Intensive Quenching Technology Accuracy Analysis Based on Study Physics of Transient Nucleate Boiling Process

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Abstract: *Three versions of intensive quenching technologies and accuracy of their performing are discussed in this paper. The first version explores water salt solutions of optimal concentration as a quenchant with the low or moderate agitation. The second version explores cold water or water salt solutions of optimal concentration agitated by very powerful pumps or high-efficiency rotating impellers. The new third version of intensive quenching explores low concentration of water polymer solutions of inverse solubility that creates insulating surface layer during quenching of steel components. The insulating surface layer drops initial heat flux density during quenching below its critical value and by such a way eliminates effectively film boiling process making quenching very intensive. Instead of powerful pumps or high-efficiency rotating impellers, the low or moderate agitation of quenchant, preferably by hydrodynamic emitters, is used combined with exploring optimal hardenability steel. It is shown in the paper that intensity of cooling in low concentration of water polymer solutions are similar to intensity of cooling in water salt solutions of optimal concentration where cooling process is intensive. New third version of technology is very simple, however it requires the high density of knowledge on quenching process in low concentration of water polymer (PAG) solution and also requires intensive process interruption at proper time. During batch quenching in low concentration of water polymer solutions, the resonance effect can be used for eliminating film boiling process. The new technology saves materials, increases service life of hardened components and makes environment green.*

I. INTRODUCTION

As known, all three versions of intensive quenching technologies are connected directly or indirectly with the duration of transient nucleate boiling mode which is often called the self – regulating thermal process (SRTP) when surface of quenched steel parts maintains at the level of boiling point of a liquid [1]. The notion SRTP simplifies significantly cooling recipes development and is a basis for cardinally new technology which is called austempering process via cold liquids [2]. However, there are no data on such simplified approach in heat treating industry. Without knowing the accuracy of calculations based on notion of self – regulating thermal process, often doubts appear and engineers will not know how correctly the technological process is performed. Especially, that is true when performing IQ – 2 technology. The IQ - 2 technique is a three-step quenching process that initially cools under the nucleate boiling mode and then the convection heat transfer mode [3]. The duration of transient nucleate boiling process (SRTP) and its accuracy of calculation are vitally important for engineers. That is why, along with discussion of the third version of intensive quenching technology, the serious attention is paid to accuracy of transient nucleate boiling duration evaluation and surface temperature changing during period of nucleate boiling process (SRTP). Obtained data will be useful for developing cooling recipes to perform correctly the new intensive quenching technologies.

II. TWO MAIN CHARACTERISTICS OF TRANSIENT NUCLEATE BOILING PROCESS

It was established by author (Kobasko, 2009) that duration of transient nucleate boiling process is proportional to square of thickness of steel part, inversely proportional to thermal diffusivity of material, depends on configuration of steel part quenched and cooling characteristics of quenchant if austenitizing and bath temperatures are fixed (see Eq. (1)) [1, 2]:

$$\tau_{nb} = \Omega k_F \frac{D^2}{a} \qquad (1)$$

The surface temperature of steel component during transient nucleate boiling process maintains at the level of boiling point of a liquid (see Eq. (2)) and cannot be below saturation temperature until heat flux density at the end of nucleate boiling process is equal to heat flux density at the beginning of convection.

$$T_s + \Delta\bar{\xi} \approx Const \qquad (2)$$

Also, it has been established by thousands of accurate experiments that transient nucleate boiling process, during cooling heated to high temperature metal in water and different kinds of water solutions, is very intensive cooling due to acting of thousands of vapor bubbles with the high frequency (Tolubinsky, 1980) [4].

Based on these physics characteristics, the new technologies of quenching were developed in last decade. They are:

- Austempering process via cold liquids [2].
- Intensive quenching (IQ – 2) process [3].
- Sonar system for controlling quality of quenching processes (Ukrainian Patent No. 119230).
- Thermal properties of materials evaluation [5], *etc.*

However, accuracy of cooling processes calculation and benefits of new technologies developed were not discussed yet in detail and are of great interest due to their radical simplifying and possibility of material savings and environment condition improvement. This paper discusses the mentioned above issues with the hope of making intensive quenching processes as a mass production in heat treating industry.

Analytical equations for calculating duration of transient nucleate boiling process were received by authors (Kobasko and Zhovnir, 1979; Kobasko, 1980) [6, 7]:

$$\tau_{nb} = \left[0.24k + 3{,}21\ln\frac{\vartheta_I}{\vartheta_{II}}\right]\frac{K}{a} \qquad (3)$$

Here

$$\vartheta_I = \frac{1}{\beta}\left[\frac{2\lambda(\vartheta_o - \vartheta_I)}{R}\right]^{0.3} \qquad (4)$$

$$\vartheta_{II} = \frac{1}{\beta}\left[\alpha_{conv}\left(\vartheta_{II} + \vartheta_{uh}\right)\right]^{0.3} \qquad (5)$$

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

$$\Omega = 0.24k + 3{,}21\ln\frac{\vartheta_I}{\vartheta_{II}} \qquad (7)$$

Kondrat'ev form coefficient K is evaluated analytically (Kondrat'ev, 1954 and 1957) or measured by experiment [8, 9]. Some useful analytical data concerning form coefficient K are provided in Table I.

TABLE I

Kondrat'ev form coefficients K for bodies of a simple configuration (results of analytical solutions)

Shape	**Coefficient K, m^2**	$\frac{S}{V}$, **m^{-1}**	$K\frac{S}{V}$, **m**
Unbounded plate of thickness L	$\frac{L^2}{\pi^2}$	$\frac{2}{L}$	$\frac{2L}{\pi^2}$
Infinite cylinder of radius R	$\frac{R^2}{5.784}$	$\frac{2}{R}$	$0{,}346\,R$
Square infinite prism with equal sides of L	$\frac{L^2}{2\pi^2}$	$\frac{4}{L}$	$\frac{2L}{\pi^2}$
Cylinder of radius R and height Z	$\frac{1}{\frac{5.784}{R^2}+\frac{\pi^2}{Z^2}}$	$\left(\frac{2}{R}+\frac{2}{Z}\right)$	$\frac{2RZ(R+Z)}{5.784Z^2+\pi^2+R^2}$
Finite cylinder, R=Z	$\frac{R^2}{15.65}$	$\frac{4}{R}$	$0.256R$
Finite cylinder 2R=Z	$\frac{R^2}{8.252}$	$\frac{3}{R}$	$0.364R$
Cube with side of L	$\frac{L^2}{3\pi^2}$	$\frac{6}{L}$	$0.203L$
Finite square plate with sides of L_1, L_2, L_3	$\frac{1}{\pi^2\left(\frac{1}{L_1^2}+\frac{1}{L_2^2}+\frac{1}{L_3^2}\right)}$	$\frac{2(L_1L_2+L_1L_3+L_2L_3)}{L_1L_2L_3}$	$\frac{2(L_1L_2+L_1L_3+L_2L_3)L_1L_2L_3}{\pi^2(L_1^2L_2^2+L_1^2L_3^2+L_2^2L_3^2)}$
Sphere	$\frac{R^2}{\pi^2}$	$\frac{3}{R}$	$0.304R$

Kondrat'ev form coefficient K can be rewritten as:

$$K = k_F D^2$$

Taking Eqs (7) and above mentioned coefficient K into account, we get a form $\tau_{nb} = \Omega k_F \frac{D^2}{a}$ which is equal to Eq. (1). New form coefficients k_F are presented in Table II.

TABLE II

Form coefficients k_F for different shapes of steel parts

Form of steel part	k_F
Plate	0.1013
Cylinder	0.0432
Sphere	0.0253
Cube	0.0338
Cylinder, Z = 0.5 D	0.0639
Z = D	0.0303
Z = 2 D	0.0391
Z = 4 D	0.0421
Z = 5 D	0.0425
Round plate, D = 2Z	0.0639
D = 4Z	0.0883
D = 6Z	0.0951
D = 10Z	0.0990
D = 20Z	0.1007

Let's now analyze the accuracy of the value of Ω calculation using equation (7). First of all, let's find out how the value of β affects the duration of transient nucleate boiling process (see Table III).

TABLE III

Duration of transient nucleate boiling τ_{nb} depending on value β when quenching from 850°C cylindrical probe one inch (25.4 mm) in diameter in water or water salt solutions at 20°C.

β	3	4.3	5	7.36
τ_{nb}, s	22.34	22.53	22.72	22.95
ε, %	- 1.3	- 0.46	+ 0.38	+ 1.39

The calculations show that during changing the value β from 3 to 7.36 (2.5 times) the durations of transient nucleate boiling process remains almost the same with the accuracy of $\pm$ 1.3% (see Table III). It means that inner characteristics of nucleate boiling and physical properties of liquid don't affect visibly duration of transient nucleate boiling process. The physical properties of liquids and some inner characteristics of nucleate boiling process are presented in Tables IV – VI, which were used for the value β calculation.

TABLE IV

Inner characteristics of transient nucleate boiling depending on concentration of water salt solutions (Tolubinsky, 1980) [4].

Substance	d_0, mm	f, Hz	W'', m/s
Water	2.5	62	0.155
25 % NaCl solution	2.4	64.5	0.155
29 % Na2CO3 solution	2.4	65	0.156

TABLE V

Surface tension used for time of transient nucleate boiling calculation depending on temperature of water [10].

Temperature, °C	0	10	20	30	40	50
$\sigma \cdot 10^4$,	756.4	741.6	726.9	712.2	696.5	676.9
$\sigma^{0.5}$	0.275	0.272	0.270	0.267	0.264	0.260

TABLE VI

Prandtl number Pr depending on temperature of water [10].

Temperature of water, °C	0	10	20	30	40	50
Pr	13.5	9.45	7.03	5.45	4.36	3.59
$Pr^{0.2}$	1.683	1.567	1.477	1.404	1.342	1.291

III. PROCEDURE FOR CONVECTIVE HTC EVALUATION

The above analysis shows that physical properties of water and water salt solutions don't affect visibly the duration of transient nucleate boiling process. Only convective heat transfer coefficient has essential effect. Taking this information into account, it is very important to have simple and not expensive method for convective heat transfer coefficient (HTC) evaluation. It can be constructed based on existing standard methods of quenchants testing [11 – 13]. As a rule, standard probes are made of Inconel 600 material or stainless steel AISI 304. Their thermal properties are presented in Table VII.

TABLE VII

Thermal properties (thermal diffusivity and thermal conductivity) of Inconel 600 and stainless steel depending on temperature in °C.

Temperature, °C	Inconel 600		Stainless steel AISI 304	
	$a \times 10^{-6}, m^2/s$	$\lambda, W/mK$	$a \times 10^{-6}, m^2/s$	$\lambda, W/mK$

100	3.7	14.2	4.55	17.5
200	4.1	16	4.63	18
250	4.3	16.9	4.66	18.8
300	4.5	17.8	4.7	19.6
400	4.8	19.7	4.95	21
500	5.1	21.7	5.34	23
600	5.4	23.7	5.65	24.8
700	5.6	25.9	5.83	26.3
800	5.8	26.3	6.19	27.8
900	6.0	28	6.55	29.3

In published literature, there is a huge amount of standards cooling rate and cooling temperature curves concerning testing of different kinds of liquid media. One of them, published in Ref. [14], is shown in Fig. 1.

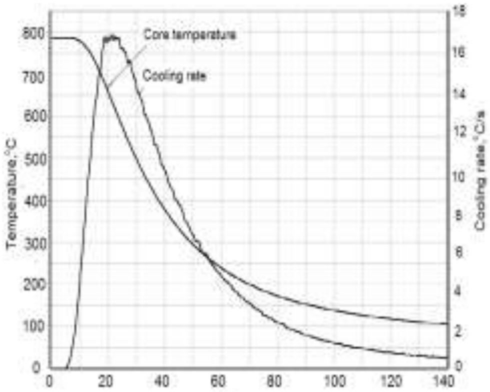


Fig. 1: Temperature and cooling rate curves versus time during quenching 50 mm cylindrical stainless probe in 1% water solution of PAG at 23°C [14].

The procedure of convective HTC evaluation consists in calculation Kondrat'ev number Kn at the end of boiling process and beginning of convection using Eq. (8) via cooling rate v:

$$Kn = \frac{vK}{a(T - T_m)} \quad (8)$$

Kondrat'ev form coefficient K and thermal diffusivity of material are available in Table I and Table VII. If dimensionless number Kn is already calculated by Eq. (8), the generalized dimensionless number Bi_V can be estimated from universal correlation (9) [8, 9, and 15]:

$$Kn = \psi \cdot Bi_V \quad (9)$$

And finally the convective HTC is calculated by Eq. (10) [15]:

$$\alpha_{conv} = \frac{\lambda Bi_V}{K} \cdot \frac{V}{S} \quad (10)$$

Also, HTCs for natural convection can be calculated by Eq. (11) [10]:

$$Nu = 0.135 \cdot (\Pr \cdot Gr)^{1/3} \quad (11)$$

Prandtl numbers Pr depending on temperature of water are shown in Table VIII [10].

Grasgof number Gr depends on physical properties of a liquid [10].

TABLE VIII
Prandtl numbers Pr depending on temperature of water

Temperature, °C	**0**	**10**	**20**	**30**	**40**	**50**
Pr	13.5	9.45	7.03	5.45	4.36	3.59
$Pr^{0.2}$	1.683	1.567	1.477	1.404	1.342	1.291

Example of convective HTC calculation
According to Fig.1, cooling rate at the center of cylindrical probe 50 mm in diameter at the moment of reaching temperature 125°C is 1 °C/s during its quenching in 1% water solution of PAG [16, 17]. Kondrat'ev form coefficient K for mentioned cylindrical probe is 108.6×10^{-6} m^2. Thermal diffusivity of stainless steel at 100°C is $4.6 \times 10^{-6} m^2/s$ and thermal conductivity is 18 W/mK (see Table VII). Calculate dimensionless number Kn and α_{conv}.
According to equation (8),

$$Kn = \frac{1^o C/s \times 108.6 \times 10^{-6} m^2}{4.6 \times 10^{-6} m^2/s \times (125^o C - 23^o C)} = 0.23$$

. From universal correlation (9) one can get generalized number Bi_V which is equal to 0.28. Then, according to Eq. (10), convective HTC is:

$$\alpha_{conv} = \frac{18W/mK \times 0.28}{108.6 \times 10^{-6} m^2} \times \frac{0.025m}{2} = 580W/m^2K$$

More useful data on convective HTCs are presented in Table IX.

TABLE IX
Convective HTC of different liquids used as a quenchant

Quenchant	HTC, W/m^2K	Author
Mineral oil	300	[18 – 20]
Water at 20^oC	803	[3,10]
Water at 30^oC	1017	[3, 10]
Water at 20^oC agitated with 0.5 m/s	2890	[3, 21]
50% water solution of $CaCl_2$ at 30^oC	380	[22 - 24]
1% water solution of PAG at 23^oC	580	[25] Current paper

IV. ANALYTICAL AND NUMERICAL INVESTIGATION OF TRANSIENT NUCLEATE BOILING PROCESSES

Standard test provides cooling rate curve and temperature curve at the center of standard probe (12.5 mm in diameter made of Inconel 600 material) [18]. Based on such standard test, it is possible to obtain very accurate data on convective heat transfer coefficients during quenching in liquid media. An example discussed above demonstrated a chain of calculations. This problem is already properly solved. Now, it is the most important to investigate Ω as a function:

$$\Omega = f(\alpha, \lambda, R)$$

Using analytical solution (3), (4) – (7), the above function is considered as dependents from dimensionless number Bi (see Fig. 2).

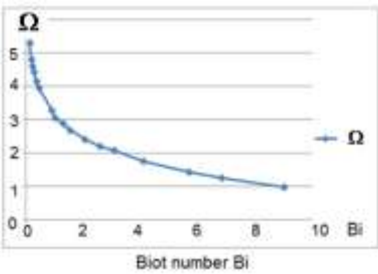


Fig. 2: Value Ω versus convective Biot number Bi that depends on size of steel part and convective heat transfer coefficient.

Table X provides calculations τ_{nb} which are true for cylindrical specimen 50 mm in diameter quenched in agitated water and water salt solutions.

TABLE X
Duration of transient nucleate boiling process depending on convective heat transfer coefficient for cylindrical probe 50 mm in diameter quenched from 850^oC in steel and agitated water salt solution 20^oC.

HTC, W/m^2K	380	1000	2000	3000	5000	10000
τ_{nb}, s	81	62	48	40	30	16
$Bi = \frac{\alpha}{\lambda} R$	0.4	1	2.17	3.26	5.43	10.9
Ω	3.82	2.9	2.78	1.83	1.54	0.68

Table X summarizes calculated d ata as a function (12) to be compared with the accurately performed experiments (see Table XI).

$$\Omega = f(Bi) \tag{12}$$

TABLE XI
Duration of transient nucleate boiling process, received by experiments, depending on diameters of probes [3].

D, mm	10	12	16	20	24	30
Time, s	4.36	6.04	10.0	14.9	21	32.1

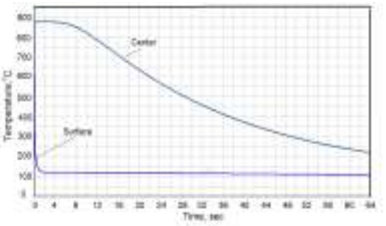
Results of experiments were compared with the numerical calculations which show a good agreement between experiments and calculations (see Table XII).

TABLE XII
Comparison of value Ω evaluated via experiment and analytical calculation.

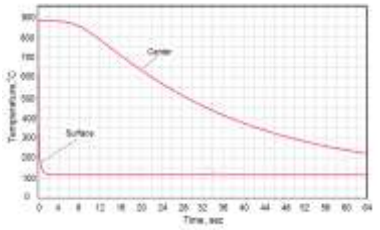
D, mm	10	12	16	20	24	30	50
Experiment	5.45	5.24	4.88	4.66	4.56	4.46	3.90
Calculation	5.,48	5.30	5.03	4.82	4.65	4.44	3.94
Accuracy, %	- 0.55	+1.1	+3	+3.3	+1.3	+0.4	- 1

As seen from Table IX., the difference between both results is insignificant. It means that Eq. (3) can be successfully used for transient nucleate boiling time evaluation during hardening processes in liquid media.

The next important issue is surface temperature changing during self – regulated thermal process. As mentioned above, this is very critical for performing austempering ocesses via cold liquids. The start and finish temperature of self regulated thermal process is evaluated by Eq. (4) and Eq.(5). Knowing this data, temperature field was reconstructed in 50 mm cylindrical specimen in still liquid with no film boiling (see Fig. 3 a)). Similar procedure was made for constant surface temperature that was average value between start and finish nucleates boiling process.



a)



b)

Fig. 3: Temperature curves vs time when quenching cylindrical specimen 50 mm in diameter in a liquid**:** a) is real surface temperature b) is average temperature.

More data on accuracy of calculations are presented in Table XIII and Table IV.

TABLE XIII

Accuracy of core temperature curves *calculation* vs time when quenching cylindrical specimen 50 mmin diameter in a liquid

Time, s	**0**	**10**	**20**	**30**	**40**	**50**	**60**
Exact	875	819.8	635.1	483.5	372.9	294.3	239.2
Simplified	875	819.6	634	481.5	370.5	291.8	236.9
Error, %	0	0.025	0.17	0.41	0.64	0.85	0.96

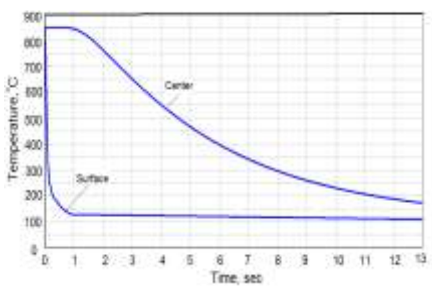
As one can see from Table X and Table XI, averaging surface temperature during transient nucleate boiling process, doesn't generate significant error.

TABLE XIV

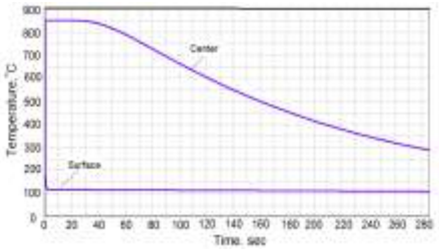
Results of analytical and numerical calculations performed for cylindrical probes of different diameters which were quenched from 850°C in still water at 20°C ($\alpha_{conv} = 800 W/m^2K$ ***).***

Probe diameter, mm	**20**	**30**	**40**	**50**	**80**	**100**	**120**
ϑ_I, °C	26.54	23.5	22.9	20.2	18.7	16.4	15.57
ϑ_{II}, °C	8.36	8.36	8.36	8.36	8.36	8.36	8.36
$(\vartheta_I + \vartheta_{II})/2$, °C	17.45	16	16	2614.3	13.5	12.4	12
Ω	4.19	3.80	3.72	3.31	3.06	2.65	2.48
τ_{nb}, s	13.4	27.4	47.7	66	184	212	286
Core temperature at the end of transient nucleate boiling in °C.	174	180	187	210	195	267	290
Error ε when core temperature of probe is 700°C	0.20%	0.13%	0.115%	0.1%	0.08%	0.076%	0.06%
Error ε when core temperature of probe is 500°C	0.75%	0.5%	0.5%	0.47%	0.15%	0.16%	0.175%

Fig. 4, which is shown below, shows core and surface temperatures for cylindrical specimens 20 mm and 120 mm at the end of transient nucleate boiling process when quenching in still water salt solution.



a)



b)

Fig. 4: Duration of nucleate boiling process for cylindrical specimens 20 (a) and 120 mm (b) in dia when quenching in water salt solution without film boiling.

Core temperature at the end of nucleate boiling process for cylindrical probe 20 mm diameter is 174°C and 290°C for diameter 120 mm when quenching in still water salt solutions (see Fig. 4 and Table XI). In this case transient nucleate boiling process is the main mode that can be used for performing austempering processes via cold liquid with acceptable for the practice accuracy [25 - 27].

V. NEW TECHNOLOGIES BASED ON RESULTS OF INVESTIGATIONS

For the first time, water salt solutions of optimal and high concentration, as uniform and fast cooling quenchants, were tested in heat treating in FSU (Ukraine, Russia, Belarus) and other countries within the period of years 1983 – 1996. Several patents were issued concerning new quenchants and accelerated cooling processes [22 - 23]. A great experience was accumulated during this long time relating to quality of quenching. Distortion of bearing rings, quenched in water salt solutions, essentially decreased, surface hardness due to uniform and accelerated cooling increased, impact strength of material increased 2 – 3 times [28]. Due to corrosion problem, water salt solutions are not widely used in heat treating industry as a quenchants. Currently, water salt solutions can be replaced by low and medium concentration of water polymer solutions which have unique characteristics and prevent quenched steel components from corrosion [29 - 32]. Quenching of optimal hardenability steels in low concentration of water polymer solutions provides high surface residual stresses in quenched steel parts that increases significantly their service life [33 – 35]. Also, low concentration of water polymer solutions can be used in quench systems designed for batch quenching processes [3, 36]. Methods of control conventional and intensive quenching processes are discussed in the published literature [37 - 39]. More investigations will be carried out in the nearest future concerning characteristics of transient nucleate boiling process which are unique for their practical use.

VI. CONCLUSIONS

1. Quenching steel parts in cold water, water salt solutions and low concentration in water of inverse solubility polymers is intensive quenching if film boiling is completely absent.
2. The main attention should be paid to investigation the critical heat flux densities that focus on complete film boiling elimination.
3. When film boiling is absent, duration of transient nucleate boiling process can be calculated by generalized equation with the accuracy less than ± 1.5 % beginning from thickness 50 mm of quenched steel parts.
4. During transient nucleate boiling process, surface temperature of steel parts maintains at the level of boiling point of a liquid insignificantly differs from saturation temperature and provides accurate calculated temperature field distribution with accuracy ± 1% if surface temperature during calculations is equal to $T_s + \Delta\bar{\xi}$.
5. Investigating the physics of quenching processes, author came to conclusion that water salt solutions of optimal concentration can be replaced by 1% of PAG water solutions providing almost the same intensity of cooling.
6. Based on received data, it is possible to reduce radically the cost of technological processes.
7. To provide positive results of quenching, chemical composition of steel should be tolerated to size and form of steel part as discussed in Refs [33, 34] and Ukrainian Patent 114174.
8. For water and water salt solutions during transient nucleate boiling process heat transfer coefficient is so large that it provides infinity Biot number during nucleate boiling. In this case duration of transient nucleate boiling (self – regulated thermal process) is essentially affected by convective Biot number Bi.
9. The third version of intensive quenching technology is a package which includes a low concentration of water polymer solution, optimal hardenability steel, and hydrodynamic emitter to provide resonance effect for any film boiling elimination during single or batch cooling. Intensive cooling is interrupted at proper time to provide fine or nano – bainitic microstructure at the core of hardened steel components.
10. The technological process should be automated, properly controlled to get repeatable and high quality hardening.

Nomenclature

Bi_V Generalized dimensionless Biot number

Bi Conventional Biot number

$\Pr$ Prandtl number

Gr Grasgof number

Kn Kondrat'ev dimensionless number

a Thermal diffusivity of steel $\left(m^2 s^{-1}\right)$

D Diameter (m)
R Radius (m)
K Kondrat'ev form coefficient (m^2)
q Heat flux density (Wm^{-2})
T Temperature (^{o}C)
$\overline{T}_{sf}$ Average surface temperature (^{o}C)
$\overline{T}_{V}$ Average volume temperature (^{o}C)
T_o Initial austenizing temperature (^{o}C)
T_S Saturation temperature (^{o}C)
T_m Bath temperature (^{o}C)
S Surface (m^2)
V Volume (m^3)
v Cooling rate $(^{o}C/s)$
α Heat transfer coefficient $(Wm^{-2}K^{-1})$
λ Thermal conductivity $(Wm^{-1}K^{-1})$
τ Time (sec)
ψ Criterion of temperature non –smoothness

List of subscriptions

nb Nucleate boiling
FB Film boiling
s Saturation
m Medium
sf Surface

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