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IDENTIFICATION OF LIQUID BOILING BY ACOUSTIC EMISSION

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Abstract – Comparisons of the acoustic emission signals from the pool and microlayer boiling and water drop evaporation are the aim of the paper. The main relationships, dependences and research results will be presented. The mechanism of acoustic emission generation in liquid boiling and evaporation is discussed. Based on a theoretical analysis, a set of random process characteristics in time and frequency domain has been selected. Their suitability for the description of the dependence of the generated acoustic emission on liquid overheating is verified by experiment. The original arrangement of the experiment enabled us to reach the critical heat flux in liquid boiling in laboratory for different type of vaporization (pool, microlayer, drop) and simultaneously scans acoustic emission with contact and contactless sensors.

Keywords: liquid boiling, acoustic emission

1. INTRODUCTION

The paper deals with the application of the acoustic emission method in analysis of processes taking place on a heat transfer surface in drop evaporation, pool and microlayer boiling. Acoustic emission (AE) is a category of phenomena accompanied with single generation of elastic waves following a sudden release of energy accumulated at a single site in the material. There is a wide range of practical applications in diagnosis and monitoring of technological processes, but it is not common knowledge that AE method being one of the few methods of identifying the initiation of boiling [1], [2]. The application of AE for the diagnosis of boiling is only marginal as compared with other AE applications. Boiling is not mentioned in any of the monographies on AE. M.F.M.Osborne and F.M.Holland were most probably the first to mention the parameters of AE generated in boiling in The Journal of the Acoustical Society of America in 1947. Later on, AE generation in pool boiling was studied e.g. by T.T.Anderson, A.Bret, B.Woodward, R.F.Saxe, S.G.Povsten, G.E.Totten, G.M.Webster, J.S.Sitter, T.J.Snyder and J.N.Chung. They focused on the identification of sodium boiling in a nuclear reactor. The wide-band hydrophone was most frequently used as a sensor. To date we have no information about a workgroup where AE application in the diagnosis and analysis of boiling, and much less microlayer boiling, is studied.

On the other hand regarding the close relationship between the boiling of liquids and an optimum design of heat exchangers and ink jet printers, this area has been widely studied, and a large number of articles, reports, papers, monographies and manuals have been published. Detailed studies have been devoted to the heat transfer relationship to the pressure, structure and position of the heat transfer surface, the hydrodynamic and chemical parameters of the heated liquid, and many other parameters. And yet the theoretical studies of the problem have not been completed, because of its intricacy many of the presented and used relationships are based on experimental and empirical data. Bubble nucleation in pool boiling, which is of the greatest importance for practical use, has been in the focus of attention [3], [4], [5], [6].

Microlayer boiling has been studied only marginally. The published data are scarce. It is of technological importance in spray cooling, in vapour generators with immediate output, in rocket jets cooling, fuel evaporation in injection engines etc. A significant application is the cooling of a nuclear reactor in case of a primary circuit accident [3].

For our opinion is utilization of AE for process analysis on heat transfer surface very useful diagnostic tool and for example an early prediction of the crisis of boiling by AE method would make it possible to significantly increase the coefficient of safe heat flux density and therefore the efficiency of heat exchangers.

2. AE GENERATION MODEL

AE is generated in boiling in the time of the dramatic growth of bubble nucleus wall, in the detachment of the bubble from the surface, and in subcooled pool boiling in the collapse of vapour bubble. Our model is based on the relationships published on the mechanism of the nucleation and growth of vapour bubble in bulk boiling, found in literature on the boiling of liquids [3], [4].

The mechanism of a pressure wave generation (AE) in bubble growth is as follows. In the growth of the vapour bubble wall, after reaching the critical radius, there comes a sharp decrease of inner capillary overpressure from the value given by Young-Laplace equation [4]

$$p_3 - p_2 = \frac{2\sigma}{r} \tag{1}$$

where p3 and p2 are the vapor and liquid pressure, σ is the surface tension. For the critical radius to an on order lower value corresponding to the maximum radius of detachment from the surface.

Simultaneously, on the moving interface vapour-liquid (bubble wall) the given pressure value is suddenly changed. The speed of the pressure change (frequency range) is directly proportional to the speed of bubble growth, and thus to the overheating of the boundary layer, see eq. 2 [3], [4]

$$r(t) = \left\{ \frac{2}{3} \left[\frac{T_W - T_{SAT}}{T_{SAT}} \right] \frac{i_{23} \cdot \rho_3}{\rho_2} \right\}^{1/2} \cdot t \qquad (2)$$

where T_W is heat wall temperature, T_{SAT} - saturation temperature, i23 – latent heat of vaporization J/kg, ρ2 (ρ3) – liquid (vapor) density. Then the amplitude increase should be directly proportional to the overheating of the liquid and indirectly proportional to the critical radius of the bubble.

In the departure of the bubble from the surface or in the breakup of the vapour stem a pressure wave will be generated strongly dependent on the distribution of surface temperature in the vicinity of the boiling nucleus. The theoretical description is rather complicated. It can be assumed that the liquid in the vicinity of the pulsing vapour nucleus induces swirl and turbulence, and the movement is of random character.

The third and most powerful source of AE in boiling is a vapour bubble implosion in subcooled liquid. In comparison to the previous examples, the mechanism of the collapse of the bubble is better described in literature. The descriptions are based on the Raleyigh dynamic model. It can be assumed that a vapour bubble implosion is very fast and the generated pressure pulses reach large amplitudes, directly proportional to subcooling and practically independent on the diameter of the collapsing bubble [5].

Based on this analysis, the generated AE can be regarded as a random pulse process, or rather a sequence of pulses whose amplitude, length and interval are random variables. In regard to a large number of active boiling nuclei the total AE signal can be described as a continuous random process with standard distribution (consequence of the central boundary theorem).

3. DESIGN OF EXPERIMENTS

In a series of experiments AE signals were recorded in various combinations of experiment conditions (pool and microlayer boiling, different temperatures, angles of inclination of the heating layer, roughness of the surface, AE sensors etc.).

The arrangement of the experiment for pool boiling is seen in Fig. 1.

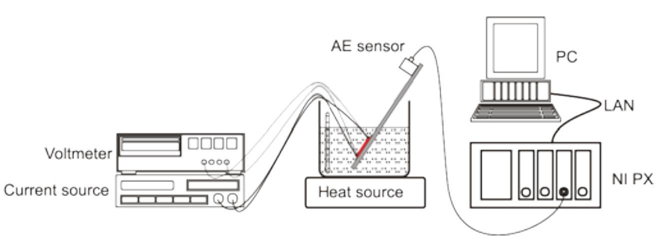

Fig 1. Arrangement of the experiment for pool boiling.

A ceramic pad with a steamed platinum film is mounted on a brass plate - an acoustic waveguide. Soldered to this layer are current and voltage conductors, see Fig. 2.

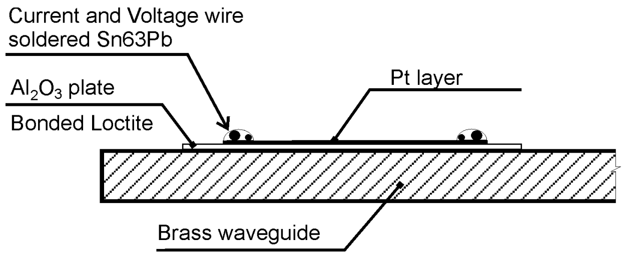

Fig 2. Experimental heat source for pool boiling

The decrease in voltage proportional to the set current and temperature-dependent resistance of the platinum film was measured by voltmeter. The generated AE is conducted through the brass plate to the AE sensor located alongside the heating element. The contact high-temperature wide-band sensor from Dakel was used. The output signal from the sensor - an AE signal was conducted to the NI PXI with PXI 5122 module enabling signal measurements in the requested frequency band and storage in real-time to computer harddisk for off-line processing in LabView program.

The microlayer boiling was simulated on a device seen in Fig. 3.

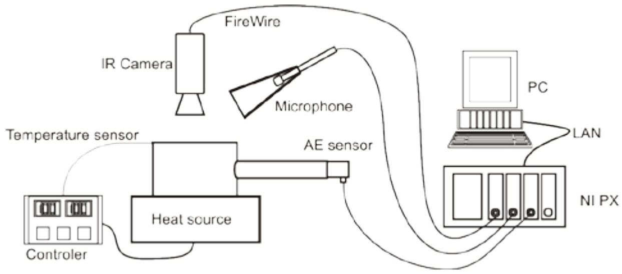

Fig 3. Arrangement of the experiment for microlayer boiling.

A duralumin cylinder was mounted on a source of heat. At the end of the acoustic conductor, a contact wide-band sensor was acoustically connected through high-temperature vaseline. In the axis of the cylinder a semi-sphere hole was made, 20 mm in diameter, with smooth surface, and next to it another one of the same diameter, but with artifical rough surface. The AE generated in dropping a drop of water of a defined volume in one of the holes was recorded by contactless sensor - a wide-band microphone 4135 from Bruel&Kjaer with the nominal frequency range of 100 kHz and with the contact wide-band sensor from Dakel. Current state of the drop –size and temperature was measured in realtime with noncontact Thermal Imagers.

The following basic AE signal parameters were calculated from raw measured data [7], [8]:

Time domain

- mean value
- dispersion
- standard deviation

- median
- skewness
- kurtosis
- AE count rate at zero level
- AE count rate at the level of the current effective value
- ratio of the AE counts on the both levels
- maximum and effective value ratio

Frequency domain
- total power spectral density
- power spectral density in the selected frequency bands

For all of this time and frequency parameters of acoustic emission signal was calculated correlation coefficients with surface overheating temperature. We seek for basic parameters of AE signal, which carry best information about surface temperature and boiling state.

4. RESULTS

4.1. Pool boiling

On the basis of the obtained relationships we arrived at the following conclusions concerning the measured AE signal in pool boiling. The parameters closely related to the heat transfer surface temperature and therefore boiling intensity (heat flux density) are mainly related with the signal energy - standard deviation and power spectral density in frequency bands, and inversely the number of active sites.

The initiation of boiling can be well identified by a sharp

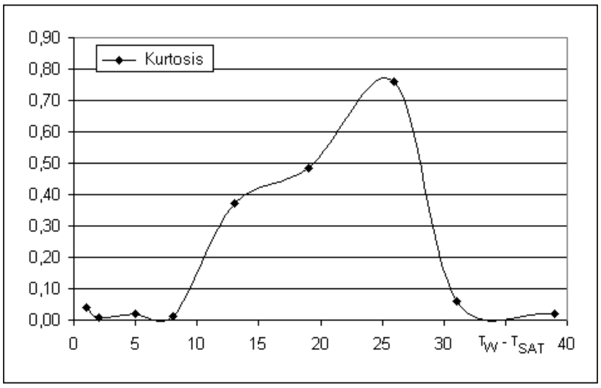

Fig. 4. Kurtosis of AE signal from contact sensor, pool boiling, liquid temperature 20°C

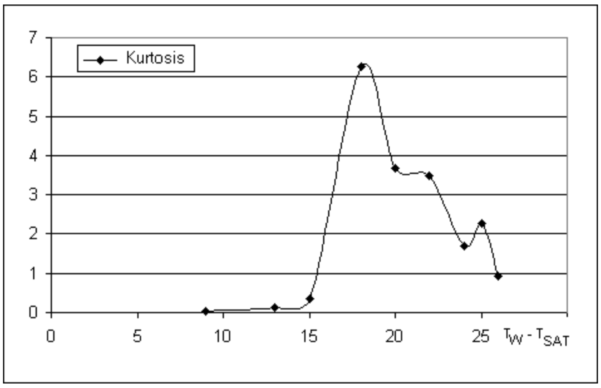

Fig. 5. Kurtosis of AE signal from contact sensor, pool boiling, liquid temperature 100°C

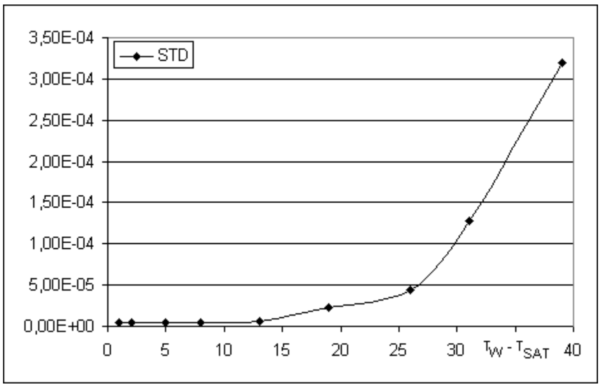

Fig.6. Standard deviation of AE signal from contact sensor, pool boiling, liquid temp. 20°C

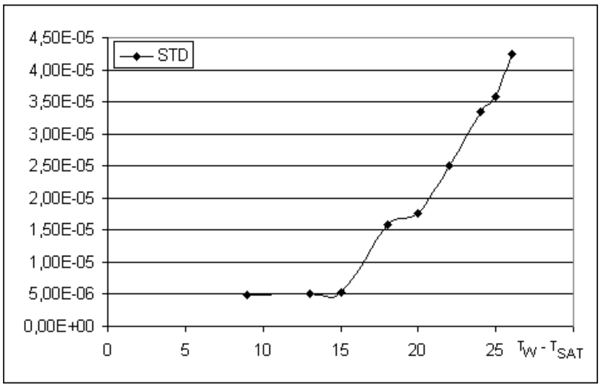

Fig. 7. Standard deviation of AE signal from contact sensor, pool boiling, liquid temp. 100°C

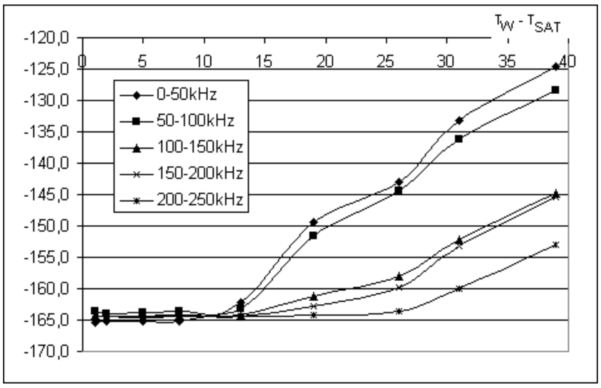

Fig. 8 Power spectral density in the selected frequency band, pool boiling, liquid temp. 20°C

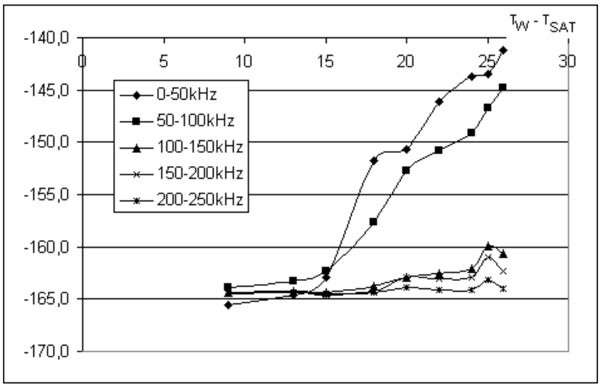

Fig. 9 Power spectral density in the selected frequency band, pool boiling, liquid temp. 100°C

increase of the kurtosis of distribution of the AE signal or rather more easily measured increase of the maximum-effective value ratio or the decrease of the number of active sites at the zero level and the level of the effective value, which might be explained by the pulse emission due to a low number of active vapour nuclei. This is mainly evident in boiling at the saturation limit temperature when the initiation of boiling is dramatic (Fig. 7). This is in agreement with the changes of the appropriate coefficient.

4.2. Microlayer boiling

In microlayer boiling the standard deviation increasing or output power in frequency bands is proportional to the heat transfer surface temperature too (Fig. 10-13). The notable decrease of the above characteristics as the critical heat flux is approached is of interest. The transition boiling phase is similarly to the initiation of boiling identified by changes in the characteristics connected with the AE signal pulse - the increased kurtosis of distribution or the decreased ratio of the number of active sites at the zero level and the level of the effective value.

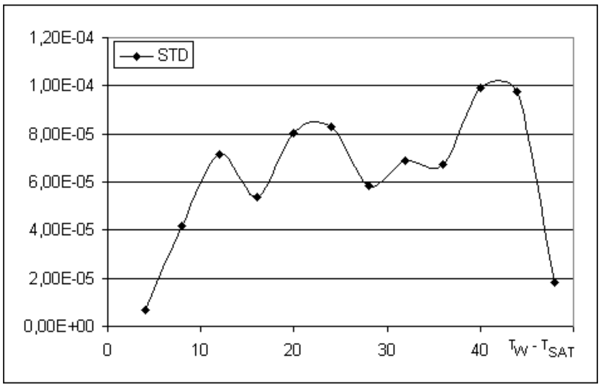

Fig. 10. Standard deviation of AE signal from microphone sensor, microlayer boiling

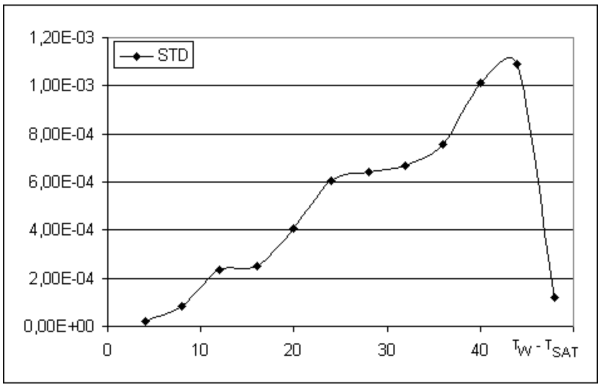

Fig. 11. Standard deviation of AE signal from contact sensor, microlayer boiling

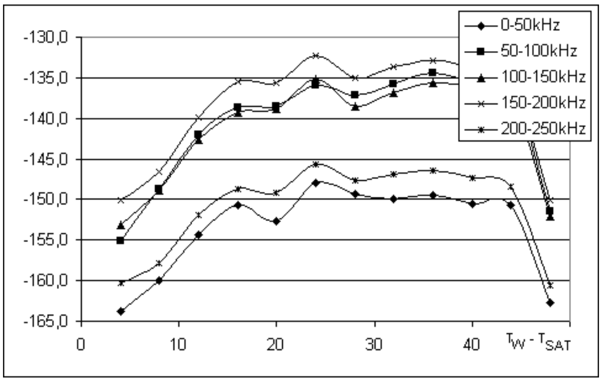

Fig. 12. Power spectral density in the selected frequency band of AE signal from microphone sensor, microlayer boiling

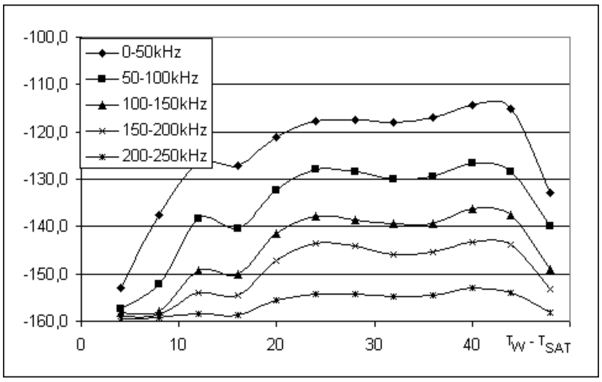

Fig. 13. Power spectral density in the selected frequency band of AE signal from contact sensor, microlayer boiling

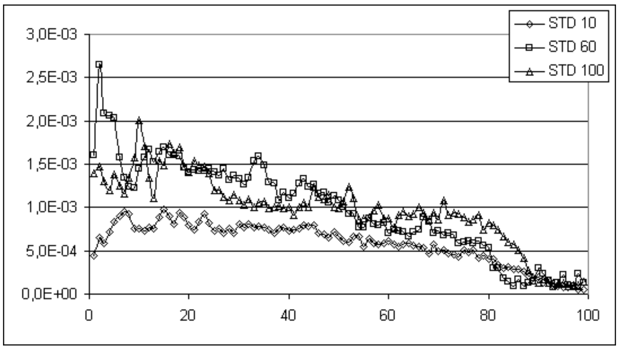

Fig. 14. Time record of drop evaporation (X-axis is normalized time), RMS of AE signal from microphone sensor, drop temperature 10°C, 60°C, 100°C, surface temperature T_W 134°C .

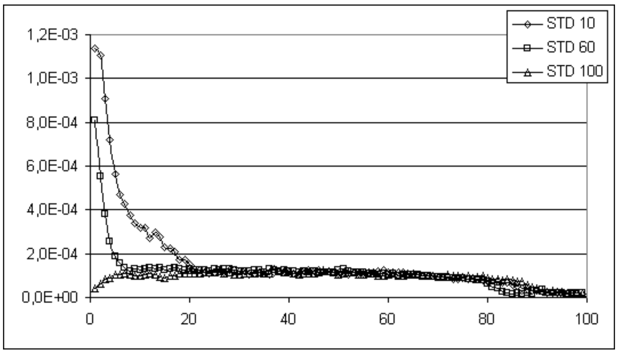

Fig. 15. Time record of drop evaporation (X-axis is normalized time), RMS of AE signal from contact sensor, drop temperature 10°C, 60°C, 100°C, surface temperature T_W 134°C .

Very illustrative characteristics are obtained by recording evaporation drops with different initial temperature. It is clearly perceptible impact AE signals resulting from the collapse of bubbles in the liquid subcooling measured by contact sensor and decrease its amplitude with increasing temperature drops (Fig. 14 and Fig.17). The ratio of time intervals needed to heat the droplets and the evaporation of very well corresponds to the ratio of the corresponding energy (cp $(T_{23}$ - $T_2)/l_{23})$. Time recordings of identical experiment measured by contactless sensor are on Fig. 16. It can be assumed that the most important source of the AE signal energy in the *contactless* measurement regime is not the bubble implosion in subcooled liquid as in the case of *contact* measurement, but the burst of the bubble on the surface of the drop and the release of the pressure wave whose amplitude is given by the radius of the bubble or by the capillary pressure. This would correspond to the record time during the amplitude of AE signal generated by a drop on the initial temperature of 20°C growing much more slowly than the temperature drops to 100°C, which reaches a maximum value almost immediately (Fig. 16).

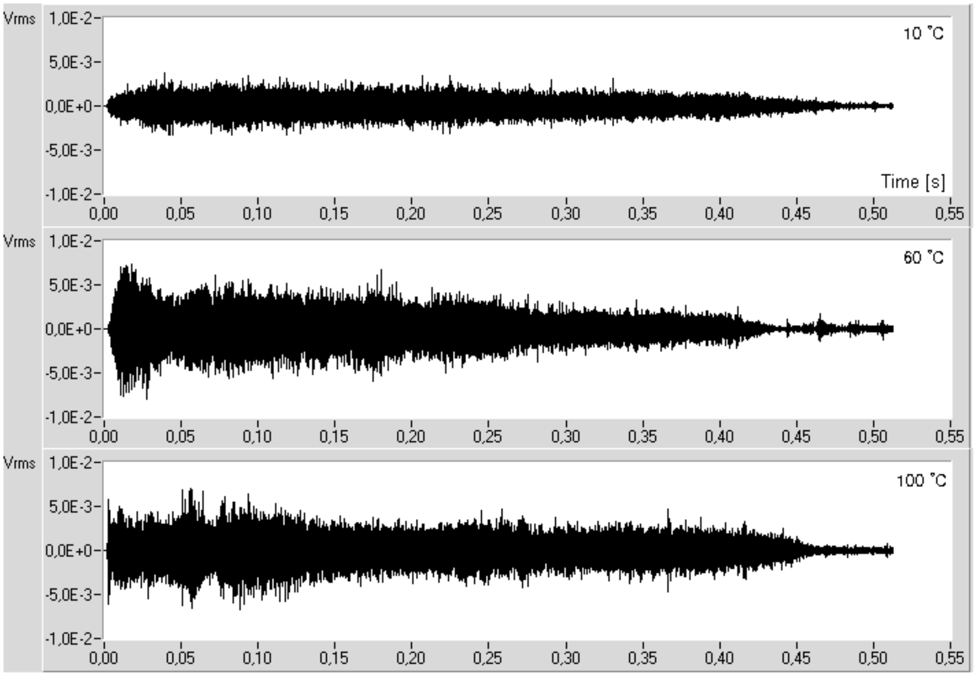

Fig 16. Drop vaporization, microphone, T_W 134°C,
drop temperature 10°C, 60°C, 100°C.

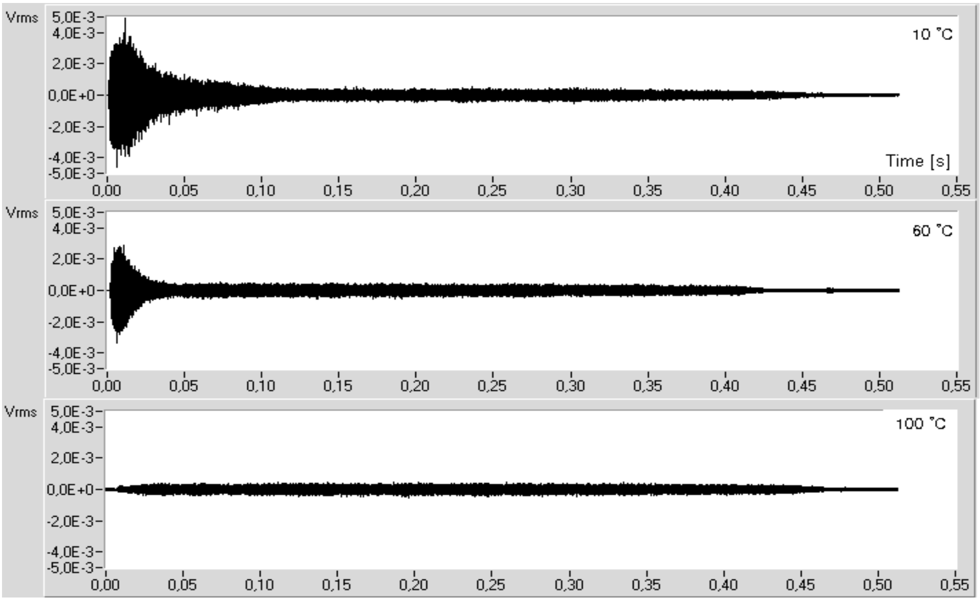

Figure 17. Drop vaporization, contact sensor, T_W 134°C,
liquid drop temp. 10°C, 60°C, 100°C
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5. CONCLUSIONS

The focus of the paper is the proposal of a model of AE generation in boiling based on the previous analysis and its verification. The parameters of the AE signal have been found having close relationship to overheating of heat transfer surface i.e. also to the passing heat. It was confirmed by experiment that the AE signal is the carrier of information on the current processes, and can be used to predict the crisis of boiling.

An experiment has been proposed and carried out to obtain in the laboratory heat fluxes nearing the critical value and simultaneously record contact and contactless generation of AE in pool and microlayer boiling.

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