
Stainless steel	Cylindrical probe 12 mm in diameter cooled in 6% water solution of Na ₂ CO ₃ at 20°C	121430	-	-	8890

As seen from Table 1, the values of HTCs obtained using steel probes of 12 diameters are in good agreement with the existing theory of the transient nucleate boiling process taking place during quenching in electrolytes. Since the temperature gradient is greater for the smaller probe, this probe's heat flux density is greater. It means that the average HTC during nucleate boiling is greater for the smaller probe [10]. When the steel probe core temperature decreases, HTC decreases as well (see Table 1). In contrast to the data obtained for steel probes, the HTC increases by almost three times with decreasing the silver probe's core temperature. That can be true for the developed film boiling process converting to a transition nucleate boiling stage, where the HTC is significantly greater. However, the values of HTCs are so large that they cannot belong to the film boiling process. Such huge HTCs can be generated only by the developed nucleate boiling process. That is why the discovered phenomenon can be explained only by a periodical change of the film boiling process with the shock boiling process performed with a high frequency [10].

The practical use of the discovered phenomenon is shown in Fig. 2. The procedure is quite simple. Before the load's immersion into the electrolyte of optimal concentration, the steel parts are negatively charged to start a forced heat exchange by creating the above high-frequency periodical process consisting of replacing the film boiling process with the shock boiling process. Note that the proposed innovation requires further detailed

investigations to be widely used in heat treatment practice.

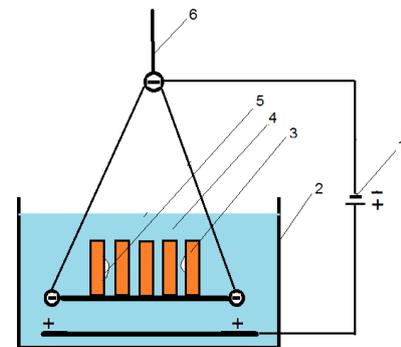


Fig. 2: Schematic installation to provide intensive and uniform cooling by exploring external electrical forces: 1 is electrical accumulator; 2 is quench tank; 3 is steel part in a load; 4 is quenchant in quench tank; 5 is vapor bubble; 6 is the element of the moving system.

IV. ELIMINATION OF FILM BOILING PROCESS BY USING OF WATER POLYMER SOLUTIONS OF REVERSE SOLUBILITY

The film boiling process can be eliminated by decreasing the initial heat flux density q_0 below its critical value q_{ct1} . This can be achieved by creating a thin surface insulating layer of a thickness δ (Fig. 3). As one can see from Eq.

(2), the insulating layer can decrease q_0 below its critical value q_{cr1} [11]:

$$q_{in} = \frac{q_o}{\left(1 + 2 \frac{\delta \lambda}{R \lambda_{coat}}\right)} \quad (2)$$

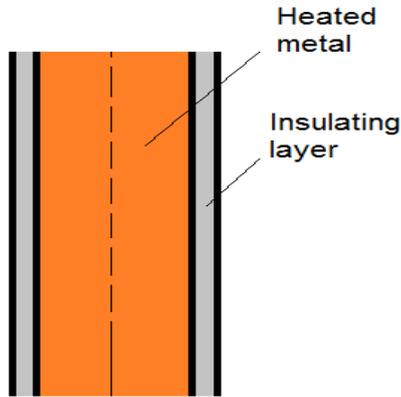


Fig. 3: Polymeric insulating layer formed during the quenching of steel parts in a water solution of inverse solubility polymers.

Polymer water solutions of 5 to 15% are widely used for the conventional quenching of steel parts. However, they are not used in IQ water tanks since the part cooling rate provided by these solutions is less than required to implement the IQ process. As shown in [12, 13, and 14], a solution of low concentration of the reverse solubility polymer in water does provide heat transfer conditions required by the IQ process. Author [15] noticed that the cooling process in water solutions of polymers should be interrupted at a proper time to prevent the dissolution of the surface insulation layer at the bottom of the load (Fig. 4), which can result in an excessive distortion of the hardened products. Optimal

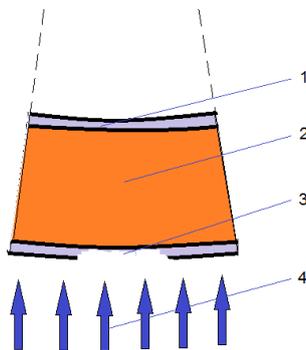


Fig. 4: A scheme explaining why a big distortion takes place during quenching in water PAG polymers solutions: 1 – polymer coating; 2 – quenched steel part; 3 – locally dissolved by water flow polymer coating; 4 – water flow

Interrupting time can be calculated using appropriate software designed by Intensive Technologies, Ltd. of

Kyiv, Ukraine, based on the regular thermal condition theory [16, 17].

V. NEW QUENCHING TECHNOLOGIES BASED ON PROPER CONTROL OF NUCLEATE BOILING PROCESS PARAMETERS

As known, a conventional Law of Fourier generates a parabolic heat conductivity equation (3), while a modified law of Fourier generates a hyperbolic heat conductivity equation (2). The parabolic heat conductivity equation takes into account the presence of free electrons in the metal, which is a reason for existing thermal waves [16, 17, and 18]:

$$c\rho \frac{\partial T}{\partial \tau} = \lambda \text{div}(\text{grad}T) \quad (3)$$

$$c\rho \frac{\partial T}{\partial \tau} + \frac{1}{w_r^2} \frac{\partial^2 T}{\partial \tau^2} = \lambda \text{div}(\text{grad}T) \quad (4)$$

Here $w_r = \sqrt{\frac{a}{\tau_r}}$ is a speed of the thermal wave

distribution in metal during its cooling [16].

When any film boiling is completely absent during quenching, and a transient nucleate boiling process takes place, the following boundary condition can be used during quenching of steel in a liquid media [1]:

$$\left[\frac{\partial T}{\partial r} + \frac{\beta^m}{\lambda} (T - T_s)^m \right]_{r=R} = 0 \quad (5)$$

In many cases, an initial condition for the quench process is written as:

$$T(r,0) = T_o \quad (6)$$

A transition from the nucleate boiling process to convection is evaluated from the equity of heat flux densities at the end of nucleate boiling and the beginning of convection [1]:

$$q_{nb} \cong q_{conv} \quad (7)$$

After the transition, when convection starts, the boundary condition (6) has the following conventional form:

$$\left[\frac{\partial T}{\partial r} + \frac{\alpha}{\lambda} (T - T_m) \right]_{r=R} = 0 \quad (8)$$

An analytical solution of equation (3) with boundary condition (5) and boundary condition (8) was proposed by authors in 1979 [19]. The solution appeared to be very complicated. However, after numerous accurate experiments, it was reduced to a rather simple form (9):

$$\tau_{nb} = \bar{\Omega} k_F \frac{D^2}{a} \tag{9}$$

Proceeding from Eq. (9), one can state that duration of the transient nucleate boiling process is a) directly proportional to the square of the thickness D of an arbitrary body and is inversely proportional to thermal diffusivity of the material a , and b) depends on a form k_F of a body, its initial temperature, and properties of the cooling system. Furthermore, it was established that during quenching, a so-called self-regulated thermal process occurs, where the part surface temperature during nucleate boiling maintains for a relatively long time at the level of the liquid saturation temperature T_s [19]. Mathematically it can be formulated as:

$$T_{sf} = T_s + \Delta \bar{\xi} \approx const \tag{10}$$

The value $\bar{\Omega}$ is a function of the convective Biot number (Fig. 5). Note that the initial austenitizing temperature and bath temperature are fixed at 850°C and 20°C, accordingly. When convective Biot number $Bi \rightarrow \infty$, the value of $\bar{\Omega} \rightarrow 0$.

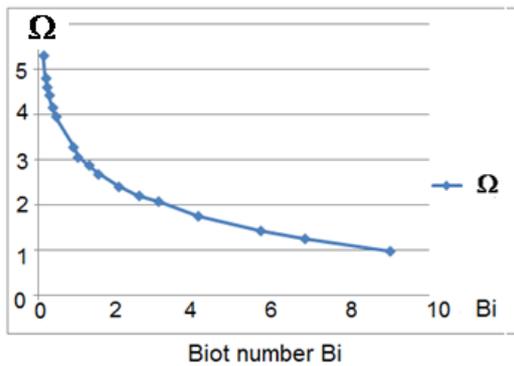


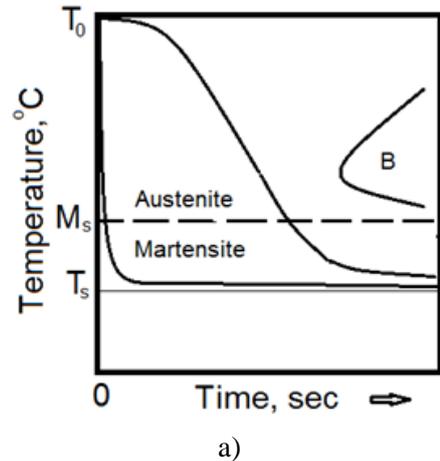
Fig. 5: Value $\bar{\Omega}$ versus Biot number Bi depending on the steel part's size and heat transfer coefficient during convection.

These new processes were carefully investigated by authors [1, 20], and, as a result, it was established that the HTC during nucleate boiling decreases with time (Table 2).

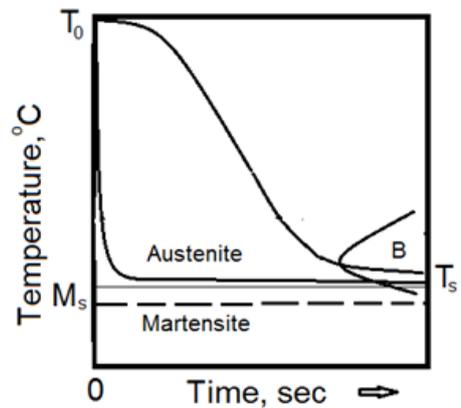
TABLE II
Real heat transfer coefficients versus time during quenching spherical steel sample 38.1 mm in diameter in water 5% water solution of NaOH at 20°C

2 s	4 s	6 s	20 s
200,000	120,000	90,000	30,000

Due to Eq. (10), a saturation temperature of the liquid T_s during quenching should be below the martensite start temperature M_s (see Fig. 2).



a)



b)

Fig.6: Relationship between martensite start temperature M_s , and self-regulated thermal process: a) self – the regulated thermal process is below martensite start temperature M_s ; b) self – the regulated thermal process is above M_s .

The discovered characteristics were used for the following:

- Developing an original IQ-2 technology increases the service life of machine components and tool products [1].

- To evaluate the thermal diffusivity of different materials.
- To explain the secrets of Damascus steel [21].
- Develop a new technology called austempering and martempering processes implemented in cold liquids instead of melted salts and alkalis [22].

As mentioned above, the accelerated cooling should be interrupted properly to avoid a quench crack formation and minimize part distortion [1]. For this purpose, a generalized Eq. (11) is used [3].

$$\tau_{eq} = E_{eq} \frac{K}{aKn} \tag{11}$$

The above investigations' main conclusion is that the IQ process can be fulfilled even in still water if any film boiling is completely absent. A saturation temperature of the liquid is below the martensite start temperature Ms.

This equation is based on the heat conduction theory and numerous accurate experiments [13, 24, 25]. Some calculated data are provided in Table 3.

TABLE III
Coefficients E_{eq} depending on the dimensionless value θ , which was decreased from 1.5 to 1000 times for different generalized Biot numbers Bi_V .

$Bi_V = 0.1$											
E_{eq}											
N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.44	0.73	0.96	1.14	1.29	1.43	1.54	1.65	2.38	4.64	6.95
Cylinder	0.49	0.77	1.00	1.18	1.33	1.47	1.58	1.69	2.42	4.68	6.99
Sphere	0.55	0.81	1.04	1.22	1.37	1.51	1.62	1.73	2.46	4.72	7.02
$Bi_V = 0.5$											
E_{eq}											
N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.53	0.817	1.04	1.22	1.38	1.51	1.63	1.73	2.43	4.73	7.03
Cylinder	0.65	0.94	1.16	1.35	1.50	1.63	1.75	1.86	2.55	4.85	7.16
Sphere	0.78	1.07	1.29	1.47	1.62	1.76	1.88	1.98	2.67	4.98	7.28
$Bi_V = 1$											
E_{eq}											
N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.57	0.86	1.08	1.27	1.42	1.55	1.67	1.78	2.47	4.77	7.07
Cylinder	0.74	1.03	1.25	1.44	1.59	1.72	1.84	1.94	2.64	4.94	7.24
Sphere	0.91	1.20	1.42	1.60	1.76	1.89	2.01	2.11	2.80	5.11	7.41
$Bi_V = 2$											
E_{eq}											
N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.61	0.90	1.12	1.30	1.46	1.59	1.71	1.81	2.51	4.81	7.11
Cylinder	0.81	1.1	1.32	1.50	1.66	1.79	1.91	2.02	2.71	5.01	7.33
Sphere	1.01	1.30	1.52	1.71	1.86	1.99	2.11	2.22	2.91	5.21	7.51
$Bi_V = 5$											
E_{eq}											

N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.63	0.92	1.14	1.32	1.48	1.61	1.73	1.83	2.53	4.83	7.13
Cylinder	0.86	1.15	1.37	1.55	1.71	1.84	1.96	2.07	2.76	5.06	7.36
Sphere	1.10	1.38	1.61	1.80	1.94	2.08	2.20	2.30	3.00	5.29	7.58
$Bi_V = \infty$											
E_{eq}											
N	1.5	2	2.5	3	3.5	4	4.5	5	10	100	1000
Plate	0.64	0.93	1.15	1.33	1.49	1.62	1.74	1.84	2.54	4.84	7.15
Cylinder	0.87	1.16	1.38	1.56	1.72	1.85	1.97	2.08	2.77	5.07	7.38
Sphere	1.11	1.39	1.62	1.80	1.95	2.09	2.20	2.31	3.00	5.30	7.60

Effective Kondrat'ev numbers Kn can be evaluated using Fig. 7 [26].

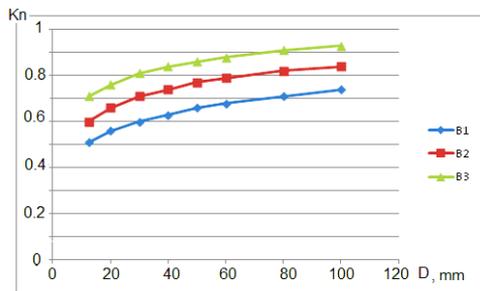


Fig. 7: Effective number Kn versus the size of cylinders for different convective heat transfer coefficients [22]: B1 is 750W/ m2K; B2 is 1500 W/ m2K; B3 is 4000 W/ m2K

Example: Calculate a cooling time of the sphere of 38.1mm (3 inches) in diameter made of steel, which is cooled from 875°C in technical water at 20°C with no film boiling process. Kondrat'ev form factor K for the given sample is $36.7 \times 10^{-6} \text{ m}^2$ and Kondrat'ev number $Kn = 0.625$ (see Fig. 7). The average thermal diffusivity of steel is equal to $5.4 \times 10^{-6} \text{ m}^2/\text{s}$. The value of E_{eq} is calculated as $N = (875^\circ\text{C} - 20^\circ\text{C}) / (300^\circ\text{C} - 20^\circ\text{C}) = 3$. When film boiling is absent, the Biot number tends to infinity, and for this condition, $E_{eq} = 1.8$ (see Table 3). Thus, the cooling time coincides very well with the accurate French experiments [27] widely discussed in the book [1]. According to French, this cooling time is equal to 20 seconds [27].

VI. DISCUSSION

As discussed in the "American Journal of Modern Physics" [28], two companies were established in 1999 and 2000 to introduce IQ processes into heat treatment practice. The first company, IQ Technologies Inc (IQT), was established in 1999 in Akron, Ohio, USA, and the second company, Intensive Technologies Ltd (ITL), was established in 2000 in Kyiv, Ukraine. Its mission is to design IQ equipment and commercialize IQ processes, while ITL focuses on academic investigations and

designing appropriate software for controlling and governing the IQ processes. Unfortunately, IQ processes are not in mass production yet, mainly because it is a disruptive technology. The author believes that innovations discussed in the paper will help to introduce IQ processes globally. Much scientific work has been done related to the hyperbolic heat conductivity equation [29, 30, and 31]. IQ processes have been thoroughly validated and are currently successfully used in the USA [32, 33]. Very interesting and important for the practice results were obtained in Germany concerning IQ processes [34, 35, and 36].

Further investigations in this field may result in material cost savings and improve the service life of different machines and solve many environmental problems. One can find more information in published papers [37, 38, and 39]. It should be noted here that fruitful cooperation between IQT and ITL will result in a smooth transition of contemporary IQ technologies to less costly technologies to be used in mass production worldwide. However, more investigations should be done in this field, and certain investments should be planned to bring proposed new technologies to a high-tech level. It makes sense to fight facing global problems (global warming, materials savings, etc.) by the young generation in our Globe.

VII. CONCLUSIONS

1. Cooling in water, water-salt solution, water polymer solutions of inverse solubility of low concentration is intensive if any film boiling is completely absent. In this case, the saturation temperature of liquid should be clearly below the martensite starts temperature M_s .
2. To eliminate any film boiling during quenching, cooling is performed in a low concentration of inverse solubility water polymer solutions that decrease an initial heat flux density below its critical value q_{crit} .
3. Any film boiling can be eliminated using hydrodynamic emitters that generate resonance effect during quenching in liquid media, destroying the film boiling process.

4. Any film boiling is also eliminated by negatively charging the load prepared for batch quenching, which initiates the forced heat transfer exchange phenomenon during quenching in electrolytes.
5. Accelerated cooling should be interrupted at a proper time to eliminate quench crack formation, creating maximal surface compressive residual stresses and decreasing steel part distortion after quenching.
6. It makes sense to start global cooperation with the big companies to save materials, make technological processes less costly, increase the quality of hardened products, and make the environment green.
7. The proposed new approaches are suitable for existing quenching technologies to accelerate and optimize them and IQ processes.

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NOMENCLATURE

a	Thermal diffusivity of solid material in m^2/s
Bi	Biot number
Bi_V	Generalized Biot number
c	Specific heat capacity in $J/kg \cdot ^\circ C$
D	Diameter or thickness in m
E_{eq}	Value depending on dimensionless temperature
Kn	Kondrat'ev dimensionless number
K	Kondrat'ev form factor in m^2
k_F	Dimensionless form coefficient
P	Pressure in MPa
R	Radius in m
T	Temperature in $^\circ C$
T_o	The initial austenitizing temperature in $^\circ C$
T_{sf}	Surface temperature
T_s	Saturation temperature in $^\circ C$
T_m	Bath temperature in $^\circ C$
θ	Dimensionless temperature
α	Heat transfer coefficient in W/m^2K
β	Value depending on the physical properties of liquid
δ	The thickness of the insulating layer
ρ	Density in kg/m^3
λ	Thermal conductivity in W/mK
$\Delta \bar{\xi}$	Average temperature difference $T_{sf} - T_s$
τ_r	Relaxation time in sec
Ω	The function of convective Bi and T_o

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