Transient nucleate boiling process as a basis for designing of high efficiency innovative technologies

Nikolai I Kobasko

PhD, Fellow of ASM International, Intensive Technologies Ltd., Kyiv, Ukraine and IQ Technologies Inc., Ohio, United States

Abstract
It is shown in the paper that during quenching metal samples in liquid media, such as water salt solutions, nanofluids and low concentration of water polymer solutions, the main attention should be paid to critical heat flux densities and convective heat transfer coefficients which should be combined with the self – regulated thermal process (SRTP). No one can affect duration or intensity of cooling during transient nucleate boiling by adding any additives or nanoparticles to a liquid because nucleate boiling process by itself is very intensive due to acting thousands of vapor bubbles with the high frequency and intense liquid vaporization. Only two options are left which can affect cardinally cooling process via maximizing critical heat flux densities and increasing convective heat transfer coefficients. When any film boiling during quenching in still water or water solutions is completely absent, process of cooling is intensive due to intense acting thousands of vapor bubbles during nucleate boiling. These conclusions are very important for investigators who are focused on development intensive low temperature thermo-mechanical and cryogenic treatment of materials. The ideas discussed in this paper can be useful for engineers, scientists and students.

Keywords: liquid media; two direction; new technologies; critical heat flux density; convection; maximizing

1. Introduction
In last two decades the serious attention is paid to intensive quenching process that significantly increases service life of machine components and tools due to creation surface compression residual stresses and super strengthening effect taking place during intensive quenching in liquid media. Many investigators, excited by such possibilities, started to explore very powerful pumps and impellers to intensify cooling processes during hardening metal components and tools. Also, many investigators focused their efforts in investigations of nanofluids to intensify heat transfer coefficients during transient nucleate boiling process. However, heat transfer during nucleate boiling process depends on many parameters such as surface tension, frequency of bubbles departure, diameter of a vapor bubble, and thermal conductivity of a liquid, viscosity of a boundary layer and so on. So many parameters require costly experiments to evaluate them. Author of this paper came to conclusion that there is no need to do such costly experiments and in the reality one should focused on critical heat flux densities and convective heat transfer investigations. Serious attention is paid to convective heat transfer investigations of quenchants to be widely used in the practice. Unfortunately, no investigation is carried out at all-in heat-treating industry. This problem has priority in nuclear power stations where preventing overheating in channels is a critical issue. Step by step, it is below explained why two physical values, critical heat flux density and

convective heat transfer coefficient combined with the self – regulated thermal process, are so important for the new technologies development. In the paper intensive low temperature thermo-mechanical and cryogenic treatment are discussed based on specific characteristics of transient nucleate boiling process.

2. Initial and critical heat flux densities
There are two ways in elimination film boiling during quenching steel parts in liquid media. The first way is increase the first critical heat flux density and the second way is decrease initial heat flux density below its critical value. The second way is more effective and can be easily performed. To clearly understand these processes, let's consider physics of metals quenching. According to statistical physics [1, 2], free electrons in metal in heated area are under pressure P which is calculated as:

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

Here n is a number of electrons in one sm^3 of metal; k is the Boltzmann constant which is equal to
$k = 1.3806488\,(13)\,\mathrm{x}10^{-23}\,[\mathrm{K}^{-1}]$ [1]; T is temperature in $^{\circ}$K.
During immersion heated to high temperature metallic probe into electrolyte, a double electrical layer is formed on the boundary liquid – metal which looks like is shown in Fig. 1[3, 4].
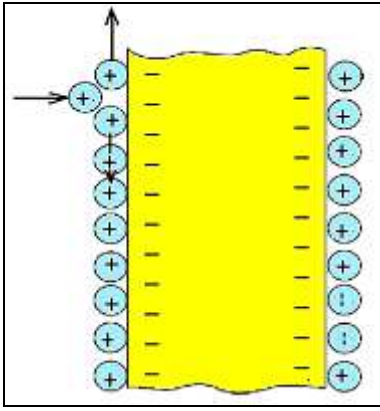
Fig 1: A double electrical layer formed during immersion of heated metallic probe into cold electrolyte [3].

There is an optimal concentration of electrolyte where the first critical heart flux density is maximal. Physics of such behavior was explained by authors [4, 5]. Optimal concentration of electrolytes exhibiting maximal critical heat flux densities are used in heat treating industry as a quenchant for uniform and accelerated cooling [5].

The second way of elimination the film boiling process is decreasing initial heat flux density q_0 below its critical value by creation a thin surface insulating layer of thickness δ that, as one can see from Eq. (2), decreases q_0 [6,7]:

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

Here q_{in} is initial heat flux density after coatings; λ is thermal conductivity of steel; λ_{coat} is thermal conductivity of coating.

For this purpose the low water concentration of inverse solubility Poly (Alkylene) Glycol (PAG) polymer is used as a quenchant [6].

3. Importance of Self – Regulated Thermal Process and Its Use in Practice

As known, austempering processes are performed by exploring melted salts or alkalis as a quenchant. Sometimes high temperature oils are used for this purpose [8, 9]. Temperature of melted salt or hot oil must be equal or little bit higher of martensite start temperature M_S to prevent transformation austenite into martensite during quenching to get very fine bainitic microstructure. However, cooling rate in melted salts and alkalis is slow that requires high alloy steels to perform correctly austempering process. The same is true when performing low temperature thermo – mechanical treatment (LTMT). As a result, austempering and LTMT technologies are rather costly, complicated and are not suitable for the forging shops. Moreover, the hot alkalis and hot oils are not environment friendly and in many cases are hazardous. To solve this problem, the self – regulated thermal process can be used for developing austempering and LTMT green technologies just by use of plain water under pressure [5, 10].

The self – regulated thermal process (SRTP) is transient nucleate boiling when surface temperature of a solid sample maintains relatively a long time at the level of boiling point of a liquid and never can be below this point until heat flux density at the end of nucleate boiling is equal to heat flux at the beginning of convection. It is understandable when considering generalized Eq. (3) [11]:

$$\frac{\overline{T}_{sf} - T_m}{\overline{T}_V - T_m} = \frac{1}{\left(Bi_V{}^2 + 1.437 Bi_V + 1\right)^{0.5}} \qquad (3)$$

where $Bi_V = \dfrac{\alpha}{\lambda} K \dfrac{S}{V}$ is generalized dimensionless Biot number; $Bi_V{}^{conv} << Bi_V{}^{nb}$; $\overline{T}_{sf}$ is average surface temperature; $\overline{T}_V$ is average volume temperature; T_m is bath temperature.

Assume that at the beginning of cooling the surface temperature of the probe drops below the saturation temperature T_s providing condition $Bi_V{}^{conv} << Bi_V{}^{nb}$ or $Bi_V \to 0$. In this case surface temperature $T_{sf} \to T_V$. It means, when the surface temperature at the beginning of quenching is below saturation T_s, that surface temperature T_{sf} must increase immediately to satisfy Eq. (3). However, when surface temperature during initial process of quenching is significantly larger the saturation temperature T_s, the generalized Biot number $Bi_V \to \infty$ because overheating of a boundary layer provides extremely large heat transfer coefficient during transient nucleate boiling. It means that $T_{sf} \to T_m$.

So, surface temperature at the beginning of quenching should be very close to saturation temperature and should maintain at this level until heat flux density at the end of nucleate boiling process is equal heat flux density at the beginning of convection. Thus, the self – regulated thermal process (SRTP) is transient nucleate boiling when surface temperature of a solid sample maintains relatively a long time at the level of boiling point of a liquid. This regularity is very useful for the practice. The self – regulated thermal process (SRTP) consists of two phase: its establishing and developed transient nucleate boiling process. According to French [12], time of establishing SRTP is almost the same for different sizes and forms of steel components (see Table 1) and its duration is 1 – 2 seconds if any film boiling is completely absent.

Table 1: Time required for the surface of steel spheres of different sizes to cool to different temperatures when quenched from 875 ºC in 5 % water solution of NaOH at 20 ºC agitated with 0.914 m/s (French, 1930) [3].

Size, Inches, (mm)			Time, sec					
	700ºC	600ºC	500ºC	400ºC	300ºC	250ºC	200ºC	150ºC
0.25" (6.35)	0.027	0.037	0.043	0.051	0.09	0.15	0.29	0.69
0.5" (12.7)	0.028	0.042	0.058	0.071	0.11	0.15	0.26	0.60
4.75" (120.6)	0.043	0.066	0.09	0.12	0.17	0.21	0.29	0.95
7.15" (181.6)	0.040	0.070	0.100	0.140	0.240	0.310	0.42	1.15
11.25" (285.8)	0.043	0.120	0.190	0.330	0.570	0.960	1.26	2.18

Note that from experimental data of French one can get heat transfer coefficients (HTCs) up to 200 kW/m²K [10].

As known, a nanofluid contains nanometer-sized particles which create colloidal suspensions of nanoparticles of metals, oxides, carbides, or carbon nanotubes in a base fluid such as water, ethylene glycol and oil [13]. They can be used to optimize heat transfer during convection and maximize critical heat flux densities and cannot be used to affect visibly self – regulated thermal process without changing convective heat transfer coefficient. When film boiling is absent, the duration of transient nucleate boiling process τ_{nb} is determined by generalized equation (4) which was proposed by author [14, 15]:

$$\tau_{nb} = \Omega k_F \frac{D^2}{a} \tag{4}$$

Eq. (4) includes Ω that depends on convective Biot number Bi_{conv}, value β that includes physical properties of a liquid responsible for nucleate boiling process, heating and bath temperatures and is rather complicated function (5):

$$\Omega = f\left(Bi_{conv}, T_o, T_m, \beta\right) \tag{5}$$

Author [15] investigated effect of value β on duration of transient nucleate boiling process and came to conclusion that expected effect is miserable which can be neglected with an error of $\pm$ 1.3% when value β changes within $3 \le \beta \le 7.36$. The value β depends on many physical properties of a liquid which can affect essentially nucleate boiling process (see Eq. (6)):

$$\beta = \frac{75\lambda\left(\rho' - \rho''\right)^{0.5} g^{0.5}}{\sigma^{0.5}\left(\rho'' r^* W''\right)^{0.7} Pr^{0.2}} \tag{6}$$

If hardening process is performed under pressure, the vapor bubble growth rate W'' is evaluated by Eq. (7) [16]:

$$\frac{W''}{W''_{0.1}} = \left(\frac{\rho''_{0.1}}{\rho''}\right)^{2.3+0.5 lg \frac{P}{P_{cr}}} \tag{7}$$

The question is. Why so many parameters don't affect duration of transient nucleate boiling process? The matter is that nucleate boiling in water provides condition $Bi \to \infty$. Additional increase HTC during nucleate boiling doesn't increase cooling rate of steel parts. The same conclusion is true when calculating duration of transient nucleate boiling process using Eq. (8) and Eq. (9) [15]:

$$\vartheta_I = \frac{1}{\beta}\left[\frac{2\lambda\left(\vartheta_o - \vartheta_I\right)}{R}\right]^{0.3} \tag{8}$$

$$\vartheta_{II} = \frac{1}{\beta}\left[\alpha_{conv}\left(\vartheta_{II} + \vartheta_{uh}\right)\right]^{0.3} \tag{9}$$

Here $\vartheta_o = T_o - T_s$; $\vartheta_I = T_I - T_s$; $\vartheta_{II} = T_{II} - T_s$; $\vartheta_{uh} = T_s - T_m$.

More information on this subject is provided in recently published paper [15].

4. Temperature Field Calculation Based on Self – Regulated Thermal Process

Using knowledge on transient nucleate boiling process (see Eq. (4) – Eq. (9), it is possible to calculate temperature field in quenched steel probe. For this purpose experimental data of French (see Table 1) are used in the interval of time 0 – 2 seconds. Then duration of self – regulated thermal process is calculated using Eq. (4). Both results are used for reconstruction surface temperature and creating the first type of boundary condition as shown in Fig. 2.
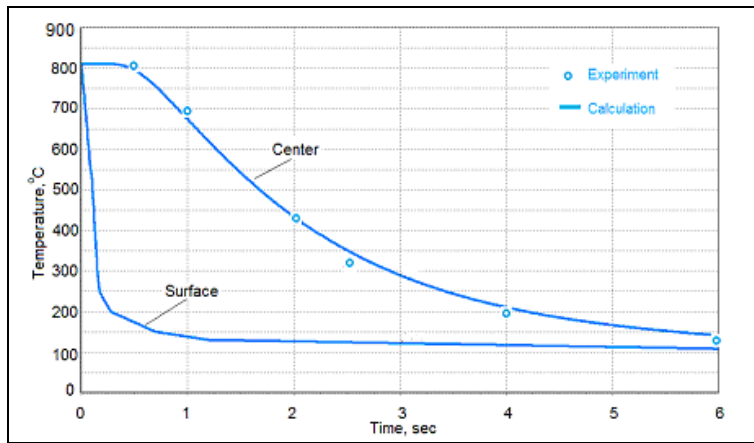
Fig 2: Cooling curves versus time during quenching under normal pressure the cylindrical probe 12 mm in diameter and 80 mm length in water at 20ºC. Core temperature at the end of nucleate boiling is 148ºC.

Since probes or steel parts are heated through to thermal equilibrium T_o, the initial condition is taken as

$$T(r,0) = T_o \qquad (10)$$

Numerical calculation of a core cooling curve for cylindrical probe 12 mm in diameter, using the first kind of boundary condition, is shown in Fig. 2. Results of calculations were compared with the results of experiments which were carried out with the cylindrical probe shown in Fig. 3.
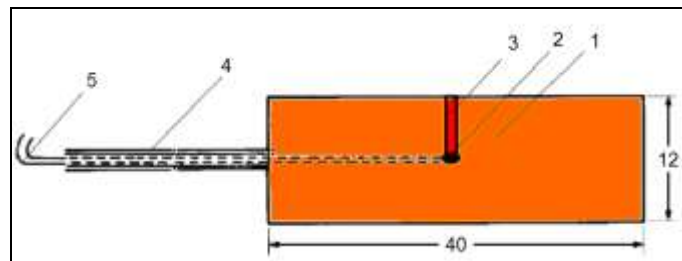

Fig 3: A probe made of AISI 304 steel for obtaining accurate data on core cooling curves and core cooling rate curves: 1 is probe; 2 is thermocouple; 3 is a pin to press velded thermocouple; 4 is tube; 5 are xromel and alumel wires

For the first time, quenching process in liquid media under pressure was investigated in 1980 by author [13] using stainless cylindrical probe 20 mm in diameter with the thin thermocouple instrumented on the middle surface of the probe. The results of careful investigations are presented in

Fig. 4. As seen from Fig. 4, surface temperature during transient nucleate boiling process can be governed by adjustment pressure that increases saturation temperature of a liquid (see Table 2).
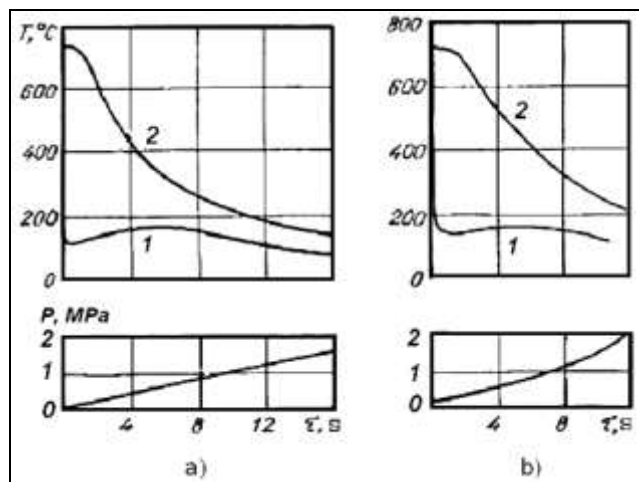

Fig 4: Effect of variable pressure P on surface temperature during quenching 20-mm-diameter cylindrical probe, made of AISI 304 steel, in water at 20ºC [5]: a, numerical calculation; b, experiment; 1, at the surface; 2, at a point a distance of 6.2 mm from the center.

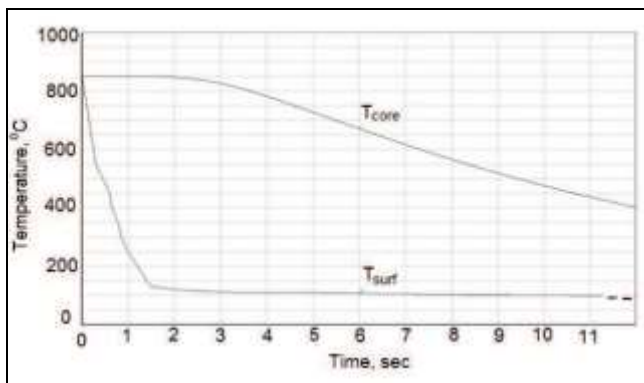**Table 2:** Water saturation temperature Tₛ versus pressure P.

P, MPa	Tₛ, ºC
0.1	100
0.2	120.2
0.3	133.5
0.4	143.6
0.5	151.8
0.6	158.8
0.7	165
0.8	170.4
0.9	175.4
1.0	180
2.0	212.4

By adjusting pressure, it is possible to delay martensitic transformation during self – regulated thermal process for high carbon steels with the martensite start temperature $M_S \leq 200^o C$. Martensite start temperature M_S and martensite finish temperature M_F versus carbon concentration in steel are provided in Table 3.

Table 3: Martensite start temperature Mₛ and finish temperature M_f versus amount of carbon in steel (%, wt) [5].

Carbon, %, wt	0.20	0.40	0.60	0.80	0.90	1.2	1.8
M_S, ºC.	430	350	300	260	250	180	60
M_F, ºC.		350	110	0	- 80	- 90	- 110	- 120

To check existence the self – regulated thermal process during quenching, in 2011 accurate experiments were carried out in Idemitsu lab (Japan) which were published in Ref [17].

Fig 5: Cooling curves obtained in Idemitsu Kosan Co., Ltd. Lab (Japan) for cylindrical specimen of 28 mm diameter and 112 mm length when quenching in water flow of 1.5 m/s at 20 º C [17].

Theoretical background of the transient nucleate boiling and experimental data support the idea that surface temperature during nucleate boiling can be considered as:

$$T_{sf} = T_s + \Delta \overline{\xi} \approx const \qquad (11)$$

Here T_{sf} is surface temperature of probe or steel part during transient nucleate boiling process; T_s is saturation temperature of a liquid; $\Delta \overline{\xi}$ is average superheat of a liquid

in the boundary layer within the interval of nucleate boiling process.

Accurate experimental data presented in Fig. 5 support the idea on existence of SMTP which is very important for the practice.

5. Austempering process via cold liquids

Austempering process via cold liquid can be performed exploring existing equipment used for performing IQ- 2 processes (see Fig. 6) [10].

Fig 6: Integral quench atmosphere furnace equipped with 41 m3 IQ water tank built by AFC-Holcroft and installed at Euclid heat treating Co [10].

Fig. 6 presents a picture of the atmosphere integral quench 91×91×183 cm furnace equipped with a 41 m3 IQ water tank and installed at Euclid Heat Treating Co. of Cleveland, Ohio, USA. The furnace is equipped with an intermediate chamber connecting the heating chamber with the IQ tank to ensure that quenchant vapor does not contaminate the furnace atmosphere. The furnace atmosphere enters the intermediate chamber through two openings in the furnace door and leaves through the vent. The IQ tank is equipped with four propellers rotated by four powerful motors and with a loading unloading mechanism that provides a very fast introduction of the load into the quench tank and removal of the load from the tank. The loading/unloading time is within about two or three seconds regardless of the load weight, which ensures a small difference in cooling times between the lower and upperlayers of the load.

The austempering process via cold liquid for cylindrical steel sample 80 mm in diameter and 80 mm length made of high carbon steel with martensite start temperature 100ºC is performed as follows:

- First, one should calculate duration of transient nucleate boiling using Eq. (4) and experimental data of French (see Fig. 7) [12].
- Then calculate initial heat flux density for given steel sample which should be $q_{in} < q_{cr1}$.
- A load should be made with sufficient room between steel samples to prevent overheating a liquid that could result in film boiling process.
- One should cool load for 100 seconds and provide immediate tempering at a temperature that exceeds martemsite start temperature Ms.

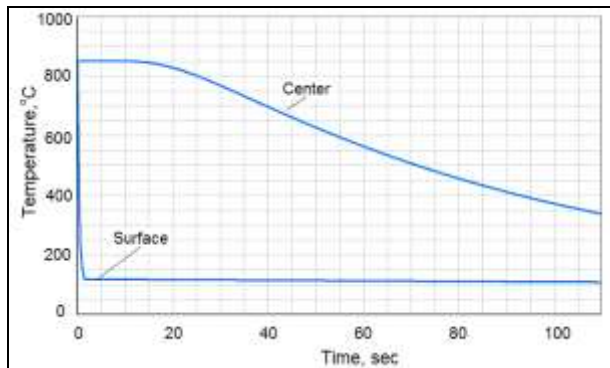Information on bainitic microstructure after tempering depending on time and temperature is available in a book [18].

Fig 7: Cooling curves versus time during quenching under normal pressure the cylindrical probe 80 mm in diameter in 80 mm length in water at 20ºC. Core temperature at the end of nucleate boiling is 337ºC.

Similar calculations are made for different forms and sizes of steel parts.

Austempering via cold liquid is easily performed for relatively simple forms. For complicated forms equipment differs from presented in Fig. 6.

6. Possible Intensive LTMT Process

To understand the idea of low temperature thermo-mechanical treatment (LTMT), let's consider an example of its performing using data of Fig. 8 and quench system shown in Fig. 9. Fig. 9 presents the basic scheme of an automated process for steel heat treatment under controlled pressure. The quenching process is conducted as follows. When the cover is at starting position I, the part (5), which was previously forged, is immediately delivered to the tray (1). At this time, the driving mechanism is turned on, and the cover occupies work position II, hermetically closing the top of the quench tank. Simultaneously, through an aperture (2), compressed air is introduced, creating the necessary pressure between the quenchant and the cover. Pressure is delivered so that the quenchant saturation temperature is equal to martensite start temperature M_S. When quenching in water under pressure, there is a delay in the transformation of austenite into martensite during nucleate boiling. Quench cracks under these conditions are not formed. Let's consider an example of LTMT quench process which can be easily performed in forging shops. Assume that the cylindrical specimen 80 mm in diameter and 80 mm length was already prepared by forging using high temperature thermomechanical treatment (HTMT) with 30% deformation at a temperature 925ºC in forging shop. The sample was made from steel containing 1.2% carbon. Martensite start temperature for steel containing 1.2% carbon is 170ºC plus overheating of the boundary layer (see Table 4). To prevent completely transformation austenite into martensite, pressure in the system should be 0.8 MPa (see Fig. 7 and Tables 2, 3)). Overheating at the beginning of transient nucleate boiling process for specimen 80 mm in diameter and 80 mm length is evaluated using equation (8) and is equal to 17ºC. Overheating 8.3ºC of the boundary layer at the end of transient nucleate boiling process is evaluated using appropriate convective heat transfer coefficient (see Table 4

and Eq. (9)): $\vartheta_{II} = \dfrac{1}{3.41}\left[790\left(\vartheta_{II} + 80\right)\right]^{0.3} = 8.3^{o}\,C$.

Table 4: Convective HTCs versus pressure (MPa) and temperature of water [10]

P, Mpa	Water 10ºC, W/m² K	Water 20ºC, W/m² K	Water 30ºC, W/m² K
0.1	548	640	1015
0.2	586	690	1105
0.3	609	719	1156
0.4	625	740	1196
0.5	638	756	1223
0.6	648	769	1246
0.7	657	780	1265
0.8	664	790	1280
0.9	670	798	1295
1.0	677	806	1310

Duration of transient nucleate boiling process for specimen 80 mm in diameter and 80 mm length, when convective heat transfer coefficient is equal 790 W/m²K and pressure is 0.8 MPa, is equal to 100 seconds [5]. Taking into account these data and experimental data of French (see Table 1), the first kind of the boundary condition was constructed (see Table 5).

Table 5: Surface temperature versus time during quenching cylindrical probe 80 mm in diameter and 80 mm length in cold water (20ºC) under pressure 0.8 MPa.

Time, s	0	0.1	0.16	0.3	0.6	1.5	100
Temperature, ºC	850	400	300	250	200	187	178.3

Numerical calculation of core temperature versus time during quenching cylindrical probe 80 mm in diameter and 80 mm length in cold water (20ºC) under pressure 0.8 MPa, when using the first kind of boundary condition provided in Table 5, is presented in Fig. 8. When core temperature of the cylindrical probe during intense quenching probe in quench system (see Fig. 9) become 500ºC, process of cooling is interrupted and cylindrical probe is delivered to press machine for making round plate of 15 mm in thickness. Such thermomechanical process is designated as LTMT that increases significantly strength and plastic properties of material. For other geometrical forms, some data are presented inTable 6.
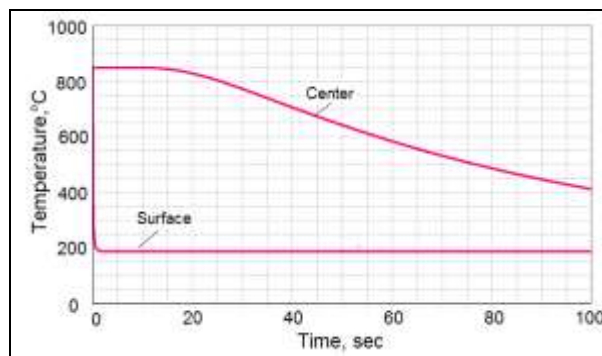

Fig 8: Surface and core temperatures versus time during quenching cylindrical probe 80 mm in diameter and 80 mm length in cold water (20ºC) under pressure 0.8 MPa.
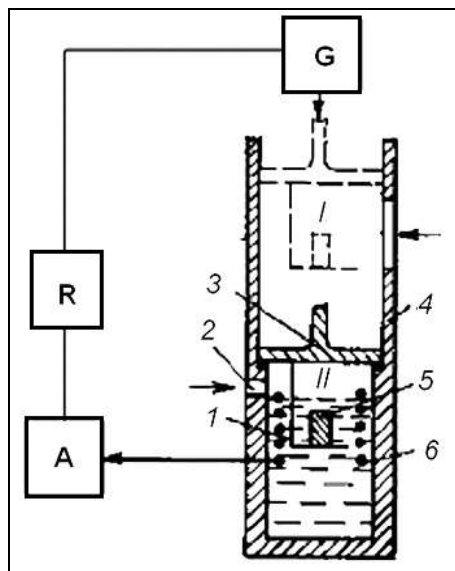
Fig 9: Basic scheme of the automated process of steel quenching in water and aqueous solutions under pressure: 1, tray; 2, aperture for pumping in compressed air; 3, mobile piston (cover); 4, case of the quench tank; 5, the part to be quenched; 6, solenoid for fixing the initial time of transformation of austenite into martensite; A, the amplifier of a signal of the martensite start; R, relay of current; G, driving mechanism; I, starting position; II, work position [5,10].

Table 6: Duration of transient nucleate boiling process τ_{nb} and core temperature of steel parts at the end nucleate boiling for different geometrical forms as the dependence of the liquid overheating ϑ_I and Kondrat'ev form coefficient K.

Form and size of probe in mm	K, m²	ϑ_I, oC	τ_{nb}, s	Temperature at the end of NB, oC
Plate, L= 20 L= 40 L=80	40.52×10^{-6} 162.8×10^{-6} 648.32×10^{-6}	26.6 21.6 17.6	33.2 112.6 371	150 168 200
Cylinder, D = 20, Z = 80 D = 40, Z = 160 D = 80, Z = 320	16.84×10^{-6} 67.36×10^{-6} 269.4×10^{-6}	26.6 21.6 17.6	11 46.5 152	200 210 235
Cylinder, D = 80, Z = 80	193.9×10^{-6}	17.6	111	334
Cube, L = 80	216.2×10^{-6}	17.6	114	290
Sphere, D = 80	162.1×10^{-6}	17.6	90	260

Results of calculations were validated with the experiments published in the books [5, 10].
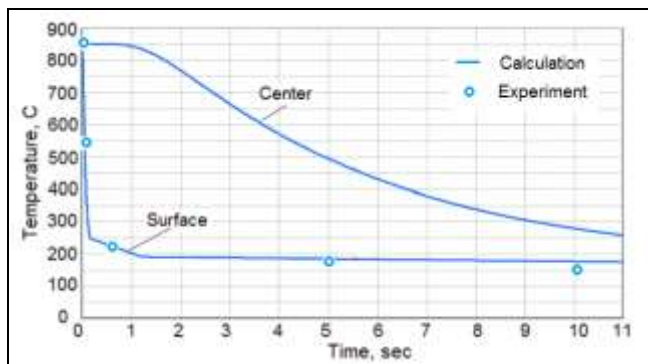

Fig 10: Cooling curves versus time during quenching under pressure 0.7 MPa for cylindrical probe 20 mm in diameter in water at 20ºC. Core temperature at the end of nucleate boiling is 258ºC.

As one can see from Fig. 10, results of calculations coincide very well with the results of experiment that makes simplified method of calculation acceptable.

7. Accelerated cooling within the martensite range
Accelerated cooling within the martensite range is performed during cryogenic treatment to obtain super – strengthened materials [5]. Usually, it is two step quenching. At the first step steel components are cooled in cold liquid and then after self – regulated thermal process is finished steel components or tools go for cryogenic treatment. Cooling rate v is calculated by Eq. (12) [5]:

$$v = \frac{aKn}{K}(T - T_m) \tag{12}$$

Author [18] established relationship between effective Kondrat'ev dimensionless number Kn versus form and size of steel components which is used for cooling time calculation (see Fig.11) [18].
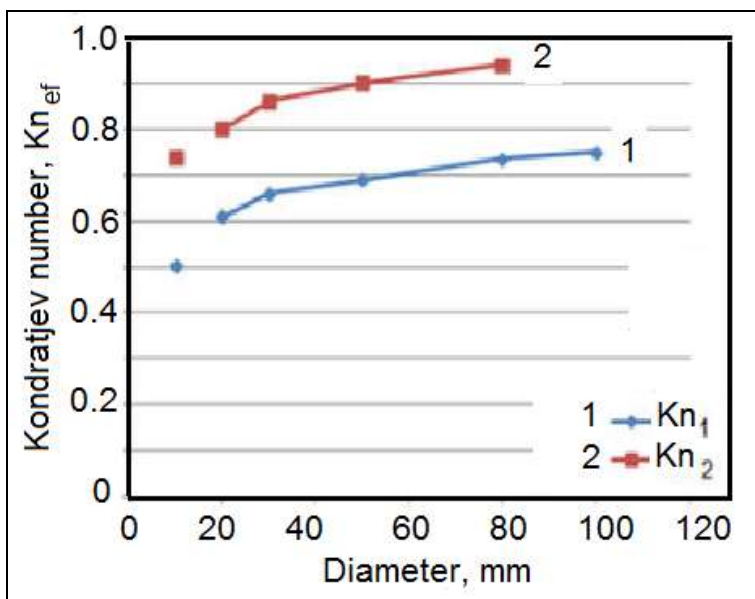
Fig 11: Effective Kondratjev number Kn versus diameter of cylindrical probes made of AISI 304 steel when quenching in 8 % water solution of NaNO3 at 20 oC: 1 – quenching in still solution; 2 – quenching in solution flow 1.5 m/s [18].

Kondrat'ev numbers Kn for cryogenic treatment can be evaluated using Table 7 [19].

Table 7: Heat transfer coefficient (HTC) in W/m^{2}K depending on state of cooling medium [19].

Cooling medium	Temperature of medium. ºC	Cooling condition	Frequency of vibration. Hz	HTC. W/m^{2}K
Liquid nitrogen	- 196	No vibration	-	160 – 230
Liquid nitrogen and vapor	- 196	Vibromixing	72	331 – 532
Liquid nitrogen and vapor of helium	- 196	Vibromixing	72	334 – 544
Water and air	20	Vibromixing	60 – 70	5890 – 8640

Table 8 allows prediction hardness at the core of cylindrical steel parts based on cooling rate measured at a temperature 700ºC [20].

Table 8: Core cooling rate at 700ºC and 200ºC vs diameter of cylindrical probe when performing one step cooling in vibromixing water and two step cooling in water solution and then in vibromixing nitrogen.

Cooling condition	Diameter of probe in mm	Cooling rate at 700ºC, ºC/s	Cooling rate at 100ºC, ºC/s
Two step cooling (water solution + still liquid nitrogen)	10	408	6.14
	20	122	3
	30	59	2
Two step cooling (water solution + vibromixing liquid nitrogen)	10	408	14.2
	20	122	7.5
	30	59	5
	40	34	3.5
Two step cooling (oil + vibromixing liquid nitrogen)	10	82	14.2
	20	38	7.5
	30	24	5
Water at 20ºC	10	408	6.4
	20	122	3
	30	59	1

More information concerning recipes development during quenching of steel parts in liquid media one can find in the literature [5, 20].

8. Discussion

As known, two main characteristics of transient nucleate boiling process, presented by equations (4) and (10), can be considered as the basis for development many new technologies and new methods for their control. The main of them are:

- The IQ – 2 technological process (two or three step cooling) that explores transient nucleate boiling to allow complete not more than 50% transformation from austenite to martensite at the first step of cooling. This measure prevents quench crack formation during intense cooling and decreases distortion of steel parts during quenching [5, 10].

- The IQ – 3 intensive technology which is performed without developed nucleate boiling process. To establish such process, Eq. (4) is used for condition $Bi \rightarrow \infty$ when $\Omega \rightarrow 0$ [5, 10].

- The austempering process via cold liquids that cardinally extends sizes of steel parts suitable for austempering procedure and improves environment condition due to eliminating melted alkalis as a coolant used for obtaining fine bainitic microstructure [21, 22].

- The cryogenic two step quenching that delays martensite transformation at the first step to allow vigorous martensite transformation within the second step in

cryogenic media [10].

- The high temperature thermomechanical treatment (HTMT) exploring intensive quenching which is called direct immediate intensive quenching after forging and is known as (DFIQ) process [23].
- The low temperature thermomechanical treatment (LTMT) exploring intensive quenching which allow significantly improve strength of materials and their plastic properties [24, 27].
- Combined HTMT and LTMT intensive processes that allow cardinally improve strength and plastic properties of plain carbon and alloy steels [27].
- Method for controlling quality of intensive quenching process that explores Eq. (4) as the ideal intensive and uniform cooling [28].

Some achievements concerning improvement of strength and plastic properties of materials are shown in Table 7 - Table 10.

Table 9: Mechanical properties of AISI 1040 steel after heavy rolling in the case of HTMT treatment and 200ºC tempering [24, 25].

Technology	R_m (MPa)	$R_{p0.2}$ (MPa)	A (%)	Z (%)	a_k (J/cm²)
HTMT	1972	1570	7	40	35
Conventional	1422	1246	2	16	30

Table 10: Mechanical properties of AISI 1040 steel after direct forging intense quenching (DFIQ) and conventional multistage heat treatment via oil [23].

Technology	R_m (Ksi)	$R_{p0.2}$ (Ksi)	A (%)	Z (%)	a_k (J/cm²)
DFIQ	266	235	10	40	11
Oil quenching	252	220	10	26	5

Table 11: Mechanical properties of AISI 9260 steel after two step cryogenic treatment [5].

Technology	R_m (MPa)	$R_{p0.2}$ (MPa)	A (%)	Z (%)
Cryogenic treatment	1920	1740	4	26
Conventional treatment	1580	1410	7	38

Table 12: The improvement in wear for various tool steels after deep cold treatment [28].

Steel (AISI)	Improvement in wear rate (%)
D2	817
S7	503
52100	420
M1	225
H13	209
M2	203

It is underlined in Ref [5, 10]. that delaying martensite transformation at the first step of cryogenic treatment increases significantly strength and plastic properties of steel.

Two and three step intensive quenching technologies are innovative and belong to high-tech technique that require complete automation of technological processes and significant reduce the cost of currently used expensive equipment. Small enterprises are not willing and sometimes are not able to invest funding into further development of intensive quenching processes that is why they'll not able to compete more with those enterprises which are being paid

serious attention to deep knowledge and physics of new technological processes. Below, in glance, are discussed some problem which have to be solved in the nearest future.

The first important problem is the theoretical support of an idea on possibility to eliminate completely film boiling process during quenching in cold liquid media without use of powerful and costly pumps and powerful rotating impellers for agitation of liquids to fight film boiling processes. Such support goes from solving hyperbolic heat conductivity equations instead of parabolic which always predict quenching path as: film boiling – nucleate boiling - convection. From hyperbolic heat conductivity equation follows that initial heat flux density is final value which in many cases is below q_{cr1} providing absence of film boiling during quenching steel in cold liquids. There are many solutions of hyperbolic heat conductivity equations, however they are so complicated that even authors of solutions require help of smart engineers to create special software to get from their solutions the useful data for heat treating processes. This problem requires further development.

The second important problem is experimental investigation and evaluation the critical heat flux densities needed for predicting and then eliminating any film boiling processes during quenching metal components in cold liquid media. Nowadays, many investigators are paying attention to the possibility of increasing heat transfer during transient nucleate boiling process when quenching steel parts in water, water solutions and different kinds of suspensions, sometimes called nanofluids, without considering critical heat flux densities at all. They believe that increase of heat transfer coefficients during nucleate boiling can increase cooling rate during hardening process. However, in recently published paper[15] is shown that duration of transient nucleate boiling cannot be affected by changing physical properties of liquid because nucleate boiling itself during quenching in water is intensive and creates condition $Bi \to \infty$. Further increase of heat transfer coefficient cannot add something to increase cooling rate of steel parts. Thus, the critical heat flux densities are priority number one to optimize effectively and correctly intensive quenching processes. There is a lack of such published data concerning quenching processes, especially effecting double electrical layer to increase critical heat flux densities. Serious attention should be paid to this very important problem.

The third important for the practice problem is sufficient control of quenching processes since without controlling them is impossible to design automated system. As discussed in literature, for this purpose appropriate sonar system can be used [29]. However, existing sonar system cannot filter intense noise produced by powerful pumps and propellers. To solve this problem, hydrodynamics emitters were proposed to use instead of propellers to eliminate noise and more effectively destroy film boiling processes [30]. However, hydrodynamic emitters require knowledge in their design and sufficient tests in the practice. There are several more problem to be solved, but above discussed have to be solved in the nearest future.

As seen from above consideration, initial quenching processes are not deeply and widely investigated yet and some problem arises when evaluating initial HTCs and initial heat

flux densities. As known, prior to start transient nucleate boiling process, cold liquid must be heated to saturation temperature and then boundary liquid layer must be overheated to start generation of vapor bubbles. This process before nucleate boiling is very short and, according to French, it lasts 1 – 1.5 sec independently on size and form of quenched probe (see Table 1). Since of heat distribution is final value and process is very short, very thin hardened layer appear at the beginning of cooling which can be considered as a thin unbounded plate for all sizes and classical forms. That is why initial cooling curves are similar as shown in Table 1. That is true when film boiling during quenching is completely absent. Due to these facts, recommendations are below suggested to simplify cooling recipes development. They are as follows:

▪ Create the first kind of boundary condition within austenitizing and start boiling temperature using valuable experimental data of French.
▪ Calculate duration of transient nucleate boiling process depending on size and form of steel part using law of transient nucleate boiling mode using Eq. (4).
▪ Calculate core temperature of steel part at the end of transient nucleate boiling process and begging of convection.
▪ Calculate cooling time within the transient nucleate boiling process and convection zone.
▪ Summarize obtained data and use them for recipes development.

Some useful conclusions are presented below.

9. Conclusions

1. When any film boiling during quenching in still water is completely absent, process of cooling is intensive due to intense acting thousands of vapor bubbles during nucleate boiling that provides HTCs up to 200 kW/m²K. It is impossible to affect cooling rate during transient nucleate boiling process by adding to water special additives or nanoparticles because cooling is already intensive providing condition $Bi \rightarrow \infty$. The main attention here should be paid to maximizing critical heat flux densities adding to Aliquid special additives or nanoparticles which must essentially increase the first critical heat flux density or decrease initial heat flux density. Low concentration of PAG in water creates thin insulating surface layer during quenching that drops initial heat flux density below its critical value eliminating completely film boiling [6]. It makes sense also to use hydrodynamic emitters during batch quenching in liquid media to destroy any film boiling providing resonance wave effect related to film boiling oscillation process.

2. When any film boiling is absent, the self – regulated thermal process establishes that maintains surface temperature of steel parts at the level of boiling point of a liquid. To perform austempering process via cold liquid one should increase surface temperature of steel components during self – regulated thermal process to martensite start temperature using pressure or other possible measures like changing concentration of water salt solutions or creating surface polymeric insulating

layer of optimal thickness[7].

3. The self – regulated thermal process can be used for developing new intensive technologies called low temperature thermo-mechanical treatment which eliminates melted salts and alkalis, and improves environmental condition. Delaying martensite transformation at the first step of quenching and acceleration cooling rate during its transformation at the second step cardinally improves cryogenic treatment.

4. Further careful investigation of self – regulated thermal processes taking place during quenching complicated steel parts in liquid media can make IQ processes as a mass production, simplifying technological processes and reduce their cost.

Nomenclature

A Elongation in %

a Thermal diffusivity of solid material in m²/s

a' Thermal diffusivity of liquid in m²/s

a_k Impact strength in J/cm²

Bi Biot number

Bi_V Generalized Biot number

D Diameter or thickness in m

Kn Kondrat'ev dimensionless number

K Kondrat'ev form factor in m²

k_F Dimensionless form coefficient

P Pressure in MPa

P_{cr} Critical pressure in MPa

Pr Prandtl number

R Radius in m

R_m Ultimate strength in MPa

$R_{p0.2}$ Yield strength in MPa

S Surface in m^2

T Temperature in °C

T_o Initial austenitizing temperature in °C

T_s Saturation temperature in °C

T_m Bath temperature in °C

$\overline{T}_{sf}$ Average surface temperature

$\overline{T}_V$ Average volume temperature

V Volume in m^3

W'' Vapor bubble growth rate in m/s at a given pressure

Z Contraction in %

Z, L Length in m

α Heat transfer coefficient in W/m²K

β Parameter depending on physical properties of liquid

λ Thermal conductivity of solid material in W/mK

λ' Thermal conductivity of a liquid in W/mK

ρ' Liquid density in kg/m^3

ρ'' Vapor density in kg/m^3

ϑ_I Superheat at the beginning of the boiling process

ϑ_{II} Superheat at the end of the boiling process

σ Surface tension in N/m

v Cooling rate in ^{o}C/s

Ω Parameter depending on convective Biot number, initial and bath temperature

d_o Diameter of a bubble in m

f Frequency of a bubble departure in Hz

$r^\bullet$ Latent heat of evaporation in J/kg

r Coordinate in m

g Gravitational acceleration in m/s^2

References

1. Nozdrev BF, Senkevich AA. Course of Statistical Physics. Vysshaya Shkola, Moscow, 1969.
2. Kobasko NI. Effect of free electrons in steel on its quenching process in water and water salt solutions. EUREKA: Physics and Engineering, 2018, 1:39-46. DOI: 10.21303/2461-4262.2018.00529
3. Frenkel YaI. Kinetic Theory of Liquids. Nauka, Leningrad, 1975.
4. Fedorov VI, Kovalenko GV, Kostanchuk DM. Boiling of fluid on a metal surface. Journal of Engineering Physics. 1977; 32(1):10-14. DOI: 10.1007/bf00860120.
5. Kobasko NI. Steel Quenching in Liquid Media under Pressure. Naukova Dumka, Kyiv, 1980.
6. Kobasko NI. Uniform and Intense Cooling During Hardening Steel in Low Concentration of Water Polymer Solutions. American Journal of Modern Physics. 2019; 8(6):76-85. DOI: 10.11648/j.ajmp.20190806.11.
7. Kobasko NI. Uniform and Intense Cooling During Hardening Steel in Low Concentration of Water Polymer Solutions. Ibtissem BELGACEM, Prime Archives in Physics. Vide Leaf, Hyderabad, India, 2020.
8. Wikipedia. https://en.wikipedia.org/wiki/Austempering
9. Kobasko N. Austempering processes that are performed via cold liquids. Lambert Academic Publishing, Germany, 2019. ISBN: 978-620-0-11330-6.
10. Kobasko NI, Aronov MA, Powell JA, Totten GE. Intensive Quenching Systems: Engineering and Design. ASTM International, W. Conshohocken, USA, 2010.
11. Kondrat'ev GM, Teplovye Izmereniya. (Thermal Measurements). Mashgiz, Moscow, 1957.
12. French HJ. The Quenching of Steels. American Society for Steel Treating, Cleveland, Ohio, USA, 1930.
13. Totten GE, Bates CE, Clinton MA. Handbook of Quenchants and Quenching Technology. ASM International, Materials Park, OH, USA, 1993.
14. Kobasko NI. Self - Regulated Thermal Processes During Quenching of Steels in Liquid Media. International Journal of Microstructure and Materials Properties. 2005; 1(1):110-125.
15. Kobasko NI. Intensive Quenching Technology Accuracy Analysis Based on Study Physics of Transient Nucleate Boiling Process. SSRG International Journal of Applied Physics. 2020; 7(1):27-35. DOI: 10.14445/23500301/IJAP-V7I1P105.
16. Tolubinsky VI. Heat Transfer at Boiling. Naukova Dumka, Kyiv, 1980.
17. Kobasko NI, Aronov MA, Ichitani K, Hasegawa M, Noguchi K. High compressive residual stresses in through hardened steel parts as a function of Biot number. Resent Advances in Fluid Mechanics, Heat & Mass Transfer and Biology. WSEAS Press, Harvard, 2012, 36-40. ISBN: 978-1-61804-065-7.
18. Kobasko N. Cooling intensity of inverse solubility polyalkylene glykol polymers and some results of investigations focused on minimizing distortion of metal components. EUREKA: Physics and Engineering. 2017; (1):55-62. DOI: 10.21303/2461-4262.2017.00294
19. Ganiev RF, Kobasko NI, Kulik VV, et al., Oscillation Phenomena in Multi-Phase Media and Their Use in Technology. Tekhnika, Kyiv, 1980.
20. Kobasko Nikolai, Guseynov Sharif, Rimshans Janis. Core Hardness and Microstructure Prediction in Any Steel Part. Lambert Academic Publishing, Germany, 2019, 94. ISBN: 978-613-9-94751-5.
21. Bhadeshia HKDH. Bainite in Steels: Theory and Practice. 3rd Edition. Money Publishing, 2015.
22. Kobasko NI. Isothermal Method for Hardening of High Carbon Steels and Irons. UA Patent No. 109935, 2015.
23. Aronov MA, Powell JA. Forging Process Improvement Using Intensive Quenching Immediately After Forging Operations are Completed. Proceedings of Forging Technical Conference, Columbus, Ohio, 2016.
24. Bernshtein ML. Thermomechanical Treatment of Metals and Alloys. Moscow: Metallurgiya, Vol. 1, 1968.
25. Bernshtein ML. Thermomechanical Treatment of Metals and Alloys. Metallurgiya, Moscow, Vol. 2, 1968.
26. Tamura Imao, Sekine Hiroshi, Tanaka Tomo. Thermomechanical Processing of High - Strength Steels, First Edition. Butterworth - Heinemann, London, 1988.
27. Kobasko NI. Thermal and Metallurgical Basics of Design of High-Strength Steels. Intensive Quenching Systems: Engineering and Design, Kobasko NI, Aronov MA, Powell JA, Totten GE (Eds.). ASTM International, W. Conshohocken, USA, 2010, 1-23.
28. Stratton PF. Process optimization for deep cold treatment of tool steels. Proc. of the 1st International Conference on Heat Treatment and Surface Engineering of Tools and Dies. Pula, Croatia, June 8 – 11, 2005.
29. Povsten SG, Kobasko NI, Moskalenko AA, Tyltin AA. On the Use of Monitoring Noise Effects for Realization of New Steel Quenching Methods. Proc. of the 7th International Congress on Heat Treatment, Moscow, December 11–14, 1990.
30. Kobasko NI. Intensive Hardening Method for Metal Components. UA Patent No. 109572, 2015. Filed: 07.10.2013. Bull. No. 17.