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RESEARCH ARTICLE

SELF – REGULATED THERMAL PROCESS, ITS MAIN CHARACTERISTICS AND PRACTICAL APPLICATION

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ABSTRACT

In the paper an overview on self – regulated thermal process and new its characteristics are provided. These specific characteristics of self – regulated thermal process are widely discussed concerning real and effective heat transfer coefficients and Kondratjev numbers Kn. It is underlined that the real heat transfer coefficients (HTCs) should be considered when calculating temperature fields during transient nucleate boiling process and they should refer to boiling point of liquid, not to bath temperature. It is shown that during recipes development for quenching technology, initial austenitizing temperature may be fixed at 850°C for all existing steel grades and irons with the accuracy of calculation $\pm 1\%$. In this case the duration of transient nucleate boiling mode (self – regulated thermal process) is directly proportional to squared size of steel part, inversely proportional to thermal diffusivity of a material and depends on form of product and convective Biot number. Since in heat treating industry historically engineers are dealing with effective HTCs, the new data on effective Kondratjev number are provided to calculate approximately core cooling time and core cooling rate during quenching of steel parts. The obtained results of calculations can be used by engineers and scientists in the field of material and thermal sciences to predict processes within the transient nucleate boiling mode and convection.

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INTRODUCTION

The self – regulated thermal process is duration of transient nucleate boiling mode during which surface temperature of steel part maintains at the level of boiling point of liquid and cannot be below it until core temperature of steel part is low and corresponds to convective Biot number. Fundamental investigation in this field were made by French in 1928 (French, 1930) who measured surface temperature during quenching of small and large spherical steel samples. French for the first time published the data showing that film boiling is completely absent and surface temperature of samples drops from 875°C to 150°C for less than 0.82 seconds (see Table 1). Further with the passing of time the surface temperature maintains at the level of boiling point of liquid (see Fig. 1). In his time, it was impossible to measure correctly overheat of boundary layer to analyze transient nucleate boiling processes. That is why measurement were done in the interval 875°C - 150°C. It was noticed that film boiling is absent when quenching steel samples and film boiling exists when quenching spherical samples made of copper. The film boiling takes place due to high thermal conductivity of copper that provides high heat flux density exceeding critical value. As known, thermal conductivity of steel is almost 20 times lesser as compared with copper. That provides lesser initial heat flux density which is below the critical value that is why no film boiling at all. It was noticed by French that surface temperature within one second drops almost instantly to 150°C. Using accurate experimental data received by French (French, 1930), the real heat transfer coefficients (HTCs) were evaluated which are shown in Fig. 2 (Kobasko, 2012). During nucleate boiling process, HTCs are huge as compared with convection.

Later, it was shown that classical law of Fourier should be modified to provide finite value of heat distribution (Vernotton, 1961 and Lykov, 1967). The modified Fourier law is written as:

$$q = \lambda \nabla T - \tau_r \frac{\partial q}{\partial \tau} \quad \text{....(1)}$$

The modified law of Fourier generates the hyperbolic heat conductivity equation (Lykov, 1967) which is considered below.

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Table 1. Surface temperature versus time of steel spheres of different diameters when quenching from 875°C in 5% NaOH water solution at 20°C moving with 0.9 m/s (French, 1930

Diameter, mm	700°C	600°C	400°C	300°C	150°C
6.35	0.027	0.037	0.051	0.09	0.69
12.7	0.028	0.042	0.071	0.11	0.60
25.4	0.033	0.042	0.074	0.13	0.82
63.5	0.023	0.039	0.093	0.14	0.59

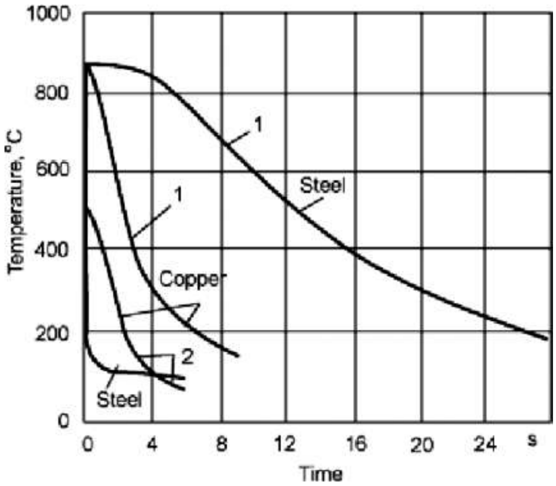

Fig. 1. Temperature at the surface and in the core versus time for steel and copper balls of 38.1-mm in diameter, quenched from 875°C in water at room temperature (French, 1930): 1, core; 2, surface

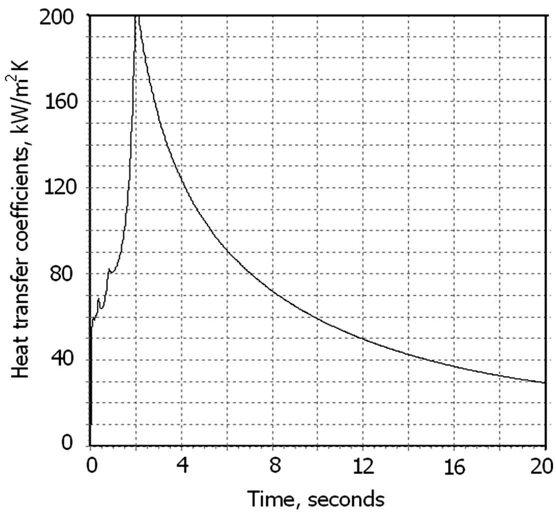

Fig. 2. Shock and nucleate boiling heat transfer coefficients versus time for a sphere of 38.1 mm in diameter quenched from 875°C in a 5 % aqueous NaOH solution at 20°C

Mathematical models of quenching processes

If film boiling is absent, the mathematical model, namely the heat conductivity equation, for quenching process can be written as:

$$\frac{\partial\theta(r,\tau)}{\partial\tau}+\tau_r\frac{\partial^2\theta(r,\tau)}{\partial\tau^2}=a\left(\frac{\partial^2\theta(r,\tau)}{\partial x^2}+\frac{j-1}{r}\frac{\partial\theta(r,\tau)}{\partial r}\right) \quad .....(2)$$

($j=1,2,3$; j = 1 for a plate; j= 2 for a cylinder; j =3 for a sphere) with the boundary condition (3) that were firstly formulated by authors (Kobasko and Kostanchuk, 1973):

$$\left[\frac{\partial T}{\partial r}+\frac{\beta^m}{\lambda}\left(T-T_S\right)^m\right]_{r=R}=0\cdot \quad ....(3)$$

After the transient boiling process is finished, convection starts and the third kind of boundary condition for convective heat transfer mode is used with the boundary condition (4):

$$\left[\frac{\partial T}{\partial r}+\frac{\alpha_{conv}}{\lambda}\left(T-T_m\right)\right]_{r=R}=0\cdot \quad ....(4)$$

A transition from nucleate boiling to convection is determined by equalizing the heat fluxes (Eq. (5), *i.e.*

$$q_{nb}\equiv q_{conv} \quad ....(5)$$

Also, initial austenitizing temperature should be added (Eq. (6):

$$T(r,0)=T_0\,. \quad .... (6)$$

Analytical solutions and their analysis

Analytical solutions of hyperbolic Eq. (2) with the boundary and initial conditions (3) and (6) were obtained and analyzed by authors (Buikis, 2009; Guseynov and Kobasko, 2008; Guseynov, Rimshans *et al*., 2010). Based on experimental data of French (French, 1930) and analytical solutions of hyperbolic heat conductivity equation, one can come to conclusion that film boiling can be absent completely when quenching steel parts in cold liquid media.
Following reason is for such phenomenon:

- 5% NaOH water solution at 20°C has twice higher critical heat flux density as compared with cold water which exceeds initial heat flux density.
- Speed of heat distribution is a finite value that cannot provide extremely high heat flux density which can be less than critical one.
- Prior to boil cold solution should be heated to boiling point and during this time surface temperature drops almost instantly to boiling point of liquid.
- Agitation increases critical heat flux density that decreases probability of film boiling process.

Taken into account these facts, authors (Kobasko and Zhovnir, 1979) received an analytical solution of parabolic heat conductivity equation with the boundary condition (3) and boundary condition (4) to calculate duration of transient nucleate boiling process when film boiling is completely absent. As a result, simplified equations Eq. (7) – Eq.(9) were constructed to calculate duration of self – regulated thermal process (Kobasko, 1992).

$$\tau_{nb}=\left[0.24k+3.21\ln\frac{\vartheta_I}{\vartheta_{II}}\right]\frac{K}{a}, \quad ....(7)$$

$$\vartheta_I=\frac{1}{\beta}\left[\frac{2\lambda\left(\vartheta_0-\vartheta_I\right)}{R}\right]^{0.3} \quad ....(8)$$

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

To make correctly calculations, convective HTC should be evaluated at first. When quenching in still water, convective heat transfer coefficient is calculated by Eq. (10) or Eq. (10a):

$$Nu = 0.13\left(Gr\Pr\right)^{1/3}, \quad \text{.........(10)}$$

$$\alpha_{conv} = 0.13\lambda\left(\frac{g\beta\Delta T}{a\nu}\right)^{1/3}. \quad \text{...(10a)}$$

Convective heat transfer coefficients (HTCs), when quenching in water flow, is evaluated by equation (11):

$$Nu = 0.021\mathrm{Re}^{0.8}\Pr^{0.43}\left(\frac{\Pr_m}{\Pr_{sf}}\right)^{0.25}\varepsilon_l \quad \text{.........(11)}$$

Using convective HTCs, it is possible to calculate duration of transient nucleate boiling process.

The generalized equation for calculating the duration of self – regulated thermal process

When initial austenitizing temperature is fixed at 850oC and bath temperature at 20oC, then results of calculations, based on equations (7) - (9), can be presented in simple form (Kobasko, 2009):

$$\tau_{nb} = \Omega k_F \frac{D^2}{a} \quad \text{.......(12)}$$

The value Ω is a function of convective Biot number and is provided in **Fig. 3**.

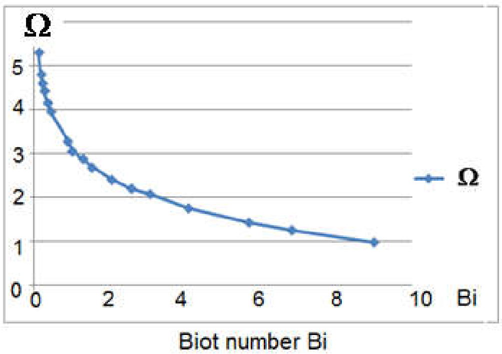

Fig. 3. The value Ω versus convective Biot number Bi depending on size of steel part and HTC during convection

Core temperature versus time during self – regulated thermal process

Fig. 3 and Eqs. (12), (13) allow engineers to perform simplified calculations. Temperature at the core of steel parts during self – regulated thermal process can be calculated at any time approximately by equation Eq. (13) which was provided by author (Kobasko, 1980):

$$\frac{aKn}{K}\tau = \left(\frac{k_1 Bi_V}{2.095 + 3.873 Bi_V} + \ln\theta_o\right) \quad \text{.........(13)}$$

or

$$\tau = \left[0.24k + \ln\frac{T_0 - T_m}{T - T_m}\right]\frac{K}{aKn} \quad \text{.........(13a)}$$

Within the self - regulated thermal process Eq. (13a) is used with effective Kondratjev numbers Kn_{ef} that is considered below.

Analysis of obtained solutions

Effect of initial temperature

First of all, let's see (Table 2) how initial austenitizing temperature affect duration of transient nucleate boiling process τ_{nb} when quenching from 800°C and 900°C . The matter is that more than 90% steels and irons are heated within the interval of temperatures 800°C – 900°C and then executed by quenching process. For such interval of temperatures, calculated data are presented in Table 2.

Table 2. Effect of initial temperature T_0 on duration τ_{nb} of transient nucleate boiling process when quenching cylindrical 20 mm stainless specimen in water salt solutions at 20°C from different temperatures

T_0, °C	ϑ_I, °C	ϑ_{II}, °C	τ_{nb}, sec
800	25.64	8.28	13.15
850	26.19	8.28	13.40
900	26.72	8.28	13.56

Error of calculation is $\pm 1\%$.

Thus, for all steel parts and iron products austenitizing temperature during making calculations can be fixed at 850°C that results in $\pm 1\%$ incorrectness of recipes development.

Effect of physical properties on duration of self – regulated thermal process

Thermal and physical properties of quenchant represented by value β doesn't affect significantly duration of self – regulated thermal process (see Table 3).

Table 3. Duration of transient nucleate boiling process versus parameter β for cylindrical stainless (AISI 304) probe 20 mm in diameter when quenching in still water ( )

β	ϑ_I, °C	ϑ_{II}, °C	τ_{nb}, sec
3	29.76	9.43	13.34
3.41	26.19	8.28	13.40
4.3	20.81	6.54	13.43
7*	12.8	3.99	13.50
9*	9.99	3.08	13.60

Error of calculation is $\pm 2\%$

Core temperature versus size at the end of self – regulated thermal process

To predict cooling time consisting of boiling process and convection, core temperature at the core at the moment of transition from boiling to convection is needed. Some results concerning core temperatures are provided in Table 4 and Fig. 4.

Table 4. Temperature at the core of cylindrical samples at the end of transient nucleate boiling process during quenching in water and water solutions at 20°C when convective HTCs are 776 W/m²K and 5000 W/m²K

Diameter in mm	10	20	30	50	80	100
Temperature in °C when HTC is 776 W/m²K	116	124	132	165	183	204
Temperature in °C when HTC is 5000 W/m²K	167	223	276	384	546	630

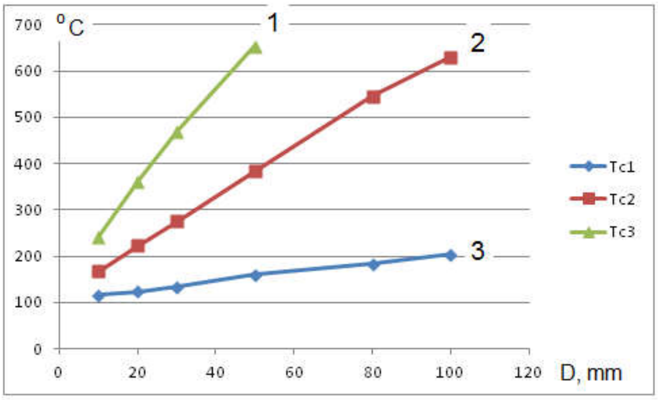

Fig. 4. Core temperature at the end of the self – regulated thermal process versus diameter of cylindrical steel parts: 1, HTC is 10000 W/m²K; 2, HTC is 5000 W/m²K; 3, HTC is 776 W/m²K

Effective Kondratjev numbers Kn_{ef} during transient nucleate boiling

When using equation (13a) during transient nucleate boiling process, the average effective Kondratjev numbers should be available. Such data are presented in Table 5.

Table 5. Average surface temperature and effective Kondratjev number depending on diameter of cylindrical steel parts when convective HTC is 776 W/m²K

Diameter, mm	ϑ_I, °C	$\frac{\vartheta_I + \vartheta_{II}}{2}$, °C	Ω	Kn_{ef}	T_{core}, °C
10	32.17	20.23	4.84	0.54	116
20	26.19	17.23	4.18	0.61	124
30	23.22	15.75	3.79	0.66	132
50	20	14.14	3.30	0.69	165
80	17.34	12.81	2.86	0.736	183
100	16.2	12.14	2.65	0.75	204

Knowing the core temperature T_{core}, °C of steel part at the moment of finish nucleate boiling process, one can calculate effective Kondratjev number Kn_{ef} suitable only for core cooling time calculation during boiling process (see Table 5). It is received by equalizing Eq. (7) and Eq. 13a)

$$\left[0.24k + 3.21\ln\frac{\vartheta_I}{\vartheta_{II}}\right] = \left[0.24k + \ln\frac{T_0 - T_m}{T_{core} - T_m}\right]\frac{1}{Kn} \quad ....(14)$$

The results of calculations are provided in Fig. 5 where curve 1 is true for still coolant when heat transfer coefficient is 776 W/m²K and curve 2 for agitated coolant when heat transfer coefficient is 5000 W/m²K.

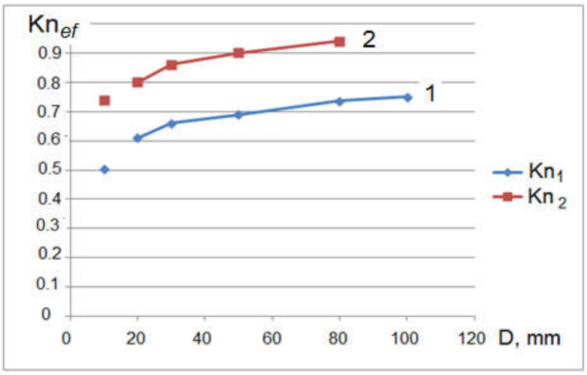

Fig. 5. Effective Kondratjev number Kn_{ef} versus diameter of cylindrical steel parts in still and agitated coolants: 1 is still liquid quenchant, convective HTC is 776 W/m²K; 2 is agitated liquid quenchant, convective HTC is 5000 W/m²K

As seen from Fig. 5, effective Kondratjev numbers change insignificantly with changing diameters of cylindrical samples. It creates opportunity to use average Kn numbers dividing curve Kn versus D for several intervals.

Real and effective Kondratjev numbers

Real Kondratjev numbers during quenching of steel parts in water and water salt solutions are within $0.8 \le Kn \le 1$. Effective Kondratjev numbers during quenching of steel parts in water and water salt solutions are within $0.5 \le Kn \le 0.8$. It is due to $T - T_m > T - T_s$. During immersion of steel parts into cold quenchant shock boiling takes place during which within two seconds heat transfer coefficient riches huge value which exceeds 200 kW/m²K and then decreases to 6000 W/m²K and less. Only such huge HTCs can provide immediate decrease surface temperature almost to boiling point as shown in Table 1. Everything is easily explained. The first critical heat flux density of cold NaOH water solution reaches 15 MW/m² and initial heat flux density can be equal 15 MW/m²K too. According Tolubionsky's equation, heat transfer coefficient in this case is equal to 193.9 kW/m²K and 242.6 kW/m²K according to Shekriladze equation (Shekriladze, 2012). Equations of Tolubinsky and Labuntsov show approximately the same result (see Table 6).

Table 6. Real heat transfer coefficients according to different well known thermal scientists at the beginning of transient nucleate boiling process during quenching 20 mm probe made of AISI 304 from 850°C in water at 20°C

Author	α_I ,kW/m²K	Comments
(Kutateladze, 1963)	261.5	Hot water
(Labuntsov,2000)	207.4	
(Shekriladze, 2012)	242.6	
(Tolubinsky, 1980)	193.9	Cold water

As it was explained above, average effective Kondratjev numbers Kn_{ef} are within $0.5 \le Kn \le 0.8$ and they can be used only for core cooling rate and cooling time evaluation during nucleate boiling process.

Cooling time calculation within the nucleate boiling and convection

Cooling time of steel parts during quenching is evaluated as

$$\tau_c = \tau_{fb} + \tau_{nb} + \tau_{cv} \qquad \text{......(15)}$$

As known, film boiling during IQ – 2 and IQ – 3 intensive quenching processes should be completely absent, *i.e.*

$$\tau_{fb} = 0$$

Duration of transient nucleate boiling process is evaluated using Eq. (7) or Eq. (12) and duration within the convective heat transfer mode is evaluated as

$$\tau_c = \ln\theta_c \frac{K}{aKn} \qquad \text{......(16)}$$

and summarized cooling time is

$$\tau_c = \Omega k_F \frac{D^2}{a} + \ln\theta_c \frac{K}{aKn} \qquad \text{.......(17)}$$

In this case simplified Eq. (16) is used because after finishing boiling process regular thermal mode is already established and there is no need to take into account irregular time which contains Eq. (13). Note that initial core temperature in Eq. (16) is 415.6°C when convection at the surface starts. It was calculated by considering the first time of boundary condition (Lykov, 1967). Substituting initial temperature 415.6°C into Eq. (17), we receive:

$$\tau_c = \Omega k_F \frac{D^2}{a} + \ln\theta_c \frac{K}{aKn} = 1.5 \times 0.0432 \times \frac{(0.041m)^2}{5.36 \times 10^{-6} m^2/s} + \\ + \ln\frac{415.6 - 20}{200 - 20} \times \frac{76.2 \times 10^{-6} m^2}{5.36 \times 10^{-6} m^2/s \times 0.88} = 33\sec$$

here Kn = 0.88.

During direct convection (Kobasko, Aronov *et al.*, 2010) cooling time is 32 sec:

$$\tau_c = \left[0.42 + \ln\frac{860^o C - 20^o C}{200^o C - 20^o C}\right] \times \frac{76.2 \times 10^{-6} m^2}{5.36 \times 10^{-6} m^2/s \times 0.88} \approx 32\sec$$

that coincides very well with each other.

Such approach provides accurate calculated data which coincide with the experiments as well.

DISCUSSION

Analytical temperature field calculation for different forms of steel parts is complicated mathematical problem since analytical solutions are available mainly for classical forms. But the practice requires cooling time calculation as for simple and for very complicated forms. In this paper, a general approach is developed to calculate duration of transient nucleate boiling process and period of pure convection. By using this method one can get rather accurate data for any configuration of steel parts. The method was verified in the practice during the last decade. What is the most important here, it is possibility to provide intensive quenching in low agitated liquid coolants when any type of film boiling is absent. Absence of film boiling, especially local film boiling decreases distortion of steel parts after quenching. When film boiling is absent, surface temperature drops almost instantly to boiling point of liquid and maintains at this level relatively a long time. It is this characteristic of self – regulated thermal process that was used for the development of new technologies, called IQ – 2 and IQ – 3 processes. Moreover, that characteristic and other investigated characteristics were used by engineers to develop appropriate software for recipes elaboration. It should be underlined that such approach provides very precise data when cooling time calculation which is connected with obtaining maximal residual stresses after intensive quenching. The procedure of calculations is as follows:

- Using dimensionless Eq. (10) – Eq. (11), convective heat transfer coefficients are calculated for still, agitated quenchant or directed water flow in quenching chambers.
- Initial and finish temperature of self – regulated thermal process is evaluated to calculate its duration.
- Water flow velocity and criterion which is condition for providing direct convection is calculated.
- Average surface temperature of self – regulated thermal process is evaluated and heat conductivity problem with first type of boundary condition is solved to obtain core temperature at the end of nucleate boiling process and a value of Kondratjev form factor K.
- Cooling time for any configuration and for any quenchant is calculated which includes duration of nucleate boiling process and convection.

Software provides all mentioned above characteristics. The developed approach is suitable both for intensive quenching processes and for existing conventional quenching technologies. Method of calculation works perfectly when film boiling and local film boiling are absent. As known, they harm the process of hardening. To eliminate full film boiling and local film boiling, it is recommended to use hydrodynamics emitters creating resonance effect (Kobasko, 2016).

Conclusion

1. Self – regulated thermal process is transient nucleate boiling when surface temperature of quenched steel part maintains at the level of boiling point of liquid and cannot be below it until heat flux density going from inside of the part can be taken out by convection without help of departing bubbles.
2. The initial and finish temperatures of self – regulated thermal process differ insignificantly that allows using average surface temperature as the first type of boundary condition to calculate correctly temperature fields in the quenched steel part.
3. According to French, the time of establishing the self – regulated thermal process doesn't depend on size of steel part and its duration is within 2 seconds.
4. The initial temperature of self – regulated thermal process depends considerably on size of steel part. The finish temperature of self – regulated thermal process depends considerably on convective heat transfer in quench tank.
5. When initial austenitizing temperature of steel parts is fixed at 850°C and bath temperature at 20°C, the duration of transient nucleate boiling process in directly

proportional to squared size of a steel part, inversely proportional to thermal diffusivity of material and depends on form of steel part and convective Biot number in quench tanks filled with a liquid quenchant.

6. The real heat transfer coefficient during transient nucleate boiling process is very large and can exceed 200 kW/m^{2}K and is evaluated as a ratio of heat flux density to overheat of a boundary layer. The cooling process during nucleate boiling is intensive because real Kondratjev numbers are within $0.8 \le Kn \le 1$.
7. The effective heat transfer coefficient is evaluated as a ratio of heat flux density to the difference of steel surface temperature and bath temperature which can be more than 10 times higher as compared with the overheat in a boundary layer.
8. Effective HTCs can be used only for core cooling time calculations and cannot be used for temperature field calculation in steel parts during nucleate boiling process since big errors appear when surface temperature prediction.
9. Thermal and physical properties of liquid represented by β value don't affect extensively the duration of self – regulated thermal process since $\alpha_{nb} >> \alpha_{conv}$ that considerably simplifies calculations.
10. A simplified and accurate method for cooling time calculation, within transient nucleate boiling process and pure convection mode, is proposed. This approach is a basis for designing a software to be widely used for intensive and conventional quenching processes monitoring.

List of Symbols

T is temperature; τ is time; τ_r is time of relaxation; τ_{nb} is duration of transient nucleate boiling process in sec; k = 1; 2; 3 for plate like form, cylindrical form and spherical form; $\vartheta_I = T_I - T_S$, T_I is nucleate boiling start temperature; T_S is saturation temperature; $\vartheta_{II} = T_{II} - T_S$; T_{II} is nucleate boiling finish temperature; K is Kondratjev form coefficient in m^2; a is thermal diffusivity of material or liquid in m^2/s; $\beta = 3.41$ depends on physical properties of quenchant or volumetric expansion coefficient of a quenchant in 1/K; λ is thermal conductivity of material or liquid in W/mK; R is radius in m; D is diameter in m; α_{conv} is convective heat transfer coefficient (HTC) in W/m^{2}K; $\vartheta_{uh} = T_S - T_m$; T_m is bath temperature; $g = 9.81 m/s^2$; ν is kinematic viscosity in m^2/s; ΔT is difference between sample surface temperature and bath temperature; Nu is Nusselt number; Pr is Prandtl number; Gr is Grashof number; Re is Reynolds number; ε_l is equal to 1 if L/D > 50; fb means film boiling; nb means nucleate boiling; c and conv mean convection.

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