Contemporary Intensive Methods of Steel Hardening in Cold Fluids

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Abstract: **-** In the paper, the new intensive quenching technologies are discussed which are based on controlling the self-regulated thermal process (SRTP) which exists for a long time if any film boiling is absent. It is rather intensive until convection starts. Despite the intense process (Kn > 0.8), when the heat transfer coefficient and Biot number tend to infinity, there are several ways of controlling the surface temperature of steel components by varying the boiling temperature of the fluid. To eliminate any film boiling process and provide SRTP, the author of the paper explores the resonance effect, a thin surface insulating layer that covers the surface of machine components and electrical negative forces to control the double electrical layer that is responsible for destroying the film boiling mode. Based on SRTP control it is possible to delay the transformation austenite into martensite or even accelerate these transformations. The most important are possibilities to control surface temperature during the boiling process. All of this opens great opportunities for increasing significantly service life of machine components and tools. In the paper also the simplified method of cooling time calculation is proposed. It is based on the new principles concerning pure transient nucleate boiling taking place during the hardening steel in cold fluids. Since the paper simply explains everything, results of investigations will be widely used in the heat-treating industry.

Key-Words: **-** Film boiling absence, Surface temperature control, Intense quenching, New technologies, Service life, Environment.

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1 Introduction

Due to several discoveries made in the field of material science and in the field of heat and mass transfer, it was possible to write this paper. In 1964 in Ukraine was experimentally discovered the bell - shaped curve, which was unexpected for material scientists because it contradicted the existing theory concerning the effect of cooling rate on the crack formation and strengthening of materials. Recently (2023), three principles of heat transfer taking place during the transient nucleate boiling process, were published by London Press, [1]. These discoveries open great opportunities for intensive quenching technologies design and for providing tools for accurate recipe development. The paper discusses three main directions of contemporary hardening processes that provide great benefits and improve essentially environmental condition. As a rule, the strengthening of machine components is performed by quenching them in cold fluids which include oils, polymers for slow cooling, water and water salt solutions, jets, or water flow for intensive quenching. The last procedures require special installations like powerful pumps, and rotating propellers used for intense agitation of fluid. The paper considers alternative intensive quenching which is based on the fact that intensive quenching can be performed in still water if any film boiling during quenching is completely absent, [1]. Therefore, the main task is increasing the first critical heat flux density responsible for the developed film boiling, [2], [3]. Also, the deleting of the film boiling process can be performed by creating a thin insulating surface layer during quenching machine components in low concentrations of inverse solubility polymers, [4]. This thin surface layer decreases initial heat flux which drops below the first critical value and by this way eliminates any film boiling process. In the last decades some new unexpected phenomena were discovered according to which crisis of boiling can be governed by electrical forces that are more effective in terms of film boiling elimination, [5]. More effectively film boiling can be eliminated by using the resonance effect that destroys any film boiling during quenching machine components in cold fluids. Thus, the plan of discussion includes:

1. Explaining why during quenching steel from high temperatures in cold fluid film boiling in many cases is absent.
2. Providing experimental data of different

authors to show readers that during quenching in low agitated fluids any film boiling can be completely absent.

3. Discussion of new less costly installations for performing uniform and intensive quenching to obtain super - strengthened material, radically decrease the cost of technological procedure, and increase essentially service life of machine components.

These problems are discussed below.

2 Absence of Film Boiling Process during Quenching in Cold Fluids

It was widely and firmly disseminated opinion among the leading experts that during quenching from high temperatures of metal components in cold fluids always three stages exist: developed film boiling, transient nucleate boiling, and convection. This opinion is based on well-known law of Fourier. According to the conventional law of Fourier, the heat flux is calculated using equation (1):

$$q = -\lambda \frac{\partial T}{\partial x} S d\tau \quad (1)$$

Since, during immersion of heated steel components in cold fluid at the very beginning of cooling, the temperature gradient tends to infinity, initial heat flux density tends to infinity too significantly prevailing the first critical heat flux density. That means immediate appearance of a developed film boiling mode. Engineers from the heat-treating industry often obtained evidences on developed film boiling existence. However, in 1930 French performed accurate experiments with spherical steel samples of different sizes which were quenched from 875ºC in water solution of NaOH at 20ºC where any film boiling process was completely absent, [6]. It was shown by French that surface temperature during quenching for all spherical samples (6 mm and 120 mm) drops from 875ºC to 200ºC for 0.29 s. Within such a short time there is no possibility for vapor bubble growth and developing film boiling process. Later similar results were reported by different authors who quenched cylindrical samples in water salt solutions of optimal concentration and didn't observe any film boiling process during cooling from 850ºC. It looks extraordinary because film boiling during cooling from high temperatures in fluids should be present. Such strange behavior can be explained by considering modified law of Fourier 2, [7]:

$$q_x = -\lambda \frac{\partial T}{\partial x} - \tau_r \frac{\partial q_x}{\partial \tau} \quad (2)$$

According to equation (2), the initial heat flux density is a finite value that can drop below the first critical heat flux density that provides the absence of the film boiling process. For accurate evaluation of initial heat flux density, scientists solve the hyperbolic heat conductivity equation generated by the modified law of Fourier which was considered by author, [7].

As well known, the amount of thermal energy can be calculated as:

$$q = c\rho dVdT = c\rho SdxdT \quad (3)$$

Using the energy conservation law, one can get the following energy balance equation from formulas (1) and (3):

$$-\lambda \frac{\partial T}{\partial x} S d\tau = c\rho SdxdT \quad (4)$$

Equation (4) can be rewritten as:

$$-\frac{\partial q_x}{\partial x} = c\rho \frac{\partial T}{\partial \tau} \quad (5)$$

Substituting Eq. (2) into Eq. (5) leads to:

$$\lambda \frac{\partial^2 T}{\partial x^2} + \tau_r \frac{\partial^2 q_x}{\partial x \partial \tau} = c\rho \frac{\partial T}{\partial \tau} \quad (6)$$

The value τ_r is called a relaxation time. It is a characteristic of the free electrons movement, and it is a constant which depends on the nature of the material.

By differentiating Eq. (2) by τ, one can get the following:

$$\frac{\partial^2 q_x}{\partial x \partial \tau} = -c\rho \frac{\partial^2 T}{\partial \tau^2} \quad (7)$$

It means that Eq. (6) can be rewritten as hyperbolic heat conductivity equation presented in [7]. This hyperbolic heat conductivity equation along with the boundary condition (8) representing the transient nucleate boiling process, can be used for accurate evaluation of initial heat flux densities to be compared with the first critical heat flux density.

$$\left[\frac{\partial T}{\partial r}+\frac{\beta^m}{\lambda}\left(T-T_s\right)^m\right]_{r=R}=0 \qquad (8)$$

The solving of the hyperbolic heat conductivity equation (6) with the appropriate boundary and initial conditions is a rather complicated task. Therefore, mathematicians proceed to develop new methods of solving them, [8].

Thus, the developed film boiling process during the quenching of steel components from high temperatures in cold fluids can be completely absent if the initial heat flux density q_{in} is below the first critical value q_{cr1}, *i.e.* $q_{in} < q_{cr1}$.

3 Intense Quench Process in Cold Fluids when any Film Boiling is Absent

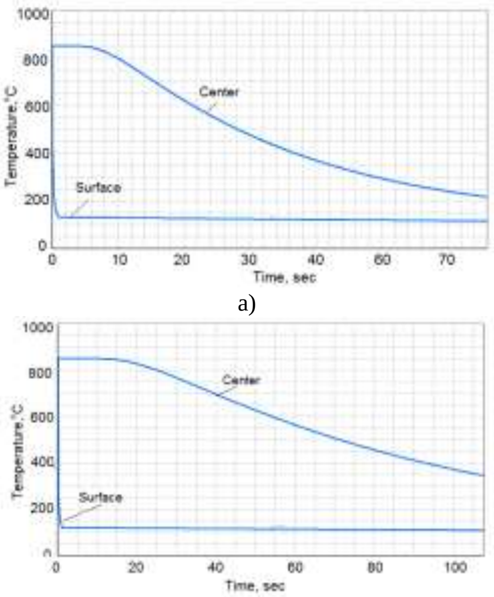
The above consideration of the initial process of quenching was needed to explain absence of film boiling when hardening metal in cold fluids. Now, it is very important to show that transient nucleate boiling is an intensive heat transfer mode if any film boiling is completely absent. For this purpose, it is enough to consider the cooling process using regular condition theory, [9], [10] which manipulates with Kondrat'ev number Kn ($0 < Kn < 1$). According to authors, [11], cooling is intensive if $Kn \geq 0.8$. Taking this fact into account, real and effective numbers of Kn were evaluated on the base of accurate experiments (Figure 1).

As seen from Table 1 and Figure 2, the real average Kondrat'ev numbers Kn for both sizes 12.5 and 50 mm exceed the value 0.8 therefore cooling process is intensive despite small value of convective HTC which was equal 500 W/m^{2}K.

Table 1. Real and effective Kondrat'ev numbers Kn and convective HTCs in still water versus the size of the cylindrical probe

D, mm	Type of Kn	Kn_I	Kn_{II}	Average Kn	HTC, W/m^{2}K
12.5	Real	0.95	0.81	0.88	20420
	Effective	0.90	0.225	0.562	3956
50	Real	1.0	0.87	0.935	9660
	Effective	0.96	0.3	0.63	1288

As seen from Figure 1, the cooling process is very intensive.

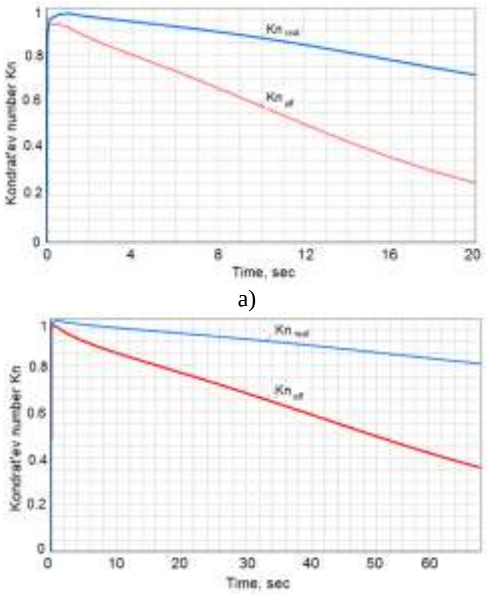


a)

b)

Fig. 1: Surface and core cooling for cylindrical probe of different diameters quenched from 850ºC in water salt solution at 20ºC: a),50 mm; b), 80 mm

Real and effective Kondrat'ev numbers vs time are presented in Figure 2. For example, for a cylindrical probe 50 mm in diameter the real Kondrat'ev number Kn$_{real}$ is equal to 0.995 which is responsible for correct cooling time and cooling rate calculations, [1].



a)

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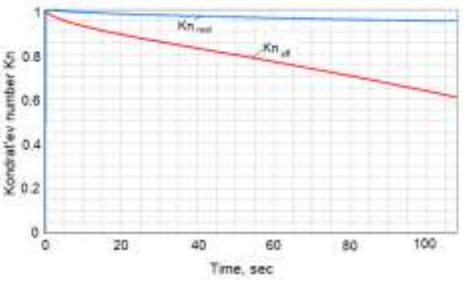

c)

Fig. 2: Real and effective Kondrat'ev numbers Kn for cylindrical probe of different diameters quenched from 850°C in water salt solution at 20°C: a) 25 mm; b) 50 mm; c) 80 mm

Table 2 presents initial $\vartheta_I, ^oC$ and end $\vartheta_{II}, ^oC$ overheating temperatures during nucleate boiling when convective heat transfer is 500 W/m^{2}K..

Table 2. Initial $\vartheta_I, ^oC$ and end $\vartheta_{II}, ^oC$ overheating temperatures during the transient nucleate boiling process.

Diameter, mm	10	12.5	20	25	30	40	80
$\vartheta_I, ^oC$	33.5	31	27	25	24	22	21
$\vartheta_{II}, ^oC$	8.5	8.5	8.5	8.5	8.5	8.5	8.5

During the transient nucleate boiling process surface temperature changes insignificantly (Table 2).

4 Conventional Batch Quenching Process

The conventional batch quenching process is performed in quench tanks equipped with rotating propellers or pumps with agitated fluid (Figure 3).

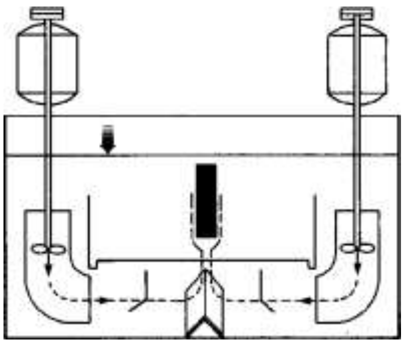

Fig. 3: Illustration of a typical batch immersion time quenching system. Agitation is provided by two or more continuously variable impeller stirrers, [12]

A typical load consisting of a large number of steel parts is shown in Figure 4.

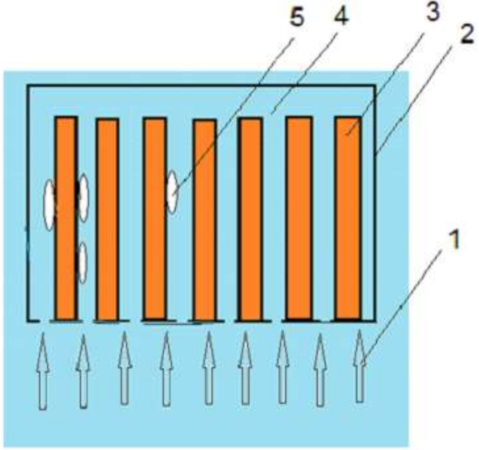

Fig. 4: A load consisting of a large number of steel parts

When quenching in still water, the convective heat transfer coefficient is calculated by equation (9), [20], [21]:

$$\alpha_{conv} = 0.135\left(\frac{g\beta\Delta T}{a\nu}\right)^{1/3} \qquad (9)$$

Some results of calculations are presented in Table 3.

Table 3. Convective HTCs in W/m^{2}K versus water temperature and pressure in MPa

P, MPa	Water 10°C	Water 20°C	Water 30°C
0.1	548	640	1015
0.2	586	690	1105
0.3	609	719	1156

Convective heat transfer coefficient (HTC), when quenching in water flow, is evaluated by equation (10), [13]:

$$Nu = 0.021\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.43}\left(\frac{\mathrm{Pr}_m}{\mathrm{Pr}_{sf}}\right)^{0.25}\varepsilon_l \qquad (10)$$

CFD modeling shows that cooling in water flow is not uniform (Figure 5), [14]. Not uniform cooling can generate a local film boiling process which results in essential distortion of steel components during hardening in agitated fluids, [14], [15].

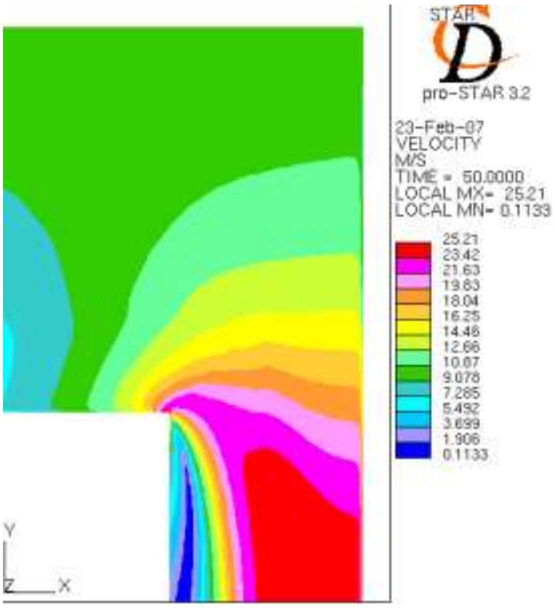

Fig. 5: Water flow velocities distribution during intensive quenching of the forging, [14]

5 Contemporary Methods of Steel Hardening

5.1 Hydrodynamics Wave Emitters

When quenching load consists of large number of parts (especially relatively thin parts), a local film boiling process takes place at the beginning of the quenching process even in the IQ water tanks with vigorous agitation of the water-salt solution. It has been revealed by authors, [14], [15] that local film boiling is the main reason for the excessive part distortion. For gear products, a “double” distortion occurs sometimes when the local film boiling takes place between two teeth of the gear. That is why, the author of the current paper suggested using oscillatory waves produced by a hydrodynamic emitter for destroying local large film bubbles by a resonance effect in addition to the quenchant agitation during the IQ – 2 process (Figure 6 and Figure 7), [16].

Hydrodynamics emitters generate waves in liquid with a frequency equal to the oscillating frequency of local film boiling. One of them is shown in Figure 6 where 1 is a water flow rate provided by the pump; 2 is a tube, 3 is a circulated water stream; 4 is a generator of waves in liquid; 5 is a regulator of the wave frequency; 6 is a water flow combined with the generated waves and directed to the load being quenched, [16].

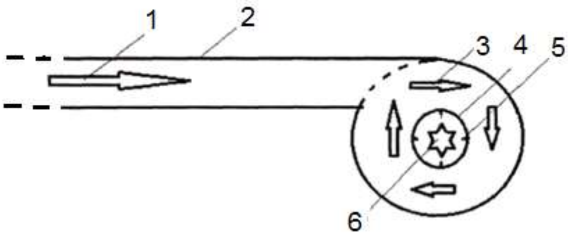

Fig. 6: Emitter for generating waves with a frequency equal to the frequences of films to provide resonance effect, [16].

The resonance effect destroys local and developed film boiling more effectively as compared with fluid agitation because resonance penetraces througtout the load. Directed water flow water faces hydrodynamic resistance if the load is not spread enough.

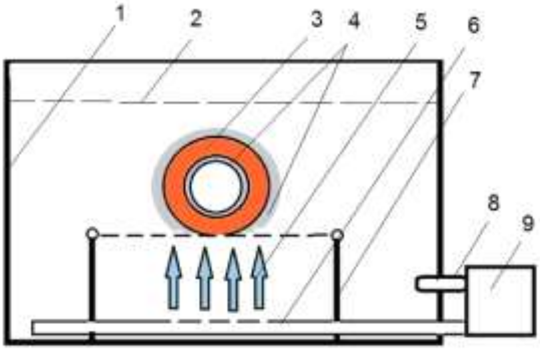

Fig. 7**:** Emitters arrangement in quench tank, [16]: *a* is the emitter, where 1 is liquid flow, 2 is a tube, 3 is circulated liquid stream, 4 is generator waves in liquid, 5 is regulator of wave frequency, 6 is liquid flow combined with generated waves; *b* is quench tank with located in it emitters, where 1 is quench tank; 2 is water salt solution of optimal concentration; 3 is fixture; 4 is steel part; 5 is local film boiling; 6 is emitter.

For calculating a frequency that provides a resonance effect, equation (12) can be used, [16]:

$$f_{Hz} = \frac{nV_C}{\pi D}. \tag{12}$$

Here f_{Hz} is a resonance frequency for the film boiling process in Hz; n is a number of restrictions or openings on the round nozzle required for providing a resonance wave (Figure 6**)**; V_C is a circulated water flow velocity in m/s; D is a diameter of the nozzle in m.

Note, that each restriction or opening generates packages of waves. The primary one is calculated by equation (9).

5.2 Quenching Steel Covered with a Thin Surface Insulating Layer

The absence of any film boiling process during quenching probes in low concentration of water polymer solutions is explained by a decrease of initial heat flux density q_o which is calculated by Eq. (11), [4]:

$$q_{in} = \frac{q_o}{\left(1 + 2\frac{\delta}{R}\frac{\lambda}{\lambda_{coat}}\right)} \qquad (11)$$

$$\Delta l = \left(1 + 2\frac{\delta}{R}\frac{\lambda}{\lambda_{coat}}\right) \qquad (11a)$$

When $\lambda_{coat} = 0.2 W/mK$ and $\lambda_{sl} = 20 W/mK$ then $\frac{\lambda_{sl}}{\lambda_{coat}} = 100$. When the thickness of the insulating layer is 100 μm and 2R = 0.020 m then $\frac{\delta}{R} = \frac{100 \times 10^{-6} m}{10 \times 10^{-3} m} = 0.01$. In this case $\Delta = (1 + 2 \times 0.01 \times 100) = 3$. It means that the initial heat flux density during the quenching of a given example (Figure 8) can be reduced 3 times that eliminates completely any film boiling process since $q_{in} < q_{cr1}$. More data on value Δ are provided in Table 4.

Table 4. Possibility of film boiling (FB) elimination by creation a thin insulating surface layer during quenching in low concentration of water polymer solutions

No	$\frac{\delta}{R}$	$\frac{\lambda_{sl}}{\lambda_{coat}}$	Δl
1	0.001	100	1.2
2	0.005	100	2
3	0.01	100	3
4	0.001	200	1.4
5	0.005	200	3
6	0.01	200	5

Poly(Alkylene Glycol) polymers (PAG) of optimal concentrations provide ideal uniform cooling for minimizing distortion and preventing crack formation during hardening machine components and tools due to their inverse solubility which is a reason for polymeric surface layer formation, [4].

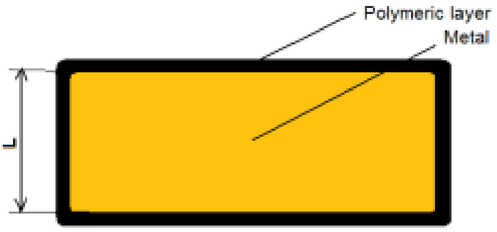

Fig. 8: Section of steel part of height L covered with the polymeric layer of thickness

Note that an insulating layer in many cases prevents crack formation because existing microcracks are plugged by viscous polymer.

5.3 Use Electrical Forces to Control the Double Electrical Layer

The discovered phenomenon can be used for designing new quenching technology governed by external electrical forces (Figure 9), [5]. The negative charge is directed to load 7 which generates electrical forces in the double electrical layer that compresses electrolyte to the hot metal surface destroying the film boiling process.

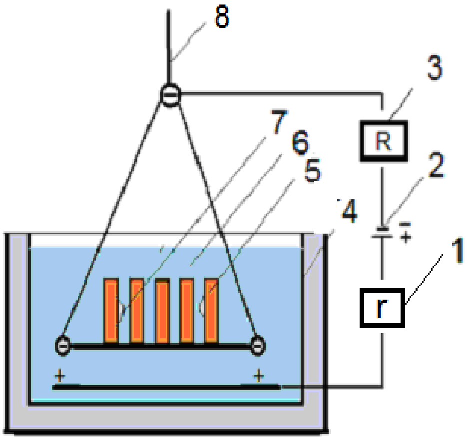

Fig. 9: Schematic installation to provide intensive cooling via exploring electrical forces: 1 is a resistor; 2 is an electrical accumulator; 3 is a relay to interrupt electrical force in 2 seconds; 4 is insulation; 5 is steel part; 6 is electrolyte; 7 is local film boiling; 8 is moving system, [5].

The proposed method requires more additional information which can be obtained by accurate experiments.

6 Simplified Method for Cooling Time Calculation

The generalized equation for such a statement can be mathematically written as (Eq. (13):

$$\tau_{nb} = \Omega k_F \frac{D^2}{a} \qquad (13)$$

Here τ_{nb} can be considered as a width of noise generated by vapor bubbles which is equal to its duration measured in seconds; Ω is a dimensionless parameter depending on convective HTC; k_F is a dimensionless form coefficient; D is the thickness of steel part in m; a is thermal diffusivity of steel in m^2s^{-1}. To calculate the full time of cooling, one should evaluate the core temperature at the core of the steel part at the end of nucleate boiling which now will serve as an initial temperature for equation (14). For such initial temperatures (Figure 10).

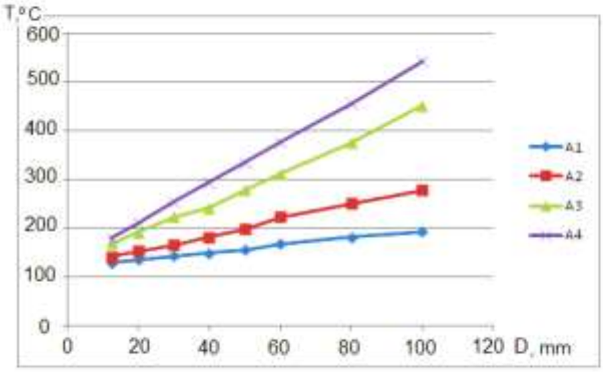

Fig. 10: Core temperature at the end of self-regulated thermal process versus size in mm of ylinder when convective heat transfer coefficient is 750 W/ m^2K (A1); 1500 2W/ m^2K (A2); 3000 W/ m^2 K (A3); and 4000 2W/ mK (A4)/

$$\tau = \left[\frac{kBi_V}{2.095 + 3.867Bi_V} + \ln\frac{T_o - T_m}{T - T_m} \right] \cdot \frac{K}{aKn} \qquad (14)$$

Here τ is cooling time in s; k = 1, 2, 3 for plate, cylinder accordingly; Bi_V is generalizes Biot number; T_o is initial temperature; T_m is medium bath temperature; K is Kondrat'ev form factor; a is the thermal diffusivity of steel; Kn is the dimensionless Kondrat'ev number Kn is also used for cooling rate v evaluation (Eq. (15):

$$v = \frac{aKn}{K}\left(T - T_m\right) \qquad (15)$$

The summarized time is calculated as:

$$\tau_{full} = \tau_{nb} + \tau_{conv} \qquad (16)$$

For more information on critical heat flux densities evaluation, [17], [18], [19]. Intensive quenching was used by authors, [20], for direct quenching of forging eliminating last lasting process of hardening in oils. It improved environment condition and saved energy. Further investigations connected with the control of double electrical layer, based on discovered of new phenomenon, and exploring resonance effect will bring to heat-treating essential benefits. Some useful information on convective boiling one can find in [21].

7 Conclusions

1. If any film boiling during quenching steel in water and water salt solution of optimal concentration is absent, the cooling process is intensive, and the average value of dimensionless number Kn is within 0.8 < Kn < 1.
2. To eliminate any film boiling process during quenching, the resonance effect can be explored which, as a rule, is generated by the hydrodynamic emitter. Its hydrodynamic resistance is minor compared with the directed fluid moving throughout the load.
3. The film boiling process during quenching can be eliminated by creating a thin insulating polymeric layer to decrease initial heat flux density below its critical value. For this purpose, inverse solubility polymers are used as the quenchants.
4. One should control the double electrical layer that exists during quenching steel in electrolytes to increase essentially the first critical heat flux density. It can be done by electrical forces to charge negatively the quenched steel.
5. There is the possibility to control intensive self-regulated thermal processes by controlling the boiling point of fluid using pressure or variation concentration of additives.
6. In this case the self-regulated thermal process is used to delay martensite transformation to obtain a more bainitic fine microstructure with extraordinary mechanical properties.
7. The self-regulated thermal process is used to obtain high compressive residual stresses and fine or nano-microstructure at the core of machine components.
8. The simplified method of cooling time calculation during quenching in cold fluid machine components of any size and form is proposed. The main idea consists of evaluating duration of the self-regulated thermal process and cooling time in the convective zone to summarize them.

9. If the cooling process is interrupted in the nucleate boiling zone, then is used universal correlation for cooling time calculation within the transient nucleate boiling zone.
10. The main attention in the future one should be pay to critical heat flux densities to be compared with the initial heat flux density aiming elimination of any film boiling process together with the powerful pumps and rotating propellers.

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Conflict of Interest

The author has no conflict of interest to declare that is relevant to the content of this article.

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