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DETERMINATION OF THE STATISTICAL CHARACTERISTICS OF TEMPERATURE FLUCTUATION IN POOL BOILING

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Abstract—The measurement of temperature fluctuation within the superheated boundary layer in pool boiling of water is presented. For the purpose of this measurement a specially developed microthermocouple probe has been employed. The statistical method was used for the analysis of the temperature fluctuation. By the determination of probability density distribution and power spectral density function it was shown that the temperature fluctuation in the superheated boundary layer in pool boiling of water has statistical feature characteristics. From the statistical analysis of the temperature e.m.f. the most probable temperature difference between water and vapor phase is determined. It is shown that the statistical characteristics of the temperature fluctuation at the vicinity of the heated wall in pool boiling of water depend on the distance from the heated wall.

NOMENCLATURE

T,	temperature [°C];
τ_0,	record time [s];
f,	frequency [1/s];
P,	probability distribution function;
p,	probability density function;
G,	power spectral density function;
f,	frequency range;
t,	time [s];
N_1,	number of the same amplitude;
N,	total number of $\Delta\tau$ in one record;
ΔT,	temperature range of one cell;
$\Delta\tau$,	sampling time.

INTRODUCTION

THERE are many fluctuating variables in the two-phase boundary layer which are necessary to be taken into consideration in the analysis of boiling process. It is known that many typical boiling characteristics such as bubble departure diameter, frequency of the bubble, velocity and temperature of the fluid have a statistical nature. Their effect on the field variables in the two-phase boundary layer has caused appreciable fluctuation of these variables in the vicinity of the heated wall. In the selection between these variables in the boiling two-phase system we have decided to investigate and to analyse the temperature fluctuation in this system. The temperature of the fluid is one of the essential variables which define the intensity of the heat transfer in this condition. In many recent investigations of pool boiling [1–3] significant temperature fluctuations in the two-phase boundary layer has been observed. These fluctuations are mainly induced by the violent liquid and vapour motion in the vicinity of the heated wall. In order to investigate these fluctuations it is necessary to apply a statistical method in the analysis.

The present paper shows that the temperature fluctuation in boiling two phase system has a statistical character which depends on the distance from the heated wall. It also points out

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that significant liquid superheat exists within the two-phase boundary layer. Further investigation of the liquid superheat may be of considerable help in explaining the mechanism of the boiling process.

ANALYSIS OF THE TEMPERATURE FLUCTUATION

Temperature fluctuation in a two-phase system can be analysed as a random variable with the stochastic character. It is also assumed that temperature fluctuation is stationary random variable with ergodic property. This assumption can be checked by the obtained results. It is known that any random variable has the statistical character so that it can be described by the statistical methods. These methods are divided in two groups, the first of which describes the amplitude and the second of which the frequency of the random variable.

A typical signal of the temperature fluctuation is shown in Fig. 1. For the amplitude analysis the

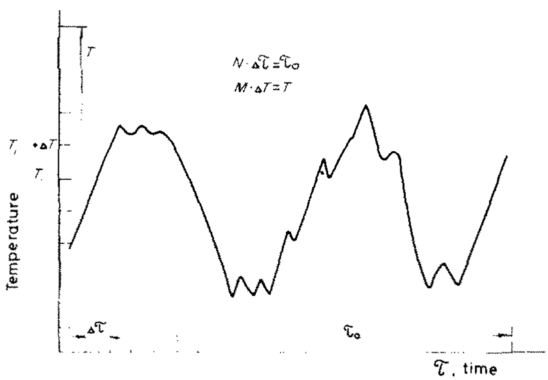

FIG. 1. Typical signal of temperature fluctuation in boiling water.

range of the temperature fluctuation histogram is divided into M value of ΔT and sample time τ_0 is divided into N value of $\Delta\tau$. Then the probability that the amplitude $T(\tau)$ will be between T_i and $T_i + \Delta T$ is as follows:

$$P(T_i, T_i + T) = \frac{\sum_i \Delta\tau_i}{\tau_0}$$

or

$$P(T_i, T_i + \Delta T) = \frac{\Delta N_i}{N}$$

where ΔN_i represents a number of $\Delta\tau$ with the amplitude T_i. Taking ΔT to be very small, probability density function is given as:

$$P(T) = \frac{P(T_i, T_i + \Delta T)}{\Delta T}.$$

The second method in the analysis of the random variable relates to the determination of the power spectral density. It is known that any time function of the random variable can be developed by the Fourier series, and it can be shown that the mean square value of the random variable is equal to the sum of individual mean squares of the described harmonics. Thus we can write the following expression:

$$\overline{T^2(t)} = \overline{T_1^2(t)} + \overline{T_2^2(t)} + \cdots$$

where

$T(t)$ —time function of the random variable
$T_1(t)$—the first harmonic function
$T_2(t)$—second harmonic function.

The temperature fluctuation signal does not contain harmonics with the described frequency so that frequency spectrum is a continuous function. In that case the mean square value for the frequency range between f and $f + \Delta f$ is

$$\overline{T^2(f, f + \Delta f)} = \frac{1}{\tau_0}\int_0^{\tau_0} T^2(t, f, \Delta f)\, dt.$$

For the small value of Δf we can define the power spectral density as

$$T^2(f, f + \Delta f) = G(f)\,\Delta f$$

so that

$$G(f) = \frac{T^2(f, f + \Delta f)}{\Delta f}.$$

The mean square value of the temperature fluctuation is

$$\overline{T^2(t)} = \int_0^\infty G(f)\,df.$$

This is the second statistical characteristic of the temperature fluctuation which describes the fluctuation character of the temperature at any fixed point in the two-phase system.

TEMPERATURE FLUCTUATION MEASUREMENT

The temperature measurements are performed by a chromel–alumel microthermocouple specially designed for the high frequency measurements. From the temperature fluctuation measurements performed earlier [1] it is shown that the microthermocouple is suitable for the temperature measurement in the two-phase flow. The microthermocouple was made from chromel and alumel wire of 12·5 μ dia. The thermocouple probe consists of two glass tubes with the outer diameter of 0·1 mm connected by glass melting so that a hot junction was made at the end of these two tubes. The microthermocouple probe is connected to the support by which continuous displacement was possible.

Special attention is drawn to the calibration of the microthermocouple. In addition to the static characteristic of the thermocouple for temperature fluctuation measurement, it is necessary to know the dynamic characteristic of the thermocouple as well. For the microthermocouple which was used for this measurement a particularly developed method for the determination of the dynamic characteristics was applied [5].

The essential idea of the calibrating method consists of successive heating of the thermocouple junction by radiation and cooling by convection. This was achieved by focusing a light beam to the thermocouple and cooling it simultaneously with a gas stream. Choosing the light beam with the prescribed frequency, temperature of the hot junction is changed. Comparing this signal with that of a photodiode placed beside the hot junction of the thermocouple in the light beam direction, the response time of the microthermocouple is obtained. Dynamic characteristic for the thermocouple chromel–alumel, 12·5 μm dia. wire is shown in Fig. 2. For the registration of the microthermo-

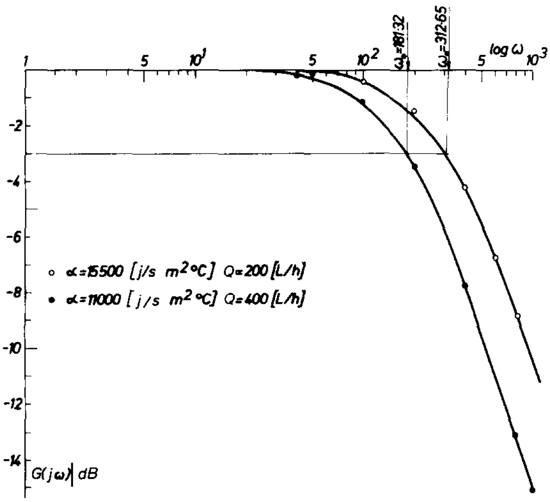

FIG. 2. Dynamic characteristic of microthermocouple.

couple signal a standard instrumentation was used which consisted of the following units: potentiometer, DC amplifier, band-pass filter, instrumental tape recorder and storage oscilloscope (Fig. 3). The DC component of the e.m.f. of the thermocouple was eliminated by the potentiometer compensation while the fluctuation part of the signal was brought to the DC amplifier. The DC amplifier was with minimum

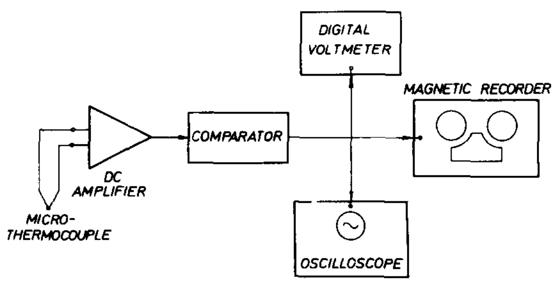

FIG. 3. Registration set-up.

zero drift and frequency range from DC to 10 kHz with maximum amplification of 1000 times. For most of the measurement the maximum amplification was used. The thermocouple signal was modulated by 300 Hz noise which was conducted by the water from the heater. Due to this, the band-pass filter was used to eliminate the noise interference with the reading of the thermocouple. After this the operation signal was fed to the instrumental magnetic tape recorder.

Experimental determination of the temperature fluctuation in pool boiling was performed in the stainless steel vessel with a vertical stainless steel tube heater ∅ 5·5 mm (Fig. 4). A

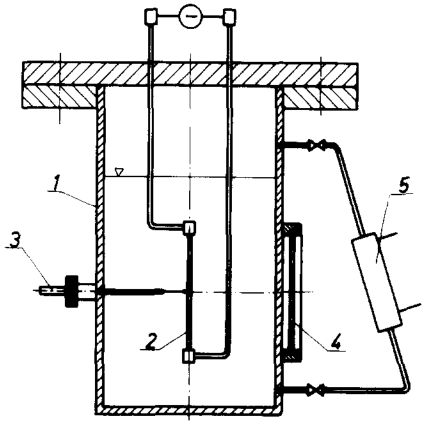

FIG. 4. Experimental vessel. 1. vessel, 2. heater, 3. microthermocouple, 4. glass window, 5. condenser.

heater was connected to the low voltage DC current rectifier as a power supply. The thermocouple probe was placed at the middle of the test section. The support of thermocouple provided the placing of thermocouple hot junction at different distances from the heated wall. The vessel was provided with transparent windows for visual observation of the process at the heating surface and for high speed camera photography.

EXPERIMENTAL ANALYSIS OF TEMPERATURE FLUCTUATION

The flow sheet for the amplitude analysis of the microthermocouple signal is shown in Fig. 5.

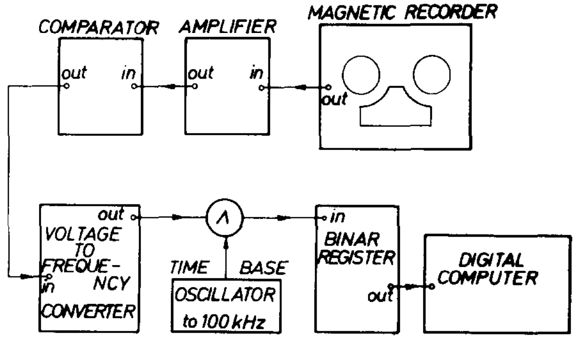

FIG. 5. Block diagram for frequency analysis.

This circuit comprises the following units: DC amplifier, comparator, voltage-to-frequency converter, i-circuit, binary register, oscillator and digital computer. The amplified signal from the magnetic tape recorder is taken into the comparator in order to bring it to the voltage level for the voltage-to-frequency converter. In the voltage-to-frequency converter the signal is transformed into digital form and then put through an i-circuit by a controlled impulse oscillator with a frequency of 200 Hz and fed to a binary register. In binary register the signal is coded for the digital computer. For each measurement in binary register 16000 digital samples are located with the sampling time of 0·3 ms. The programme for the computer is adapted so that the computer is selecting between 16000 samples those which lay within the temperature range of any single cell. The whole range of temperature fluctuation is divided into 300 cells so that the range for a single cell corresponds to $\Delta T = 0{\cdot}03°C$.

For the frequency analysis of the microthermocouple signal the following flow sheet was used (Fig. 6). Signal from the magnetic tape recorder was passed through a band-pass filter with the defined frequency band Δf. After the band pass filter the signal was led to a amplifier and multiplier for squaring of the instantaneous value of the filtered signal. Averaging the squared

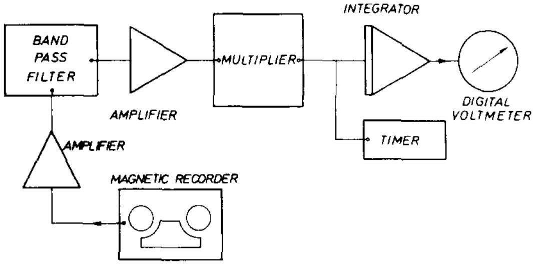

FIG. 6. Block diagram for power spectral analysis.

instantaneous value over the sampling time was performed by an integrator connected with digital voltmeter and timer. By this procedure the mean square value of a sample time history record in a frequency range between f and $f + \Delta f$ is obtained. Hence, the mean square value of the microthermocouple signal is equal to the total area under a plot of the power spectral density function versus frequency.

At the present time, analog signal from magnetic tape is digitalized, on the same way, but the amplitude and frequency analyses are performed on the digital computer and the results are plotted.

history was recorded with a magnetic tape speed of 19 cm/s within the period of 5 s of real time. During the temperature fluctuation measurement all parameters of the system were constant. Heat flux at the heated surface was 24 W/cm^2.

A typical diagram for the amplitude probability distribution is shown in Fig. 7. Real time

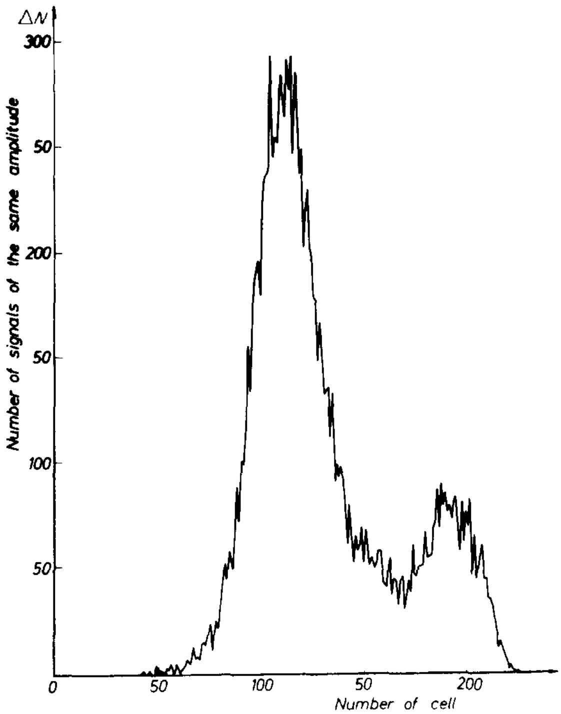

FIG. 7. Typical amplitude distribution of temperature fluctuation (heat flux: 24 W/cm^2).

EXPERIMENTAL RESULTS OF TEMPERATURE FLUCTUATION IN WATER POOL BOILING

Measurement of the temperature fluctuation in pool boiling of water at the atmospheric pressure has been conducted. The time history of the temperature fluctuation was measured at six different distances of the microthermocouple hot junction from the heated wall. Starting from 0·5 mm from the heated wall to 9·5 mm, the hot junction position was selected for making a more detailed measurement in the vicinity of the heated wall. For each measurement the time for the record of the time histogram which was taken in the analysis was 4·8 s. In order to test the steadiness of the microthermocouple signal several records were analysed for the same measurement. Such verification shows that there were no significant variations of the probability distribution from record to record. The second method for the verification of the steadiness which was also used was the determination of the mean square value for the individual record of the signal obtained by integration area under the power spectral density function. Some scattering of the points on the amplitude probability distribution occurs due to presence of the electronic noise within the signal and some variation of the behaviour of the individual sample records as well.

From Fig. 7 it is obvious that the amplitude probability distribution function has two pronounced maxima; these may be thought to correspond to the most probable liquid and vapour temperature. Therefore it is possible to determine the most probable temperature difference between the liquid and vapour phase for any fixed point in the two-phase boundary layer. If we assume that the probability distribution function for the predominant phase has a normal distribution it is possible to separate the liquid and vapour distribution. By integration of the separated distributions we obtain the residence time which the hot junction of the thermocouple spends in the liquid and vapour phase respectively. Using this method the local void fraction can be obtained at any particular point in the system. From the same sample of the microthermocouple signal, the power spectral density function is obtained which is shown in Fig. 8.

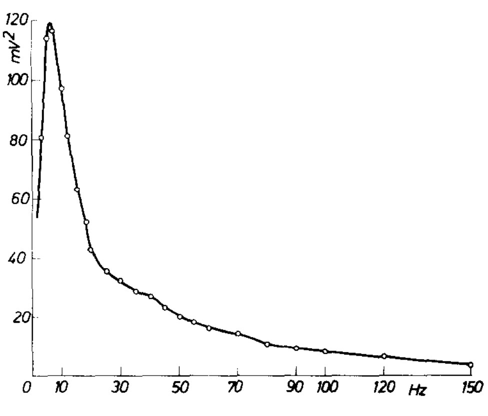

FIG. 8. Typical power spectral density distribution curve (heat flux: 24 W/cm²).

The power spectral density function was determined for the frequency region from 3 to 200 Hz. The frequency band for the range from 3 to 200 Hz was 0·51 f Hz. The maximum of this function appears at the frequency ~5 Hz which may be explained by the effect of the bubble velocity in natural circulation of two phase mixture flowing around the test section. There is also some change in the power spectral density function at the frequency of 50 Hz which corresponds to the frequency of bubble nucleation.

The amplitude probability distribution is shown in Fig. 9 which represents the different

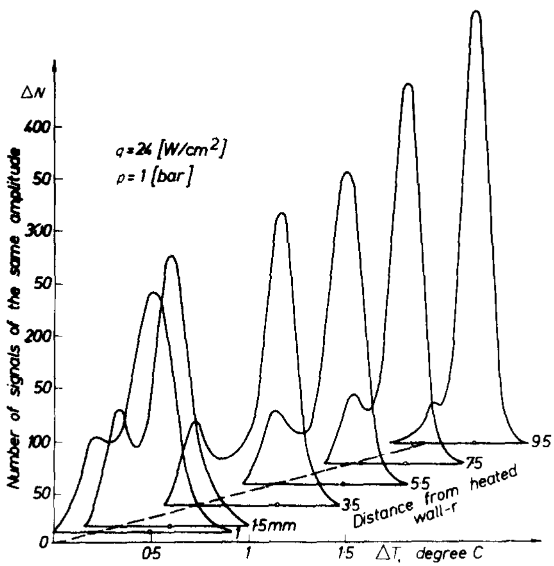

FIG. 9. Distribution of temperature fluctuation in pool boiling.

positions of the microthermocouple probe. The temperature fluctuation is much more pronounced in the vicinity of the heated wall. Increasing the distance from the wall this fluctuation decreases. The most probable temperature difference between the liquid and vapour phase also depends on the distance of the hot junction from the heated wall. In Fig. 10 the most probable temperature differences are plotted versus the distance of the hot junction from the heated wall. It is obvious that there exists a minimum of the most probable tem-

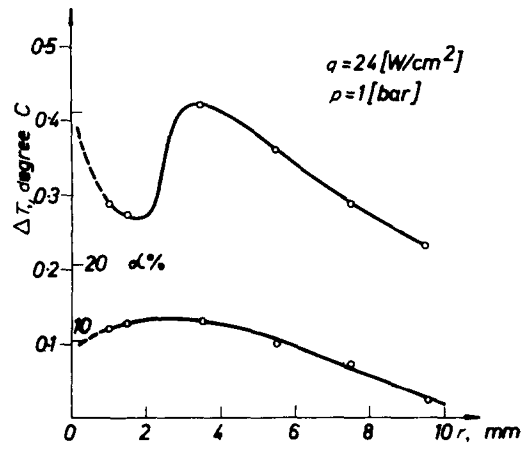

FIG. 10. The most probable water–vapor temperature difference and void distribution as a function of distance from the heated wall in pool boiling.

perature difference at the distance of 2 mm from the wall. This can be explained by the high void fraction at this place. This conclusion can be confirmed by applying the previously explained concept for the void fraction determination to this measurement. The void fraction also varies with the distance from the wall. There is a maximum of the void fraction for the most probable temperature difference minimum.

CONCLUSION

The major conclusions drawn from this experimental investigation may be stated as follows:

1. The microthermocouple technique can be applied for the determination of the temperature fluctuation in the boiling two-phase system.

2. Analysis of the temperature fluctuation has proved the statistical nature of this fluctuation. Through the amplitude analysis of the temperature fluctuation it is possible to determine the most probable temperature difference between the liquid and vapour phase.

3. It is shown that the statistical characteristics of the temperature fluctuation in the vicinity of the heated wall in the pool boiling of water depend on the distance from the wall.

REFERENCES

1. R. SEMERIA, Relationship between the structure of the two-phase layer near a heating wall and the mechanisms of thermal exchange, Proc. Heat and Mass Transfer in Turbulent Boundary Layers, Beograd (1970).
2. S. J. D. VAN STRALEN and W. M. SLUYTER, Local temperature fluctuation in saturated pool boiling of pure liquids and binary mixtures, *Int. J. Heat Mass Transfer* 12, 187–198 (1969).
3. R. SEMERIA and J. FLAMAND, Phase detection at junction of microthermocouple, 11th Nat. Heat Transfer Conference, Minneapolis (1969).
4. N. AFGAN, Boiling heat transfer and burnout heat flux of ethyl alcohol–benzene mixtures, Proc. Third Int. Heat Transfer Conference, Vol. III, p. 175–185 (1966).
5. V. PIŠLAR *et al.*, Determination of microthermocouple dynamic characteristics, Int. Seminar on Heat and Mass Transfer, Herceg-Novi, Yugoslavia (1969).
6. J. S. BENDET and A. G. PIERSON, *Measurement and Analysis of Random Data*. John Wiley, New York (1966).

Résumé—On présente une mesure des fluctuations de température dans une couche limite surchauffée lors de l'ébullition d'eau en réservoir. Pour cette mesure, on a spécialement conçu une sonde à microthermocouple. La méthode statistique est développée pour l'analyse des fluctuations de température. Par la détermination de la distribution de la densité de probabilité et de la fonction de densité spectrale de la puissance, on a montré que les fluctuations de température dans la couche limite surchauffée pour l'ébullition d'eau en réservoir ont des caractéristiques d'ordre statistique. A partir de l'analyse statistique de la température, on détermine la différence de température la plus probable entre l'eau et la phase vapeur. On montre que les caractéristiques statistiques des fluctuations de la température au voisinage de la paroi chauffée lors de l'ébullition de l'eau en réservoir dépendent de la distance à la paroi chauffée.

BESTIMMUNG DER STATISTISCHEN EIGENSCHAFTEN DER TEMPERATURSCHWANKUNGEN BEIM BEHÄLTER-SIEDEN

Zusammenfassung— Es wurden Messungen der Temperaturschwankungen in der überhitzten Grenzschicht beim Behälter-Sieden in Wasser durchgeführt. Für die Messungen wurde ein speziell entwickeltes Mikro-Thermoelement verwendet. Für die Analyse der Temperaturschwankungen wurden statistische Methoden herangezogen. Durch die Bestimmung der Häufigkeitsverteilung und der Funktion des Leistungsspektrums zeigte sich, dass die Temperaturschwankungen in der überhitzten Grenzschicht beim Behälter-Sieden in Wasser statistische Haupteigenschaften besitzen. Aus der statistischen Analyse der Temperaturverteilung wurde die charakteristische Temperaturdifferenz zwischen Wasser und Dampfphase bestimmt. Es wurde gezeigt, dass die statistische Charakteristik der Temperaturschwankung nahe der Heizwand beim Behälter-Sieden von Wasser von der Entfernung von der Heizwand abhängt.

ОПРЕДЕЛЕНИЕ СТАТИСТИЧЕСКИХ ХАРАКТЕРИСТИК КОЛЕБАНИЯ ТЕМПЕРАТУРЫ ПРИ КИПЕНИИ В БОЛЬШОМ ОБЪЕМЕ

Аннотация—Описывается измерение колебаний температуры в перегретом пограничном слое при кипении воды в большом объеме. Для измерения использовался специально сконструированный датчик-микротермопара. Анализ колебаний температуры проводился с помощью статистического метода. Определение распределения плотности вероятности и степенной функции спектральной плотности показало, что колебания температуры в пограничном слое при кипении перегретой воды в большом объеме имеет статистический характер. Из статистического анализа Э.Д.С. термопары установлен наиболее вероятный перепад температур в жидкой и паровой фазах. Показано, что статистические характеристики колебаний температуры вблизи нагретой стенки при кипении воды в большом объеме зависят от расстояния от стенки.