Natural Sciences and Advanced Technology Education *Volume 30 Number 4, 2020* *Обучение по природни науки и върхови технологии*

https://doi.org/10.53656/nat2021-4.02

Experiments

ANALYSIS OF THE LIQUIDS COMPOSITION BY THE SOUND PRODUCED BY THEIR HEATING

Grigori Matein[1)], **Asen Pashov**[2)]
[1)]*Atos Quantum (France)*
[2)]*Sofia University "St. Kliment Ohridski" (Bulgaria)*

Abstract. When a liquid is heated and the power of the heater is high enough (about $1MW/m^2$), bubbles are formed at the surface of the heater. Their expansion and collapse are the source of a specific sound, known to everybody who uses a kettle to prepare water for tea or coffee. The main goal of this study is to investigate whether it is possible to judge about the composition of the heated liquid by this sound. A specialized experimental set up is assembled and a systematic study of all known factors, influencing the sound is carried out. It is found out that the most crucial parts of the set up are the container for the liquids and the heater. They are discussed in detail and considerations for further improvements are given. It is demonstrated that with the present apparatus it is possible to detect changes in the sound spectrum when changing the composition of the liquid. For example, one can distinguish between pure water and water with less than 0.1% of ethanol. Along with admixtures of different alcohols, experiments with a soap solution in water and carbonated water are performed.

Keywords: sound; analysis; heater; liquid; alcohol; composition; concentration

1. Introduction

There are several papers related to the sound, produced by heated water (Walker 1982; Aljishi 1991; Van Wijngaarden 1978). The phenomenon is familiar to everybody who prepares water for tea or coffee, but its detailed understanding is still challenging. The papers concentrate on a qualitative description of the problem, explaining the origin of the sound, but there is no full quantitative understanding of all processes influencing the sound of heated liquids. Generally, it can be expected that the sound depends on the properties of the liquid such as boiling temperature, viscosity, surface tension, presence of dissolved gases and small particles and so on.

In this paper an experimental study is presented with the main goal to answer the question: is it possible to analyze the composition of liquids by the sound produced during heating? The idea is rather simple: record the sound from different liquids and compare the corresponding spectra. The realization is not as simple, however, since the sound spectrum depends also on other factors, which have nothing to do with the composition of the liquid, for example power of the heater, temperature of the liquid, shape of the container (due to acoustic resonances) etc. Therefore, to investigate the composition of the liquids, it is important first to find all factors which influence the spectrum of the sound and then to build an experimental set up, where all these factors, apart from the specific liquid properties, are kept under control. In section 2, the mechanical part of the apparatus and the systematic study of these factors are described. The set-up is tested with three types of liquids: water solutions of various alcohols, a soap solution in water and different concentrations of carbonated water. The results are presented in section 3. A discussion of these results, the overall set up and possible developments can be found in section 4.

2. Experimental set-up

A crucial point in building a set-up, appropriate for studying the sound of heated liquids, it to ensure stable experimental conditions, i.e. the same liquid should produce always the same spectrum and differences should be observed only if the liquid properties have been changed. After many experiments, the main factors (apart from the liquid properties) which influence the spectrum were determined. The higher the *power of the heater* the louder the sound is. At smaller powers it is possible to bring the water to boiling with no sound at all. At constant power of the heater the sound changes with the *temperature of the liquid*. The sound depends strongly on *the shape and the material of the container*, on the *position of the heater in the container* (distance from the walls and from the surface) and on the *amount of the liquid*. The sound also varies with the *shape of the heater, its size and the quality of its surface*.

The most challenging part of the set-up is the heater, because its requirements are somewhat contradictory. It should ensure sufficient heat flux (otherwise no sound is produced) in a small volume of water and it should not rise the temperature of the liquid (at least not too fast). The obvious solution is a compact heater (few cubic millimeters) with low power in order to prevent the overall heating of the liquid and with high heat flux (about $1 MW/m^2$) to heat the liquid locally and to produce the sound. The estimations show that with a 10 – 20 W heater the average temperature of 100 ml of water rises with no more than 2 – 3 K in 50 – 100 seconds, which is sufficient for a record. Initially, a tungsten wire from a 5 W car lamp with removed bulb was used as a heater. Afterwards, self-made kanthal heaters turned out to be more appropriate. The heaters are produced from a 0.14 mm thick kanthal wire approximately 150 mm long. The central part is turned 12 – 15 times to produce a coil with an inner diameter of 0.6 mm. The wire at the end of the coil is connected by twisting it several times with a thicker kanthal conductor (0.2 mm inner diameter, 50 mm long). In this way the voltage drop falls mainly on the small coil.

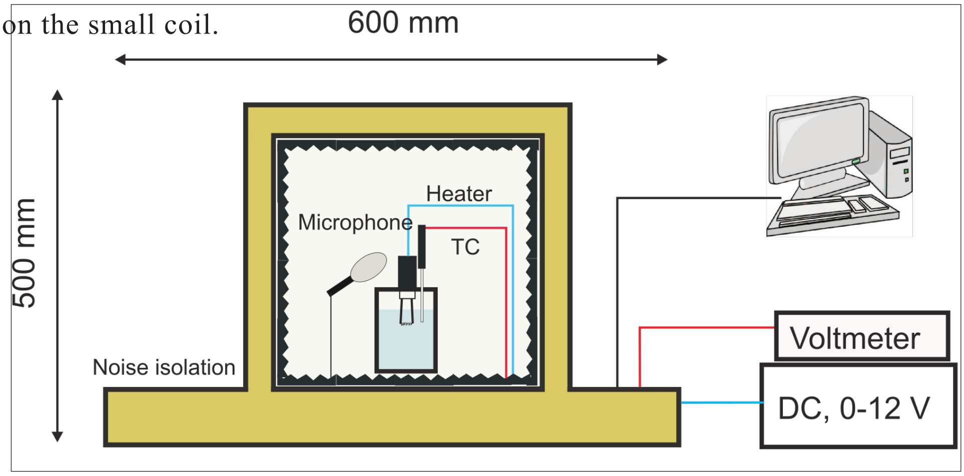


Figure 1. Scheme of the experimental set-up. With TC the thermocouple is designated

Of course, a small heater generally means weak sound, so the second important part of the set-up is a sensitive microphone and a good noise isolation of the whole apparatus. The microphone used in this experiment is the AT2020USB model of Audio-technica. The whole set-up is assembled in a box with detachable top and with dimensions 500 x 500 x 600 mm (see Figure 1). For better noise isolation the walls are made of a double layer of Medium-Density Fibreboard (MDF) with mineral wool in between and the inner side of the box is covered with pyramids from polyurethane foam.

The third important item is the container. Initially, several cups have been used (made of plastic, glass, porcelain, styrofoam, paper), but the sound spectrum was largely influenced by the acoustic modes of the container. The spectra contain few very strong resonance lines, the positions of which were very sensitive to the level of the liquid, the position of the heater relative to the walls and the surface. Finally, the best results were obtained with a container made of thin latex (a condom). No sharp resonances are observed and the spectra are much less sensitive to the level of the liquid and the position of the heater.

All mechanical parts of the set-up are fixed firmly on a plate and put in the box. A 300 W DC regulated power supply is used in a current mode. Because the heating coil is connected to the kanthal wires via twisting, the resistance of the connection may change for example due to oxidation, but the constant current mode ensures constant power on the heater. The temperature of the liquid is controlled with a thermocouple mounted close to the heater. With the latex container (75 ml) the temperature of the liquid rises by 2 – 3 K within 30 sec for 15 – 25 W of applied power. The signal from the microphone is recorded by a PC and then the spectrum is calculated by a custom program based on a fast Fourier transformation routine (Press 1992). A record lasts up to 30 sec. It is split into 12 pieces (2.5 sec each) and then their spectra are compared. If no systematic changes are observed – the spectra are averaged.

In Figures A and B of the Appendix one can see a very good signal-to-noise ratio (up to 10^6) of the recorded spectra. In Figures C and D spectra taken at different temperatures of the water in the container and at different powers of the heater are shown. The influence of these parameters is significant, so for correct measurements, the power of the heater and the temperature of the liquid should be kept constant. In Figure E four consequent spectra of filtered water are shown. The measurements are performed by changing the water in the container with fresh one before every measurement. The spectra are very similar and this demonstrates that reproducible conditions are achieved.

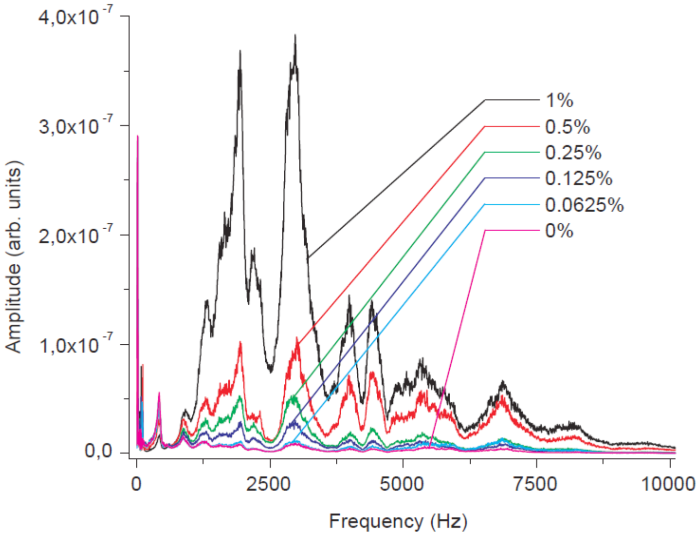
During the study it was found that it is difficult to produce heaters with exactly the same size and shape. So the spectra of the same liquid, heated with different heaters turned out to be different. Moreover after some hours of operation the spectra recorded with the same heater gradually become slightly different, likely due to deformations or corrosion of its surface. Therefore it was decided to perform relative measurements and to compare two spectra (e.g. pure water and water with alcohol) taken in a short time interval. Several such pairs of spectra are then analyzed and if the spectrum of the reference liquid (i.e. the water) shows no significant changes, the experimental conditions are considered to be stable and the spectra recorded at these conditions are averaged.

With the current kanthal heater it is not possible to analyze electrolytes due to the erosion of the heater which changes the sound spectrum rapidly and makes the comparison with the reference impossible. The electrolysis also changes the liquid composition. A solution may be an electrically isolated and chemically resistant heater, but thus far it was impossible to find one with the desired dimensions and power.

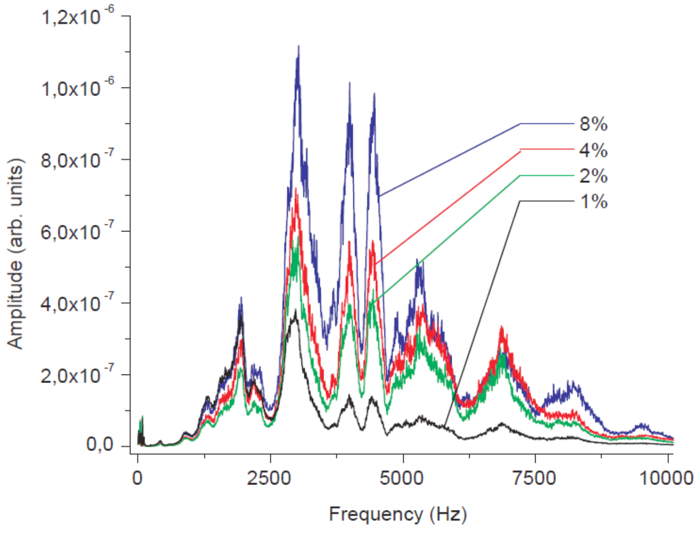
3. Results

3.1.Alcohol-water mixtures

The first series of experiments is carried out in alcohol-water mixtures. In Figure 2a the sound spectra coming from different small concentrations of ethanol in water (up to 1% in volume) are shown. It is surprising how rapidly the overall sound level changes with the amount of the alcohol. In Figure 2b the same mixture is investigated at higher ethanol concentrations. It is obvious, that the increase of the sound level is slower. At even higher concentrations the sound level reaches a maximum at about 12% of ethanol and then gradually decreases (see Figure G of

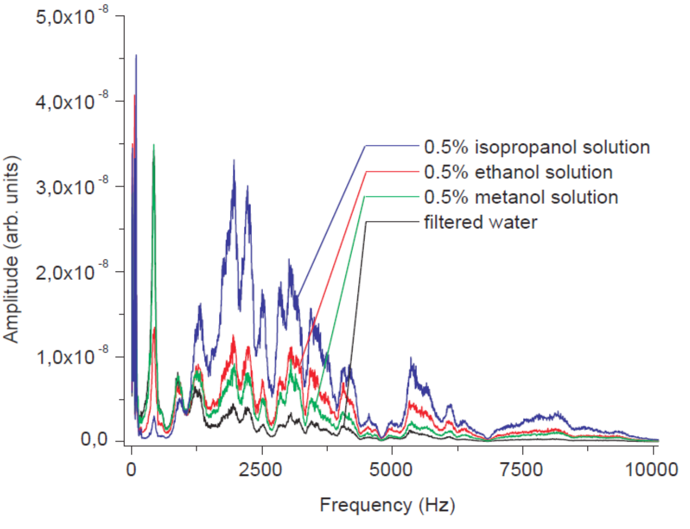


a.

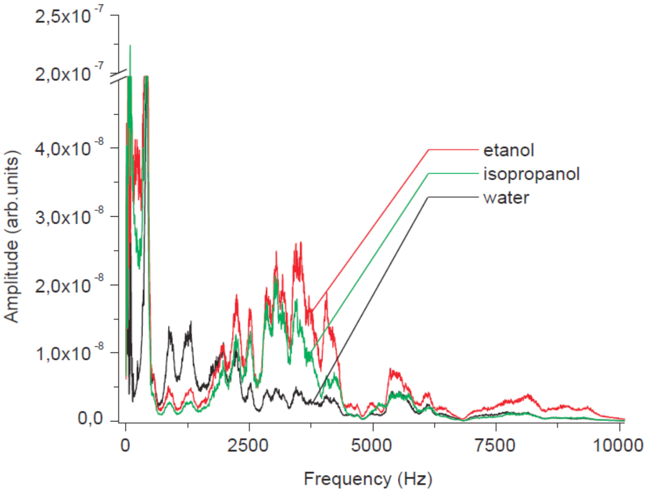


b.

Figure 2. The sound spectra of water with different admixtures of ethanol (% related to the ratio of volumes). At small concentrations (a) the overall sound level changes rapidly. At higher concentrations (b) saturation is observed



a.



b.

Figure 3. Comparisons between the sound spectra of 0.5% solutions of ethanol, methanol and isopropanol (a) and pure ethanol, isopropanol and water (b) (% related to the ratio of volumes)

the Appendix). The changes in the spectra are mainly quantitative and no changes in the overall appearance of the spectral composition are seen.

Similar results are observed in isopropanol, Figure F, namely: rapid increase of the sound level at small concentrations, saturation at higher concentrations and mainly quantitative changes. In Figure 3a, 0.5% solutions of three different alcohols in filtered water are compared. It is curious to see that the sound from the most volatile of them (methanol) has the lowest sound level. Apparently, the sound level is not directly connected to the vapor pressure of the alcohols. An answer can be found when comparing the phase diagrams of the corresponding alcohol-water mixtures (Flick 1998). Initially, the boiling temperature T_b of the mixture drops abruptly at small concentrations of alcohol in volume ratio ($x \approx 1 – 5\%$) and then slowly approaches the boiling temperature of the pure alcohol at higher concentrations. The slope of $T_b(x)$ is about -0.72 K/% for methanol, -0.88 K/% for ethanol and -1.23 K/% for isopropanol. Therefore the highest sound levels at small concentrations of isopropanol can be explained by the lowest boiling temperature of the mixture. The dependence of $T_b(x)$ can explain also the saturation of the sound level by the slow change of the boiling temperature at higher x.

In Figure G of the Appendix the spectra of ethanol-water mixtures at high concentrations of ethanol are compared. After the growth of the sound level at lower concentrations (see Figure 2), at higher concentrations of ethanol (higher than about 15%) the sound gets weaker. One can see that the boiling point of the liquid is not the only factor, influencing the sound.

Finally, it is worth drawing attention to the lower frequency part of the spectra below 500 Hz in Figures 2 and 3a. One can see that the behavior of the few peaks there is just the opposite to the rest of the spectrum. Their amplitudes drop with the concentration and this is not well understood for now. In Figure 3b the spectra of pure ethanol, isopropanol and water are compared. It can be noticed that the overall sound levels are comparable. Alcohols dominate the low frequency region at about 3000 Hz, while the water produces more sound at around 1200 Hz. Why a 1% of ethanol in water makes much more sound than the pure ethanol and water alone is also not clear and needs further study.

3.2. Carbonated water

The effect of dissolved gases in the water (air, CO_2) on the sound spectrum is not straightforward. It is expected that once formed, the air bubbles will head to the surface of the liquid where they will explode (Walker 1982). This would mean no significant change of their shape during their life and therefore no sound would be produced.

The experiments are carried out with filtered water and small amounts of carbonated water are added to increase the concentration of the dissolved gas. The results are shown in Figure 4a. The only visible effect is the drop of the sound level with the concentration of carbonated water, but no qualitative changes. This phenomenon may be explained by the damping function of the gas bubbles, which prevent the sound of the vapor bubbles to escape from the volume.

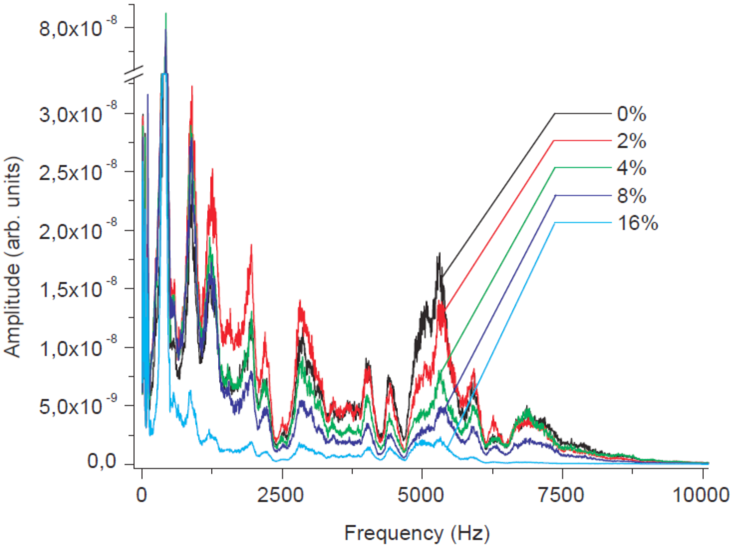
3.3. Soap solution

The soap will change the surface tension of the mixture, therefore qualitative changes in the sound spectrum are expected. The experiments are carried out with solutions of liquid soap in filtered water at 1% and 2% and the results are shown in Figure 4b. Generally, the sound level becomes lower by increasing the soap concentration, but two features (around 400 Hz and 3000 Hz) remain almost the same. Contrary to the experiments with water-alcohol mixtures, the differences in the spectra are now qualitative. It may be speculated that different parts of the spectrum correspond to different sources of sound and therefore different factors change the corresponding spectral parts. This hypothesis needs further investigation.

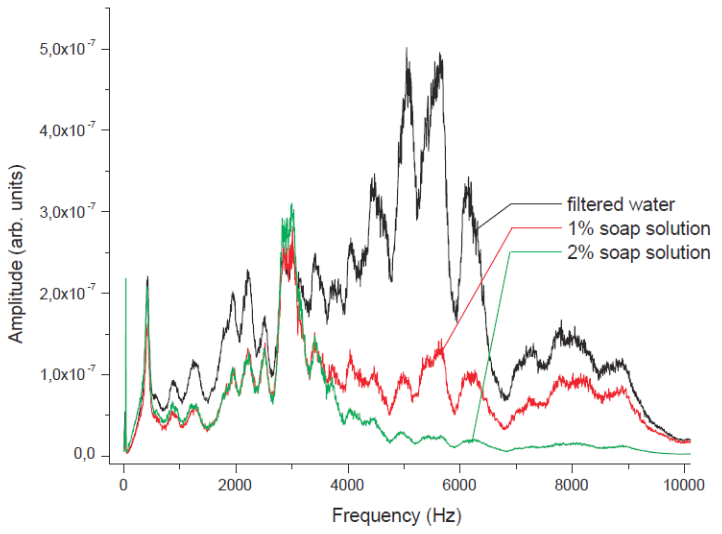
4. Discussion

The presented results demonstrate that with the constructed experimental set-up it is possible in some cases to detect changes in the sound spectrum of heated water when small admixtures are added. The effect is particularly clear in water-alcohol mixtures – down to 0.1% of alcohol is detectable. However, additional work is needed to clarify whether an analytic tool for studying the composition of liquids may be based on this method.

First of all, it is important to improve the reproducibility of the set-up. At present, we believe that the small changes between records with the same liquid composition are mainly due to ageing and/or deformation of the heater. Within this study, we compared the spectra of two nearly identical kanthal heaters when the surface of one of them was made rough by a sandpaper – Figure H of the Appendix. The differences in the spectra are significant and they exceed the changes observed in the spectra of two consequent measurements of the same liquid. Therefore, slow degradation of the heater surface may influence the recorded spectra. We also tried to compare spectra taken with the same heater, but its shape was changed by bending it at about 90^0, Figure I in the Appendix. It can be observed that the overall level of the spectrum is different. This could be explained by the somewhat lager contact surface of the bended heater. Due to it, the water would be heated over a lager volume, its temperature would be lower hence the sound would be weaker.



a.



b.

Figure 4. The sound spectra of water with different concentrations of carbonated water (a) and soap (b) (% related to the ratio of volumes)

An interesting result was obtained by comparing the spectra of three heaters prepared from identical 50 mm kanthal wires, but wound in coils with different inner diameters: 0.6, 0.85 and 0.99 mm (Figure J of the Appendix). The idea of this experiment is to compare heaters with identical power (about 30 W), but different enclosed volume. It was expected that the sound by the more compact heater would be louder because its cooling by the surrounding liquid would be less efficient, so the heater would reach higher temperatures. In fact the interpretation of the results is not as straightforward. First of all, one can notice that the sound level of the 0.8 mm and the 0.95 mm heaters was not much lower than the one with 0.6 mm inner diameter. Moreover, in the spectra of these heaters two pronounced peaks at lower frequencies appeared – at 16 Hz and 42 Hz. The height of the 0.99 mm heater became more than 100 times higher than the height of the peaks at 2 – 4 kHz.

Finally, the reproducibility of the recorded spectra was very good with the 0.6 mm heater, somewhat worse with the 0.8 mm heater and very bad with the 0.99 mm heater, Figure J of the Appendix. In order to explain these observations we looked carefully how the bubbles are formed in all three cases and we found a difference. In the 0.6 mm heater, small bubbles are formed on the heater surface and they leave the surface very soon. The bubbles formed by the 0.99 mm heater are larger, they grow slower (attached to the surface) and it was repeatedly noticed that below the bubble the kanthal wire was locally glowing. Since, on average, the heat dissipated per unit volume in the liquid around the heater was lower, the formation of the bubbles would be slower. But once a bubble starts growing on the surface, the direct contact with the liquid is lost and the wire gets hotter. So the slower it grows, the hotter the heater gets. This local overheating of the heater may lead to oxidation of the surface and may explain the bad reproducibility of the spectra taken with the heaters with larger diameter. The effect of the heater volume may be illustrated by one comprising a straight 50 mm kanthal wire. Such a heater produces almost no sound at 30 W. Its surface is the same like before, but the volume of the water heated directly by the heater is much larger, so the temperature of the wire is lower and the formation of bubbles is negligible.

We also tried to estimate the temperature of the heater by measuring its resistance. This was done with the tungsten heater, because its resistance changes significantly with the temperature. We measured the current through the heater and the voltage drop first at small currents (5 – 10 mA), which cause negligible heating of the heater and in this way the resistance at room temperature was estimated. Then, the same experiment was performed in a boiling water (heated by an external heater) and from these two measurements we obtained the slope α defining the linear dependence of the resistance: $R = R_0 + \alpha(T - T_0)$. Once calibrated, this heater was used at higher currents, where sound by the heated water was produced. From its resistance it was found, that at fixed current, when the water temperature was about 20^0C, the temperature of the heater was very close to the water boiling temperature

(98.3^{0}C in Sofia). When, however, the water temperature was 60^{0}C, the temperature of the heater was estimated to be about 110^{0}C. This observation explains the large influence of the water temperature on the sound spectrum.

5. Conclusion

This paper focuses on the quality of the sound produced by heated liquids. It was attempted to isolate all side factors which influence this sound apart from the liquid properties while keeping them under control. By changing the physical properties of the heated liquid it was possible to register significant changes in the sound spectra of water-alcohol mixtures, carbonated water and soap solutions. The study suggests that after improving the experimental set-up and more deeply understanding the relation between the liquid properties and the sound spectrum, the analysis of the latter may be used to judge about the composition of the liquids.

6.Acknowledgments. We are grateful to G. Biandov from Kazanlak for inspiring G.M. for this study, T. Mishonov, D. Mladenov, S. Roussev (Sofia University) and A. J. Ross (LASIM, University of Lyon I) for the fruitful discussions and encouragement and K. Janev for his advice on how to build the noise isolation of the apparatus.

Appendix

Additional figures

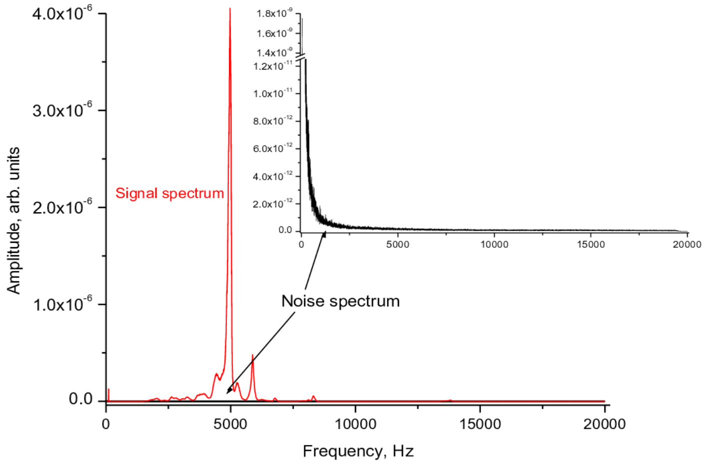


Figure A. Signal-to-noise ratio (SNR) of the recorded spectra. For most of the frequency range the noise is more than 10^6 times smaller than the strongest peak. At higher frequencies the SNR is even better

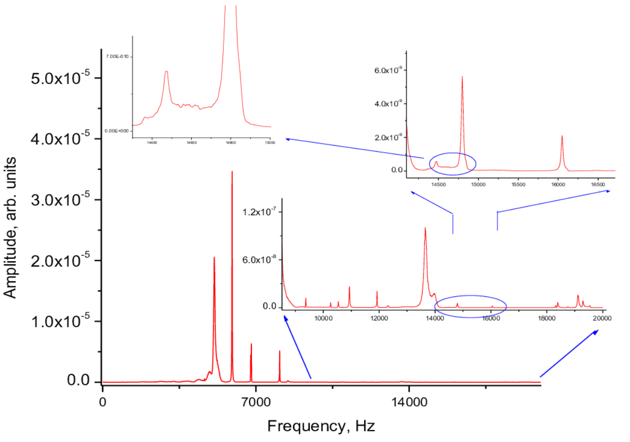


Figure B. Dynamic range of the recorded spectra is over 10^6. In this figure we demonstrate simultaneous record of peaks with ratio in amplitudes about 10^5 and one can see that the weakest peak is well above the noise level

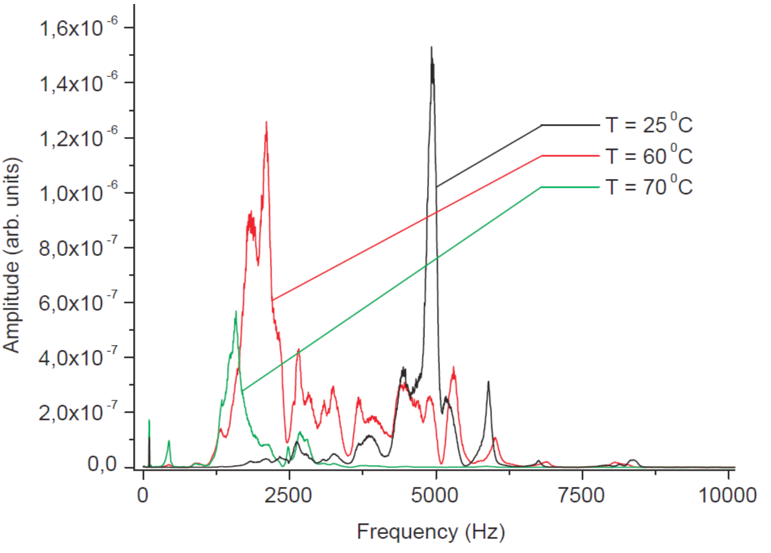


Figure C. Spectra of three water samples taken at different temperatures of the liquids. One can see the dramatic change of the sound spectrum. At lower temperatures the sound is more intense at the higher frequencies. When the water temperature is closer to the boiling point the spectrum shifts to the lower frequencies. In order to ensure reproducible conditions one should keep the temperature of the liquid constant during the experiment

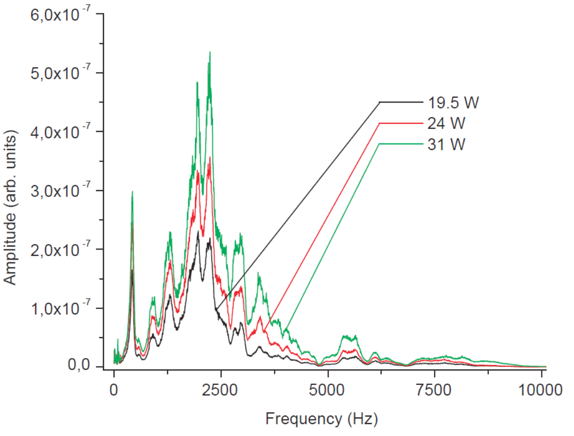


Figure D. Spectra of three water samples taken at different powers of the heater. By increasing the power of the heater only the overall intensity of the produced sound increases, there are no qualitative differences. In order to ensure reproducible conditions the power of the heater should also be kept constant during the experiment

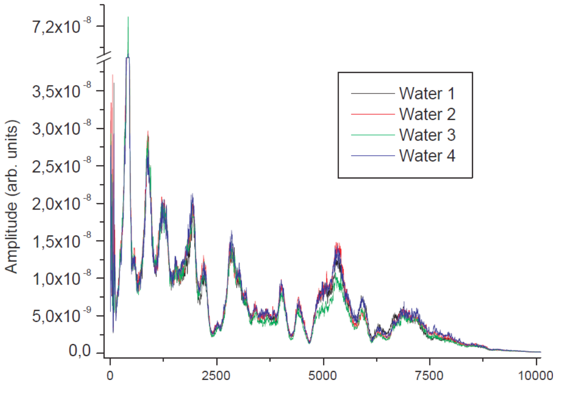


Figure E. Spectra of four different water samples, recorded at the same experimental conditions, i.e. constant power of the heater, constant temperature of the water, the same container, the same amount of water, the same position of the heater and the microphone. This is an example of good reproducibility of the experimental results. In some cases the reproducibility is not as good and one can see gradual changes in consequent measurements of the same liquid. We attribute this to changes of the properties of the heater and in the paper we give evidences supporting this hypothesis. Usually the reproducibility improves when changing the used heater with a new one. Generally, smaller heaters show better reproducibility

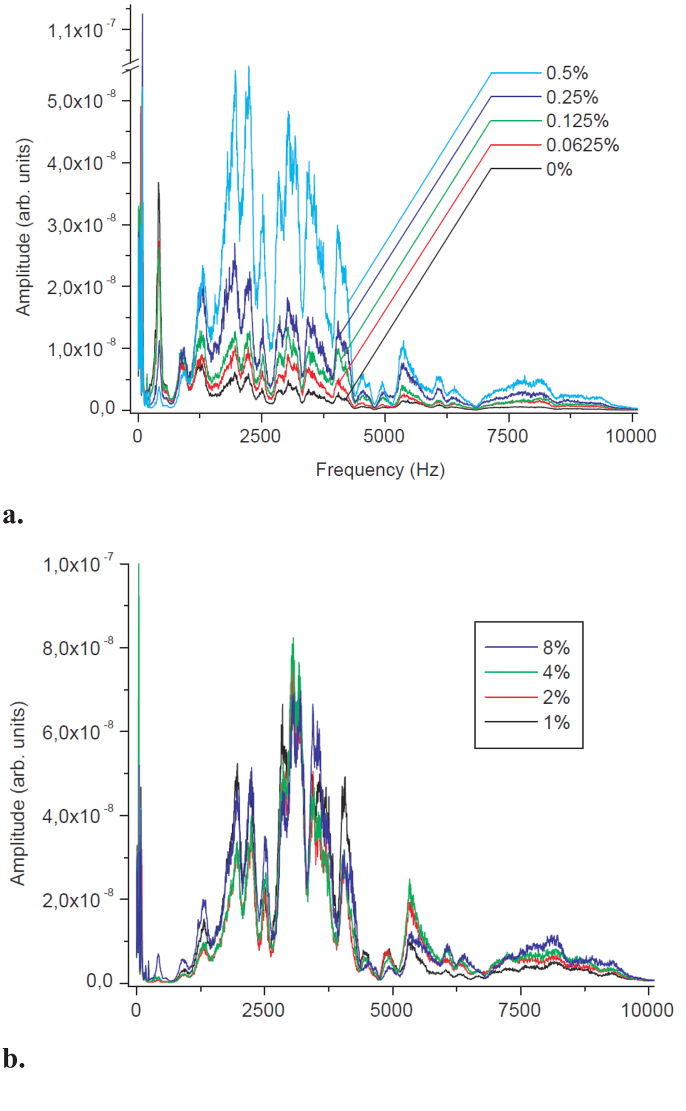


Figure F. Spectra of the sound from isopropanol-water mixtures with different concentrations. At low concentrations (a) the sound level changes rapidly with the increase of the amount of isopropanol. At higher concentrations (b) the changes are small. This could be explained by the change in the boiling temperature of the mixture, which initially drops abruptly at low concentrations of isopropanol and then slowly approaches the boiling temperature of pure isopropanol

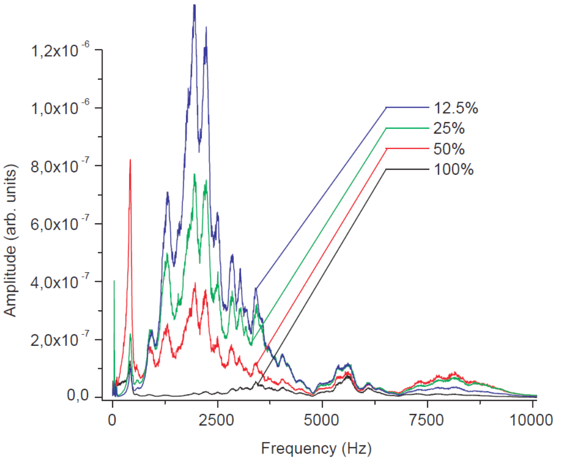


Figure G. Spectra of the sound from ethanol-water mixtures at high concentrations of ethanol. By adding small amounts of ethanol, the sound level increases (see Figure 2 in the article). This may be explained by the rapid decrease of the boiling temperature of the mixture. After some point the growth of the sound level stops and at even higher concentrations of ethanol (> 15%) the sound gets weaker. Apparently, the boiling point of the liquid is not the only factor influencing the sound

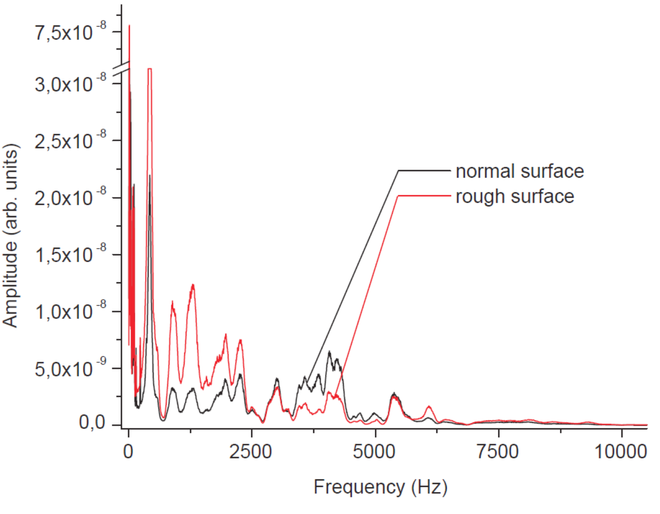


Figure H. Comparison between the sound spectra from filtered water with new kanthal heater and with a heater, the surface of which was made rough by sandpaper. The differences are significant

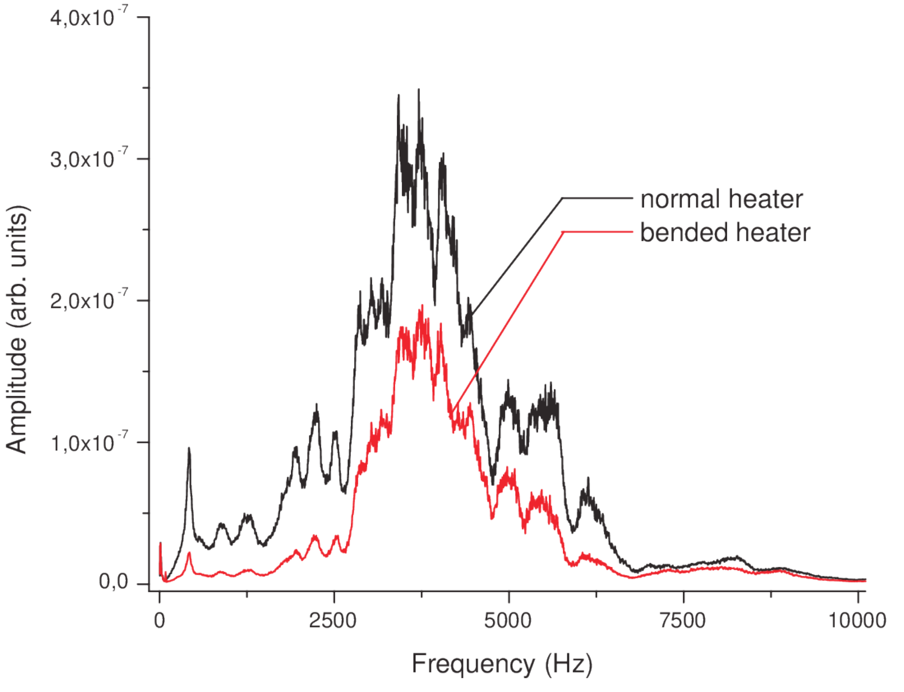


Figure I. Comparison of the sound spectra from filtered water with new kanthal heater and the same heater, but bended at 90^0. It can be observed that the spectrum changes its overall level. This could be explained by the somewhat lager contact surface of the bended heater, it heats the water in a larger volume, therefore its temperature is lower

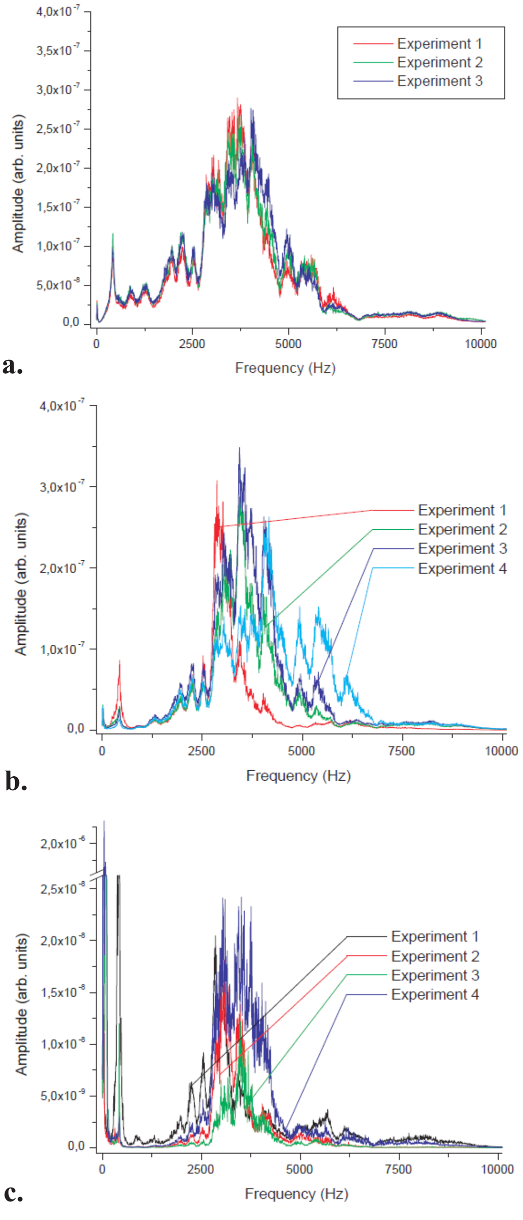


Figure J. Comparison of the reproducibility of the sound spectra from filtered water with three different kanthal heaters with inner diameter of the heating coil 0.6 mm (a), 0.8 mm (b) and 0.99 mm (c). The reproducibility of the smallest heater is better

REFERENCES

Walker, J., 1982. The amateur scientist – What happens when water boils is a lot more complicated than you might think. *Scientific American* **247**(6), 162 – 171.

Aljishi, S. & Tatarkiewicz, J., 1991. Why does heating water in a kettle produce sound? *American Journal of Physics* **59**(7).

Van Wijngaarden, L. & Voosers, G., 1978. Mechanics and physics of gas bubbles in liquids: a report on Euromech 98. *Journal of Fluid Mechanics* **87**, 695 – 704.

Press, W. H., Teukolski, S. A., Vetterlingand, W. T. & Flannery, B. P., 1992. *Numerical Recipes in Fortran 77*. Cambridge Unversity Press.

Flick, E.W., 1998. *Industrial Solvents Handbook, 5th ed.* William Andrew Publishing/Noyes.

✉ **Grigori Matein**
Atos Quantum R&D
Les Clayes-sous-Bois
78340 France
E-mail: grigori.matein@gmail.com

✉ **Asen Pashov, Prof.**
Faculty of Physics
Sofia University
5, James Bourchier blvd.
1164 Sofia, Bulgaria
E-mail: pashov@phys.uni-sofia.bg