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Original Article

Fundamental Characteristics of Transient Nucleate Boiling Process used for Cooling Recipes Development

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Abstract - *This paper discusses the fundamental characteristics of the transient nucleate boiling process. It is shown that discovered characteristics were used for new technologies development, evaluation of materials' thermal properties, and control of the quality of hardened steel parts. The current paper proposes a new simplified method of recipe development based on discovered characteristics combined with numerical calculations. There are several computer codes for temperature 3-D fields calculations; however, up-to-date boundary conditions for the cooling process during hardening steel parts in liquid media are unknown or used incorrectly. In the paper core cooling time of any steel part is considered as a duration consisting of transient nucleate boiling process and convection. It is assumed that film boiling is completely absent. The main result of the current investigation is the possibility of correctly evaluating the core temperature of the steel part at the end of the nucleate boiling process to switch from boiling to convection. The proposed simplified cooling time calculation method is used to achieve maximal surface compression residual stresses and fine bainitic microstructure at the core of steel parts and evaluate the duration of severe agitation. Engineers in the heat tre4ating industry can use the obtained results.*

Keywords - *Cooling time, Fundamental characteristic, Recipe, Simplified method.*

1. Introduction

The author discovered the fundamental characteristics of the transient nucleate boiling process in the last decade [1,2]. They were used for new technologies development which includes intensive quenching (IQ) technology IQ-2 [3]; austempering process via cold fluids [4,5]; quality control of quenching processes in liquid media [6]; performing the low-temperature thermomechanical treatment in the condition of accelerated cooling [6]; evaluation thermal properties of materials. The discovered characteristic states: that the duration τ_{nb} of the transient nucleate boiling process is directly proportional to square thickness D of quenched steel part, inversely proportional to thermal diffusivity of steel a, depends directly on the form coefficient k_F of quenched steel part and intensity of the cooling system. Initial temperatures T_o T_m are fixed here at 20ºC and 850ºC, and then the duration of the transient nucleate boiling process is evaluated by equation (1):

$$\tau_{nb} = \overline{\Omega} k_F \frac{D^2}{a} \tag{1}$$

Here $\overline{\Omega}$ is a function of the convective Bi number [7].

The surface temperature of transient nucleate boiling maintains at the level of the boiling point of a liquid, *i.e.*

$$\overline{T}_{sf} = T_s + \Delta\overline{\xi} \approx const \tag{2}$$

Here T_{sf} is surface temperature, T_s saturation temperature, and average overheat of a boundary layer responsible for nucleate boiling. It's true when critical heat flux densities are maximal, and any film boiling is absent [8,9]. When surface temperature during nucleate boiling maintains at the level of the boiling point of a liquid, it is called self – a regulated thermal process [10]. More information on the cooling time calculation of any steel part can be found in publications [11,12]. The paper's author considers characteristics fundamental because they exist independently of people's will (volcano activity in oceans and meteorites falling into the water of rivers and see).

Moreover, the process of nucleate boiling can be seen (thousands of vapor bubbles are acting during nucleate boiling), can be heard (they produce specific noise), can be felt (bubbles produce vibration), and can smelled due to existing vapor. So, the transient nucleate boiling process is unique and not investigated enough. Especially, shock nucleate boiling and critical heat flux densities require detailed investigations. This time in the current paper is shown that very complicated processes, which require extremely complicated calculations, can be reduced to simple and very clear procedures to be widely used in the heat treating industry by engineers.

2. Simplified Method of Cooling Time Calculation

The paper considers the cooling process when film boiling is absent, and there is a need to calculate the duration of transient nucleate boiling and convection. The duration of nucleate boiling is easily calculated using equation (1), while the duration of convection is calculated using equation (3):

$$\tau = \left[\frac{kBi_V}{2.095 + 3.867 Bi_V} + \ln \frac{T_o - T_m}{T - T_m} \right] \cdot \frac{K}{aKn} \quad (3)$$

At the end of transient nucleate boiling and beginning of convection, Eq. (3) can be rewritten as:

$$\tau = \frac{K}{aKn} \cdot \ln \frac{T_o - T_m}{T - T_m} \quad (4)$$

Here $k = 1,2,3$ for plate, cylinder and sphere Bi_V are generalized Biot number; K is Kondrat'ev form factor in m^2; Kn is Kondrat'ev number; c is specific heat capacity; ρ is density; λ is thermal conductivity.

In this case, the initial temperature To is at the convection and should be designated as T_o^{reg}. Approximately it can be calculated from Eq. (3) if the duration of transient nucleate boiling is known or by solving differential Eq. (5)

$$c\rho \frac{\partial T}{\partial \tau} = div(\lambda gradT) \quad (5)$$

with the first type of boundary condition (6)

$$T(r,\tau)_{r=R} = f(R,\tau) \quad (6)$$

and initial condition (7):

$$T(r,0) = T_o \quad (7)$$

Combining experimental data of French (see Table 1) with the duration of transient nucleate boiling (see Eq. (1)), it is possible to create the first type of boundary condition (6). Scientists, for a long time, forgot the valuable data of the French.

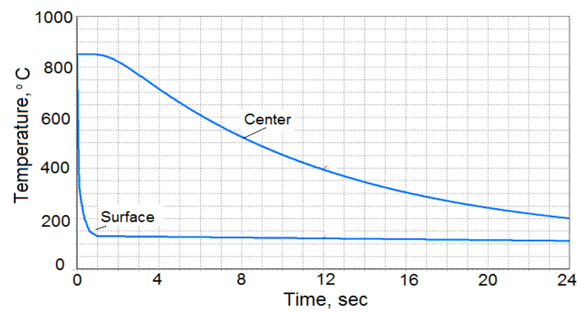
Table 1. Time is required for the surface of steel spheres of different sizes to cool to different temperatures when quenched from 875 ºC in a 5 % water solution of NaOH at 20 ºC agitated with 0.914 m/s (French, 1930) [13].

Size in mm and temperature	Time, sec							
	700ºC	600ºC	500ºC	400ºC	300ºC	250ºC	200ºC	150ºC
6.35	0.027	0.037	0.043	0.051	0.09	0.15	0.29	0.69
12.7	0.028	0.042	0.058	0.071	0.11	0.15	0.26	0.60
120.6	0.043	0.066	0.09	0.12	0.17	0.21	0.29	0.95

There is numerous computer program that allows making temperature field calculations for the 3-D domain [14,15]. They are used for numerical study of phase changes, current and residual stresses formed during complex configuration quenching steel parts and achieving fine bainitic microstructure [14 -16].

3. Results of Calculations and Discussion

For calculating temperature fields and core temperatures at the end of the transient nucleate boiling process, a numerical method that represents Eq.(5)-Eq was explored. (7). The first type of boundary condition was constructed using experimental data of French (see Table 1) [13] combined with the duration of the transient nucleate boiling process (see Eq. (1)). A computer program IQLab was used for the core cooling curve rebuilding and evaluation the core temperature at the end of nucleate boiling. Numerical calculations were performed for different shapes: plate, cylinder and sphere 20 mm in thickness quenched in French's cooling condition. Since the duration of transient nucleate boiling depends on convective Biot number Bi, calculations were performed for the wide interval of convective Biot numbers: 0.5; 1; 2; 3; 4; 5, and 6. Results of calculations are presented in Fig. 1 – Fig. 4.



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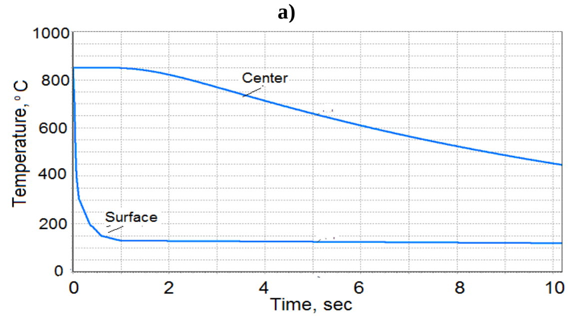

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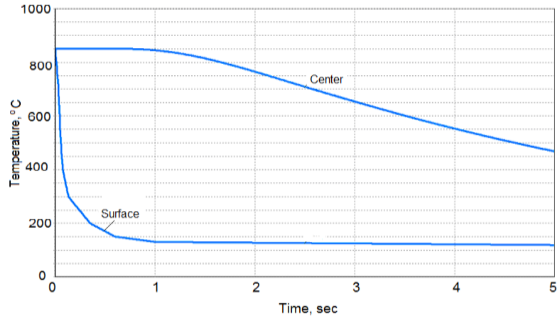
Fig. 1. Core and surface temperatures vs time during nucleate boiling process when quenching plate 20 mm in thickness from 850ºC in fluids at 20ºC with different convective Biot numbers Bi: a), Bi = 1; b) Bi = 6.



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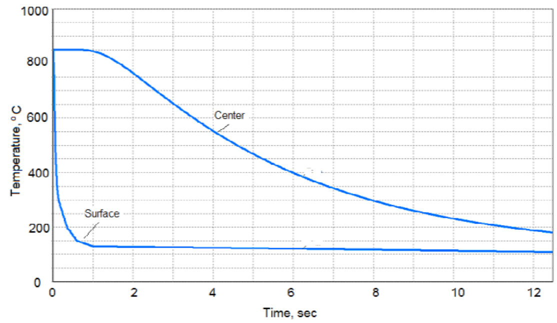

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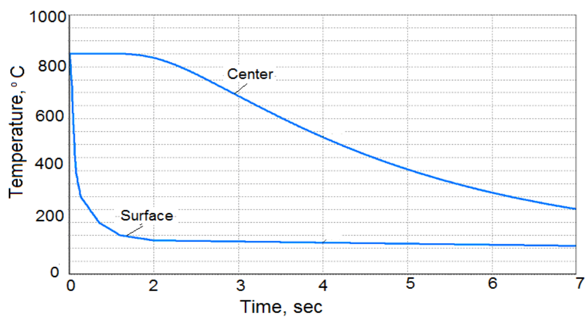
Fig. 2 Core and surface temperatures vs time during nucleate boiling process when quenching cylinder 20 mm diameter from 850°C in fluids at 20°C with different convective Biot numbers Bi: a), Bi = 0.5; b) Bi = 6



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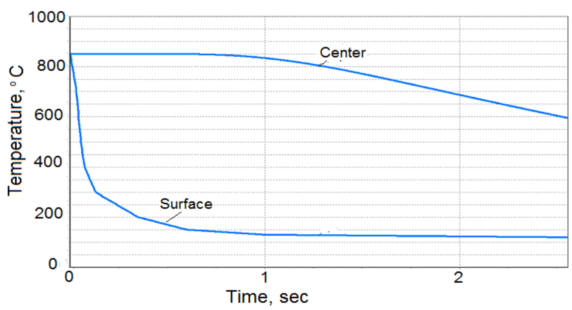
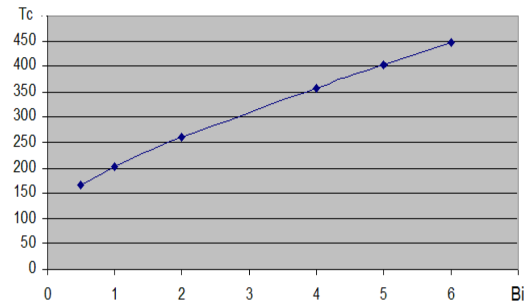


b)

Fig. 3 Core and surface temperatures vs time during the nucleate boiling process when quenching spheres 20 mm diameter from 850°C in fluids at 20°C with different convective Biot numbers Bi: a), Bi = 1; b) Bi = 6

Using obtained data presented in Fig.1 – Fig. 3, a linear correlation between the core temperature at the nucleate boiling and Biot number Bi was achieved (see Fig. 4).



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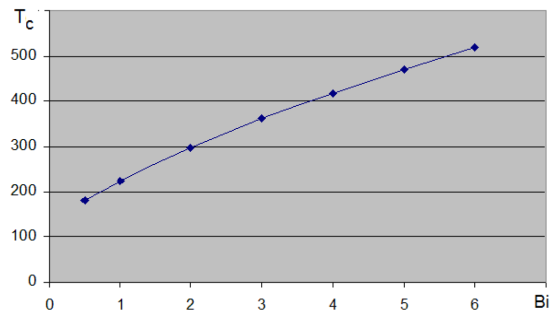

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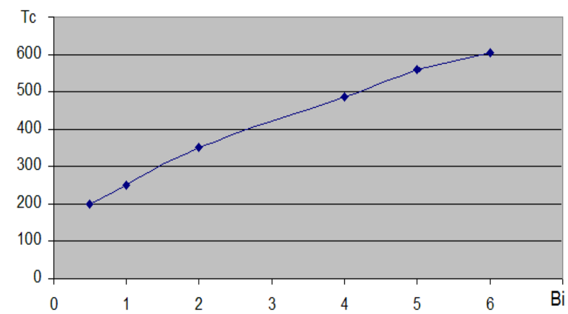

c)

Fig. 4 Core temperature T_c vs convective Biot numbers Bi when quenching samples 20 mm in diameter of different shapes from 850°C in fluids at 20°C: a) plate; b) cylinder; c) sphere.

As shown in Fig. 4, the core temperature at the end of the transient nucleate boiling process is a linear function of convective Biot number Bi. According to patented technology [20], the transient nucleate boiling process is absent when criterion (8) is satisfied:

$$Bi = \frac{2(\vartheta_o - \vartheta_I)}{\vartheta_I + \vartheta_{uh}} \qquad (8)$$

$\vartheta_o = T_o - T_s$; $\vartheta_I = T_I - T_s$; $\vartheta_{uh} = T_s - T_m$; ϑ_I is overheat of a boundary layer at the beginning of nucleate boiling; ϑ_{uh} is underheat of a liquid; T_o is initial temperature; T_s is saturation temperature; T_m is bath temperature.

4. Interrupted Agitation during Technological Process

As a rule, during batch quenching of steel parts in liquid media, agitation is performed within 0.5 1.5 m/s to provide uniform and intense cooling via elimination of the film boiling process [3]. Agitation is not interrupted, and powerful propellers are working full time. The technology is rather expensive and complicated, which requires modification. To do this, the author [17] proposed using the resonance effect, generated by hydrodynamic emitters, to destroy film boiling. In 1997 authors [18] discovered the shock boiling process, which produces oscillation at 13.6 kHz. To prevent film boiling, using different hydrodynamic emitters or vibrating systems that cardinally increase the first critical heat flux density makes sense. A question arises: "how long-time hydrodynamic emitters or vibrating systems should be at work when conventional agitation already exists?" As shown in Fig. 5, in both cases, initial heat flux density q reduces from 18 MW/m^2 to 3 MW/m^2 within 1 second. The heat flux density of 3 MW/m^2 is far below the first critical value q_{cr1}, and powerful agitation at this moment can be stopped to continue further conventional agitation. Such an approach guarantees the absence of any film boiling and saves a huge amount of energy. Table 2 shows agitation interruption for investigated samples where agitation lasts only 2 seconds.

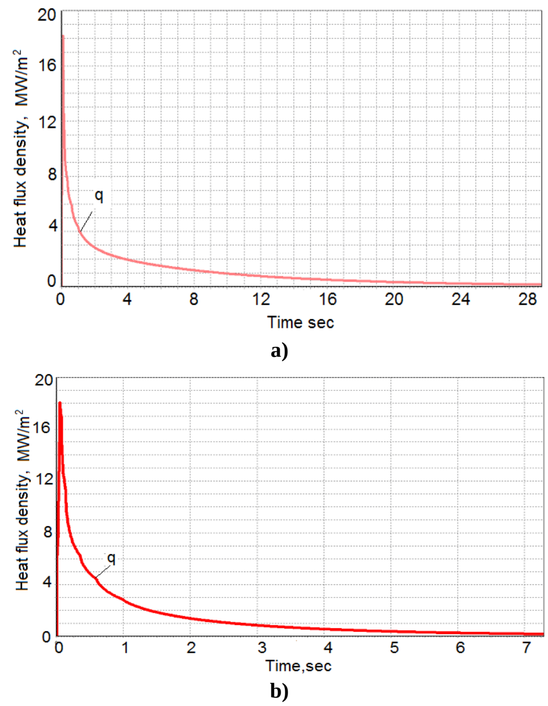

Fig. 5 Heat flux densities vs time during quenching from 850°C in fluids at 20°C samples of different shapes: a) plate 20 mm in thickness; b) spere 20 mm in diameter.

The new technology can harden optimal hardenability steel to compete with the IQ-3 process [19,20].

Table 2. Cooling time interruption at 450°C and 300°C, and quenchant agitation interruption during quenching in water solutions of different forms samples 20 mm in thickness when convective number Bi equals 6.

Form	K, x10^{-6}m^2	T_c	Cooling time from 850°C to 450°C, s	Cooling time from 850°C to 300°C, s	Time of agitation interruption, s
Plate	40.53	450	10	14.8	2
Cylinder	17.29	517	7.5	8.5	2
Sphere	10.13	602	3.3	4.5	2

5. Conclusion

The simplified method of cooling time calculation during quenching steel parts in liquid media is proposed in the paper. It consists of transient nucleate boiling calculation and cooling time calculation during convection. To stick both processes together, the core temperature of steel parts at the end nucleate boiling is evaluated, serving as an initial temperature for convection. As a result, a linear correlation between the core temperature at the end of nucleate boiling and convective Biot numbers is used for simplified calculations.

Additionally, a proposal is made consisting of use powerful vibrating systems with their interrupted action in 2-5 seconds from beginning of cooling.

The main attention during quenching should be paid to maximizing critical heat flux densities to be sure that any film boiling process during quenching is completely absent.

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