Int. J. Heat Mass Transfer. Vol. 16, pp. 187–194. Pergamon Press 1973. Printed in Great Britain

AN APPROACH TO THE ANALYSIS OF TEMPERATURE FLUCTUATION IN TWO-PHASE FLOW

N. AFGAN,* LJ. JOVANOVIĆ, M. STEFANOVIĆ and V. PIŠLAR
Boris Kidrič Institute, Beograd, Yugoslavia

(*Received* 18 *February* 1972)

Abstract—In this paper an approach to the analysis of temperature fluctuation in two-phase system is presented. It is assumed that resulting temperature fluctuation in two phase boiling boundary layer can be divided into two independent fluctuating function. One is the square wave function obtained as a result of crossing the liquid–vapor interface and the other function represents the random fluctuation of temperature in water and vapor. Taking this assumption into consideration the resulting variance of the temperature fluctuation is sum of the variances of these independent functions.

Experimental verification of this approach is obtained by the amplitude and frequency analysis of the microthermocouple signal placed at the different position from the heating wall. It is shown that the presented approach of the analysis of temperature fluctuation is in fair agreement with the experimental measurement.

NOMENCLATURE

T,	temperature [°C];
τ_0,	record time [s];
N_1,	number of the same amplitude for hot junction being in the liquid;
N,	total number of $\Delta\tau$ in one record;
σ_y,	variance of rectangular wave;
σ_x,	variance of normal distribution;
G_T,	power spectral density function;
f,	frequency.

INTRODUCTION

THE STATISTICAL nature of temperature fluctuation has been recognized in many recent investigations of boiling processes [1–3]. The scope of the present investigation is based on the statistical method and suitable experimental technique for the determination of the statistical characteristics of temperature fluctuation in two phase boiling system [4]. In order to verify a validity of the hypothesis taken in this approach the simultaneous high-speed motion picture was used for the photography of the physical interaction of two-phase mixture with the microthermocouple probe and the obtained e.m.f. This study intends as a preliminary step to investigate the possibility of separating different causes which affect the temperature fluctuation in two-phase boiling system. In several experimental works [1, 3, 4] it was shown that in the vicinity of the heated wall the temperature of the boiling liquid is larger than corresponding saturation temperature of the vapor. The thermocouple hot junction in one fixed point near the heated wall will be simultaneously in liquid and vapor phases. Each crossing of the interface between the liquid and vapor phase by thermocouple hot junction will cause the temperature change at this fixed point. Due to the violent motion of the two-phase mixture during the boiling process there will be many crossing of the interface at the fixed point of the system, so that this is one of the causes for the temperature fluctuation in the two-phase boiling system. It is very often recognized that bubble formation at the heating surface acts as a turbulence promoter in boiling liquid. Turbulence motion of the liquid and vapor in the two-phase system can be

---

* Also professor at the Faculty of Technology and Metallurgy, University of Beograd.

taken also as a cause for the temperature fluctuation at a fixed point of the system.

The purpose of this study is to analyse the temperature fluctuation for pool boiling heat transfer and to obtain some fundamental knowledge about the boiling phenomena mechanism. Although the method for the determination of the statistical characteristics of temperature fluctuation is based on the assumption of a random variable, it will be shown that regularities which exist in this fluctuation are the result of the processes which are taking place in the system.

EXPERIMENTAL STUDY OF THE TEMPERATURE FIELD IN THE VICINITY OF HEATED SURFACE

In order to verify the main assumption on which this study is based an experimental apparatus was designed. The experimental set-up of the boiling vessel and the high speed motion picture camera is shown in Fig. 1. The heating surface is 6 cm^2 of the stainless steel plate with a copper beam as a heater of the same cross section silversoldered from the lower side. At the distance of 30 mm from the silversoldered end of the copper beam the heating coil was wrapped with the heating power of 1000 W. At five points along the copper beam the temperature was measured from which the reading of the heat flux at the heating surface was calculated. The side surface of the boiling vessel was made of pyrex glass. In order to hold the desired temperature of the boiling liquid, a glass tube preheater was used with the heating surface large enough to prevent boiling at the preheater surface. The microthermocouple probe was mounted at the cover plate of the boiling vessel. The thermocouple was made of chromel–alumel 12·5 μ dia. wire electrically insulated with glass tubes and, as is shown in Fig. 2, connected to the support.

The response time of this thermocouple was determined by a specially developed method for the determination of the dynamic characteristics of the thermocouple [5]. The basis of this method consists in successive heating the hot junction of the thermocouple by radiation and cooling it by convection. This is achieved by focusing a light beam on the hot junction and simultaneously cooling it with a gas stream. By chopping light beam by the desired frequency, the time dependence of e.m.f. is obtained. In comparing this signal with the signal of a photodiode placed in the light beam direction behind the hot junction the response time of the microthermocouple is obtained. The dynamic characteristics of the microthermocouple used in this measurement are shown in Fig. 3.

The distance of the hot junction of the microthermocouple to the heating surface could be adjusted accurately by using a special screw micrometer design. The construction permits a horizontal displacement of the probe so that it was possible to place the hot junction at any point over the heating surface.

The cold junction of the microthermocouple was immersed in melting ice. The signal was amplified by factor 1000 and fed simultaneously to the oscilloscope screen and magnetic tape recorder.

The two lens "Hycam" camera with the time marking accessories was used for the simultaneous recording of the real process with the signal from the microthermocouple displayed

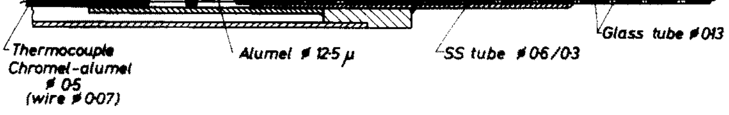


FIG. 2. Microthermocouple probe.

FIG. 1. Experimental set-up of boiling vessel, high speed camera, magnetic recorder and oscilloscope.

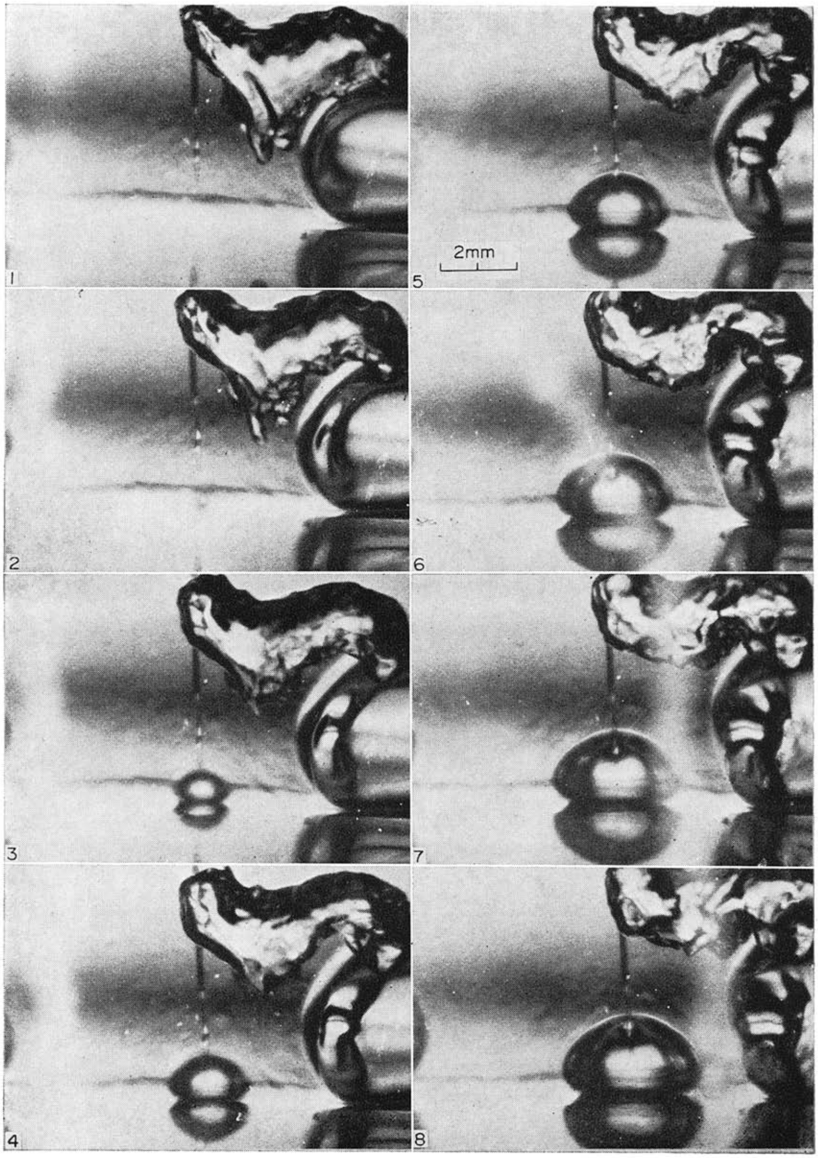


FIG. 4. Photographs taken from high speed motion picture (4000 frame/s Flux: 15 W/cm^2).

at the oscilloscope screen. The final rate of the camera move was 4000 frames per s. The time-marking pulse of 1000 Hz was used. One of the camera objective was focused on the hot junction of the microthermocouple which was illuminated by the 200 W lamp and placed opposite to the camera objective. The second objective was focused on the oscilloscope screen with high illumination of the signal trace. In order to obtain corresponding enlargement of the bubble and hot junction the 102 mm lens and the 80 mm extension tube were used.

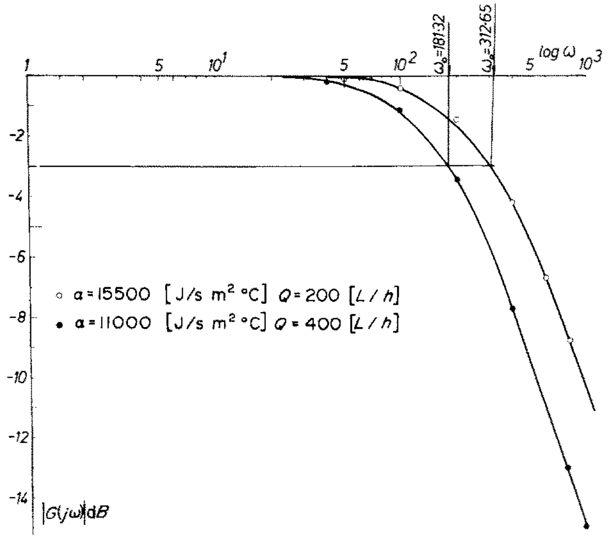


FIG. 3. Dynamic characteristic of microthermocouple.

Figure 4 gives a demonstration of the photographs taken in boiling water at heat flux $q'' = 15$ W/cm^2. This series of photographs shows consecutive pictures of bubble growth and its interaction with the hot junction of the microthermocouple. The hot junction in this case was at 1 mm distance from the heating surface. At the left side of the photographs a strongly illuminated trace represent the e.m.f. signal of the thermocouple. Photograph No. 1 corresponds to the moment just preceding formation of the bubble nucleus. The following four photographs, namely No. 2, 3, 4, 5, correspond to the early stage of the bubble growth. The temperature at the hot junction at this time is the temperature of liquid in the vicinity of the heated wall. In photograph No. 6 it is obvious that the hot junction has crossed the liquid vapor interphase and a corresponding decrease in temperature is recorded. Due to the time lag of the microthermocouple, the temperature change at the liquid–vapour interface is not as sudden as it would be without this delay caused by thermal inertia of the thermocouple. Photograph Nos. 7, 8, 9, 10, 11 and 12 correspond to the later stage of bubble growth after the hot junction has crossed the liquid vapour interface. The temperature of the hot junction corresponds the vapor temperature in the bubble during the period of bubble growth.

This illustration confirms the main assumption that the temperature change at the liquid vapor interface can be considered approximatively as a step change of the temperature at any fixed point in the two-phase boundary layer. From this experimental verification it can be derived that the temperature fluctuation in the two-phase system contains also, a stepwise fluctuation as a result of the intersection of liquid–vapor interface. In the time coordinate this stepwise fluctuation can be regarded as a rectangular wave with the frequency of bubble interaction with the microthermocouple. The amplitude of the rectangular wave is the most probable temperature difference between the liquid and vapour phase. It is assumed that this regular rectangular wave has a pulse with the amplitude $+\Delta T$ corresponding to the hot junction passing through the liquid and pulse with the zero amplitude corresponding to the hot junction passing through vapor.

Having this in mind it can be assumed that the temperature fluctuation is mainly due to the following two reasons:

> The crossing of the hot junction through the liquid–vapor interface causes the stepwise change of the temperature in the two-phase system. The frequency of these changes corresponds to the change of void fraction at any fixed point in the system.
>
> The violent motion of the liquid and vapor in the two-phase flow induces the random temperature fluctuation.

Assuming this picture of the temperature field in the two-phase system, the analysis of the temperature fluctuation can be based on the following assumptions:

1. Resulting measurement of the temperature fluctuation in the two-phase boundary layer can be divided into two independent fluctuating functions. One is the square wave function obtained as a result of crossing the liquid vapor interface and the other function represents the random fluctuation of temperature of water and vapor.
2. Resulting probability density distribution of the temperature random fluctuation is a sum of two distributions corresponding to the fluctuation in the liquid and vapor phase.

Taking this into consideration we can write

$$T(\tau) = X(\tau) + Y(\tau) \tag{1}$$

where

$T(\tau)$—resulting temperature fluctuating variable
$X(\tau)$—random fluctuating variable
$Y(\tau)$—variable fluctuating as a result of crossing the liquid–vapor interface.

Variable $Y(\tau)$ is a rectangular wave so that we can write

$$T(\tau) = \sum_{n=-\infty}^{n=+\infty} \frac{\Delta T\,.\,b}{\tau_1}\left(\frac{\sin n\pi(b/\tau_r)}{n\pi(b/\tau_r)}\right) \times \exp\left|jn\omega_r\left(\tau - \frac{b}{2}\right)\right| \tag{2}$$

where

b—liquid phase width
τ_r—period of rectangular wave.

Mean value of this variable is

$$\overline{Y(\tau)} = \frac{\Delta T\,.\,b}{\tau_r}. \tag{3}$$

If we take a sample of the signal with the period τ_0 and assume that τ_1 is the time which corresponds to the hot junction passing through the liquid phase, it is

$$\overline{Y(\tau)} = \Delta T \frac{\tau_1}{\tau_0}$$

or

$$\overline{Y(\tau)} = \Delta T\,.\frac{N_1}{N_0}$$

$$|\overline{Y(\tau)}|^2 = \left|\Delta T \frac{N_1}{N_0}\right|^2. \tag{4}$$

On the other hand it is

$$\overline{Y(\tau)^2} = \Delta T^2 \frac{N_1}{N_0}. \tag{5}$$

So that the variance of the rectangular wave is

$$\sigma_Y^2 = \overline{Y(\tau)^2} - |\overline{Y}(\tau)|^2 = \Delta T^2 \frac{N_1}{N_0}\left(1 - \frac{N_1}{N_0}\right). \tag{6}$$

In accordance with the second assumption we can write that the probability density distribution for the random variable is

$$P(x) = \frac{1}{2\pi\sigma_x}\exp\left| -\frac{X^2}{2\sigma_x}\right| \tag{7}$$

taking that $\mu = 0$.

In our case, the samples of the random fluctuating variable in the liquid and vapor are two parts of the same fluctuation. The probability density distribution of this variable is obtained by adding together the probability density distributions in the liquid and in the vapor resulting from the amplitude analysis of the temperature fluctuation in the two-phase system [4].

Since, it is assumed that X and Y are independent variables, the variance of their sum is equal to the sum of their variances, so it is

$$\sigma_T^2 = \sigma_x^2 + \sigma_y^2 = \sigma_x^2 + \Delta T^2 \frac{N_1}{N_0}\left(1 - \frac{N_1}{N_0}\right). \tag{8}$$

The mean square value of the temperature fluctuation is obtained from the power spectral density function. So we have

$$\int_0^{\alpha} G_T(f)\,\mathrm{d}f = \sigma_x^2 + \Delta T^2 \frac{N_1}{N_0}\left(1 - \frac{N_1}{N_0}\right). \tag{9}$$

The experimental verification of this relation has been investigated in order to prove that the assumption used in this analysis is in consistency with the real measurement.

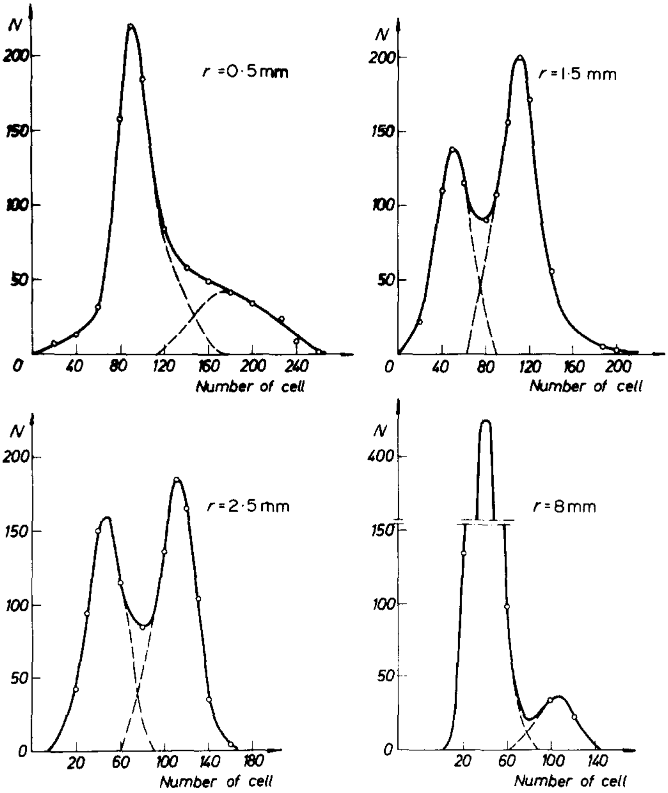


FIG. 5. Amplitude probability distribution functions of temperature fluctuation in boiling water at atmospheric pressure (Flux: 24 W/cm^2).

RESULTS AND DISCUSSIONS

Measurement of the temperature fluctuation has been performed in the water pool boiling from the vertical tube. The amplitude and frequency analysis of the temperature fluctuation was made according to the procedure described in paper [4]. The steadiness test was applied by comparing the different samples measured at the fixed point in the system. It was proved that the significant difference in the probability density distribution does not exist. Measurement was performed at 0·5; 1; 1·5; 2·5; 3·5; 4; 6; 8; mm distance from the heated wall. In Fig. 5 the amplitude probability distribution functions are shown for distances of 0·5; 1·5; 2·5 and 8 mm. The obtained amplitude probability distribution functions were graphically divided into two normal distributions. By this procedure it was possible to determine ΔT, the most probable temperature difference between the liquid and vapour phases.

The power spectral density functions were obtained for the same measurement and presented in Fig. 6. In this analysis the band pass filter with a band width 0·51 f was used. By integrating the area under the power spectral

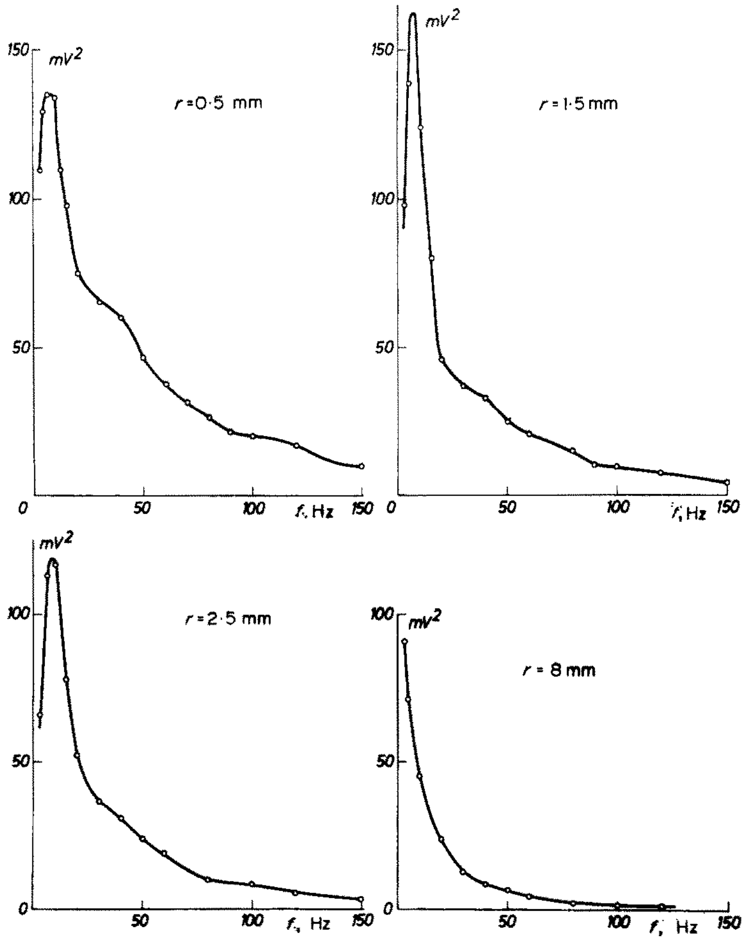
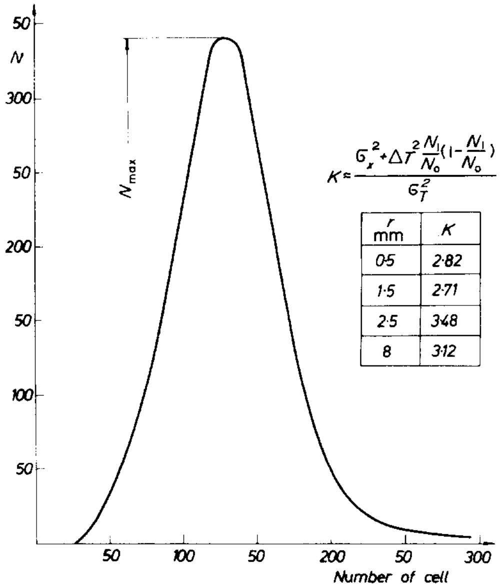


FIG. 6. Power spectral density of temperature fluctuation in boiling water at atmospheric pressure (Flux: 24 W/cm^2).

density function, the mean square value of temperature fluctuation was determined.

The relation (9) has been applied to these results in order to show the validity of the assumption taken in the evaluation of the approach to the analysis of the temperature fluctuation in two-phase system. In Fig. 7 it is shown that the mean square value obtained from the frequency analysis is in fair agreement with the same value obtained from the amplitude analysis. At a distance of 2·5 mm from the heated wall some discrepancy exists which might be explained by the appreciable difference between the real signal and the square signal which was assumed in this analysis.



$$K \approx \frac{\sigma_x^2 + \Delta T^2 \frac{N_1}{N_0}\left(1 - \frac{N_1}{N_0}\right)}{\sigma_T^2}$$

r mm	K
0·5	2·82
1·5	2·71
2·5	3·48
8	3·12

FIG. 7. Relation (9) applied to the temperature fluctuation in boiling water ($p = 1$ bar, Flux: 24 W/cm^2).

It should be noted that the telegraphic square wave with the Poisson distribution of pulses could significantly improve agreement between the experimental measurement and the developed approach. Nevertheless, it should be mentioned that for this type of approach it would be necessary to prove that the Poisson distribution of pulses is in agreement with the measurement.

It should be pointed out also that by measuring the other fluctuating parameters, such as the velocity, pressure and void fraction, and developing their cross correlation we can advance the knowledge needed for justification of this method of approach to the analysis of temperature fluctuation in the two phase flow in the vicinity of the heated wall.

CONCLUSIONS

The temperature fluctuation in saturated pool boiling of water at atmospheric pressure was measured and an approach was developed for the analysis of this fluctuation from which some interesting considerations were made. The significant conclusions can be summarized as follows:

1. The temperature change at the liquid–vapor interface can be taken as a step change between the liquid and vapour temperatures.
2. With fair agreement it was proved that the resulting temperature fluctuation in the boiling boundary layer can be divided into two independent time-dependent functions, one, being a square wave and the other being the random fluctuating variable.
3. It is clearly revealed that the random fluctuating variable has the normal probability density distribution.

REFERENCES

1. 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).
2. J. M. DELHAYE, Hot-film anemometry in two-phase flow, 11th Nat. ASME, AICHE Heat Transfer Conf. (1969).
3. R. SEMERIA and J. C. FLAMAUD, Utilisation d'un micro thermocouple pour l'étude de l'ebolution locale de l'eau en convection libre Rep. T.T. no 81, Centre d'Etudes Nucleaires de Grenoble (1967).
4. N. AFGAN, M. STEFANOVIĆ, LJ. JOVANOVIĆ and V. PIŠLAR, Determination of the statistical characteristics of temperature fluctuation in pool boiling *Int. J. Heat Mass Transfer* (to be published).
5. PIŠLAR, N. AFGAN, M. STEFANOVIĆ and LJ. JOVANOVIĆ, Determination of microthermocouple dynamic characteristics, Int. Seminar on Heat Mass Transfer, Herceg-Novi (1969).

UNE APPROCHE DE L'ANALYSE DE LA FLUCTUATION DE TEMPERATURE DANS UN ECOULEMENT BIPHASIQUE

Résumé—On présenté dans cet article une approche de l'analyse de la fluctuation de température dans un système biphasique. On suppose que la fluctuation de température dans une couche limite biphasique d'ébullition peut être séparée en deux fonctions de fluctuation indépendantes. L'une est la fonction onde carrée résultant de la traversée de l'interface liquide-vapeur et l'autre fonction représente la fluctuation désordonnée de la température dans l'eau et la vapeur. En partant de cette hypothèse, la variance résultante de la fluctuation de la température est la somme des variances de ces fonctions indépendantes.

Une vérification expérimentale de cette approche est obtenue par analyse de l'amplitude et de la fréquence du signal d'un microthermocouple placé à différentes distances de la paroi chauffante. On montre que cette approche de l'analyse de la fluctuation de température est en bon accord avec les mesures expérimentales.

EINE NÄHERUNGSLÖSUNG ZUR ERMITTLUNG DER TEMPERATURSCHWANKUNGEN BEI DER ZWEIPHASENSTRÖMUNG

Zusammenfassung—Diese Arbeit befasst sich mit einer Näherungslösung zur Ermittlung der Temperaturschwankungen in einem Zweiphasensystem. Es wird angenommen, dass die resultierende Temperaturschwankung in der Zweiphasengrenzschicht in zwei unabhängige Schwankungsfunktionen unterteilt werden kann. Eine davon ist die quadratische Wellenfront, die als Ergebnis beim Überschreiten der Phasentrennfläche erhalten wird, die andere Funktion stellt die zufälligen Temperaturschwankungen im Wasser und im Dampf dar. Unter Berücksichtigung dieser Annahmen ergibt sich die resultierende Änderung der Temperaturschwankungen aus der Summe der Änderungen dieser unabhängigen Funktionen.

Die experimentelle Bestätigung dieser Näherung wurde durch die Amplituden- und Frequenzanalyse des Signals eines Mikrothermoelementes an verschiedenen Stellen der Heizfläche erhalten. Es zeigte sich, dass die vorgeschlagene Näherungslösung zur Analyse der Temperaturschwankungen in angemessener Übereinstimmung mit den experimentellen Ergebnissen steht.

МЕТОД АНАЛИЗА КОЛЕБАНИЙ ТЕМПЕРАТУРЫ В ДВУХФАЗНОМ ПОТОКЕ

Аннотация—В статье описан метод анализа колебаний температуры в двухфазной системе. Предполагается, что результирующее колебание температуры в двухфазном пограничном слое при кипении можно разделить на две независимые функции: квадратиуную волновую функцию, полученную в результате пересечения поверхности раздела жидкость-пар, и функцию случайных колебаний температуры в воде и паре. При этом допущении результирующее изменение колебания температуры представляет собой сумму изменений этих независимых функций. Экспериментальная проверка этого метода проведена с помощью амплитудного и частотного анализа сигнала микротермопары, установленной на разном расстоянии от нагретой стенки. Показано, что результаты данного метода анализа колебаний температуры находятся в хорошем соответствии с экспериментальными измерениями.