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RESEARCH ARTICLE

PHYSICS OF "POKER" EFFECT

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ABSTRACT

In the paper, a physics of the "poker" effect was investigated experimentally and discussed by authors. Some unusual effects were discovered during experiments when heated end of the probe was quenched in an electrolyte of the optimal concentration. It's impossible to explain the results obtained using solutions of the parabolic heat conductivity equation. The physics of the "poker" effect can be clearly explained if to take into account an existence of free electrons in the metal and the instant formation of a double electric layer. It is shown that the discovered effects can be used for an accurate evaluation of the relaxation time, which is constant for a given material. The discovery can be also used for predicting film boiling processes. A proposal is formulated to combine the evaluation of the material physical properties and Jominy curves. The importance of continuing further theoretical and experimental investigations in this field is underlined.

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INTRODUCTION

A long time ago, metallurgists noticed that quenching of a poker end that was heated to a high temperature produces an instant burning effect on another cold end of the poker. This effect is called a "poker" effect. The poker effect was explained for the first time by authors (Kobasko and Guseynov, 2012; Kobasko, 2018,a). However, nobody carried out properly painstaking experiments to collect data concerning this unusual phenomenon. To understand better the "poker" effect, let's consider some well-known facts of the statistical physics (Nozdrev and Senkevich, 1969). Proceeding from the classical statistical thermodynamics, it is possible to explain thermal waves as the movement of free electrons. According to the statistical thermodynamics, the average kinetic energy E of electrons is (Nozdrev and Senkevich, 1969):

$$\overline{E} = \frac{3}{2}kT \qquad \text{.............................. (1)}$$

On the other hand, the movement of free electrons in metal creates very high pressure P, which can be calculated by equation (2):

$$P = \frac{2}{3}n\bar{E} \qquad \text{...................................... (2)}$$

Here n is a number of electrons in one sm3 of metal; k is the Boltzmann constant, which is equal to $k = 1.3806488(13) \times 10^{-23}[JK^{-1}]$. As it follows from equations (1) and (2):

$$P = nkT \qquad \text{....................................... (3)}$$

It means that the pressure created by free electrons in metal is directly proportional to the absolute temperature T.

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When quenching in an electrolyte the heated end of the poker (shown in red and orange colors in Fig. 1), the electrons move to the poker colder area where the electron pressure is less. These electrons create a negative charge (a double electric layer (Frenkel, 1959)), which kicks the next coming electrons to the opposite cold end of the poker.

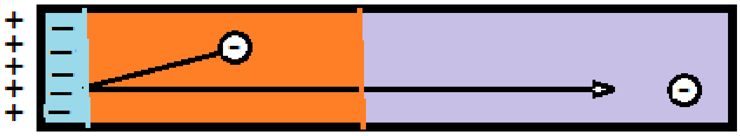


Fig. 1. Schematic explaining a poker effect based on statistical physics laws

The double electric layer is like a mirror that resends electrons to the cold end of the poker increasing slightly the temperature in that area. A possible explanation of the "poker" effect can be derived also by solving a hyperbolic heat conductivity equation. The hyperbolic heat conductivity equation was derived by considering a modified law of Fourier that takes into account the existence of free electrons in metal (Kobasko and Guseynov, 2012; Kobasko, 2018,a). According to the conventional law of Fourier, the heat flux is calculated using the following formula (Lykov, 1967):

$$q = -\lambda \frac{\partial T}{\partial x} S d\tau \qquad \text{...} (4)$$

On the other hand, the amount of thermal energy can be calculated as:

$$q = c\rho dVdT = c\rho SdxdT \qquad \text{...} (5)$$

Using the energy conservation law, one can get the following energy balance equation from formulas (4) and (5):

$$-\frac{\partial q_x}{\partial x} = c\rho \frac{\partial T}{\partial \tau} \qquad \text{...} (6)$$

Equation (4) doesn't take into account the free electrons in metal. Authors (Vernotton, 1961 and Lykov, 1967) modified the Fourier law as

$$q_x = -\lambda \frac{\partial T}{\partial x} - \tau_r \frac{\partial q_x}{\partial \tau} \qquad \text{...} (7)$$

where the second term of Eq. (7) is responsible for the additional heat flux density generated by the movement of free electrons. The value τ_r is called a relaxation time. It is a characteristic of the free electrons movement, and it is a constant which depends on the nature of the material.

Substituting Eq. (7) into Eq. (6) leads to

$$\lambda \frac{\partial^2 T}{\partial x^2} + \tau_r \frac{\partial^2 q_x}{\partial x \partial \tau} = c\rho \frac{\partial T}{\partial \tau} \qquad \text{...} (8)$$

By differentiating Eq. (6) by τ , one can get the following:

$$\frac{\partial^2 q_x}{\partial x \partial \tau} = -c\rho \frac{\partial^2 T}{\partial \tau^2} \qquad \text{...} (9)$$

It means that Eq. (8) can be rewritten as

$$\frac{\partial T}{\partial \tau} + \tau_r \frac{\partial^2 T}{\partial \tau^2} = a \frac{\partial^2 T}{\partial x^2} \qquad \text{...} (10)$$

For the dimensionless temperature $\theta = \frac{T - T_m}{T_0 - T_m}$, equation (10) can be considered as:

$$\frac{\partial \theta}{\partial \tau} + \tau_r \frac{\partial^2 \theta}{\partial \tau^2} = a \frac{\partial^2 \theta}{\partial x^2}, \qquad \text{...} (11)$$

which is a hyperbolic heat conductivity equation. Here T_m is a medium temperature; T_0 is an initial temperature.

A similar approach can be used for cylindrical and spherical configurations, and then the hyperbolic heat conductivity equation has the following form (12):

$$\frac{\partial\theta(r,\tau)}{\partial\tau}+\tau_r\frac{\partial^2\theta(r,\tau)}{\partial\tau^2}=a\left(\frac{\partial^2\theta(r,\tau)}{\partial r^2}+\frac{j-1}{r}\frac{\partial\theta(r,\tau)}{\partial r}\right) \qquad (12)$$

$j = 1,2,3$; $j = 1$ for a plate; $j= 2$ for a cylinder; $j =3$ for a sphere.

A boundary condition for the transient nucleate boiling process can be written as:

$$\left[\frac{\partial T}{\partial r}+\frac{\beta^m}{\lambda}\left(T-T_S\right)^m\right]_{r=R}=0 \qquad (13)$$

After the transient boiling process is completed, a convection mode of heat transfer starts, and the third kind of the boundary condition for the convective heat transfer mode takes place:

$$\left[\frac{\partial T}{\partial r}+\frac{\alpha_{conv}}{\lambda}(T-T_m)\right]_{r=R}=0 \qquad (14)$$

The transition from nucleate boiling to convection is determined from the following condition:

$$q_{nb}\equiv q_{conv} \qquad (15)$$

Also, the initial thermal condition and symmetrical conditions should be taken into account:

$$T(r,0)=T_0 \qquad (16)$$

$$\frac{\partial T(0,\tau)}{\partial r}=0 \qquad (17)$$

Solving the hyperbolic heat conductivity equation, authors (Kobasko and Guseynov, 2012) derived the following approximation for the thermal wave distribution:

$$\theta_{zero}(x,\tau)=\frac{\sqrt{\tau_r}e^{-\frac{x^2}{4a\tau}}}{\sqrt{\tau}} \qquad (18)$$

The speed of wave is $w_r=\sqrt{\frac{a}{\tau_r}}$.

When $\tau=\tau_r$, Eq. (18) can be rewritten in a simpler form (Kobasko and Guseynov, 2012):

$$\theta_{zero}(x,\tau)=e^{-\frac{x^2}{4a\tau}} \qquad (19)$$

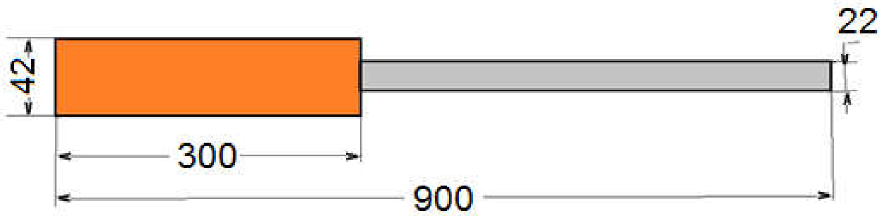
which resembles an instant impulse of the temperature known from the parabolic heat conductivity equation. Here T is a temperature; τ is a time; α is a heat transfer coefficient (W/m^2K); λ is a thermal conductivity of steel ($\frac{W}{mK}$); ρ is a material density (kg/m^3); q is a heat flux density (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.

More information on solving of the hyperbolic heat conductivity equation suitable for conventional and intensive quenching processes is presented in Refs. (Guseynov *et.al.,* 2010; Buikis *et.al.,* 2014, 2017, 2018). This paper discusses the first results of experiments, which were focused on studying the "poker" effect.

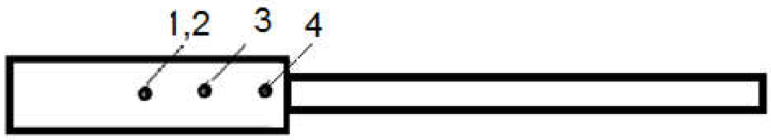
Probe and set-up for investigating of "poker" effect

To investigate the poker effect, a special probe made of carbon steel was prepared as shown in Fig. 2a. A section of the thicker probe end having a length of 120mm was immersed into an electric furnace with the temperature of 500°C. Two different heating times were used: 30 and 120 minutes. Two thermocouples were located at the distance of 150 mm from the probe hot (left) end:

thermocouple 1 at the core of the probe and thermocouple 2 on the surface of the probe (Fig. 2b). Thermocouples 3 and 4 were located on the surface of the probe at the distance of 220 mm and 290 mm from the probe hot end.



a)



b)

Fig. 2 Probe made of carbon steel used to investigate the "poker" effect during cooling in water and water salt solutions: a) Probe dimensions; b) Locations of thermocouples instrumented in the probe, 1 is a thermocouple located at the core of the probe at the distance of 150 mm from the left end of the probe, 2 is a thermocouple located on the surface of the probe at the same distance; 3 is a surface thermocouple located at the distance of 220 mm from the left end of the probe; 4 is the surface thermocouple located at the distance of 290 mm from the left end of the probe

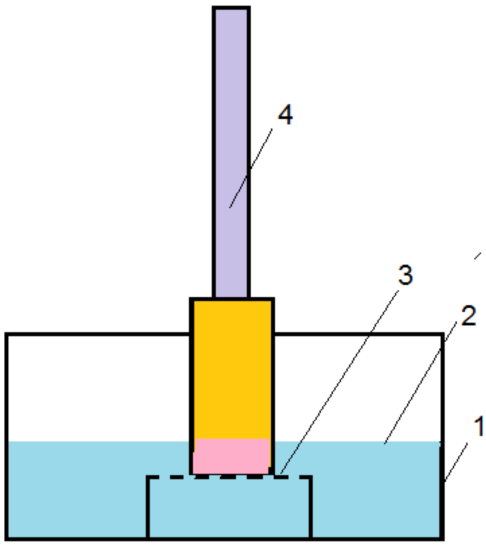


Fig. 3. Experimental set-up for investigation of the "poker" effect during cooling in water and water salt solutions: 1 is a small tank, 2 is a water salt solution, 3 is a perforated holder, 4 is a probe (see Fig. 1)

After heating in the electric furnace, the probe was immersed into a still water salt solution of 12% NaCl concentration at 23°C to a depth of 100 and 120 mm (see Fig. 3). Results obtained were analyzed using the software IQlab.

Analysis of experimental data obtained

Authors of this paper obtained unusual experimental data which are presented and discussed below in Fig. 4 – Fig. 7.

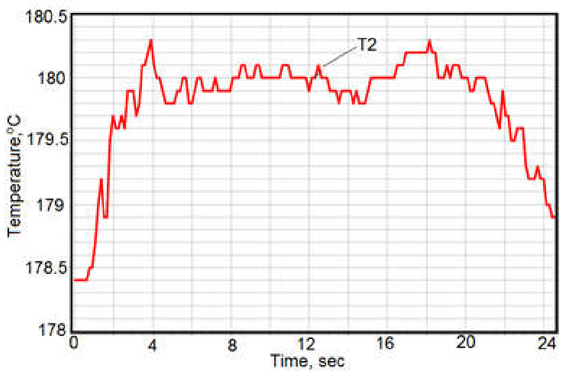
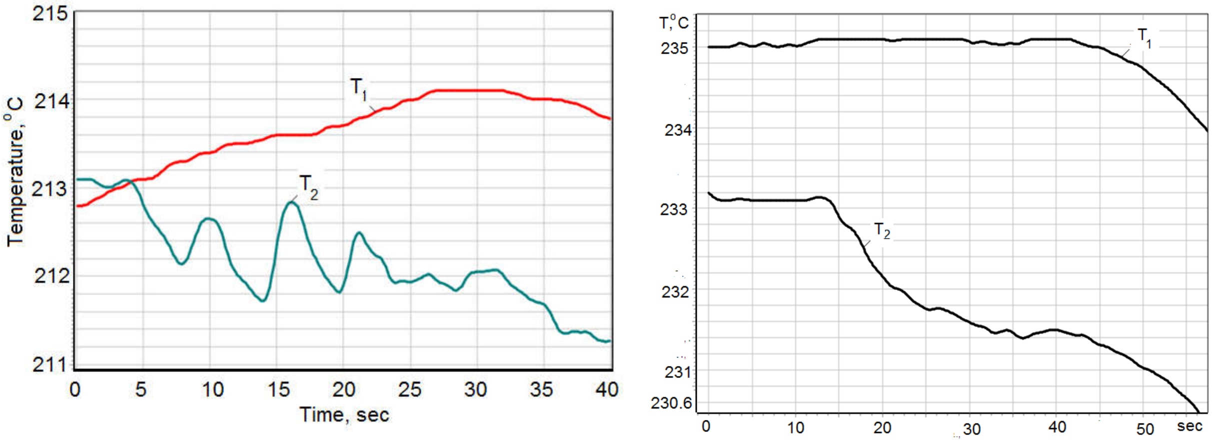


Fig. 4. Instant increase and oscillation of the surface temperature at point 2 during cooling of the probe in 12% water solution of NaCl at 20°C which was immersed into solution to the depth of 120 mm (see Fig. 2)

Fig. 4 shows that the probe surface temperature (point 2) increases instantly by 2°C like an impulse and then oscillates for a relatively long time and then it decreases again. It cannot be explained proceeding from the classical heat conductivity theory because the probe is too large resulting in a long-lasting thermal inertia. Only free electrons can provide such effect. It is not a pure heat energy impulse because the double electric layer constantly generates the thermal energy kicking free electrons from the left hot end of the probe to the right cold probe end (as shown in Fig. 1) until the double electric layer is destroyed.



a) b)

Fig. 5. Behavior of the core and surface temperatures of the probe immersed for cooling into 12% water NaCl solution at 20°C to a depth of 100 mm: a) the probe was heated in the electric furnace for 30 minutes; b) the probe was heated in the electric furnace for 2 hours; 1 is the core temperature at the distance of 150 mm from the end, 2 is the probe surface temperature at the same distance

Fig. 5 presents the core (1) and surface (2) temperatures versus time in areas 1 and 2 (see Fig. 2), which differ significantly from each other. According to the classical heat conductivity theory, they should be identical because cooling in the still air is a very slow process (the Biot number is equal approximately to 0.02). To provide identical cooling curves, the Biot number should be less than 0.2. It is ten times lesser. In the first experiment (Fig. 5a), the probe was heated in the electric furnace for 30 minutes, and in the second experiment (Fig. 5b), the probe was heated for 2 hours to provide a stationary condition. In both experiments, the end of the probe was immersed into the water salt solution to a depth of 100 mm. In both experiments, the surface temperature decreases early as compared with the core temperature of the probe. It means that electrons are moving in the surface layers of the probe and, probably, decreasing of the temperature relates to the transition from nucleate boiling to convection. Electrons moving in the probe surface layers provide immediate information on the transition from nucleate boiling to convection, while the probe core temperature is conventional heat conduction with the high thermal inertia.

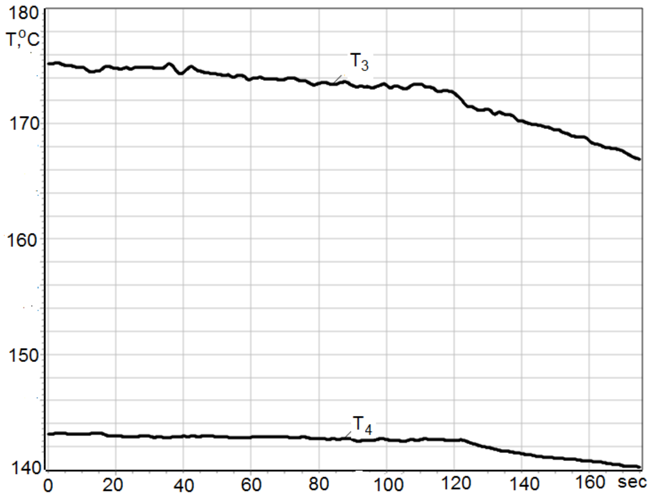


Fig. 6. Surface cooling curves at the distance of 220 mm and 290 mm from the end of the probe: T3 is thermocouple 3, T4 is thermocouple 4

Fig. 6 present temperatures curves recorded by thermocouples 3 and 4 installed at the not heated end of the probe showing the transition from the nucleate boiling process to convection at a time 120 sec. As seen from these data, the difference in time when this transition took place is very small between these two points. It can be explained by a very high speed of the thermal wave movement. The distance between thermocouple 3 and thermocouple 4 is 0.07m, and the speed of the thermal wave movement, according to authors (Kobasko and Guseynov, 2012), is 140m/s. It follows from these data that the above time difference should be 0.0005sec, which means that the transition from the nucleate boiling process to convection took place virtually at the same time in these two points. This fact can be used for evaluating of material physical properties. It can be done taking into account the wave speed $w_r = \sqrt{\frac{a}{\tau_r}}$ where *a* is a material thermal diffusivity of and τ_r is relaxation time in sec.

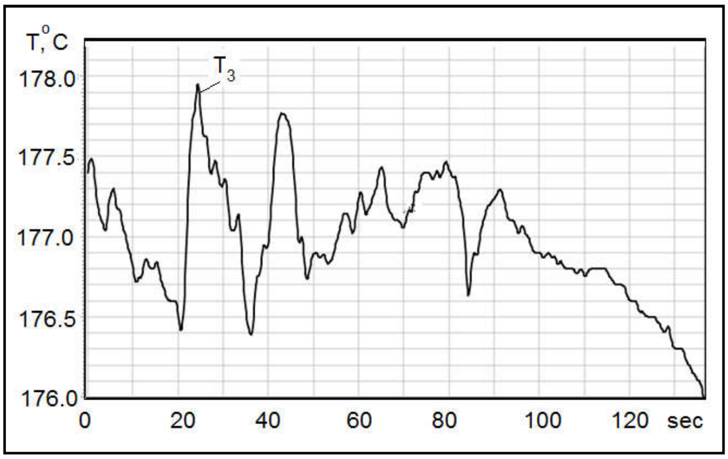


Fig. 7. Oscillation of the surface temperature at the distance of 220 mm (thermocouple 3) when cooling the probe in the 12% water solution of NaCl at 20°C

In all experiments, the surface temperature (recorded by the thermocouples located at areas of the probe (which were not immersed into the electrolyte) was oscillating as shown in Fig. 7. A question is arising regarding the nature of the observed temperature oscillations since the above thermocouples were in the still air, the probe was properly fixed and the thermocouples were properly welded to the probe surface. Since the probe was fixed after its immersion into the electrolyte and thee electrolyte was not agitated, a local film boiling could appear at the bottom of the probe. These local vapor bubbles are usually unstable and could affect significantly the double electric layer (see Fig.1), which was recorded as a mirror by welded thermocouples due to free electrons in steel.

DISCUSSION

The aim of the paper was conducting an accurate experimental study of the "poker" effect to find a possibility for evaluating of the constant relaxation time for different materials in the nearest future. The point is that the initial heat flux density can be evaluated by solving a hyperbolic heat conductivity equation, which requires a knowledge of the relaxation time for different grades of steel. To predict film boiling processes, the evaluated initial heat flux density should be compared with the first critical heat flux density (Kutateladze, 1963; Tolubinsky, 1980 and Liscic, 2003). . This procedure is the first step in designing and monitoring of new quenching technologies. Since the problem is very important for the heat-treating practice, authors propose to combine measuring of the constant relaxation time with the measuring of Jominy curves (see Fig. 8). A standard Jominy probe should be longer in this case and instrumented with several thermocouples along the extended probe.

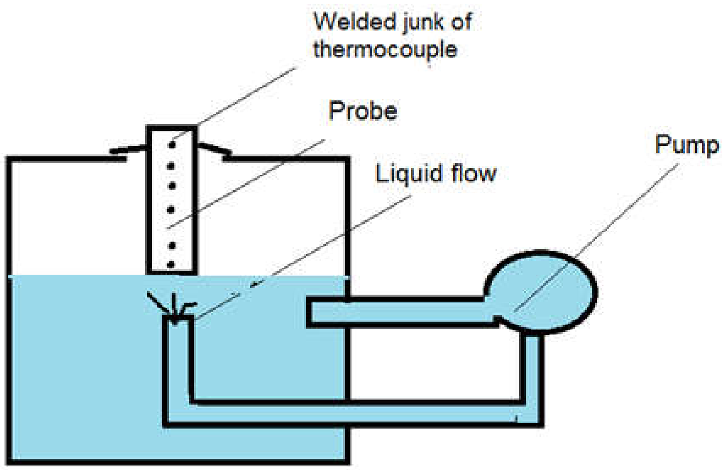


Fig. 8. Suggested combined testing of the cylindrical probes to obtain Jominy curves and information on the "poker" effect during cooling of the probe end

Such measurements will provide a useful information for testing of new materials like patented alloy low hardenability steels which are making progress in heat-treating industry (Kobasko, 2018 b). Authors will continue investigations in this field to get more information on the discovered phenomena (Kobasko, 2018 c).

Conclusion

1. The "poker" effect can be explained based on the statistical thermodynamics and by solving the hyperbolic heat conductivity equation with appropriate boundary conditions.
2. The double electric layer formed immediately after the beginning of quenching of the poker hot end in the water salt solutions is the reason for moving bumped free electrons with the high energy to the opposite cold end of the poker (**Fig.** 1).
3. A classical theory of the heat conductivity based on the conventional Fourier law describes the real thermal processes approximately and, in many cases, it can be successfully used for calculations of technological processes in different industrials systems.
4. Contribution of free electrons to changing of the temperature field is insignificant.
5. Free electrons can increase instantly the surface temperature and can show changes taking place in the double electric layer caused by local film boiling processes.
6. A fast delivery of the thermal energy by free electrons takes place in the surface layers of steel parts while the core temperature is governed by the parabolic heat conductivity model.
7. If further investigated, obtained results can be used to accurately measure thermal properties of material since the speed of the thermal wave depends on the material thermal diffusivity and relaxation time, which is constant for the given material.
8. The effect of thermal wave movement in current study is insignificant because relaxation time τ_r is extremely small value and initial temperature in electrical furnace was not enough high.
9. Improved analytical solution presenting data on "poker" effect can be achieved by taking into account electrical forces in the boundary condition.

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