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Steel Quenching in Liquid Media under Pressure Considering Process from the Point of View of Physics

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Abstract
Quenching in liquid media under pressure requires accurate cooling time interruption calculation to perform the correctly technological process. The paper shows that real and effective heat transfer coefficients can be used for this purpose. The last provides approximate core cooling time calculation of steel part during quenching. The possibility of performing the low-temperature thermomechanical treatment in forging shops is discussed in the paper. The physics of the nucleate boiling process and critical heat flux densities are considered. Examples of cooling time calculations in the paper are provided. The proposed approach can be used in forging and heat-treating industries and useful for scientists and engineers.

I. INTRODUCTION

Quenching in liquid media under pressure is very promising for performing high-temperature thermomechanical treatment (HTMT) and low temperature thermo- mechanical treatment LTMT) in forging shops using a procedure called direct quenching after forging. The mentioned processes were investigated by many authors [1, 2, 3]. The intensive cooling during performing HTMT and LTMT processes is discussed in Refs. [4, 5]. When performing HTMT and LTMT, one should calculate interruption time. Otherwise, it will be impossible to execute the mentioned technologies. For calculating cooling time, the real and effective heat transfer coefficients are used [6]. They differ drastically from each other. This problem is discussed in detail in detail, aiming to perform quenching of steel parts and forgings in liquid media under pressure.

II. MAIN CHARACTERISTICS OF THE NUCLEATE BOILING PROCESS

As it was discussed many times [6], the real heat transfer coefficient (HTC) during the transient nucleate boiling process is evaluated as a ratio of the heat flux density produced by bubbles to the overheat of the boundary layer, *i.e.*

$$\alpha_{nb} = \frac{q}{T_{sf} - T_s}. \qquad (1)$$

while the effective heat transfer coefficient (HTC) during the transient nucleate boiling process is evaluated as:

$$\alpha_{ef} = \frac{q}{T_{sf} - T_m},\ T_m << T_s. \qquad (2)$$

Here α_{nb} is real HTC during the transient nucleate boiling process; α_{ef} is an effective HTC; q is heat flux density; T_{sf} is surface temperature; T_s is saturation temperature; T_m is bath temperature.

Early, effective HTC cannot be used for correct temperature gradients calculation during the transient nucleate boiling process. It can be used only for approximate prediction of cooling time and the cooling rate at the core of quenched steel parts. This issue was not discussed in detail in the literature yet. Since it has a great impact on the practical results, the appropriate discussion is provided below.

According to Tolubinsky [7], the real HTC during nucleate boiling is calculated from Eq. (3):

$$\alpha = 75\lambda\left[\frac{g(\rho^{'} - \rho'')}{\sigma}\right]^{0.5}\left(\frac{a}{v}\right)^{0.2}\left(\frac{1}{r^{*}\rho''w''}\right)^{0.7}\cdot q^{0.7} \qquad (3)$$

or

$$\alpha = cq^{0.7} \qquad (3\ a)$$

where

$$c = 75\lambda^{'}\left[\frac{g(\rho^{'} - \rho'')}{\sigma}\right]^{0.5}\cdot\left(\frac{a}{v}\right)^{0.2}\left(\frac{1}{r^{*}\rho''w''}\right)^{0.7}$$

$$W^{''} = d_o f$$

Proceeding from the existing theory of nucleate boiling processes, the real heat transfer coefficient during nucleate boiling is calculated by Eq. (3) or Eq. (4) [8] :

$$\alpha = c^{10/3}\left(T - T_s\right)^{10/3-1}. \qquad (4)$$

Overheat of a boundary layer at the beginning of the transient nucleate boiling process is approximately evaluated as [8]:

$$\vartheta_I = 0.293\times\left[\frac{2\lambda\left(\vartheta_o - \vartheta_I\right)}{R}\right]^{0.3} \qquad (5)$$

When quenching cylindrical sample 20 mm diameter in cold water under pressure 1 MPa, the overheat is equal to 25.6 °C, *i.e.*

$$\vartheta_I = 0.293 \times \left[\frac{2 \times 23 \times 645}{0.01}\right]^{0.3} = 25.6^o C$$

Such overheat of a boundary layer generates thousands of vapor bubbles oscillating with the high frequency that increases HTC cardinally during the nucleate boiling process.

Results of calculations of real HTCs are shown in Table 1.

TABLE I

Heat transfer coefficients (W/m^{2}K) at the beginning and the end of the transient nucleate boiling process when pressure is 1 MPa for cylindrical probe of 20 mm diameter.

$T - T_s$, °C	25.6	10
α, W/m^{2}K (Experiment)	109375	12500
α, W/m^{2}K (Analytical)	113570	12800

Heat transfer coefficient during natural convection is evaluated exploring well known Eq. (6) [9]:

$$\alpha_{conv} = 0.135 \cdot \left(\frac{g\beta\Delta T}{a\nu}\right)^{1/3} \tag{6}$$

Convective heat transfer coefficients (W/m^{2}K) versus pressure and water temperature at the beginning of convection are collected in Table 2 [10].

TABLE II

Convective heat transfer coefficient (W/m^{2}K) versus pressure and water temperature at the beginning of convection [10].

P, MPa	Water 10°C	Water 20°C	Water 30°C
0.1	548	640	1015
0.2	586	690	1105
0.4	625	740	1196
0.6	648	79	1246
0.8	664	790	1280
1.0	677	806	1310

As seen from Table 1 and Table 2, $\alpha_{nb} >> \alpha_{conv}$, $Bi_{nb} >> Bi_{conv}$, $Bi_V{}^{nb} >> Bi_V{}^{conv}$. And we can conclude that

$$Bi_V{}^{conv} << Bi_V{}^{nb} \tag{7}$$

Here $Bi_V{}^{conv}$ is the generalized Biot number during convection; $Bi_V{}^{nb}$ it is the generalized Biot number during the nucleate boiling process.

Considering the big difference between convective HTC and HTC observed during the transient nucleate boiling process, it was formulated a notion called the self–regulated thermal process. Information was published in many scientific papers [8]. To understand what is the self – regulated thermal process, let's consider a well known universal correlation (8) [11] :

$$\frac{\overline{T}_{sf} - T_s}{\overline{T}_V - T_s} = \frac{1}{\sqrt{Bi_V{}^2 + 1.437 Bi_V + 1}} \tag{8}$$

Here $\overline{T}_{sf}$ is the average surface temperature; $\overline{T}_V$ it is the average volume temperature.

Taking into account Eq. (7), assume that during the transition to convection $Bi_V \to 0$. In this case, according to Eq. (7), $\overline{T}_{sf} \to \overline{T}_V$. It means that surface temperature must increase immediately when it drops below T$_s$. Assume now that the overheat of the boundary layer is rather large. In this case, the generalized Biot number Bi_V tends to infinity, *i.e.* $Bi_V \to \infty$. According to Eq. (8), in this case, $\overline{T}_{sf} \to T_s$ it means no nucleate boiling. Thus, the steel part's surface temperature must be very close to the boiling point from the very beginning of cooling. The overheat $\Delta\zeta$ is small as compared with the initial temperature T$_0$, which can be formulated as [8]:

$$T_{sf} = T_S + \Delta\zeta \approx const \tag{9}$$

The intensive quenching during nucleate boiling is explained by acting thousands of vapor bubbles. Such a process's main characteristic is the average vapor bubble growth rate $\overline{W}'' = d_o f$ which is essentially affected by pressure. When liquid overheating $\Delta T = T_w - T_s$ increases, the number of nucleating centers also increases too. The number n of nucleating centers increases by direct proportion to the cube of the temperature difference [7]:

$$n \sim \Delta T^3 \tag{10}$$

That is while it is true Eq. (9).

It is of great practical interest to know the effect of aqueous salt solution concentrations on the nucleate boiling process's inner characteristics. Results of experiments dealing with NaCl and Na$_2$CO$_3$ at normal pressure are presented in Table 3 [7].

TABLE III

Effect of concentration on boiling inner characteristics [7].

Substance	d_0, **mm**	$f, 1/s$	$W'' = d_o f$, **mm/s**
Water	2.5	62	155
25% NaCl solution	2.4	64.5	155
29% Na$_2$CO$_3$ solution	2.4	65	156

For high-concentration solutions of NaCl and Na$_2$CO$_3$, their vapor bubble growth rates during quenching are the same, and they are equal to W'' water. Also, it was shown that for different materials, the vapor bubble growth rates are almost the same (see Table 4)

TABLE IV

Effect of heated surface material upon bubble release diameter and release frequency of vapor bubblers [7].

Material	d_o, mm	$f, 1/s$	$W'' = d_o f$, mm/s	Average value d_o, mm	Average value $f, 1/s$	Average value $W'' = d_o f$, mm/s
Permanite	2.5	61	153			
Brass	2.3	67	157	2.5	62	155
Copper	2.8	56	157			

III. QUENCHING IN WATER AND WATER SOLUTIONS UNDER PRESSURE

Quenching in liquid media under pressure is based on the self – regulated thermal process. The self-regulated thermal process (SRTP) is a transient nucleate boiling process when the film boiling is absent. The part surface temperature remains at the level just above the liquid boiling point for a relatively long time. It never drops below the boiling point until the temperature gradient within the part satisfies the convection mode of heat transfer (see Fig. 1 and Fig. 2) [8, 12]. As discussed, the SRTP occurs when the HTC during transient nucleate boiling is very large, and HTC during convection is small. In this case, a big difference between the HTCs acts as a relay, retaining the surface temperature at the level of the boiling point of the liquid.

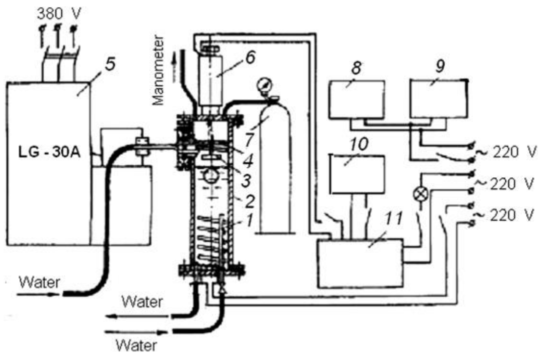

Fig. 1: Schematic illustration of the installation used for quenching steel test specimens in liquid media using controlled pressure [8]: 1, coil pipe; 2, chamber casing; 3, test specimen; 4, inductor; 5, induction installation; 6, solenoid; 7, tank with compressed air; 8 and 9, potentiometers EPP-09 and PS-11; 10, oscillograph N105; 11, rectifier V-26.

Pressure increases significantly critical heat flux densities that were a reason for the absence of film boiling process when quenching steel samples (see Fig. 3). Combining pressure with the optimal concentration of water salt solutions, it is possible to eliminate any film boiling process that makes cooling intensive and uniform. Interruption cooling at the end of transient nucleate boiling allows a delay of martensite transformation and performing the LTMT process.

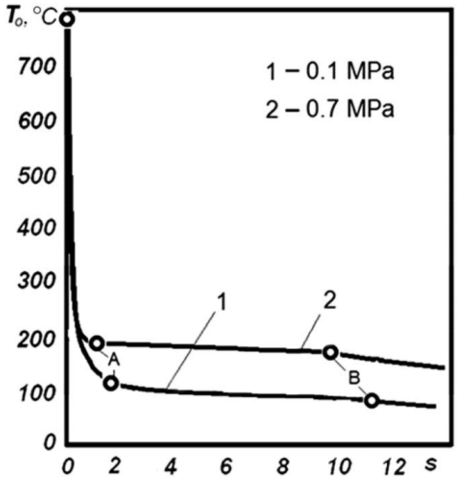

FIG. 2: Effect of redundant pressure on the elevating surface temperature of a 20-mm stainless probe during the self-regulated thermal process [12]: 1. surface temperature at normal atmospheric pressure (0.1 MPa); 2. surface temperature at redundant pressure (0.7 MPa); A is the start of the transient nucleate boiling process; B is the finish of the transient nucleate boiling process; AB is a "shoulder]."

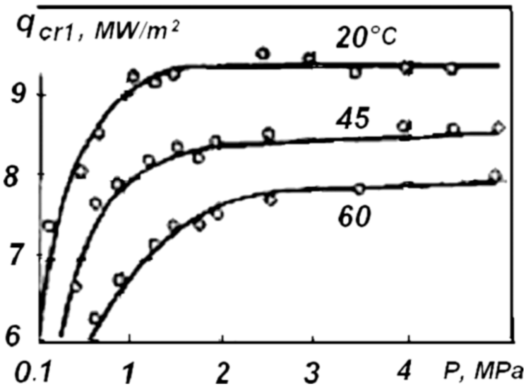

Fig.3: First critical heat flux density qcr1 versus pressure and temperature of water [8].

When film boiling is absent, the double electrical layer is formed when cooling in electrolytes at the very beginning of quenching. Within the initial time of immersion probe into liquid, the boundary layer is heated above its boiling point, developing a transient nucleate boiling process which is self –regulated. It is used for quenching steel parts or forgings under pressure. Pressure increases saturation temperature T_s which can be equal to martensite start temperature Ms (see Table 5).

TABLE V
Water saturation temperature versus pressure

P, *MPa*	0.1	0.2	0.4	0.6	0.8	1.0
T_s, °C	99.6	120.2	143.6	158.8	170.4	180

As one can see from Fig. 2, the cylindrical specimen's surface temperature drops within 1.5 sec, almost to the boiling point of water. It then maintains at that level for 9 seconds until convection starts. The higher the convective heat transfer coefficient (HTC) is, the shorter the self-regulated thermal process is, and the quicker convection starts. Also, the increase in saturation temperature decreases the self–regulated thermal process (see Table 6).

TABLE VI
Initial and ending temperature of the full transient nucleate boiling process and its duration versus pressure (MPa) for an infinite cylinder of 20 mm in diameter when quenching in the water at 20 oC

Pressure, Mpa	Initial temperature, oC	Ending temperature, oC	Duration of transient nucleate boiling, sec
0.1	126	108	14
0.4	169	155	12
0.7	190	175	11
1.0	205	190	10.5

Core and surface temperature versus time of cylindrical probe during its quenching in cold water under pressure I MPa are provided in Fig. 4.

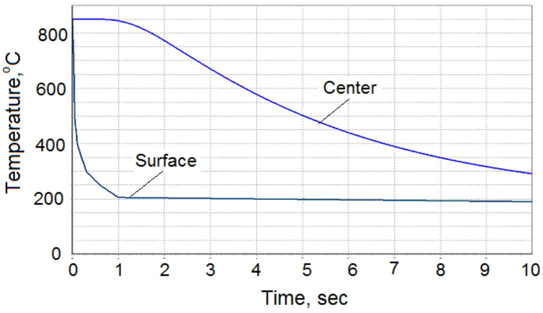

Fig. 4: Surface and core temperature versus time of cylindrical probe during its quenching in cold water under pressure1 MPa.

Heat flux density versus time during quenching in water under pressure I MPa are provided in Fig. 5.

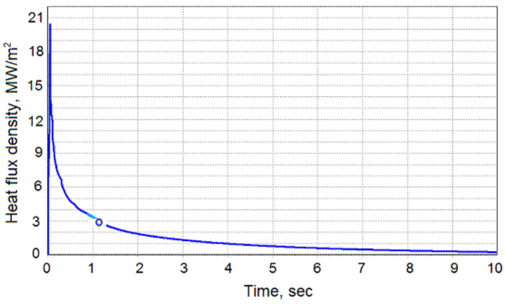

Fig. 5: Heat flux density versus time during quenching in water under pressure I MPa.

Note that heat flux density rapidly decreases vs. time and becomes 3 MPa in 1 second, far below the first critical heat flux density q_{cr1}. It means that maximal heat flux density and maximal Biot numbers (see Fig. 5 and Fig. 6) are observed during shock boiling, and measures for preventing film boiling should be taken at the initial period of quenching.

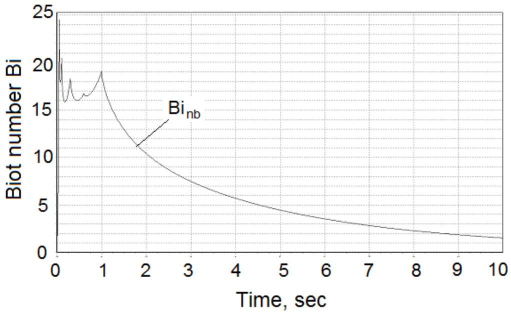

Fig. 6: Real Biot number versus time during quenching cylindrical probe 20 mm diameter in water 20°C under pressure 1 MPa.

Real HTC at the beginning of the self-regulated thermal process (SRTP) is rather high and is equal to

$$\alpha_{real} = \frac{2{,}800{,}000 W/m^2}{26^o C} = 107{,}690 W/m^2 K$$

, while effective HTC is 8 times smaller:

$$\alpha_{eff} = \frac{3{,}000{,}000 W/m^2}{206^o C} = 14{,}634 W/m^2 K$$

At the end of SRTP, the real HTC is

$$\alpha_{real} = \frac{236{,}000 W/m^2}{10\ ^o C} = 23{,}600 W/m^2 K$$

Both HTCs can provide intensive quenching processes. Temperature gradients in steel parts during quenching are governed by real HTCs not effective. Effective HTCs can be used only for core cooling time approximate calculation. Some results concerning effective HTC are discussed below.

Effective HTC vs. time is shown in Fig. 7.

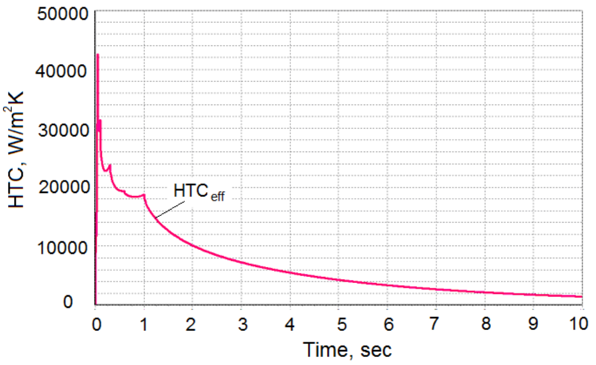

Fig. 7: Effective HTC versus time of cylindrical probe during its quenching in cold water under pressure 1 MPa.

Effective HTC decreases exponentially versus time while Kondrt'ev number Kn is a linear function (see Fig. 7 and Fig. 8).

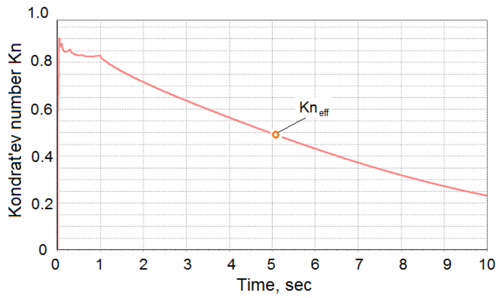

Fig. 8: Effective Kondrat'ev number versus time of cylindrical probe during its quenching in cold water under pressure 1 MPa.

Fig. 9 shows that effective Kondrat'ev number Kn depends on the thickness of the quenched sample and doesn't depend visibly on the form of a sample [13].

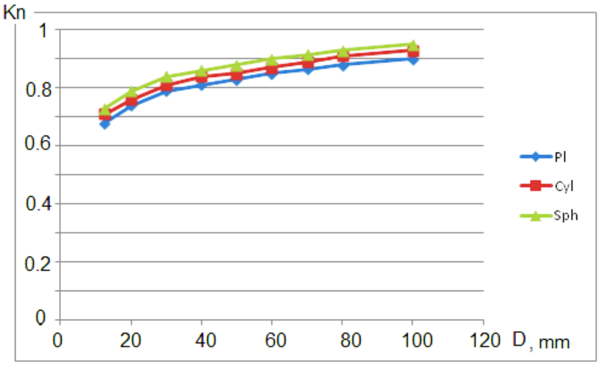

Fig. 9: Effective number Kn versus the size of the plate (Pl), cylinder (Cyl), and sphere (Sph) when convective heat transfer coefficient is 4000 W/ m2K [13].

Steel parts can be quenched in liquid media under pressure where any film boiling process is eliminated using achievements of science that includes:

- Water salt solutions of optimal concentration provide the maximal value of the first critical heat flux density q_{cr1} [8, 14, 15].
- Water solutions of inverse solubility polymers of low concentration decrease initial heat flux density below its critical value qcr1 due to creating the thin polymeric surface insulating layer [16, 17].
- Hydrodynamic emitters destroy any film boiling process due to the resonance effect [18].
- External electrical forces that negatively charge the load prepared for quenching in water-salt solutions of optimal concentration [19].

All of the considered factors can be used in forging shops. They easily destroy a film boiling process that makes technology cheaper in mass production.

Quenching in liquid media (water and water solutions) has a great future because:

- It is possible to reduce distortion of steel parts after quenching [8].
- It is possible to perform a more effectively low-temperature thermomechanical treatment to save alloy elements.
- Quenching in liquid media under pressure can perform an austempering process via cold liquid [20, 21].
- It can be widely used in forging shops to improve the mechanical properties of steel.

Especially promising is quenching optimal hardenability steels under pressure in liquid media [22].

VIII. CONCLUSIONS

1. Cooling in water, water-salt solution of optimal concentration under pressure can be used in forging shops to perform LTMT to increase the strength of materials, decrease alloy elements in steel, and reduce the cost of technology.
2. Effective HTCs can be used for approximate core cooling time calculation of steel parts or forgings.
3. It makes sense to start cooperation with the big forging companies focusing on saving and strengthening materials and making the technological process less costly.

NOMENCLATURE

Bi	Biot number
Bi_V	Generalized Biot number
Kn	Kondrat'ev number
α	Heat transfer coefficient
α_{nb}	Heat transfer coefficient during NB

a	Thermal diffusivity of solid material
c_p	Specific heat capacity
λ	Thermal conductivity of a solid material
ρ'	Density of liquid
ρ''	Vapor density
$r^{\bullet}$	Latent heat of evaporation
σ	Surface tension
D	Diameter or thickness
d_o	Diameter of bubble
R	Radius
f	Bubble release frequency
τ	Time in seconds
K	Kondrat'ev form coefficient
q	Heat flux density
T_w	Wall temperature in ^{o}C
g	Gravity acceleration
W''	Vapor bubble growth rate
ν	Kinematic viscosity

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