A Method for Evaluation of Critical Heat Flux Densities

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Abstract:- A method for evaluating critical heat flux densities is developed. It is shown that cooling capacity of quenchants must be characterized by the complex of parameters: critical heat flux densities, heat transfer coefficients during both film and nucleate boiling, and single-phase convection. The new technique of the determination of critical heat flux densities in non-stationary conditions of heat transfer is suggested. It consists of use cylindrical silver specimens having thermocouple at the distance of R/2 which measured average temperature vs. time. Developed method can be used for creation new standard of measuring critical heat flux densities.

Key-Words: - Critical heat flux densities, Method of measuring, Silver probes, Optimal condition, Standard, International project.

1 Introduction

As is known, cooling capacity of quenchants should be characterized by several parameters including critical heat flux densities q_{cr1} and q_{cr2}, heat transfer coefficients at film and nucleate boiling, and also a heat transfer coefficient at a single-phase convection. This paper describes a new technique of the determination of critical heat flux densities in non-stationary conditions of heat transfer with regard to tests of cooling properties of quenchants. The technique developed can be used for the creation of databases of different kind of quenchants. The paper also discusses regularities of film boiling since for the determination of critical heat flux densities it is necessary to determine heat transfer coefficients at the full film boiling. Despite of the briefness of this presentation, its material can be useful for heat treaters and also researchers studying cooling properties of quenchants or finding optimal quenchants on the basis of all possible substances soluble in water.

2 Critical heat flux densities and regularities of heat transfer during film boiling

2.1 Crisis of a heat transfer at boiling in conditions of free movement

A crisis of a heat transfer at nucleate boiling is caused by change of the mechanism of heat transfer at transition from nucleate boiling to film boiling. While the heat flux density increases, in some time the heat transfer coefficient reaches its maximum, and then intensity of heat exchange goes down. The maximal heat flux at nucleate boiling is called the first critical heat flux density and designated as q_{cr1}. The first critical heat flux density depends on a sort of a boiling liquid, pressure, condition of a surface, presence of impurities in the quenchant. Temperature difference $\Delta T = T_{Sf} - T_S$ at the time of achievement of the first critical heat flux density is called the first critical temperature ΔT_{cr1}. The heat transfer coefficient at the time of the beginning of boiling crisis is determined as follows [1, 2]:

$$\alpha_{cr} = \frac{q_{cr1}}{\Delta T_{cr1}}.$$

There are two approaches in the explanation of the mechanism of the occurrence of boiling crisis.

The first approach is based on the fact that high intensity of heat transfer characteristic for nucleate boiling is kept until bubble filling (population) on the surface of heating reaches the limit. The critical heat flux density corresponds to limit number of nucleating centers formed on the surface of heating.

The second approach is based on the consideration of crisis as hydrodynamic phenomenon. According to this idea, the crisis of heat transfer comes when access of a liquid to a surface of heating ceases and steady film boiling is established, i.e., the liquid is pushed off from a surface of heating by a continuous steam layer.

Tolubinsky and his disciples have used the first approach and have received dependence for the calculation of the first critical heat flux density, which is given below [1]:

$$q_{cr1} = 7r^* \sqrt{af\rho'\rho''}, \qquad (1)$$

where q_{cr1} is critical heat flux density, W/m^2;
r^* is heat of steam formation, J/kg;
f is a frequency of dispatch of steam bubbles, 1/s;
a is thermal diffusivity of liquid, m^2/s;
ρ' is density of liquid, kg /m^3;
ρ'' is density of steam, kg/m^3.

The second approach in the determination of the first critical heat flux density is based on the hydrodynamic theory of crises suggested by S.S.Kutateladze [2]. The following equation for the first critical heat flux density has been obtained:

$$q_{cr1} = kr^* \sqrt{\rho''} \sqrt[4]{g\sigma(\rho' - \rho'')}, \qquad (2)$$

where $k \approx 0.14$; the heat flux density is expressed in W/m^2;
g is a gravity factor , m/s^2;
σ is a superficial tension, N/m.

Table 1 First critical heat flux density q_{cr1} (MW/m^2) versus underheating at normal atmospheric pressure for water

Formula of calculation	Underheating, ^{o}C					
	0	20	40	60	80	100
Tolubinsky (1)	1.27	2.40	3.57	4.72	5.90	7.06
Kutateladze (2)	1.185	2.25	3.33	4.40	5.50	6.60

The above-mentioned equationa (2) is true at temperature of saturation of a liquid, i.e., at its boiling. A cold liquid has higher values of critical heat flux densities. To characterize this fact, thermal scientists introduced the concept of underheating, which is expressed in a difference between temperature of saturation (boiling) and temperature of a quench bath, i.e.

$$\vartheta_{u.h} = T_S - T_m,$$

where $\vartheta_{u.h.}$ is underheating of a cooling liquid;
T_S is temperature of saturation (boiling);
T_m is temperature of a liquid far from a boiling layer.

The first critical heat flux density raises while underheating of a liquid increases, and is determined as follows [1,2]:

$$q_{cr1}^{u.h} = q_{cr1}\left[1 + 0.065\left(\frac{\rho'}{\rho''}\right)^{0.8} \frac{Cp\,\vartheta_{u.h}}{r^*}\right], \qquad (3)$$

where $q_{cr1}^{u.h}$ is the first critical heat flux density of a cold liquid (quenchant);
Cp is thermal capacity of a liquid, kJ/(kg•°C);

The transition back from film boiling to nucleate one is called the second crisis of a heat transfer at boiling. This transition has also crisis character because at the destruction of a steam film and return to nucleate boiling the heat transfer sharply raises, and the temperature of a surface accordingly goes down. The minimal heat flux at film boiling is referred to as the second critical heat flux density and designated as q_{cr2}. There is an interrelation between the first and second critical heat flux densities, which is expressed by the ratio [2, 3]:

$$\frac{q_{cr2}}{q_{cr1}} \approx 0.2 \qquad (4)$$

3 Technique of Measurement of Critical Heat flux Densities in Non-Stationary Conditions of Heat Transfer

To measure critical heat flux densities in non-stationary conditions of heat transfer, it is necessary to have the full film boiling. Otherwise, there will be nothing to measure, as the transition from the full film boiling to nucleate one will not be observed. With the purpose of the maintenance of the full film boiling, samples for quenchant test are made of materials of high thermal conductivity. A silver ball of 20-mm diameter became widely used as a standard sample [4]. In later studies it has been shown that as for a standard sample, it is better to use a cylindrical sample [4, 5]. The cylindrical sample, having oval cuts at end faces changes hydrodynamics less when it is immersed into a liquid stream. Thermal conductivity and thermal diffusivity of silver versus temperature are presented in Tables 2 and 3.

Table 2. Thermal conductivity λ (W/m·K) for nickel and silver versus temperature

Temperature, °C	0	100	200	300	400	500	600	700
λ, W/m·K (nickel)	-	82.9	73.3	63.3	59.4	62	66	70
λ, W/m·K (silver)	410	392	372	362	362	366	374	-

Table 3. Thermal diffusivity a (m^2/s) for nickel and silver versus temperature

Temperature, °C	0	100	200	300	400	500	600	700	800
$a \cdot 10^3 (m^2/s)$ (nickel)	1.78	1.46	1.27	1.21	1.15	1.95	1.24	1.32	1.41
$a \cdot 10^3 (m^2/s)$ (silver)	0.169	0.158	0.151	0.142	0.141	0.141	0.141	0.141	0.141

. The average value of thermal conductivity in the temperature range of 100 - 600ºC is equal 371 W/m K. The thermal conductivity of stainless steel of austenite class for these temperatures is equal to 20 W/m K.

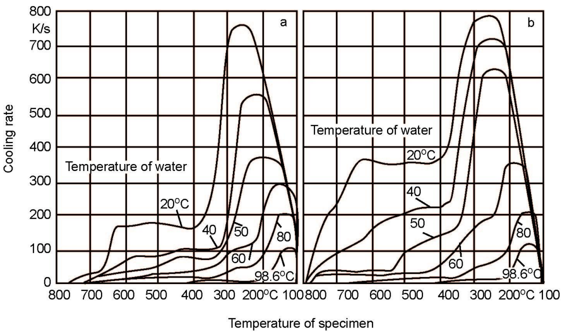


Fig. 1 Cooling rates of a silver ball of 20-mm diameter in still water at different temperatures (a), and circulating water at the rate of 0.25 m/s (b)[4].

Let length of the cylinder be much more than its diameter $2R$, i.e $\ell >> 2R$. In this case it can be counted unbounded, and the temperature inside it is a function of r and τ, i.e., $T(r,\tau)$. Then the average temperature of the cylinder $\overline{T}_V$ will be equal

$$\overline{T}_V(\tau)=\frac{1}{\pi R^2 \ell}\int_0^R\int_0^{2\pi}\int_0^{\ell} T(r,\tau) r\,dr\,d\theta\,dz=\frac{2}{R^2}\int_0^R r\,T(r,\tau)dr, \tag{5}$$

Equating the average temperature $\overline{T}_V$ with the analytical solution $T(r,\tau)$, one can calculate a coordinate where the thermocouple should fix to measure average temperature. It should be placed at a point of $R/2$.. There is a direct relation between the rate of the change in average temperature $\left(\frac{d\overline{T}}{d\tau}\right)$ and heat flux density as follows:

$$c\rho V d\overline{T} = \lambda \frac{\partial T}{\partial r} S d\tau,$$

where c is specific heat;

ρ is density;

$d\overline{T}$ is change in average temperature for the time of $d\tau$;

V is volume; S is surface area;

$\frac{\partial T}{\partial r}$ is temperature gradient at the surface.

Whence

$$q = \lambda \frac{\partial T}{\partial r} = c\rho \frac{V}{S}\frac{d\overline{T}}{d\tau} = c\rho \frac{V}{S}\overline{\upsilon}, \tag{6}$$

where $\overline{\upsilon}$ is the cooling rate of average temperature. Finding the minimum value of q, one can determine the value of q_{cr2}.

Taking into account (10) and a known ratio between q_{cr2} and q_{cr1} (see Eq. (4)), we find

$$q_{cr1} = \frac{1.48 MW/m^2}{0.2} = 7.4 MW/m^2.$$

The obtained result of calculations agrees well at accuracy of 25 % with results of the calculations presented with calculations in Table 1, where the result of 5.9 MW/m^2 was obtained by Tolubinsky's formula. Taking into account that cooling rate of a silver sample was recorded at the center of a ball and the temperature of a surface was unknown at the time of transition from film boiling to nucleate one, results of calculations are satisfactory. We made similar calculations at cooling a silver ball in water at temperature of 40°C. For the specified conditions cooling rate at the center of a ball is $\vartheta = 105$ °C/s, and transition to nucleate boiling is observed at temperature of 473°C. It follows that a heat transfer coefficient α=2436 W/m^2K and q_{cr2} in this case is equal to q_{cr2}=908600 W/m^2 or q_{cr2} = 0.909 MW/m^2. Taking into account again ratio (4), we find:

$$q_{cr1} \approx \frac{0.909}{0.2} \approx 4.54 \text{ MW/m}^2,$$

which is much closer to values in Table 1. So, by Kutateladze's formula it follows that water at temperature of 40°C has q_{cr1}≈4.40 MW/m^2, and by Tolubinsky's formula q_{cr1}≈ 4.72 MW/m^2. The average value of both calculations evenly is 4.56 MW/m^2, which agrees very well with our calculations. Thus, using silver samples, one can determine critical heat flux densities precisely enough.

4 Regularities of heat transfer at the full film boiling

At the full film boiling the heat transfer coefficient depends only on physical properties of the liquid and steam and does not depend on the material of surface. To confirm this point, we consider experiments accurately carried out by F. Moreaux and I. Beck [6]. The authors carried out experiments with cylindrical samples of 16-mm diameter and 48-mm height. The ends of cylindrical samples were rounded. Some samples were covered with nickel, and some with heat-insulated material. All stated above meets our requirements concerning the shape and sizes of a sample.

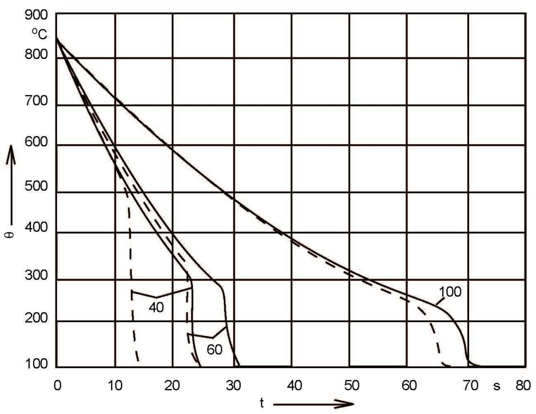


Fig. 2 Cooling curves for quenching in water at: 40ºC, 60ºC, 100ºC.
_________ silver sample; - - - - - - - - silver sample coated with nickel (thickness of 10 º µm) [6]

Fig. 2 presents curves of cooling at the center of a cylindrical sample in water at different temperatures in case of absence and presence of a nickel covering. Samples were heated up to temperature of 850°C and cooled in quiet warm and hot water [6]. One can easily estimate the value of the average heat transfer coefficient if applying the theory of regular thermal conditions [5]. For this purpose we calculate the cooling rate using the tabulated data received from Fig. 2 (see. Table 5).

Table 5 Average value of the cooling rate calculated by data of the experiment presented in Fig. 2 for water at 100 °C

Time, s	$T(\tau)$	$T-T_S$	$\ln(T-T_S)$	m, s^{-1}	Average value of m, s^{-1}
0	850	750	6.62	-	0.025
10	711	611	6.418	0.0205	
20	580	480	6.173	0.0223	
30	472	372	5.919	0.0233	
40	389	289	5.67	0.02375	
50	317	217	5.38	0.0248	
60	255	155	5.04	0.0263	

Table 6 Average value of the cooling rate m, s^{-1}, calculated by data of the experiment presented in Fig. 2

Time , s	$T(\tau)$ °C	$T-T_S$ °C	$\ln(T-T_S)$	m, s^{-1}	Averag e value of m, s^{-1}
0	850	750	6.62		0.0453
10	600	500	6.215	0.040	
14	500	400	5.99	0.045	
20	389	289	5.67	0.047	
27,5	300	200	5.3	0.048	

Knowing the cooling factor m of a cylindrical sample, we calculate Kondratjev number Kn:

$$Kn = \frac{m}{m_\infty}, \qquad (7)$$

where m_∞ is cooling factor of a sample, when $\alpha \to \infty$.

In turn, $m_\infty = \frac{a}{K}$,

where a is thermal diffusivity of silver;
$\bar{a}$ =141·10^{-6} m^2/s;
K =75.08·10^{-6} m^2;
m_∞ =1.878 s^{-1}.

Whence, according to (11), we have

$$Kn = 0.0134 .$$

Kondratjev number $Kn = 0.0134$ corresponds to a certain generalized Biot number, which is equal

$$Bi_V \approx 0.0136 .$$

Whence, we have

$$\alpha_{FB} = 0.0136 \frac{\lambda V}{KS} = 0.0136 \frac{\lambda \cdot RZ}{K \cdot 2(Z + R)},$$

Here λ =371.3 W/ m·K;
R =0.008 m;
Z =0.048 m;
K =75.08·10^{-6} m^2.

Substituting these values in the last formula, we find

$$\alpha_{FB} = 219 \text{ W/m}^2\text{K}.$$

Thus, at cooling a cylindrical silver sample of 16-mm diameter and 48-mm height from temperature of 850°C in boiling water the heat transfer coefficient appears equal

$$\alpha_{FB} \approx 219 \text{ W/m}^2\text{K}.$$

Let us compare this result with the well known equation [2]:

$$\alpha_{FB} = 0.25 \sqrt[3]{\frac{\lambda''^2\, Cp''\, g(\rho' - \rho'')}{V''}}, \qquad (8)$$

where λ'' is thermal conductivity of steam, W/mK;
Cp'' is thermal capacity of steam, J/kg•K;
g is a gravity factor, g =9.81 ;
ρ' is density of a liquid, kg/m^3;
ρ'' is density of a steam, kg/m^3;
V'' is a factor of kinematical viscosity of the steam, m^2/s.

Let us substitute in the formula (8) corresponding values, i.e.,
λ'' =0.02372 W/m•K;
Cp'' =2135 J/kg•K;
g =9.81 m/s^2;
ρ' =958.4 kg/m^3;
ρ'' =0.598 kg/m^3;
V'' =20.02·10^{-6} m^2/s

Also we calculate

$$\alpha_{FB} = 0.25 \sqrt[3]{\frac{5.63 \cdot 10^{-4} \cdot 2135 \cdot 9.81 \cdot 982.5}{20.02 \cdot 10^{-6}}} \approx 208$$
W/m^{2}K

Comparing the obtained result with the experiment, we find that the difference between them is $\varepsilon \approx \frac{(219 - 208)100\%}{219} \approx 5\%$, which is very good agreement since the dispersion of heat transfer coefficients is within the range of 20 % [1,2].

Using the experimental data presented in Fig.2, we similarly calculate a heat transfer coefficient at cooling a cylindrical sample in water at 60°C [6].

Table 6 presents results of calculations of main cooling factor m and the current temperature in the area of film boiling (see Fig. 2). As well as in the first example m_∞ =1.878 s^{-1}, therefore, Kondratjev number here is equal to $Kn = \frac{0.0453}{1.878} = 0.024$. Number $Kn = 0.24$ corresponds generalized Biot number $Bi_V = 0.0245$. It follows that the heat transfer coefficient at cooling a silver sample of 16-mm diameter in water at temperature 60°C is equal 394 W/m^{2}K. The heat transfer coefficient calculated by equation (8) is equal 208 W/m^{2}K. The difference between experiment and calculation in this case is equal

$$\varepsilon \approx \frac{(394.3 - 208)100\%}{394.3} \approx 47\% .$$

When temperature of water drops to 40°C or 20°C the cooling rate considerably increases because at cooling silver standard samples in cold water the heat transfer coefficient at film boiling can reach 2000 W/m^{2}K and over, which differs by one order from data calculated by formula (8). How can we explain such enormous distinction?!

All the matter is that when the temperature of quenchant drops, the steam film becomes unstable, oscillation of a steam film is observed, and underheated liquid in many places contacts a surface of a test sample. As a result of it, the average heat transfer coefficient increases, and it depends on the frequency of the steam film oscillations and the total area covered by the contacting liquid. Authors of Ref. [6] have offered a diagram through which one can determine the stability of a steam film .

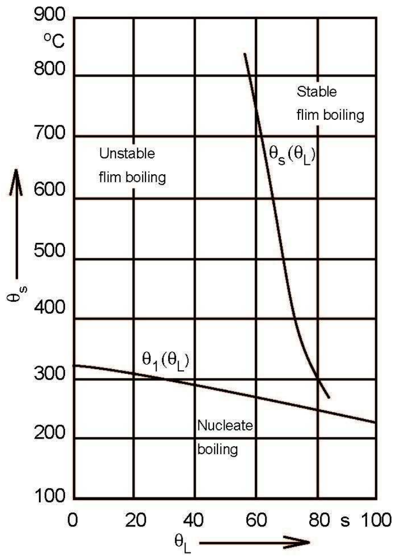
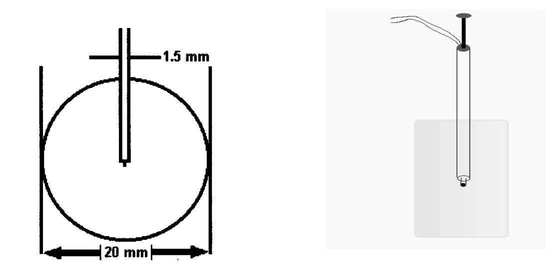


Fig. 3 Stability diagram of film boiling. Case of water (silver sample): Q_S is surface temperature of the sample; Q_L is water temperature [6]

As one can see from the diagram, the steam film is the most stable if the temperature of water is over 80°C. If the temperature of water is about 20°C or 40°C, the steam film is unstable during all the process of sample cooling, i.e., there are its oscillations and contact with the heated surface.

To prove this point, we will analyze sound effects that are observed at the oscillation of a steam film. Some results related to this issue are published in Ref.[3] where the multi-channel analysis of sound effects (see Fig. 4, Fig. 5, Fig. 6) is made.



a) b)

Fig. 4 Schematics of cast silver spherical probe (a) and cylinder (b) used for investigation of unstable film boiling

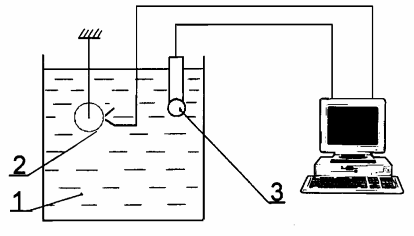


Fig. 5 Quenching System and apparatus placement:.
1 is quenchant to be studied, 2 is a silver ball of 20-mm diameter, 3 is sensor for recording acoustic effects

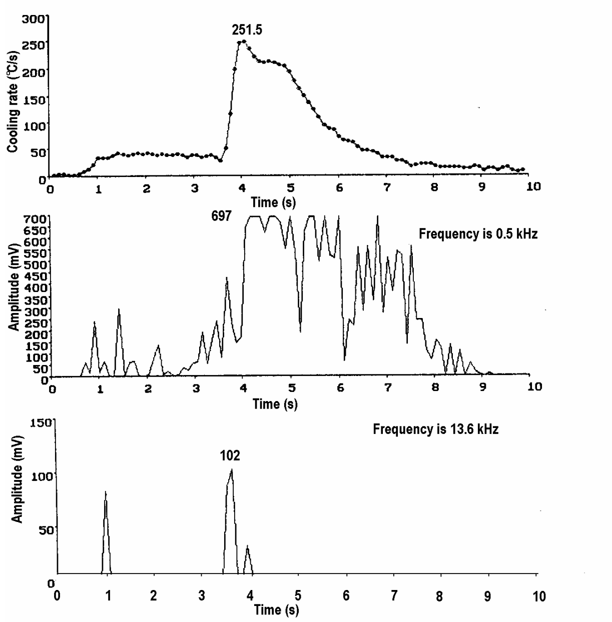


Fig. 6 Temperature – time, broad-band and narrow-band quenching data [3].

Fig. 4 presents the sphere-shaped silver sample used for the study of unstable film boiling. Sound effects were fixed by means of the sound sensor and through the amplifier the signal was transmitted to the sound analyzer and computer for data processing (see Fig. 6). . The signal width was 0 to 20,000 Hz. However, to detect the relatively narrow characteristic signal frequency for nucleate boiling, the total signal width was divided into 100 Hz bands over 200 channels as was already mentioned.

Fig. 6 provides a comparative illustration of the thermal and acoustical data obtained. It is of interest that the thermal temperature-time data show that even the very sensitive silver probe did not detect the initial shock-boiling process characterized by q_{cr1}.

As one can see from Fig. 6 at frequency of 0.5 kHz there are appreciable sound effects at the oscillation of a steam film, and signals considerably increase when the full nucleate boiling comes. At frequency of 13.6 kHz only two sound splashes were observed, which were connected with the formation and growth of nucleating centers. As in the beginning steam bubbles are very small, the frequency of their oscillations is much higher than at the established nucleate boiling. The first splash is connected with the formation of nucleating centers, which then are merged and form a steam film. The energy connected with the oscillation of nucleating centers has passed to the oscillatory energy of a steam film. The second splash is connected with the destruction of a steam film and repeated formation of nucleating centers which then have grown and began to oscillate with smaller frequency, thus the channel at frequency 13.6 kHz has not fixed sound effects at the established nucleate boiling (see Fig.6).

5 Discussion

Why is it all the same important to determine critical heat flux densities? At steel quenching three modes of heat transfer on the surface can be observed, which is connected with the first critical heat flux density q_{cr1}.

Upon immersing of a part to be quenched into the quenchant, the initial heat flux density q can be in different ranges, namely:

$q >> q_{cr1}$; $q \approx q_{cr1}$ or $q << q_{cr1}$.

In the first case the full film boiling is observed, at $q \approx q_{cr1}$ transition boiling can be observed. In the last case at $q << q_{cr1}$ film boiling is absent and at once nucleate boiling comes. If we make for the considered three cases charts of a heat transfer coefficient versus temperature of a surface, absolutely different values of $\alpha = f(T_{sf})$ will be received. It follows that there is no unique dependence of a heat transfer coefficient α on temperature at the surface of a quenched part. To understand what chart we should use at making a concrete design, it is necessary to take into account the value of q_{cr1}. Therefore, it is important and necessary to determine first of all critical heat flux densities q_{cr1} and q_{cr2}, in order to perform engineering work highly competently [3, 7, 8, 9].

6 Conclusion

1. The method of determining critical heat flux densities has been developed.
2. Silver cylinder-shaped samples of 12-16 mm diameter with rounded edges are the most suitable for measuring critical heat flux densities.
3. A thermocouple should be placed at R/2 distance from the axis to measure the average temperature.
4. By measuring the cooling rate at R/2 point, one can determine q_{cr2}.
5. Using the correlation $q_{cr2}/q_{cr1}=0.2$, one can determine q_{cr1}.
6. To provide the stability of film boiling, the medium temperature should be more than 60 Celsius degrees.
7. This paper is presented for the discussion and standardization of proposed method.

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