New Evidences which Support Existence of the Forced Heat Exchange Phenomenon

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ABSTRACT

In the paper the forced heat exchange phenomenon is validated based on experimental data shown by different authors in different countries and published in respected scientific journals. Software IQLab and regular thermal condition theory were used for solving inverse problems. The data of silver and copper spherical probes quenching in electrolytes were used. As in previous publication, it was established in the paper that heat transfer coefficients (HTCs) increase versus time during quenching of silver and copper probes in electrolytes. As noted early, all of this contradicts the theory of transient nucleate boiling processes. The problem is solved by periodical replacement of film boiling by shock boiling with the high frequency that takes place during quenching. The new idea can be used in practice for designing new and original quenching technology to save materials, increase service life of machine components and also provide an environmentally friendly solution. The importance of new technologies is widely discussed in the paper.

Keywords: New phenomenon, additional evidences, shock and film boiling replacement, advanced technology.

Published Online: January 16, 2021

ISSN: 2684-4451

DOI : 10.24018/ejphysics.2021.3.1.41

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I. INTRODUCTION

A new phenomenon of physics was discovered recently which consists in periodical replacement of film boiling by shock boiling with the high frequency [1], [2]. The idea was formulated after analysis heat transfer coefficients (HTCs) connected with the quenching of silver probe in electrolytes of optimal concentration. As known, the density of free electrons in silver probe is much higher as compared with steel. When quenching the silver probe in electrolyte of optimal concentration, the double electrical layer is immediately formed where high electrical forces appear. These electrical forces move the film boiling boundary to metal resulting in shock boiling process. On the other hand, silver, due to its very high thermal conductivity, generates very high heat flux density resulting in film boiling process. Balance between them can be created when periodical process starts. Such periodical process easily explains the contradiction consisting in increase the heat transfer coefficient (HTC) versus time during quenching because the role of film boiling decreases and nucleate boiling increases. The discussed idea was supported by data obtained during quenching of silver probe. To be sure that idea works, in this paper additional experimental data were used for solving direct and inverse problem to see similar results during quenching of copper probe. Also, elevated temperature of electrolyte should decrease average heat transfer coefficients (HTCs) during quenching of silver or copper probes if the mentioned phenomenon exists. Proceeding from this point, the experimental results of French and Petrash [3]-[5] were used for evaluating HTCs

and after appropriating their analysis is clearly seen that discovered phenomenon can be used for developing new technologies. These important problems are discussed below.

II. ANALYSIS OF FRENCH'S EXPERIMENTS

There are many published accurate experiments of French [3], [4] which can be used for solving inverse problem and analyzing results of calculation to support the idea on existence of forced heat exchange phenomenon. In the paper were used experiments of French made with steel and copper spherical samples 1.5 inches (38.1 mm) in diameter. The thermocouples were located on the surface of spherical samples and in their centers. Some results of his accurate experiments are presented in Fig. 1.

As is seen from Fig. 1, during quenching of steel sample the self – regulated thermal process is established immediately after immersion the sample into liquid. To restore the surface temperature up to end of transient nucleate boiling process, the equation (1) was used [2]:

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

For still bath the convective HTC is approximately equal to 1000 W/m²K while for agitated bath with 1 m/s it is equal to 4000 W/m²K. For both conditions the convective Biot numbers are: Bi = 0.83 and Bi = 3.3. According to Ref. [2], for given convective Biot numbers $\overline{\Omega} = 3.5$ and $\overline{\Omega} = 2$.

For the first and second cooling conditions the duration of the self – regulated thermal process is

$$\tau_{nb} = 3..5 \times 0.0253 \times \frac{(0.038.1)^2}{5.4 \times 10^{-6}} = 23.8s \text{ and } 13.6s.$$

Fig.1. Temperature at the surface and in the core versus time for steel and copper spherical samples of 38.1-mm diameter, quenched from 875 °C in water at room temperature (French's experiment [3]): 1, core; 2, surface.

Using reconstructed surface temperature of French, the core temperature curve was calculated to compare it with the experiment of French (see Fig. 2). Results of experiment and calculations coincide well enough. It means that we can expect correct data in heat flux density and HTC calculations. The calculations were fulfilled using thermal properties which are presented in Table 1 and Table 2.

Fig. 2 shows the reconstructed surface temperature which was used for heat flux density and heat transfer coefficients calculations presented in Fig. 3 and Fig. 4.

By comparing core cooling curves on Fig.1 and Fig. 2, it is seen that calculated and experimental data coincide very well enough. The small difference between them is explained by some differences between thermal properties of materials and grain sizes of microstructure of steel which was tested.

As seen from Fig. 3, the maximum heat flux density appears at the very beginning of quenching that is explained by shock boiling process. It lasts approximately one second and heat flux density during this time drops to 3 MW/m². This is worth to know when developing new quenching technology based on use external electrical forces.

The same trend in decreasing the heat transfer coefficient versus time is shown in Fig. 4. During quenching of steel spherical probe, the heat transfer coefficient decreases exponentially very rapidly beginning from the shock boiling process (see Fig. 4).

Fig. 2. Surface and core temperature cooling curves versus time during quenching from 875 °C spherical probe 38.1 mm diameter in low concentration of electrolyte at 20 °C.

Fig. 3. Heat flux density versus time during quenching from 875 °C spherical probe 38.1 mm diameter in low concentration of electrolyte at 20 °C.

Fig. 4. Heat transfer coefficient evaluated as $\alpha = q / (T - T_s)$ versus time during quenching from 875 °C the spherical probe 38.1 mm diameter in low concentration of electrolyte at 20 °C.

TABLE 1: THERMAL CONDUCTIVITY (W/MK)

Material	T, °C								
	100	200	300	400	500	600	700	800	900
AISI 304	15.6	17.6	19.4	21.0	22.3	23.6	24.8	25.2	27.0
Copper	384.9	389.6	371	365	359.4	353.5	347.7	340.8	332.6
Silver	392	372.2	361.7	361.7	366.3	374.5	-	-	-

TABLE 2: THERMAL DIFFUSIVITY OF COPPER IN M²/S

Material	T, °C								
	100	200	300	400	500	600	700	800	900
Steel 304 × 10 ⁻⁶	4.55	4.63	44.70	4.95	5.34	5.65	5.83	6.19	6.55
Copper × 10 ⁻⁴	1.11	1.08	1.04	1.01	0.98	0.94	0.91	0.89	-

In contrast to obtained results of calculations, during quenching silver spherical probes in electrolytes, heat transfer coefficient increases versus time in 2 – 3 times that contradicts the nucleate boiling theory. Solution was found by proposing phenomenon on forced heat exchange [1, 2]. If the idea is true, the same increase of heat transfer coefficient must be observed during quenching of copper spherical probes in electrolytes. Some experimental data connected with the quench process of copper spherical probe is available from Fig. 1. Using obtained by French data and regular thermal condition theory of Kondrat'ev [6]-[8], it is possible to evaluate average heat transfer coefficients.

In Table 3 are provided core cooling rates of spherical copper samples depending on core temperature of the probe.

TABLE 3: COOLING RATE OF SPHERICAL COPPER SAMPLE 38.1 MM DIAMETER DURING QUENCHING IN ELECTROLYTE OF LOW CONCENTRATION AT 20 °C.

T, °C	700	500	350
Cooling rate, °C/s	222	187	94

Based on these data, extracted from Fig. 1, it is possible to evaluate HTC's using regular thermal condition theory. The method of evaluation is rather simple and is as following. Cooling rate, according to regular thermal condition theory is calculated by Eq. (2) [6], [7]:

$$v = \frac{aKn}{K}(T - T_s) \quad (2)$$

which can be rewritten as

$$Kn = \frac{vK}{a(T - T_s)} \quad (3)$$

Here $K = \frac{R^2}{\pi^2}$. For spherical probe of thickness 38.1 mm diameter $K = 36.77 \times 10^{-6} m^2$.

After evaluation of Kondrat'ev number Kn , the generalized Biot number is evaluated from universal correlation (4):

$$Kn = \frac{Bi_v}{(Bi_v^2 + 1.437 Bi_v + 1)^{0.5}} \quad (4)$$

As known, the generalized Biot number Bi_v is a value:

$$Bi_v = \frac{\alpha}{\lambda} K \frac{S}{V} \quad (5)$$

Here α is heat transfer coefficient; λ is thermal conductivity of metal; S is surface; V is volume.

Knowing its value, the specific heat transfer coefficient approximately is evaluated as:

$$\alpha = \frac{\lambda Bi_v V}{KS} \quad (6)$$

Table 4 presents results of HTC's calculations versus core temperature of the copper spherical probe.

TABLE 4: HEAT TRANSFER COEFFICIENTS VERSUS CORE TEMPERATURE OF COPPER SPHERICAL PROBE 38.1 MM DIAMETER DURING QUENCHING IN ELECTROLYTE OF LOW CONCENTRATION AT 20 °C

T, °C (Center)	700	500
T, °C (Surface)	400	250
HTC, W/m ² K	30565	46630

When surface temperature is 250 °C or 400 °C, the developed film boiling takes place which is evaluated by Eq. (7) [9]:

$$\alpha_F = 0.25 \left(\frac{\lambda'' c_p (\rho' - \rho'')}{v''} \right)^{1/3} \quad (7)$$

It is equal to 200 W/m²K that is 150 and 230 times lesser as compared with the results obtained in Table 4. Also, it can not be the nucleate boiling process because the surface temperature exceeds several times the critical value where film boiling starts. Only phenomenon on forced heat exchange can explain such differences.

III. ANALYSIS OF PETRASH'S EXPERIMENTS

The phenomenon of periodical replacement of film boiling by shock boiling explains such strange behavior of HTC presented in Table 4. If mentioned phenomenon is true, quenching in warm and hot electrolytes should decrease HTC's because film boiling prevails in this case. To check decreasing HTC's with increasing temperature of electrolyte, Petrash's experimental results of cooling rate measurements were used (see Fig. 5). Film boiling should prevail during quenching with increasing bath temperature because critical heat flux density decreases with decreasing underheat $\mathcal{G}_{uh}$ (see Eq. (8)) [9], [10].

$$q_{cr1}^{uh} = q_{cr1} \left[1 + 0.065 \left(\frac{\rho'}{\rho''} \right)^{0.8} \frac{c_p \mathcal{G}_{uh}}{r \cdot} \right] \quad (8)$$

Here $\mathcal{G}_{uh} = T_s - T_m$ is underheat in °C.

Fig. 5. Effect of temperature water NaCl solution (15%) on cooling rate of silver spherical probe 20 mm diameter during quenching [4], [5].

The experimental results shown in Fig. 5 were used for calculating HTC's versus core temperature of silver spherical probe exploring the same method of calculation (see Eq. (6)). The results of calculations are provided in Table 5 and Table 6.

TABLE 5: EFFECT OF TEMPERATURE WATER NaCl SOLUTION (15%) AND CORE TEMPERATURE OF SILVER SPHERICAL PROBE 20 MM DIAMETER ON KONDRAT'EV NUMBER KN DURING QUENCHING IN ELECTROLYTES OF DIFFERENT TEMPERATURES

Temperature of electrolyte	Kn (NaCl)				
°C	700°C	600°C	500°C	400°C	300°C
20	0.208	0.270	0.385	0.489	0.532
40	0.137	0.210	0.236	0.315	0.402
60	0.0989	0.139	0.193	0.217	0.280

TABLE 6: EFFECT OF TEMPERATURE WATER NaCl SOLUTION (15%) AND CORE TEMPERATURE OF SILVER SPHERICAL PROBE 20 MM DIAMETER ON HTC (W/M2K) DURING QUENCHING

Bath temperature, °C	HTC (NaCl)				
°C	700°C	600°C	500°C	400°C	300°C
20	27880	43670	69830	97880	116815
40	18760	29615	34560	50030	71470
60	13270	18880	27700	30970	42880

Table 6 shows increasing HTC's vs decrease of core temperature of silver 20 mm probe. Simultaneously, with increasing bath temperature HTC decreases during quenching in electrolyte that is in good agreement with the idea on phenomenon discussed.

The effect of free electrons in metal on quenching process is considered in Refs [11]-[13]. Practical use of some innovations was discussed in publications [14]-[16]. The observed phenomenon can be further successfully investigated on the basis of solving hyperbolic heat conductivity equation with the boundary condition that takes into account electrical forces in the double electrical layer.

IV. DISCUSSION

Obtained results of calculations and their analysis have shown that maximum heat flux density appears at the very beginning of quenching and it lasts within two initial seconds. Then the heat flux density quickly drops below the critical heat flux density that prevents the film boiling formation. Author [2] recommended using short time electrical external force to prevent process of film boiling formation at the initial time of quenching. Moreover, nowadays in heat treating industry water salt solutions of NaNO_2 , NaNO_3 and Na_2CO_3 are used as a quenchant. As a rule, optimal concentration is used where dissolved cations and anions are at their maximum and the first critical density and HTC are maximal too (see Fig. 6). Note that the electrical conductivity of the water and water salt solutions depends on their temperature: the higher the temperature, the higher is the electrical conductivity. For example, the electrical conductivity of water increases by 2-3% for an increase of 1 degree Celsius of water temperature.

Fig. 6. Average heat transfer coefficients versus the concentration of NaCl and NaOH in water at 20°C [4].

According to the classical statistical thermodynamic, the pressure created by free electrons in metal is directly proportional to the absolute temperature T and is considered as:

$$P = nkT \quad (9)$$

where n is a number of electrons in one sm^3 of metal; k is the Boltzmann constant which is equal to $k = 1.3806488(13) \times 10^{-23} [\text{JK}^{-1}]$.

For the high electrical conductivity metals like silver and copper the number of free electrons n_{ml} in one sm^3 is several times larger as compared with steel, i.e., $n_{ml} \gg n_{steel}$. As a result, in a double electrical layer high electrical forces appear when quenching such metals in electrolyte of optimal concentration (see Fig. 7).

Fig. 7. Schematic explanation of creation the double electrical layer during quenching in electrolytes.

The experimental validation of existence electrical forces in the double boundary electrical layer that generates thermal waves (see Fig. 7) was made by authors [12] in 2017.

Due to free electrons in metal rather high electrical forces appear in double electrical boundary layer during quenching in electrolytes resulting in extremely high temperature gradients during immersion of metal into cold liquid. That is a reason for existence the replacement of film boiling by shock boiling. One should consider hyperbolic heat conductivity equation (5) with the boundary condition that takes into account electrical forces in the double electrical layer. It was established that during quenching probe (see Fig. 7) from 500 °C in water at 20 °C, the left end of the probe does not generate visible thermal waves or impulses. Effect was observed when heated left end of the probe was immersed into electrolyte of optimal concentration [12]. It means that the double electrical layer is acting like

amplifier bumping electrons from the left side to the right side (see Fig. 7). Several interesting effects were recorded which were discussed in [12].

The weak effect, concerning thermal wave distribution, follows from the solution of the hyperbolic heat conductivity equation. Authors [16], [17] considered hyperbolic heat conductivity Eq. (10) with the boundary and initial conditions (11) and initial condition (12)

$$c\rho \frac{\partial T}{\partial \tau} + \tau_r \frac{\partial^2 T}{\partial \tau^2} = \operatorname{div}(\lambda \operatorname{grad} T) + \frac{\partial q}{\partial T} \frac{\partial T}{\partial \tau} \quad (10)$$

At present time the boundary condition (11) is used that doesn't take into account electrical forces in the boundary double electrical layer

$$\left[\frac{\partial T}{\partial r} + \frac{\beta^m}{\lambda} (T - T_s)^m \right]_{r=R} = 0 \quad (11)$$

Here $m = 10/3$.

$$T(r, 0) = T_0 = \text{const} \quad (12)$$

Authors [16, 17] came to conclusion that the analytical solving of formulated problem (10), (11), (12) is reduced to the problem of finding the unknown function from the following integral (13):

$$h(\varphi) = g(\varphi) \cdot \left\{ 1 - \int_0^{\varphi} G(\varphi, \psi) \cdot h(\psi) d\psi \right\}^m \quad (13)$$

Here Green function $G(x, \xi, t)$ is classic Green function for heat conductivity equation with Neumann boundary conditions [16]:

$$G(x, \xi, t) \stackrel{\text{def}}{=} \frac{1}{l} + \frac{2}{l} \sum_{n=1}^{\infty} e^{-\left(\frac{a\pi n \sqrt{t}}{l}\right)^2} \cos\left(\frac{\pi n x}{l}\right) \cos\left(\frac{\pi n \xi}{l}\right) \quad (14)$$

From the solving of the hyperbolic heat conductivity equation, authors [11] derived the thermal wave distribution:

$$\theta_{\text{zero}}(x, \tau) = \frac{\sqrt{\tau_r} e^{-\frac{x^2}{4a\tau}}}{\sqrt{\tau}} \quad (15)$$

where $w_r = \sqrt{\frac{a}{\tau_r}}$ is the speed of thermal wave.

When $\tau = \tau_r$, Eq. (15) can be rewritten as [11]:

$$\theta_{\text{zero}}(x, \tau) = e^{-\frac{x^2}{4a\tau}} \quad (16)$$

which resembles an instant impulse of the temperature known from the parabolic heat conductivity equation. Here T is a temperature; τ is a time; α is a heat transfer

coefficient ($\text{W/m}^2\text{K}$); λ is a thermal conductivity of steel (W/mK); ρ is a material density (kg/m^3); q is a heat flux density (W/m^2); c is a specific heat capacity; a is a thermal diffusivity of steel (m^2/s); S is a surface, V is a volume; R is a radius; x and r are coordinates; β is equal to 3.41 for water.

As seen from Eq. (14), thermal signal is very weak because r^* is very small and exponent rapidly decreases versus time.

More information on solving of the hyperbolic heat conductivity equation suitable for conventional and intensive quenching processes is presented in Refs. [16], [17].

To successfully investigate behavior of forced exchange phenomenon and thermal wave distribution, the boundary condition should include electrical forces that take place during quenching metals in electrolytes. Currently, nobody is considered such approach which could bring many important solutions.

Further theoretical and experimental investigations should be done in this field. Especially important issue is the experimental validation the duration of external electrical force to be used at the beginning of metal quenching and its maximum value to eliminate completely any film boiling process during hardening of material. If carefully investigated, the heat treating industry will explore the most advanced technology with the many benefits being very cheap and simple as compared with existing technologies. The new technology can be controlled by patented in Ukraine system [18].

V. CONCLUSION

An idea on replacement the film boiling by shock boiling with the high frequency is supported by experimental data. The shock boiling generates forced heat transfer exchange (maximal HTC) due to oscillating with the high frequency thousands of tiny vapor bubbles. Periodical resplendent of film boiling by shock boiling, that is the essence of discovered phenomenon, increases cardinal average heat transfer coefficient and HTC versus time. The innovation can be used for designing original quenching technology to save materials, increase service life of machine components, and improve environment condition. The phenomenon is observed during quenching in electrolytes of high thermal conductivity materials like silver, copper, and others.

NOMENCLATURE

a	Thermal diffusivity of solid material in m^2/s
Bi	Conventional Biot number
Bi_V	Dimensionless generalized Biot number
c_p	Specific heat capacity in $\text{J/kg} \cdot ^\circ\text{C}$
D	Diameter or thickness in m
Kn	Kondrat'ev dimensionless number
K	Kondrat'ev form factor in m^2
k_F	Dimensionless form coefficient
P	Pressure in MPa
R	Radius in m
r^*	Latent heat of vaporization in J/kg

q_{cr1}	The first critical heat flux density in W/m^2
S	Surface in m^2
T	Temperature in $^{\circ}C$
T_o	Initial austenitizing temperature in $^{\circ}C$
T_s	Saturation temperature in $^{\circ}C$
T_m	Bath temperature in $^{\circ}C$
α	Heat transfer coefficient in W/m^2K
β	Function of physical properties of liquid
ρ	Density in kg/m^3
ρ'	Liquid density in kg/m^3
ρ''	Vapor density in kg/m^3
ν''	Kinematical viscosity of the vapor in m^2/s
λ	Thermal conductivity in W/mK
τ_r	Relaxation time in s
Ω	Function of convective Bi and temperature T_o
g_{uh}	Underheat in $^{\circ}C$

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