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exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machines

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poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

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Review of recent investigations of deterministic chaos in boiling

The paper presents recent progress in modelling of boiling phenomena. It has been pointed out that the majority of the approaches are based on static models, i.e. on the concept of searching for stationary or quasi-stationary states which determine the heat transfer. Usually, the analysis of stochastic phenomena neglects local changes of the temperature of the heating surface and local heat flux. The fundamental ideas of deterministic chaos along with their implementation in the analysis of boiling are also presented in the paper. The literature survey shows that the phenomena of chaos have been observed and analysed in boiling flow along with the fractal properties of phase separation surface and the heat wave front.

Nomenclature

A	–	area, constant,	r	–	constant,
a, b, d	–	constants	t	–	time,
D	–	fractal dimension,	T	–	temperature,
e	–	natural logarithm base,	x	–	co-ordinate,
f	–	function,	z	–	variable,
Fr	–	Froude number,	v	–	velocity,
l	–	length,	ϵ	–	constant,
N	–	population,	λ	–	Liapunov coefficient,
p	–	pressure,	τ	–	time interval.
q	–	heat flux,			

Subscripts

I	–	crisis index,	min	–	minimum,
$Ikr, IIkr$	–	crisis index,	n	–	iteration number,
kr	–	critical,	o	–	fully developed, initial,
l	–	liquid, viscous,	sat	–	saturation,
max	–	maximum,	w	–	surface.

1. Introduction

It has been acknowledged that the investigations of boiling phenomena were started by Leidenfrost in 1756 [1-2]. He investigated the behaviour of a water

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droplet on a hot and heavy metal spoon. Until the 1930s the investigations of boiling phenomena were purely scientific. An increased interest in boiling was observed in the 1940s, which can be explained by the progress in the areas such as nuclear power, cryogenics and space sciences. The interest stemmed from the fact that the process is characterised by a high value of heat transfer coefficient. For example, during nucleate boiling it is possible to obtain the heat flux from the heating surface to the boiling liquid of the order of $10^6 \mathrm{W/m^2}$. One of the characteristics of boiling is the boiling curve, which describes the relation between the heat transferred from the heating surface to the boiling liquid (q), and the temperature (T_w) of the heating surface. In the literature, usually three different kinds of boiling curves are discerned. They are observed in the processes which take place in apparatuses of different construction and principle of work. The schematic distribution of these curves is shown in Fig. 1.

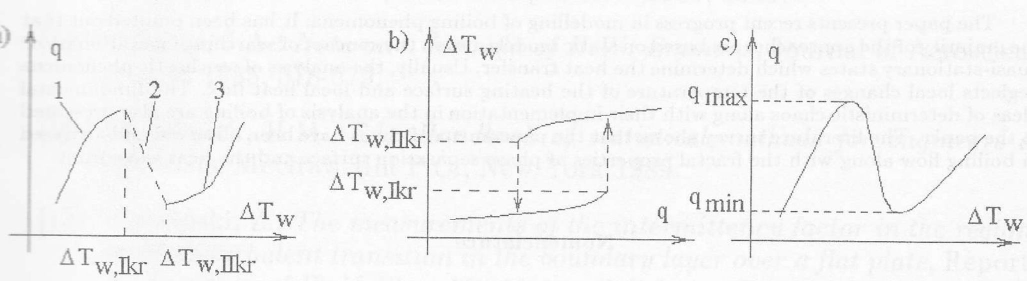

Fig. 1. Boiling curves. a) Boiling curve by Kutateladze, 1 – nucleate boiling region, 2 – transition boiling region, 3 – film boiling region.
b) Boiling curve by Nukiyama.
c) Boiling curve for non-stationary systems.

The curves shown in Figs. 1 a,b (Kutateladze and Nukiyama) can be observed in an apparatus where stationary boiling processes take place. The process of boiling is controlled by a control parameter. In Fig.1a the control parameter is ΔT_w, and in Fig. 1b the heat flux (q). The boiling curve shown in Fig.1c exists in dynamic systems, i.e. in the apparatuses where fast changes of control parameters such as $q, \Delta T_w$ take place.

Besides the way in which boiling is realised (Fig.1a,b,c) it can be divided into three regions: the nucleate boiling region, transition boiling region and film boiling region (Fig.1a). By the concept of 'existence of boiling region' the region in the space of control parameters ($T, p, ...$) is understood.

The change of type of boiling is called a boiling crisis. When the temperature of the heating surface is equal to $T_{w,Ikr}$, then the transition from nucleate to film boiling (Fig.1b) or from nucleate to transition boiling (Fig.1a) takes place. This phenomenon is called the nucleate boiling crisis or the first boiling crisis. When the temperature of the heating surface is equal to $T_{w,IIkr}$, then we have the process of transition from film to nucleate boiling (Fig.1b) or from film to transition boiling (Fig.1a). This phenomenon is called the film boiling crisis or the second boiling crisis.

Experimental investigations performed in recent years show that the critical temperature T_w and critical heat flux q are determined by the rate of change of control parameters (Fig.1c). In non-stationary processes, a decrease of heat flux q_{max} and increase of heat flux q_{min} is observed, compared to the relevant values of heat flux in stationary systems [25].

The transition boiling is a process whose existence is constrained by two phenomena – first and second boiling crisis. Investigations of this phenomenon are hindered by its vehemence and instability. According to Berenson [1], the transition boiling is a complex of phenomena characteristic for nucleate and film boiling. The latest investigations reinforce this hypothesis. Usually the transition boiling does not occur under stationary conditions, therefore the transition boiling is an unstable boiling region. Maintaining stationary parameters of a heating apparatus requires special equipment. In Figs.1a,b the transition boiling region is marked with a dotted line. In dynamic systems in the region of transition boiling, the processes take place at the same rate as in other boiling regions; in Fig. 1c this region is marked by a solid line.
Although several works have been devoted to boiling, there are still numerous fundamental problems not solved yet. The majority of these problems concern dynamic properties of boiling. It follows from the fact that with the development of new measurement techniques, the approach to the analysis of boiling phenomena has been changed. Originally, the process was perceived as a static phenomenon which can be accomplished at given initial conditions. Recently, the dynamic properties of boiling are more often investigated. The interpretation of these phenomena requires a different approach than those elaborated so far. In many cases, a new approach to the analysis of boiling is important not only from a theoretical but also practical point of view, as for example in the 1980s when disturbances of boiling water flow in water reactors were discovered. These disturbances increase the temperature of the cooling liquid, which can lead to malfunction of reactor cooling systems and eventually its breakdown. Numerous inspections of many installations showed that this phenomenon takes place very often and is dependent on the values of cooling system control parameters. Most approaches to mathematical modelling of boiling phenomena seem to be unsatisfactory in the analysis of dynamics of boiling process, and therefore more and more often the model of deterministic chaos is used.

2. Deterministic chaos

investigations in the area of non-stationary processes occurring in dynamic systems have led to the appearance of several modern methods of classification and analysis of non-stationary processes [3]. One of such methods is the so-called model of deterministic chaos, based on the analysis of the solution of differential equations describing the phenomenon. This method has been developed in the advent of computing facilities.

By the concept of deterministic chaos are understood irregular (chaotic) changes of characteristic quantities characterising a non-linear system, for which the laws of dynamics determine unambiguously its time evolution when its history is known.

The chaotic dynamic system has the following properties [3]:

- The trajectory of a chaotic system in the phase space does not form any single geometrical object such as a circle or torus, but resembles the fractal structure.
- The chaotic dynamic system is sensitive to the change of initial conditions.

In order to explain the fundamentals of chaos let us consider the dynamic system described by the equation:

$$z_{n+1} = f(z_n), \tag{1}$$

where: n - constant.

Equation (1) is used for example in the description of behaviour of the eco-system in subsequent phases of its evolution. The variable z_n describes the states of the dynamic system which are separated by a constant period of time τ.

One of the quantities describing the chaotic behaviour of the dynamic system (1) is the Liapunov coefficient defined as [3]:

$$\lambda(z_n) = \lim_{N\to\infty} \lim_{\varepsilon\to 0} \frac{1}{N} \ln \left| \frac{f^N(z_o+\varepsilon) - f^N(z_o)}{\varepsilon} \right| \tag{2}$$

It is a measure of change of the distance between two initial points (z_o) and ($z_o + \varepsilon$), which evolve correspondingly to equation (1) throughout N iterations. The Liapunov coefficient is also a measure of loss of the system information in one iteration [3]. In the case when $\lambda > 0$, we say about the dynamic system that its behaviour is chaotic.

After Schuster [3], we can discern at least three scenarios of reaching the state of chaos by a dynamic system.

The first one has been discovered in simple difference equations (1), where subsequent iterations oscillate between the stable values. The number of these values increases to infinity with the change of equation parameters, which means the transition to chaos. Fig.2. illustrates the behaviour of the dynamic system described by a logistic equation in the form:

$$z_{n+1} = r z_n (1 - z_n) \tag{3}$$

With the change of parameter r, subsequent iterations of equation (3) converge around one (Fig.2a), two (Fig.2b) or four (Fig.2c) convergence points. When the parameter r exceeds its critical value, subsequent iterations of equation (3) become chaotic (Fig.2d). Fig.2e. illustrates the diagram of stable points of equation (3), as a function of parameter r.

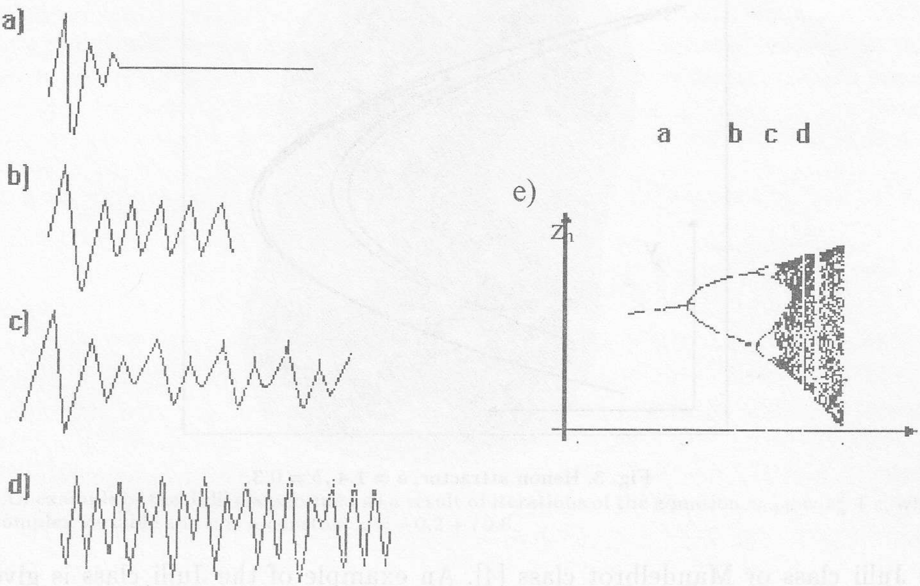

Fig. 2. The scenario of reaching the state of chaos in logistic equation (3).
a) Subsequent iterations of the equation converge around one convergence point.
b) With an increase of parameter r subsequent iterations of the logistic equation converge around two stable points.
c) A further increase of parameter r causes doubling the number of convergence points in subsequent iterations.
d) When the parameter r exceeds some critical value, then subsequent iterations of the logistic equation become chaotic.
e) Diagram of the stable points as a function of parameter r.

Another classical example of transition to chaos in the systems described by the difference equations is the behaviour of iterations, a two-dimensional equivalent of the logistic equation in the form:

$$\begin{aligned} x_{n+1} &= 1 - ax_n^2 + y_n, \\ y_{n+1} &= bx_n. \end{aligned} \tag{4}$$

Subsequent iterations of equation (4) form the so-called Henon attractor shown in Fig. 3. Subsequent iterations of equation (4) have an irregular character on the attractor.

The second scenario, the so-called intermittence scenario, exists in the case, when the regular solution is disrupted by an accidentally distributed chaotic signal. An average number of these disruptions increases with the change of equation parameters, until reaching the chaotic state.

The third scenario is connected with the existence of strange attractors, i.e. special regions in the phase space, around which the subsequent iterations of the equations describibing the phenomenon converge. Examples of such classes are:

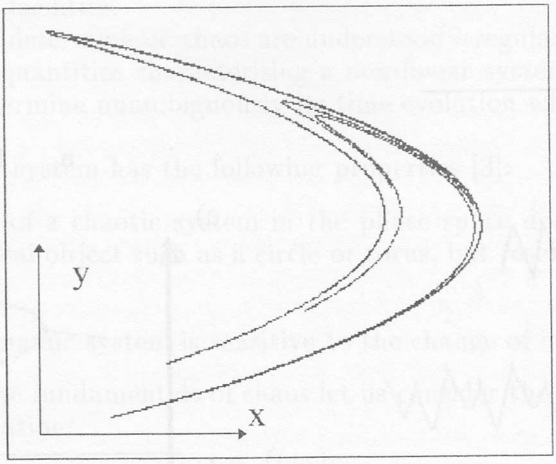

Fig. 3. Henon attractor, $a = 1.4$, $b = 0.3$.

the Julii class or Mandelbrot class [4]. An example of the Julli class is given in Fig. 4.

The phenomenon of chaos exists not only in the systems described by the difference equations, but also in the systems described by the differential equations. A classical example of such behaviour is the motion of a powered pendulum or the behaviour of liquid circulation in the Benard experiment described with the aid of the Lorenz model [3]. The fluctuations of liquid circulation in the Benard phenomenon which takes place between two plates having different temperatures are shown in Fig.5. The fluctuations have been determined based on the Lorenz model. The process of reaching stationary state by the system is shown in Fig. 5a. An increase of the temperature difference between the plates leads to irregular (chaotic) behaviour of the system (Fig. 5b).

Another result of the works on deterministic chaos is the result obtained by Takens (1981) [3, 5], which shows that after damping the transitional effects, it is possible to reconstruct the trajectory on the attractor with the aid of the measurement of one component of the vector describing the dynamic system. The utilisation of Takens works together with the capabilities of modern measurement techniques and computational methods enables the analysis of the chaotic processes based on experimental data.

The analysis of the signal enables the determination of a series of characteristics of the dynamic system such as Hausdorff dimension, Komogorow entropy, Liapunov exponents [3]. Usually the analysis of the signal starts with the construction of reverse maps, which are a special kind of Poincare maps. These maps are the graphs of $z_{n+k}(z_n)$, where k determines the length of the time period between subsequent measurements τ. Reverse maps are helpful in the analysis of the behaviour of the reconstructed attractor, but their interpretation is by no

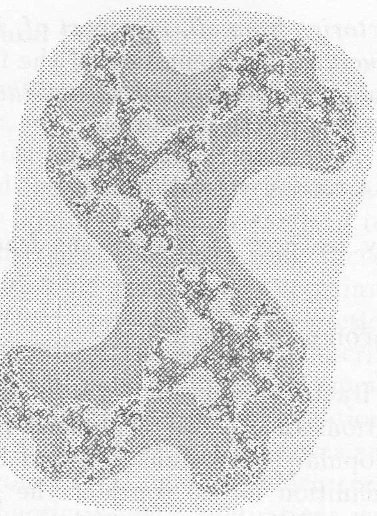

Fig. 4. An example of the Julii class formed as a result of iterations of the equation $z_{n+1} = z_n^2 + c$, where z is a complex variable and c is a constant $c = -0.2 + i\,0.6$.

means simple and requires the knowledge of other quantities which characterise the given system.

The reconstruction of reverse maps based on the results of measurements of the heating surface during nucleate boiling faces numerous difficulties coming from the inertia of measuring devices and therefore the picture of the maps is distorted [24].

According to the definition of the chaotic system given above, its trajectories do not form any single geometrical object in the phase space such as a circle or torus. They form, however, the objects called strange attractors whose structure resembles the fractal structure. There are several definitions of strange attractors and it can be assumed as in [4] that *a strange attractor is a minimal invariant*

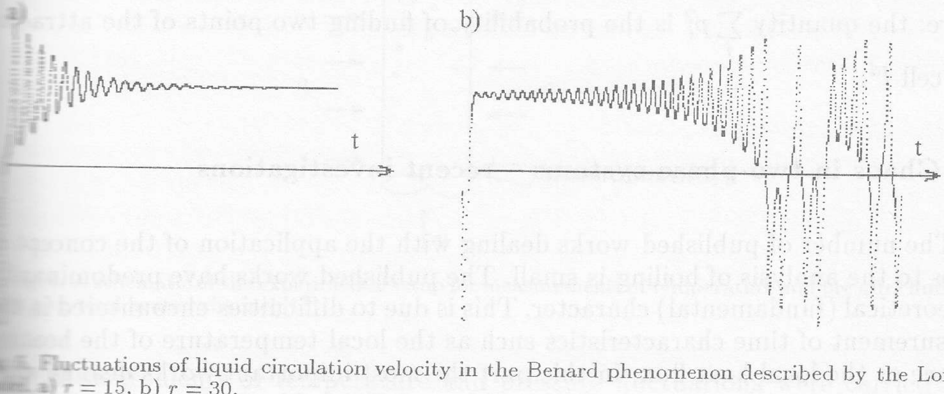

Fig. 5. Fluctuations of liquid circulation velocity in the Benard phenomenon described by the Lorenz model a) $r = 15$, b) $r = 30$.

class which attracts trajectories from all, or a part of, its neighbourhood, and has a strange geometrical structure. The definition of the fractal is *the fractal in the plane R^2 is each non-empty and compact subclass of the plane R^2* [4]. Mandelbrot assigns three properties to the fractal:

- it is determined be a recursive relation,
- it has self-similarity features (a part of the fractal is similar to a whole fractal),
- is an object with incomplete dimension.

One of the important fractal characteristics is its dimension. There have been introduced several definitions of the fractal dimension (informative, pointwise, Liapunov's). The most popular is the Hausdorff and Kolmogorow definition [4]. In order to form this definition let us consider the geometrical object in the n-dimensional Euclides space. Let us cover it with the set of n-dimensional blocks of side ε. Let $N(\varepsilon)$ will be a minimal number of blocks sufficient to cover the whole object. The fractal dimension is defined as

$$D = \lim_{\varepsilon \to 0} \frac{\log N(\varepsilon)}{\log(1/\varepsilon)}. \tag{5}$$

If a geometrical object is a part of a smooth line, then $N(\varepsilon) \approx (1/\varepsilon)$. If a geometrical object is a slice of a smooth surface, then $N(\varepsilon) \approx (1/\varepsilon)^2$. For the fractal object, the relation holds $N(\varepsilon) \approx (1/\varepsilon)^D$.
The correlational dimension is usually determined when the time signal of the measured quantity is known. The correlational dimension is defined as [4]:

$$D_c = \lim \frac{1}{\ln l} \ln \sum_i p_i^2, \tag{6}$$

where: the quantity $\sum_i p_i^2$ is the probability of finding two points of the attractor in a cell l^d.

3. Chaos in two-phase systems – recent investigations

The number of published works dealing with the application of the concept of chaos to the analysis of boiling is small. The published works have predominantly a theoretical (fundamental) character. This is due to difficulties encountered in the measurement of time characteristics such as the local temperature of the heating surface or the local heat flux. In this part the most important works dealing with the application of the concept of chaos for modelling of boiling are described.

3.1. Two-phase flow and boiling

A phenomenon known as *density-wave instability* takes place in the systems with a phase change as, for example, in water nuclear reactors [6]. In such systems there is a forced flow of liquid under conditions of boiling. As the numerous experimental results and theoretical considerations show, both the boiling process itself and the two-phase liquid-vapour flow can lead to chaotic fluctuations of the liquid flow and, as a consequence, to the strong fluctuations of the heat removed by the cooling system [9]. This problem has been investigated from the point of view of safety of the nuclear reactor [6-12]. Theoretical models are based on the analysis of the solution of differential equations describing the phenomena of heat and mass transfer. The set of partial differential equations (balance equations) is transformed into a set of ordinary differential equations relatively simple to solve.

The flow of heat and mass in a vertical pipe was analysed in the works [10-11]. For low values of the Froude (Fr) number, which corresponds to the flow with a small velocity, strong chaotic velocity fluctuations were discovered. This phenomenon takes place when the heating power of the system decreases and the limit of boiling approaches the end of the heating region. The system becomes unstable and through the cascade of subsequent bifurcations reaches a chaotic state. The strange attractor, which exists in this case, has a correlational dimension $D = 1,8$. Numerous inspections of many installations of nuclear reactor cooling systems showed that this phenomenon takes place very often and is determined by the values of the control parameters of the cooling system.

The results of experimental investigations of temperature and pressure fluctuations in the cooling system with a natural liquid circulation are described in the work [13]. The schematic of the experimental arrangement is shown in Fig. 6.

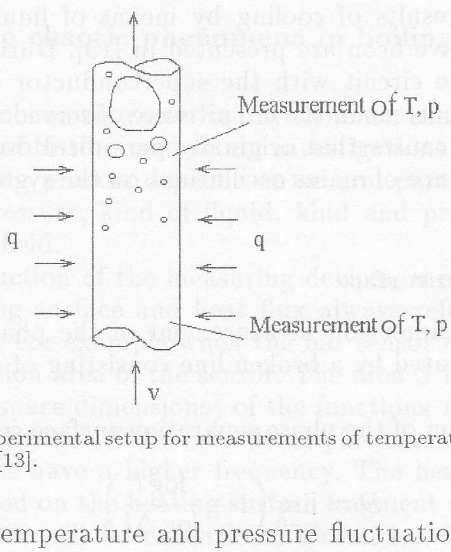

Fig. 6. A schematic of the experimental setup for measurements of temperature and pressure fluctuations in a vertical heated channel [13].

Measurements of temperature and pressure fluctuations were carried out at the beginning and the end of the heating region, which is shown in Fig. 6. During the experiment, the chaotic velocity, temperature and pressure around their mean values were observed. The front of the start of boiling did not move during the experiments (a different case to that reported in [10-11]). Its movement was observed only in the cases of appearance of additional nucleation centres when the inlet liquid velocity was reduced.

The results of pressure measurements served for the determination of the correlational dimension which exists during boiling of chaotic structures. It has been concluded that for the flow with additional nucleation centres, the correlational dimension is $D = 1.35$. For the flow existing before the appearance of additional nucleation centres, it is impossible to determine one fractal dimension (there is a lack of one fractal structure), but the behaviour of the pressure fluctuations is chaotic.

In the work [6] in order to model the two-phase flow in a heated channel, the set of ordinary non-linear equations was used, where some variables were defined as time functions. The set of equations was solved numerically for the conditions of constant, exponentially decaying and periodical changes in the pressure difference Δp. In the case of periodical changes of Δp, the system evolution can form strange attractors. The shapes of attractors change with respect to the frequency of pressure changes. In the work [6] the fractal dimension of the attractor was estimated at $D = 2.048$.

Some analysis of fractal dimension was conducted for the flow of mixtures in [14]. In the flows of gas and liquid in a vertical pipe, strange attractors of dimensions between 5 and 12 were detected. In the horizontal flow (gas, solid) a strange attractor of dimension $D = 3.7$ was detected. The results of investigations of a droplet oil-water flow in a vertical pipe were also presented in [14]. The results were analysed by means of the Grassberger-Procaccio algorithm. In this case the attractor dimension was determined as $D = 5.0$.

The experimental results of cooling by means of liquid nitrogen superconductor $YBa_2Cu_3O_{7x}$ have been are presented in [15]. During cooling the boiling process took place. The circuit with the superconductor contained inductance. The oscillations of the current in the circuit were observed. The results show that the increase of voltage causes that originally periodical oscillations transform to chaotic ones. The influence of mains oscillations on the system behaviour was also investigated there.

3.2. Phase separation surface

During the fractal dimension measurement of the phase separation surface, the surface is approximated by a broken line consisting of segments of length Δl (Fig. 7).

The fractal dimension of the phase separation surface can be determined from the relation:

$$D = \lim_{\varepsilon \to 0} \left(1 - \frac{\log l}{\log \Delta l} \right), \tag{7}$$

where: l – the length of the broken line, Δl – the length of the segment.

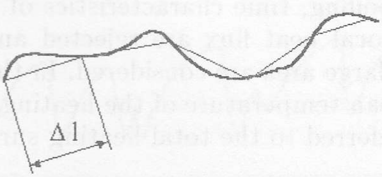

Fig. 7. Schematic for calculation of fractal dimension of the phase separation surface.

Experimental and theoretical investigations show that the fractal dimension of the phase separation surface is about $D = 1,2$ [26]. Fractal properties of the phase separation surface exist in the case of lack of surface tension. As the experimental investigations demonstrate, the surface tension leads to the decay of fractal properties of the phase separation surface.

It was shown in [16] that the fractal dimension of the phase separation surface is connected with the Reley-Taylor instabilities and that the character of the processes which occur during the initial phase of Reley-Taylor instabilities is analogous to the processes which take place in gravitational waves in deep water (in this case the fractal dimension of the phase separation surface is $D = 2.25$). The results of measurements of the fractal dimension of the heat wave front in liquid were also presented in [16]. The measurements were performed with the aid of light refraction in liquids under the presence of the temperature gradient. The obtained results show that with the increase of the temperature gradient the fractal dimension decreases. In the range of the experiments, the fractal dimension varied between 1.4 and 1.6.

4. Remarks on the chaotic phenomena in boiling

Boiling is a phenomenon characterised by dynamic changes of thermodynamic parameters. A review of historic and recent investigations of boiling can be found in [1,18-17]. The boiling process depends on several parameters where the most important are: the pressure, kind of liquid, kind and properties of the heating surface, gravitational field.

Due to the construction of the measuring devices, measurements of the temperature of the heating surface and heat flux always refer to some fragment of the heating surface S. For example when the bar sensor is used, the surface S is equal to the cross-section area of the sensor. The area S is a region where averaging (with respect to space dimensions) of the functions $T(x, y, t)$, $q(x, y, t)$ takes place. The smaller is the area S the more local phenomena can be measured and the recorded quantities have a higher frequency. The heat flux and the heating temperature determined on the heating surface fragment of diameter close to the vapour bubble diameter will be called local quantities. For the heat flux q, its local value will be denoted by a superscript s.

Usually in modelling of boiling, time characteristics of the local temperature of the heating surface and local heat flux are rejected and only the quantities determined over a relatively large area are considered. In the case of pool boiling, we usually talk about the mean temperature of the heating surface and the mean heat flux as the quantities referred to the total heating surface.

4.1. Nucleate boiling

A characteristic property of nucleate boiling is generation of single vapour bubbles from the heating surface. The process depends on the surface temperature. With the temperature increase the coalescence of single bubbles takes place. With respect to this fact, the nucleate boiling region is divided into two regions: *isolated vapour bubble region* and the region where there is an interaction between the vapour bubbles (coalescence). The processes which take place on the heating surface determine the distribution of local heat transfer phenomena between the liquid and heating surface. Del Valle and Kennig [17] discern the regions shown in Fig. 8 on the heating surface during the nucleate boiling. These are: the nucleation region, the region where there is no nucleation, the region of isolated bubbles which have an influence on the heat transfer and the region of covering of neighbouring vapour bubble interaction regions. A sample location of the measurement surface S is shown in Fig. 8.

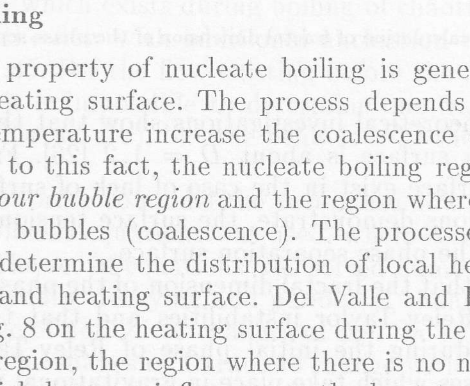

Fig. 8. The heating surface during the nucleate boiling [17]. 1. The nucleation regions. 2. The region with no nucleation. 3. The region of isolated bubbles which have an influence on the heat transfer. 4. The region of covering of neighbouring vapour bubble interaction regions 5. The region of the measurement of local value of heat flux q^s.

The phenomenon of formation and departure of the vapour bubbles from the heating surface causes local changes of the temperature. When the fragment of the heating surface S is covered by vapour, then due to a decrease of the heat transfer coefficient in the measured area, there is an increase of the local temperature of the heating surface. The contact between the liquid and the heating surface causes an increase of the heat transfer coefficient and therefore the temperature of the heating surface locally decreases. In other words, the phenomenon

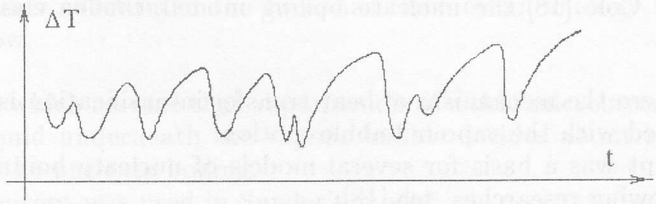

Fig. 9. Changes of the heating surface temperature underneath a single vapour bubble. The graph was made based on data from [18]. Temperature fluctuations are about 5^o, the measurement time is about 480 s.

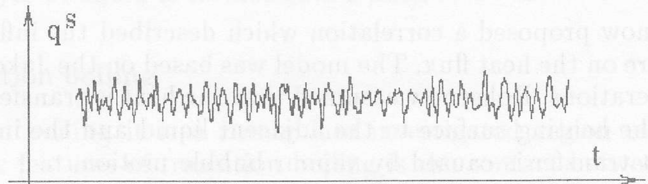

Fig. 10. Local fluctuations of the heat flux in nucleate boiling. The graph was made based on data from [19] for R-114, measurement time was 3 s.

of formation and departure of the vapour bubbles from the heating surface is accompanied by local fluctuations of heat received from the heating surface. Fig. 9 and Fig. 10 illustrate local changes of the temperature of the heating surface and heat flux q^s

Fig. 9 presents changes of the local temperature of the heating surface underneath a single vapour bubble. Despite the fact that the function is not periodical, its particular curved segments can be interpreted as a result of realisation of subsequent phases of growth of a single vapour bubble [18]. Such a process is called a quasi-periodical process.

Overlapping regions of vapour bubbles interaction disturb the nucleation process and lead to the stochastic changes of the temperature of the heating surface and local heat flux q^s. The local fluctuations of the heat flux in nucleate boiling of R-114 are shown in Fig. 10. These results were obtained owing the implementation of a computer data acquisition system and post-processing. The measurements were made with the frequency of 16 Hz [19].

The presented results of local temperature changes give rise to the conclusion that originally quasi-periodical changes of the heating surface temperature (in the isolated bubble region – Fig. 9) with the increase of temperature transform into chaotical changes (Fig. 10).

There is a variety of works devoted to the nucleate boiling. However, most models of the phenomena which occur during the nucleate boiling are *static*, i.e. they are based on the concept of stationary or quasi-stationary processes of heat transfer. Stochastic changes of the local temperature of the heating surface and local heat flux are neglected.

According to R. Cole [18] the nucleate boiling models can be classified in the following way:

1. Models where the mechanism of heat transfer intensification is assumed to be connected with the vapour bubble motion.
   This concept was a basis for several models of nucleate boiling developed by the following researches, see [18]:

   - Jakob and Linke suggested a simple model based on the analysis of liquid motion and vapour bubble motion. This model was further developed by Insiger, Bliss, Jakob, Bonilla and Perry.
   - Rohsenow proposed a correlation which described the influence of the pressure on the heat flux. The model was based on the Jakob and Linke considerations. Rohsenow assumed that the heat is transferred directly from the heating surface to the adjacent liquid and the intensification of heat transfer is caused by vapour bubble motion.
   - Gunther and Kreith conducted the investigations of boiling in a subcooled liquid. They suggested that formed and departed vapour bubbles cause microconvection in the boundary layer adjacent to the heating surface. A similar result was obtained by Ellion, Forster and Zuber.
   - Forster and Greif modified the microconvection model by treatment of the growing vapour bubble as a 'pump' transferring a warm liquid from the heating surface area into higher liquid layers and forcing a cooler liquid into the heating surface area. This model is reinforced by numerous photographic pictures.
   - Han and Griffith proposed the application of the Forster and Greif model for saturated pool boiling. They have determined the region of thermal interaction of a vapour bubble on the heating surface.

2. The models which assume that the unsteady heat conduction between the heating surface and liquid filling in the gap after departure of a vapour bubble determines the heat transfer during the nucleate boiling.
   This concept gave rise to the following models of nucleate boiling:

   - Van Stralen proposed a model based on the analysis of heat transfer in a supplementary thermal liquid microlayer (so-called relaxation microlayer) whose dimensions are adjusted so that the heat stored there should correspond to the heat carried away by the vapour bubble.
   - Judd and Hwang assumed that the total heat flux can be divided into three components: natural convection, volumetric convection, vaporisation through the microlayer.
   - Tien based his model on the analogy between the liquid flow caused by a vapour bubble motion and the inverted stagnation flow.

- Zuber substituted the two-phase flow by an analogy to the turbulent flow.

3. Models which assume that vaporisation of a thin microlayer of the superheated liquid underneath the vapour bubble decides about the heat transfer during the nucleate boiling.
This concept was used in Snyder's model:
   - He assumed that due to the capillary forces and surface tension underneath the central part of a vapour bubble, an area covered by a thin layer of liquid is formed (0.5-2 μm).

4.2. Transition boiling

Transition boiling it is a rather late investigated region of boiling. One of characteristic features of transition boiling is the contact between the liquid and heating surface. The interest in this problem was caused by increased consideration of reactor safety. The transition boiling is a very complex phenomenon. Among other things, the contact between the liquid and heating surface, two boiling curves and a very strong influence of the heating surface on the process can be observed.

Investigations of transition boiling are hindered due to the vehemence of the process. Observations of the phenomenon are possible only thanks to very refined measurement techniques. We can include here the experiments where liquid has been used as a heating system, the experiments where vapour was used as a heating system and the experiments where complicated electronics have been used for the control of heating surface temperature [19].

According to [20], in transition boiling the heating surface of the area A_h can be divided into the following regions: the region of contact between the liquid and heating surface, vapour film, formation of single vapour bubbles. This division is schematically shown in Fig. 11.

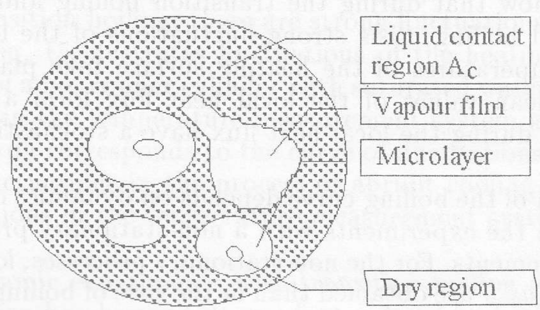

Fig. 11. A schematic of the heating surface in transition boiling [20].

In the boiling experiment with R11 described in [20], the borders of the following regions were determined: a dry region underneath the vapour bubble, a region covered by the liquid, a region covered by the vapour film and the microlayer. It was concluded, among others, that with an increase of the heating surface temperature there is a decrease of the contact area between the liquid and the heating surface. A similar result was obtained for water, where a special electronic measurement technique for the contact area was used [17]. The results of percentage share of the area of contact A_c with respect to the total boiling surface A_h, in transition boiling for R11 and water are shown in Fig. 12.

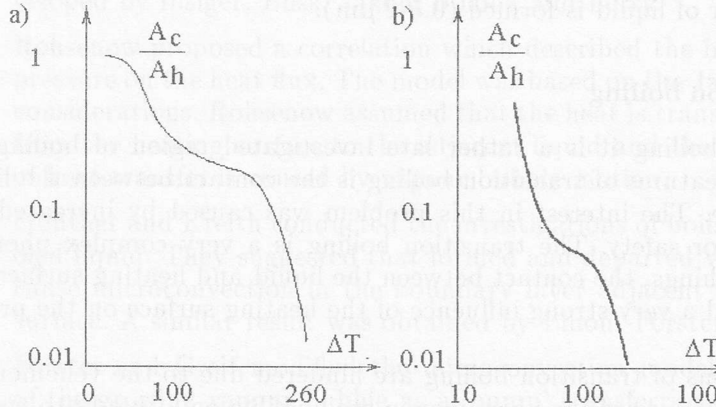

Fig. 12. The change of the contact area during transition boiling. a) R-11; the graph is based on data from [20]. b) Water; the graph is based on data from [17].

The phenomena which take place during transition boiling such as: contact between the liquid and heating surface, formation of local regions of vapour film and formation of single vapour bubbles induce strong fluctuations of the local heat flux q^s and heating surface temperature.

The results of measurements of local fluctuations for the whole boiling curve illustrated in Fig. 13 were presented in [19].

These results show that during the transition boiling and in the vicinity of the first and second boiling crisis strong fluctuations of the local heat flux and hence the local temperatures of the heating surface take place. Despite strong fluctuations, the mean values of the local heat flux form a transition boiling curve. The changes during the local heat flux have a stochastic character, which is shown in Fig. 14.

The distribution of the boiling curve depends on dynamics of the process. This effect is observed in the experiments with a non-stationary process of heating or cooling of heating elements. For the non-stationary processes, lower values of q_{max} and higher values of q_{min} are obtained than in the case of boiling in systems where stationary processes are realised. In Fig. 14, the distribution of the boiling curve during cooling of a heated copper cylinder and the boiling curve obtained in the stationary process are shown.

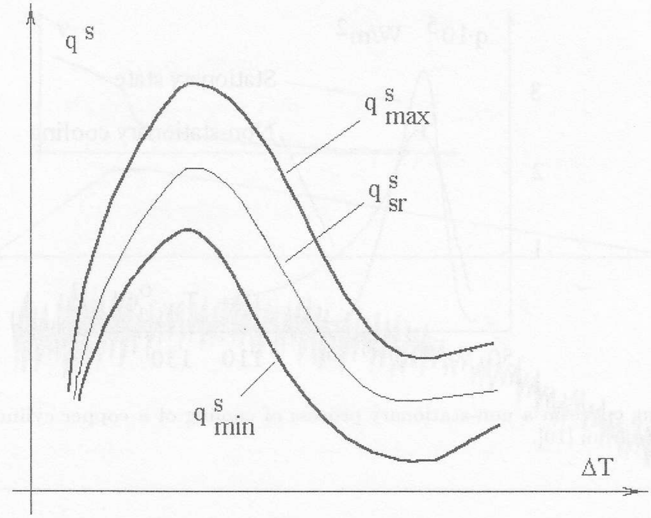

Fig. 13. Fluctuations of local heat flux for freon R-14. The graph is based on data from [19].

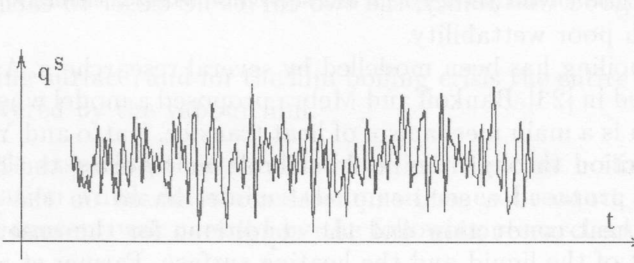

Fig. 14. Fluctuations of the local heat flux during the transition boiling for the heating surface temperature close to T_{Ikr}. The graph was made based on data from [19] for R-114, the measurement time was 3 s.

During non-stationary processes of boiling, just as in nucleate boiling, film boiling and transition boiling, there are strong fluctuations of the heating surface temperature. Fig. 15 illustrates fluctuations of the heating surface temperature during cooling of a hot copper cylinder with saturated water. In Fig. 15a, the mean voltage change in the temperature measurement system as a function of time is shown. This graph corresponds to the curve of fluctuations of the heating surface temperature fluctuations in the process of abrupt cooling. Fig. 15b presents the voltage fluctuations in the temperature measurement system with respect to the regression line.

During dynamic experiments with transition boiling a so-called effect of two boiling curves can be observed. It was first noticed by Linhard and Witte [21-22]. According to the direction of changes of the temperature (increase or decrease), a different distribution of the boiling curve is observed, which is illustrated in

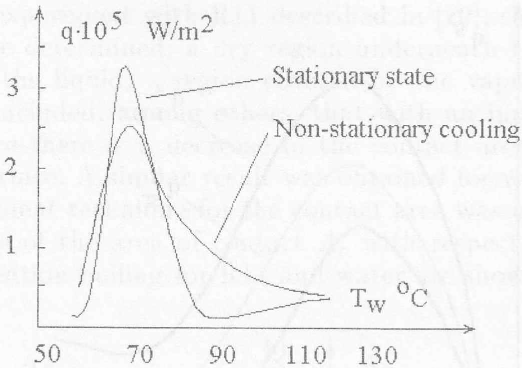

Fig. 15. The boiling curve in a non-stationary process of cooling of a copper cylinder. The graph was made based on data from [19].

Fig. 16.

The results of experimental investigations show that the phenomenon of two boiling curves strongly depends on wettability of the heating surface. In the case of surface with good wettability, the two curves lie closer to each other than for the surface with poor wettability.

Transition boiling has been modelled by several researchers. A number of models are discussed in [23]. Bankoff and Mebra proposed a model where non-stationary heat conduction is a main mechanism of heat transfer. Katto and Yokoya analysed the heat conduction through the liquid microlayer covering the heating surface. Kostyuk et al. proposed a semi-empirical model based on the analysis of the non-stationary heat conduction and the conditions for the onset of boiling during the contact of the liquid and the heating surface. Farmer et al. modelled the contact in transition boiling and film boiling. Hsu and Kim proposed a statistical approach to the modelling of transition boiling.
According to Fujita [17] the models of transition boiling can be divided into two categories:

1. The models where the heat flux in transition boiling is assumed to be controlled by the relation between the heating surface region, where there is a contact of the liquid and heating surface, and the area of the heating surface occupied by the vapour film. This concept was a basis for transition boiling models developed by the following researchers:

   - Kalinnin et al. [23] proposed that the heat flux in the phenomenon of contact between the liquid and heating surface is determined by the extrapolation of the properties relevant to nucleate boiling and film boiling.
   - Bjornard et al. [23] assumed that for the nucleate boiling crisis the contact between the liquid and heating surface takes place on the entire

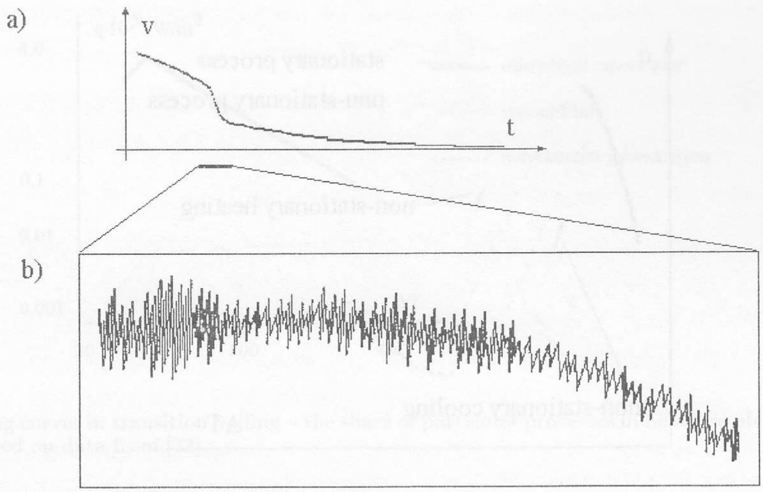

Fig. 16. Temperature changes during copper cylinder cooling. The measurement was performed using a K-type thermocouple embedded by 0.3 mm into the cylinder. Data has been made available thanks to the courtesy of Mr. D. Kisiel.
a) Voltage changes in the temperature measurement system as a function of time. b) Voltage fluctuations in the temperature measurement system with respect to the regression line for 500 data points.

heating surface, and for the film boiling crisis the entire heating surface is covered by the vapour film.

2. The models assuming that the heat flux in transition boiling is controlled by the relation which determines the mean time of contact and the vapour film. This concept was pursued by the following researchers:

   - Liaw and Dhir considered changes of the wetting angle of the heating surface during heating and cooling. Their model explains the phenomenon of two boiling curves in transition boiling.

Chin Pan et al. [23] proposed a complex model of transition boiling. The model is based on the phenomena of vapour bubble departure, contact between the liquid and the heating surface, boiling initiation, microlayer vaporisation and vapour film phenomenon. They assumed that during transition boiling, there is *a mixing of the phenomena* of great importance for heat transfer such as non-stationary heat conduction, microlayer vaporisation and heat conduction through the vapour film. The heat flux was determined using mean time of existence of particular phenomena. The share of particular processes in heat transfer is shown in Fig. 17.

The above mentioned models of transition boiling, just as the models of nucleate boiling and film boiling, predominantly neglect the dynamic analysis of changes of the heating surface temperature and local heat flux. Instead, the concept of mean times of presence of particular heat transfer structures or mean areas of important heat transfer processes is used.

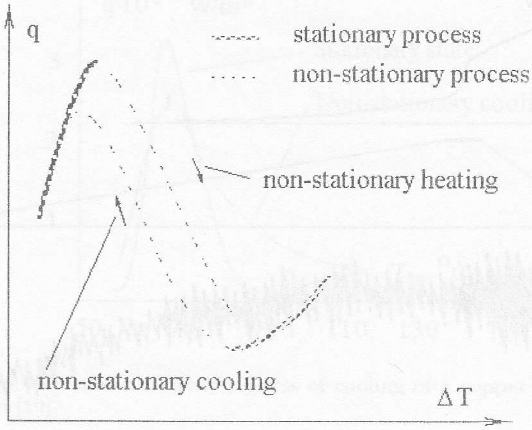

Fig. 17. Boiling curves on a smooth clean copper heating surface. The graph was made based on data from [19].

4.3. Film boiling

A characteristic property of film boiling is generation of single vapour bubbles from the vapour film which separates the boiling liquid and the heating surface. During an advanced film boiling, the process of periodical departure of vapour bubbles from the vapour film interface surface can be observed [2]. This process can be assumed quasi-stationary. With a decrease of the heating surface temperature, the contact between the liquid and the heating surface can be observed, which leads to the vapour film breakdown and hence the breakdown of the quasi-periodical vapour bubble generation. Experimental investigations show that for the heating surface temperatures approaching the temperature of the II boiling crisis, there exist strong temperature fluctuations of the heating surface, induced both by the contact between the liquid and the heating surface and the wave phenomena at the interface. Fig. 18 illustrates the local fluctuations of the heat flux q^s in film boiling for the heating surface temperature approaching $T_{w,IIkr}$. A stochastic character of changes of q^s can be observed. It can be assumed that in film boiling with the decrease of the heating surface temperature a quasi-periodical process of vapour bubble generation transforms into a stochastic process. An analogous process is observed in nucleate boiling in the case of increase of the heating surface temperature.

Numerous works have been published about the modelling of film boiling. However, most of these works draw on static models, similar as in the case of nucleate boiling and local changes of the heating surface temperature and heat flux q^s are neglected.

According to Van Stralen [18] the film boiling models can be divided into two categories:

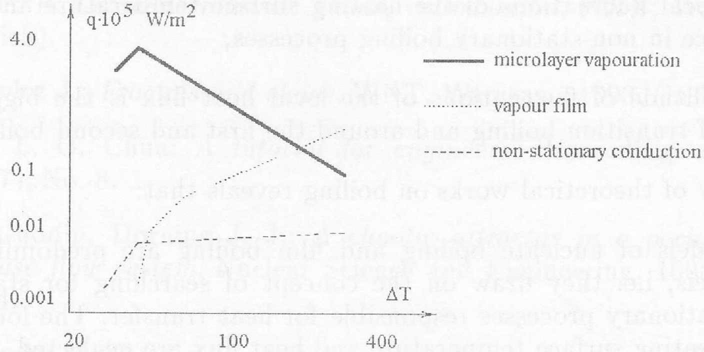

Fig. 18. Boiling curves in transition boiling – the share of particular processes in heat transfer. The graph was made based on data from [23].

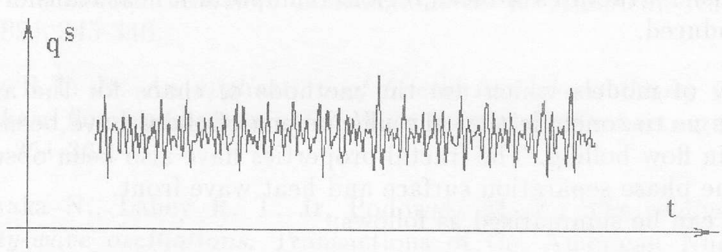

Fig. 19. Local heat transfer fluctuations. The graph was made based on data from [19] for R-114, the measurement time was 3s.

- the models assuming that the fundamental heat transfer mode is heat conduction through the vapour film (Bramley, Pitschmann and Grigull),
- the models assuming that vapour bubble generation is responsible for heat transfer. This process is connected with the hydrodynamic stability of the liquid-vapour interface (Chang, Zuber, Tribus, Berenson).

5. Conclusions

The presented selection of experimental results illustrates the stochastic character of local heat and mass transfer processes in boiling and allows us to conclude that:

- generation of single vapour bubbles causes quasi-periodical fluctuations of the heating surface temperature,
- a surface temperature increase reduces quasi-periodical temperature fluctuations,

- strong local fluctuations of the heating surface temperature and heat flux take place in non-stationary boiling processes,
- the amplitude of fluctuations of the local heat flux is the biggest in the region of transition boiling and around the first and second boiling crisis.

The survey of theoretical works on boiling reveals that:

- The models of nucleate boiling and film boiling are predominantly static models, i.e. they draw on the concept of searching for stationary or quasi-stationary processes responsible for heat transfer. The local changes of the heating surface temperature and heat flux are neglected.
- In the models of transition, the analysis of local heat and mass transfer processes is neglected and instead, the mean times of existence of particular heat transfer structures or mean regions of important heat transfer processes are introduced.

The survey of models which use the methods of chaos for the analysis of boiling enables us to conclude that the phenomena of chaos have been observed and analysed in flow boiling. The fractal properties have also been observed and analysed on the phase separation surface and heat wave front.

The above can be summarised as follows:

1. Usually in modelling of boiling phenomena, the time characteristics of local changes of the heating surface temperature and heat flux are rejected, only the quantities determined over a larger area are considered. In the case of pool boiling it is usually assumed that the mean temperature of the heating surface and mean heat flux as the quantities referred to the total heating surface are considered.
2. The approaches, elaborated so far, to modelling of boiling with the aid of the methods of chaos do not analyse the local changes of the heating surface temperature and heat flux caused by the vapour bubble generation.

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Przegląd współczesnych osiągnięć w zastosowaniu chaosu deterministycznego w dziedzinie wrzenia

Summary

W pracy omówiono dotychczasowe sposoby modelowania wrzenia pokazując, że w przeważającej mierze są to modele *statyczne*, tzn. oparte na koncepcji poszukiwania stacjonarnych procesów decydujących o wymianie ciepła. pomija się w nich analizę zjawisk stochastycznych zmian lokalnych wartości temperatury powierzchni grzejnej i lokalnego strumienia ciepła. Omówiono również podstawowe pojęcia związane z koncepcją chaosu deterministycznego oraz dotychczasowe próby zastosowania metod chaosu do analizy wrzenia. Przegląd literatury pokazuje, że: zjawiska chaosu obserwowano i analizowano własności fraktalne powierzchni rozdzialu faz oraz frontu fali cieplnej.