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# Heat Transfer Coefficients and Heat Flux Densities Evaluation during Quenching Cylindrical Probes in Liquid Media

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**Abstract**: It is shown in the paper that thermocouple instrumented at the center of standard probe cannot record many important physical phenomena such as temperature and heat flux density oscillation, self - regulated thermal process establishing and others to be studied by investigators who are greatly interested in it. The central thermocouple is unacceptable principally for solving inverse problem connected with transient boiling processes due to dumping effect. The Lumped capacitance method cannot also help because it provides very low heat transfer coefficients (HTCs) which actually differ from expected many times. Even during testing of silver probes with elevated thermal conductivity of 400 W/mK, an essential temperature gradient is observed during transient nucleate boiling process. Due to recently discovered new phenomenon on periodic replacement of film boiling with shock boiling process, a requirement appeared to use contemporary modern tools for investigation quenching processes. They include accurate surface thermocouples instrumentation, modern sonar system for recording and analyzing boiling noise effect and direct video recording of boiling processes taking place during quenching probes in liquid media. It is underlined in the paper that there is a need to switch from the old approach to contemporary modern technique.

**Keywords:** New approach; cylindrical probe; surface temperature oscillation; central thermocouple; film and shock boiling replacement; modern technique.

## 1. Introduction

In heat treating industry is widely used standard Inconel 600 probe 12.5 mm diameter to control oil and water polymer quenchants. It is assumed that cooling is performed to bath temperature and standard probe is used to keep cooling intensity of quenchant within the given requirement of technological process adopted officially by industry. For this purpose the standards are available which allow controlling changing cooling intensity of different quenchants. However, in last decades the new intensive quenching (IQ) processes were proposed and new phenomena were discovered which take place during quenching in liquid media. During the IQ process the surface compression stresses are formed and super strengthening of material is observed which can be fixed by proper time interruption. To calculate cooling time interruption, heat transfer coefficients (HTCs) are required which should be evaluated by testing special probes. For this purpose thermal properties of material are used (see Table 1 and Table 2) and surface temperature or temperature in the area located close to the probe surface versus time is recorded. Since standard probe is instrumented only by one central thermocouple, the problem of evaluating HTCs leads to creating cooling condition where surface temperature of probe is approximately equal to temperature at the center of probe during all process of quenching. From the point of view of thermal science such conditions are created when Biot number $Bi = \frac{\alpha}{\lambda} R \leq 0.2$. Such approximate approach is called Lumped capacitance method which was used by authors [1] to evaluate HTCs of brines (see Table 3).

**Table 1.** Thermal conductivity of super cooled austenite versus temperature

| T, ºC | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 |
|---|---|---|---|---|---|---|---|---|---|
| $\lambda, \frac{W}{mK}$ | 17.5 | 18 | 19.6 | 21 | 23 | 24.8 | 26.3 | 27.8 | 29.3 |
| $\bar{\lambda}, \frac{W}{mK}$ | 17.5 | 17.75 | 18.55 | 19.25 | 20.25 | 21.15 | 21.90 | 22.65 | 23.4 |

**Table 2.** Thermal diffusivity $a$ of super cooled austenite versus temperature

| T, ºC | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 |
|---|---|---|---|---|---|---|---|---|---|
| $a \cdot 10^{-6}, m^2/s$ | 4.55 | 4.63 | 4.70 | 4.95 | 5.34 | 5.65 | 5.83 | 6.19 | 6.55 |

| $\bar{a} \cdot 10^{-6}, m^2/s$ | 4.55 | 4.59 | 4.625 | 4.75 | 4.95 | 5.10 | 5.19 | 5.37 | 5.55 |
|---|---|---|---|---|---|---|---|---|---|

Note: $\bar{\lambda}$ and $\bar{a}$ at 500°C mean average values for the range of 100°C - 500°C (analogously for other temperatures).

**Table 3.** Comparison of the average effective heat transfer coefficients (HTCs) estimated for brine (NaCl) solutions according to authors [1]

| Concentration of NaCl in water, wt % | Grossmann method HTC in $W/m^2K$ | Lumped capacitance method HTC in $W/m^2K$ |
|---|---|---|
| 5 | 1906 | 1448 |
| 10 | 2532 | 2040 |
| 15 | 1950 | 1676 |
| 20 | 1986 | 1602 |

Results of investigations presented in Table 3 show extremely low values of HTCs generated by Lumped capacitance method [1]. According to Eq. (1) [2], surface temperature is almost equal to temperature at the center of probe if HTC is equal to 1448W/m$^2$K:

$$\frac{\bar{T}_{sf} - T_m}{\bar{\bar{T}}_V - T_m} = \frac{1}{\left(Bi_V{}^2 + 1.437 Bi_V + 1\right)^{0.5}} \quad (1)$$

$$Bi_V = 0.346 Bi$$

$$Bi_V = 0.346 \times 0.3 \approx 0.1$$

$$\frac{\bar{T}_{sf} - T_m}{\bar{\bar{T}}_V - T_m} = \frac{1}{\left(0.01 + 1.437 \times 0.1 + 1\right)^{0.5}} = 0.931$$

In contrast to authors [1], French [3] measured accurately surface temperature of spherical and cylindrical samples and came to conclusion that quenching in 5% water solution of NaOH is very intensive because $T_{sf}$ drops from $875\,^oC$ to $150\,^oC$ within 0.7 seconds independently from size and form of steel probe (see Table 4).

**Table 4:** Time required for the surface of steel samples to cool to different temperatures when quenched from 875$^o$C in 5 % NaOH-water solution at 20$^o$C and moving at 3 feet per second (0.914 m/s), according to French [3]

| D, mm | Time, Sec | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 700$^o$C | 600$^o$C | 500$^o$C | 400$^o$C | 300$^o$C | 250$^o$C | 200 | 150$^o$C |
| 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 |
| 25.4 | 0.028 | 0.04 | 0.048 | 0;064 | 0.14 | 0.21 | 0.34 | 0.71 |
| 50.8 | 0.025 | 0.04 | 0.06 | 0.065 | 0.08 | 0.10 | 0.29 | 0.65 |

Table 4 shows that Lumped capacitance method is not suitable for investigation water salt solutions.

Equation (2) of the regular condition theory [2] developed in 1954 by Kondrat'ev, is true within $0 \le Bi_V \le \infty$ and has a form:

$$v = \frac{\alpha \psi S}{c \rho V}\left(T_{sf} - T_m\right). \quad (2)$$

When $Bi \le 0.2$, $\psi \approx 1$ and then the heat transfer coefficient is calculated as:

$$\alpha = \frac{c\rho vV}{S\left(T_{sf} - T_m\right)} \qquad (3)$$

that in fact is Lumped capacitance method. .

This paper discusses the new contemporary tools needed for modern approach in liquid media investigations used as the quenchants.

## 2. Solution of Inverse Problems of Heat Transfer Based on the Method of Statistical Regularization

At present time the technique of solving inverse problem (IP) is highly developed and used in practice [4 – 7].

Authors [8, 9] used statistical regularization method based on accurate experiment which is discussed below.

Cylindrical probe 20 mm diameter and 80 mm long, made of stainless steel AISI 304, and was instrumented with two thermocouples. The central thermocouple was welded and plugged by pin of identical material. Surface thermocouple was instrumented using French methodic [3] of flattering.. Thermocouples location is shown in Fig. 1.

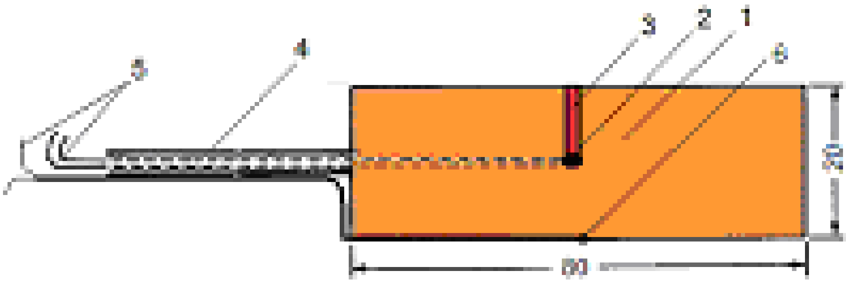



**Fig. 1.** Cylindrical probe with two instrumented thermocouples used for investigation cooling intensity of quenchant: 1 is cylindrical probe; 2 is welded conjunction of thermocouple; 3 is pin; 4 is tube; 5 are wires of thermocouples; 6 is welded surface thermocouple.

As one can see from Fig. 2 the temperature recorded by central thermocouple is not affected by oscillation of surface temperature at all.

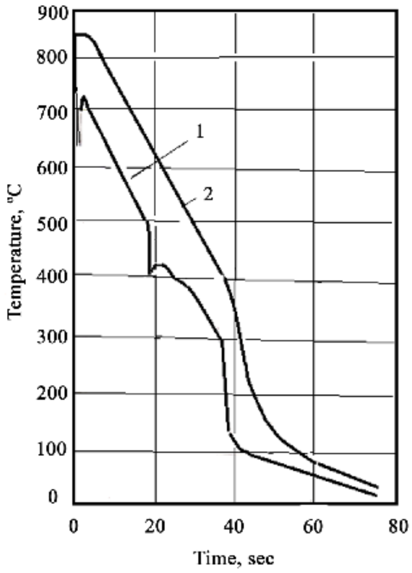



**Fig. 2.** Cooling curves versus time during quenching cylindrical probe 20 mm diameter and 80 mm long in water solution of polyoxyethylene (0.3 %) at 20 ºC: 1 is surface temperature; 2 is core temperature [9].

By solving IP problem, it was established periodic change of heat flus density versus time during quenching cylindrical probe in 0.1 % water solution of polyetilenoxide at 20ºC (see Fig. 3)..

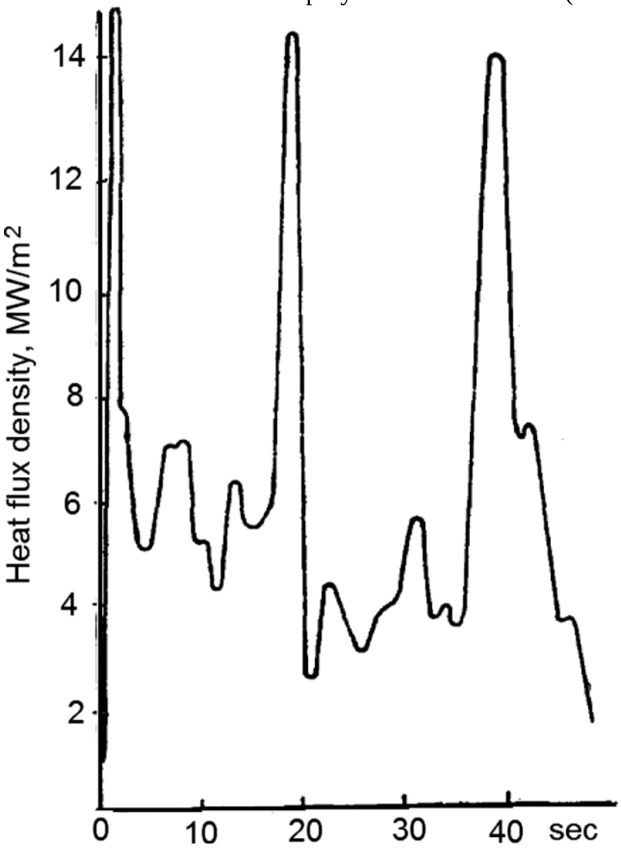



**Fig. 3**. Periodic changes versus time of heat flux density during quenching of a cylindrical probe made of AISI 304 steel in 0.1 % water solution of polyetilenoxide at 20ºC (probe diameter 20 mm, length 80 mm, initial temperature 850ºC). Periodic changes are explained by multiple transitions from film boiling to nucleate boiling [9].

Obtained results of investigation showed impossible to study some interesting phenomena taking place during quenching in liquid media when only central thermocouple is instrumented at the center of probe. The temperature signals going from surface to center of probe are dumped completely. The investigators dealing with one thermocouple at the center of probe are loosing important information and cannot solve IP problem correctly.

## 3. Temperature field restore possibility based on known transient nucleate boiling process characteristics

If any film boiling process during quenching is completely absent, there is a possibility to restore surface temperature and solve correctly direct problem with the first type of a boundary condition. For this purpose experimental data of French are used (see Table 4) and main characteristics of transient nucleate boiling process explored [10, 11].

As known, the duration of transient nucleate boiling process is used to restore temperature field during nucleate boiling (see equations (4) – (7)):

$$\tau_{nb} = \overline{\Omega} k_F \frac{D^2}{a} \tag{4}$$

$$T_{sf} = T_s + \frac{\vartheta_I + \vartheta_{II}}{2} \approx const \tag{5}$$

$$\vartheta_I = 0.293 \cdot \left[ \frac{2\lambda(\vartheta_o - \vartheta_I)}{R} \right]^{0.3} \tag{6}$$

$$\vartheta_{II} = 0.293 \cdot \left[ \alpha_{conv} (\vartheta_{II} + \vartheta_{uh}) \right]^{0.3} \tag{7}$$

According to Eq. (4), the duration of transient nucleate boiling process is equal to

$$\tau_{nb} = 5.1 \times 0.0432 \times \frac{(0.0127)^2 m^2}{5.4 \times 10^{-6} m^2 / s} \approx 6.6s$$

$$\vartheta_I = 0.293 \cdot \left[ \frac{2 \times 23(775 - \vartheta_I)}{0.00635} \right]^{0.3} = 30.6^o C$$

$$\vartheta_{II} = 0.293 \cdot [500(7.2 + 80)]^{0.3} = 7.2^o C$$

Some results of restores calculations are shown in Fig. 4.

The restored temperature – time cuves (see Fig. 4) were used to calculate heat flux density versus time and evaluating effective Kondrat;ev numbers Kn (see Fig. 5 and Fig. 6).

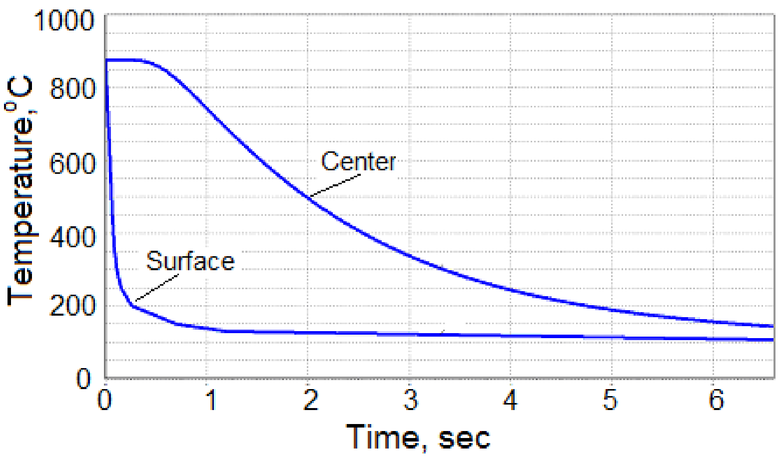



**Fig.4.** Cooling curves vs time during quenching cylindrical probe 12.7 mm diameter in still water salt solution at 20°C when convective HTC was 500 W/m²K.

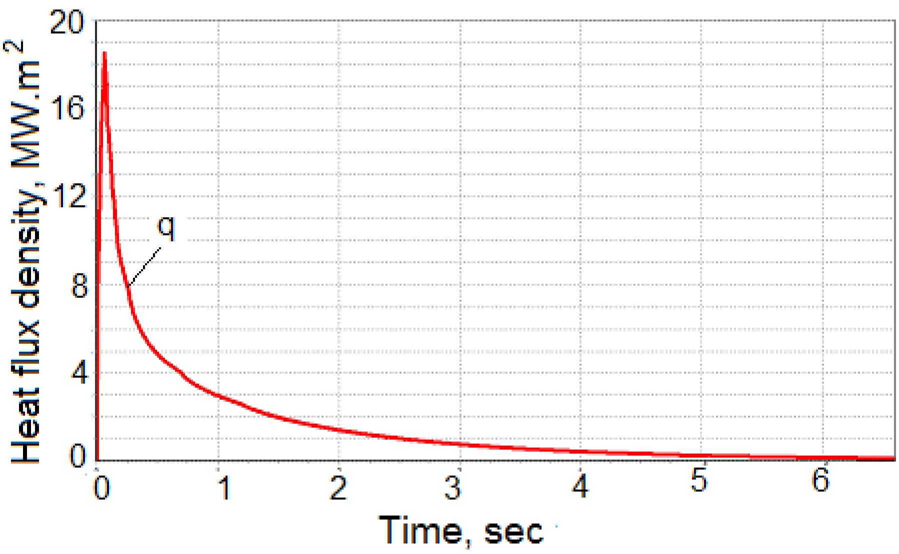



**Fig.5**. Heat flux density vs time during quenching cylindrical probe 12.7 mm diameter in still water salt solution at 20°C when convective HTC was 500 W/m²K.

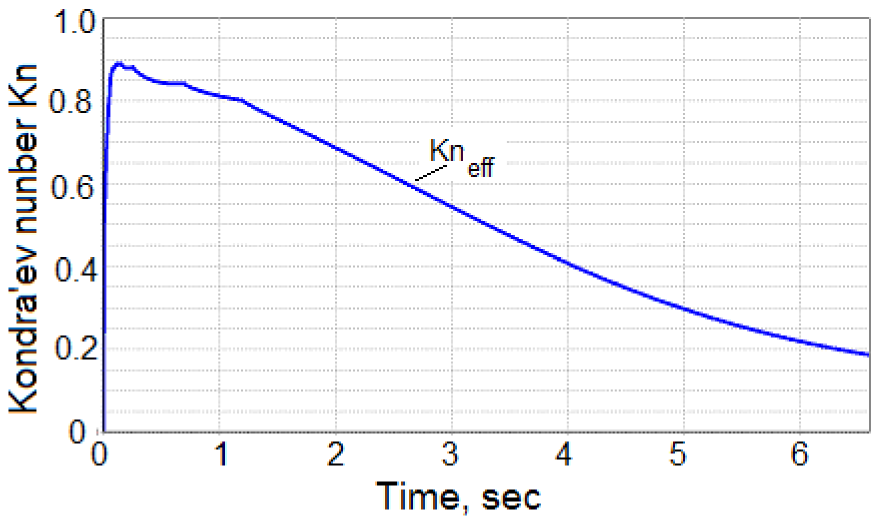



**Fig. 6.** Effective Kondrat'ev number Kn vs time during quenching cylindrical probe 12.7 mm diameter in still water salt solution at 20°C when convective HTC was 500 W/m²K.

Average Kondrat'ev number Kn is equal to $Kn = \frac{0.18 + 088}{2} = 0.53$ that corresponds to generalized Blot number $Bi_V = 0.96$ resulting in effective heat transfer coefficient that is equal to $\alpha = 9617 W / m^2 K$.

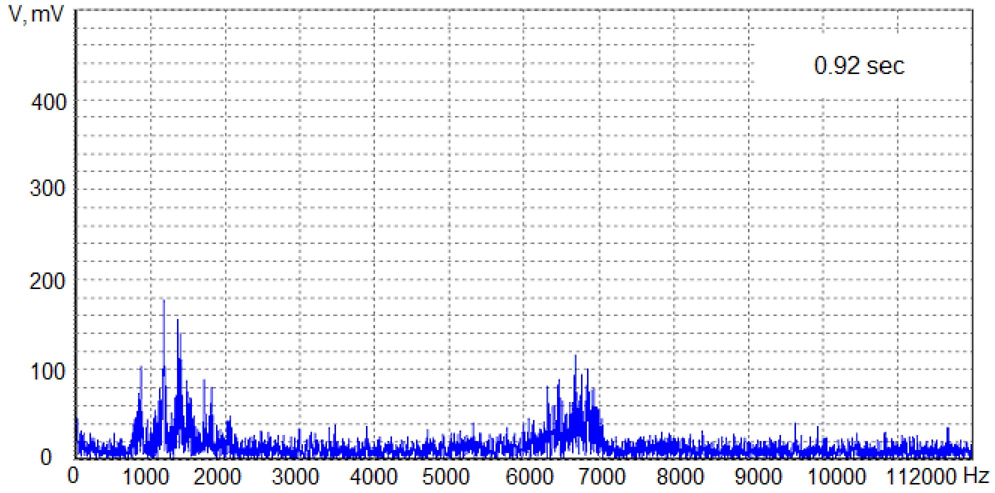
The obtained value differ from HTC calculated by Lumped capacitance method almost 6 times (see Table 3). It means that Lumped capacitance method is not suitable for standard probe 12.5 mm in diameter for calculating HTCs during transient nucleate boiling processes.

## 4. Forced exchange phenomenon

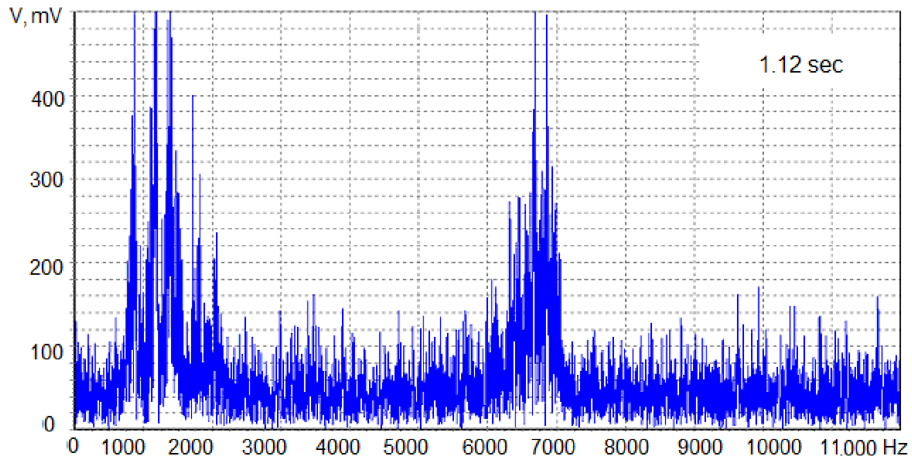
The phenomenon of periodical replacement of film boiling by shock boiling was widely discussed in Ref. [12]. It was discovered due to strange behavior of HTC presented in Table 5. According to nucleate boiling laws [13, 14] HTCs should decrease vs time, not increase like shown in Table 5.,If mentioned phenomenon on replacement film boiling by shock boiling process is true, it should be depicted by noise frequency analysis (see Fig. 6, a, b., c., and d) [11]. The author of current paper thinks that the first spike on Fig. 6 belongs to short film boiling while the second spike belongs to short nucleate boiling which replace each other with high frequency.

**Table 5.** Effect of NaCl concentration and core temperature of silver spherical probe 20 mm diameter on heat transfer coefficients (W/m²K) during quenching in solutions at a temperature 20°C [12].

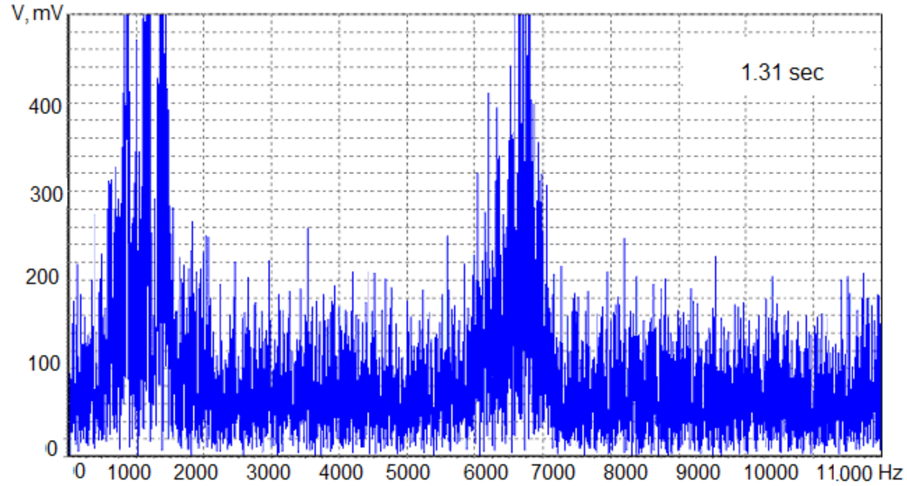
| Concentration % | HTCs (W/m²K) | | | | |
|---|---|---|---|---|---|
| | 700°C | 600°C | 500°C | 400°C | 300°C |
| 5 | 8750 | 27138 | 42140 | 64300 | 90500 |
| 10 | 15170 | 40710 | 60800 | 88120 | 92880 |
| 15 | 30470 | 42310 | 67420 | 98000 | 117050 |
| 20 | 18500 | 20230 | 22270 | 30600 | 47990 |




a)




b)



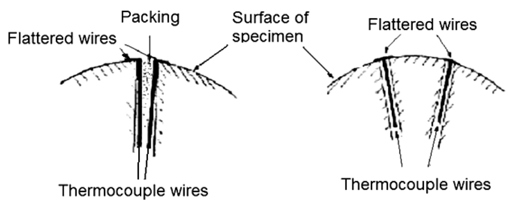

c)

**Fig. 7.** Noise integral intensity versus time during quenching from 840oC iron cylindrical sample 12.7 mm diameter and 125 long in 12% water solution of NaCl at 20$^{o}$C [11].

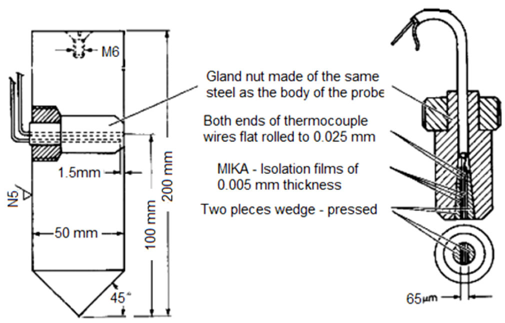
Discovered phenomenon requires special technique of its investigation.

## 5. Discussion

At present time there are several essential achievements such as self – regulated thermal process, temperature – time shoulder formation during quenching in water inverse solubility polymer solutions , periodic replacement the film boiling with shock boiling process [12, 15, 16]. All of these phenomena create a basis for designing new technologies resulting in great benefits and environment improvement. However, mentioned phenomena require exact surface temperature measurement that is a problem because no standard probes with surface thermocouple instrumentation. Very accurate investigations concerning surface temperature measurement were performed by French in 1928 [3]. He published important experimental data showing temperature -- -time records within the temperature interval 875°C – 150°C for different sizes and forms of steel samples. According to French, cooling time from 875°C to 150°C doesn't depend on size and form of steel part. Author [10] explains this unusual effect by existing shock boiling process formation which drops surface temperature of probe from 875°C to 150°C in 0.7 sec. Within this short period of time all steel samples can be considered as semi – infinity domain where core temperature is not affected by change surface temperature After that period of time the self – regulated thermal process is established where surface temperature maintains relatively a long time at the level of boiling point of a liquid. This new process cannot be investigated by standard probe with one thermocouple at its center. For such precisions investigation the French method of measurement or Liscic/ Nanmac probe could be used (see Fig. 8a and Fig. 8 b). They are considered in detail in a Refs [16,17, 18]. Two tiny thermocouples were instrumented in cylindrical probe 50 mm diameter , made of AISI 304 stainless steel (see Fig. 8 b). One thermocouple was accurately instrumented on the surface of the stainless probe, another1.5 mm below the surface. Unfortunately, it was not widely used in heat treating due to its rather high cost. .




a)

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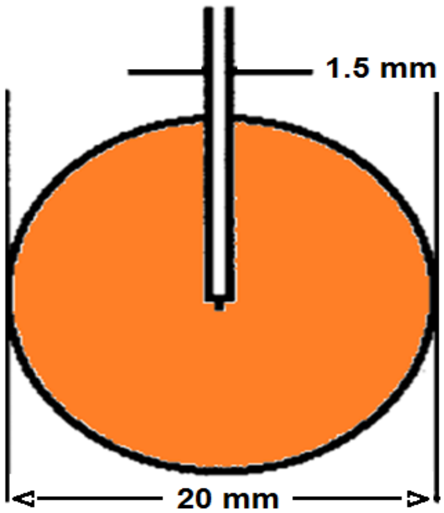


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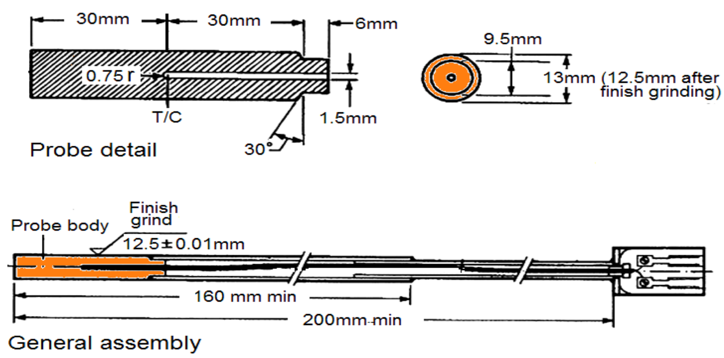


d)

**Fig. 8.** Evolution of test samples since 1928 up to date: a) are French samples with accurate thermocouples arrangement in their surfaces [3]; b) is silver standard probe 20 mm in diameter used in Former Soviet Union (FSU) [18]; c) is accurately designed Liscic/Nanmac probe (currently replaced by Liscic probe with three thermocouples) to investigate quenching processes taking place on the surface of metal [17]; d) is standard Inconel 600 probe 12.5 mm in diameter currently used for testing different kinds of quenchants [19, 20].

## 6. Conclusions

1. The thermocouple instrumented at the center of standard probe of 12.5 mm diameter doesn't react on many important phenomena taking place during quenching in liquid media. The Lumped capacitance method used for heat transfer evaluation provides low values of HTC measurements resulting in big errors of calculations.
2. The new unusual phenomenon on periodical replacement the film boiling process by shock boiling can be successfully investigated by patented sonar system (UA Patent No. 119230).
3. The French method of surface temperature measurement is the most suitable for investigation many interesting phenomena taking place in liquid media (brine in water polymer solutions).
4. The modern approach in investigation cooling intensity of liquid quenchants consists in explore surface thermocouples, sonar and video recording boiling processes taking place during quenching in liquid media.
5. There is a need in modifying standard probe to provide possibility of correct solving the inverse problem.

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