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Sensors for liquid level and analysis of thermodynamic processes during its freezing based on bulk acoustic waves

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Abstract: **A fundamental property of longitudinal bulk acoustic waves (BAW) is their inability to propagate in a gaseous medium due to strong absorption in the MHz range and, on the contrary, their ability to propagate in liquids. Based on this property, a liquid level sensor based on BAW is proposed. For these purposes, for the first time, it was used not to measure changes in the velocity and attenuation of waves, but to change the time of their propagation from the emitter to the receiver. It is shown that this acoustic parameter is ideal for such measurements, since it weakly depends on temperature, but depends on the aggregate state of the propagation medium. A technique has been developed for non-contact research of exo-, endo- and isothermal processes accompanying liquid-ice and ice-liquid phase transitions. With its help, the isothermal nature of the water-ice phase transition under normal conditions was experimentally demonstrated.**

Keywords: **bulk acoustic waves, liquid, liquid level, exo-, endo- and isothermal processes, water-ice phase transition**

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Contents

1. INTRODUCTION

The determination of the liquid level in closed tanks is an important technical problem [1,2]. Its solution is important both for the implementation of biological liquid sensors and for industrial applications in the field of nuclear energy, gas industry, etc. Various approaches are used to solve this problem. These approaches are based on the use of fiber optic sensors [3,4], a laser beam reflected from the liquid/glass structure [5], acoustic waves excited by a laser or by a piezoelectric transducer placed on the tank wall [6,7]. Depending on the problem being solved, these sensors can be placed either inside the liquid itself [8,9] or outside [6,7]. One of the most actively used methods is the use of acoustic waves. In the case of direct measurements, acoustic pulses reflected from the liquid-gas interface are used to obtain information about the position of the liquid level [10]. In this case, an acoustic wave is generated by a transducer placed at the bottom of the tank, passes through the tank walls and liquid, is reflected from the liquid-gas interface and returns to the trigger transducer. The delay time of the reflected signal provides the necessary information. Other methods are based on the transmission of an acoustic wave through the tank wall and liquid in the horizontal direction [10]. In this case, the output signal appears if the liquid level exceeds the distance between the input and output sensors.

This paper explores the possibility of determining the presence of liquid using longitudinal bulk acoustic waves. The technique is based on the fundamental property of longitudinal bulk acoustic waves (BAW), namely, their inability to propagate in a gaseous medium due to strong absorption in the MHz range and, conversely, their ability to propagate in liquids. The possibility of using BAW to analyze thermodynamic processes occurring during liquid freezing was also investigated.

2. DESIGN OF THE LIQUID LEVEL SENSOR BASED ON BAW AND THE OBTAINED RESULTS

Fig. 1 shows the design of a liquid level sensor based on longitudinal bulk acoustic waves (BAW). The sensor consists of an emitter, a liquid cell and an ultrasound receiver at frequencies from 1 to 37 MHz. The distance between the transducers was 5.3 mm. The impulse responses are shown in **Fig. 2**. In the absence of liquid (the cell is filled with air), the output signal of the sensor at the sample exit is zero due to the high absorption of ultrasound in the air (Fig. 2*a*). When the liquid reaches a certain level and blocks the path of propagation of the ultrasonic beam, the longitudinal wave begins to propagate from the emitter to the receiver, and the signal $S_{12}(\tau_L)$ is recorded at the sensor output, the delay of which τ_L(lq) corresponds to the velocity of the longitudinal wave V_L(lq) in this liquids (Fig. 2*b*). Based on the delay of the acoustic signal, its amplitude

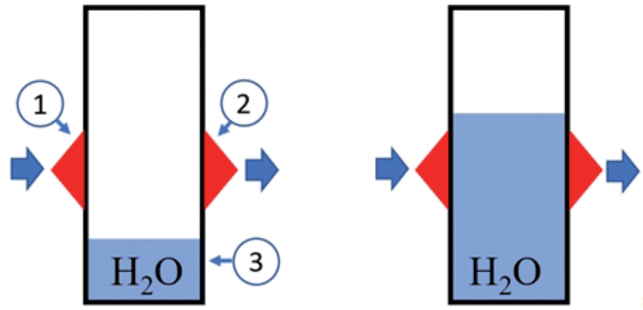


Fig. 1. *Schematic representation of an experimental sample based on longitudinal volumetric acoustic waves, intended for recording the liquid level. 1 – emitter, 2 – receiver, 3 – cell.*

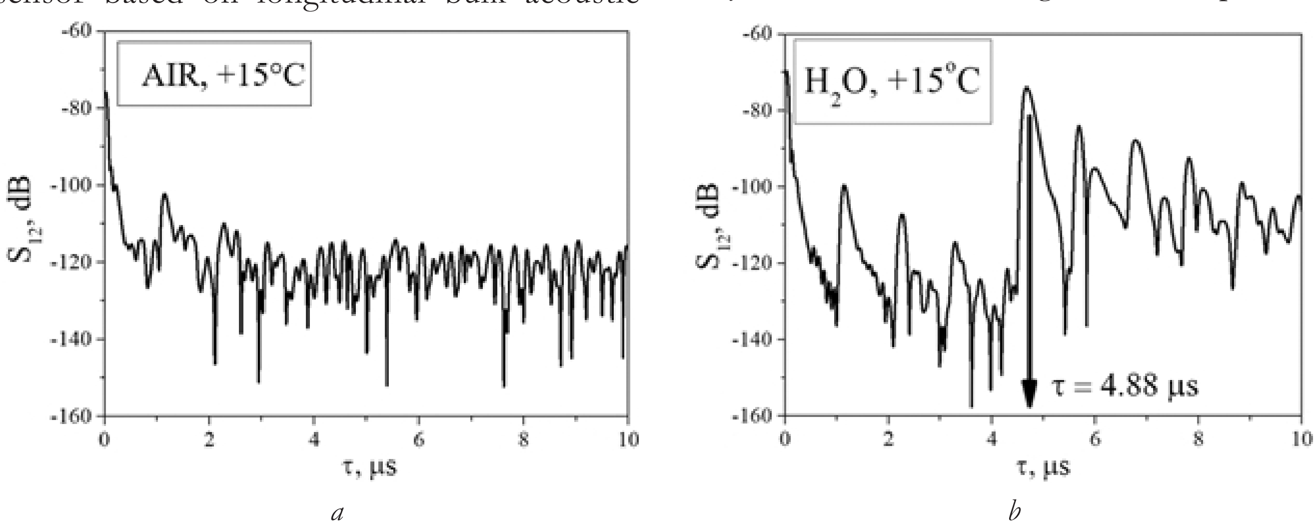


Fig. 2. *Pulse responses at the output of the experimental sample for recording the liquid level, measured using an E5061B quadripole analyzer operating in the amplitude-time format. (a) – low liquid level (Fig. 1, left), (b) – high liquid level (Fig. 1, right). The distance between the converters is 5.3 mm.*

and the size of the cell, the velocity V_L and attenuation of longitudinal (L) BAW in water were determined: $V_L(H_2O)$ = 1480 km/s and attenuation coefficient $\alpha_L(H_2O)$ = 1.9 dB/mm (at 30 MHz). The results obtained coincide with the literature values [11].

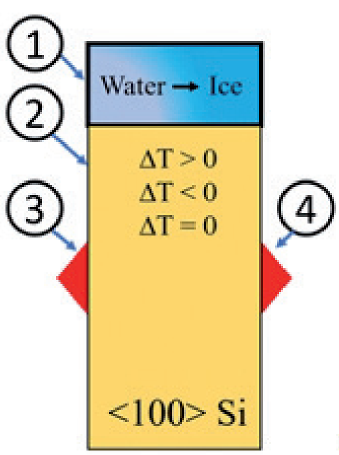
3. SENSOR FOR NON-CONTACT STUDY OF EXO-, ENDO- AND ISOTHERMAL PROCESSES ACCOMPANYING PHASE TRANSITIONS LIQUID-ICE AND ICE-LIQUID

The experimental technique for non-contact study of exo-($\Delta T > 0$), endo-($\Delta T < 0$) and iso($\Delta T = 0$)thermal processes accompanying liquid-ice and ice-liquid phase transitions was based on the sample shown in **Fig. 3.** It consisted of a silicon rod (10×10×50 mm^3), a cell made of thermal insulating material (Teflon) (diameter 5 mm, height 10 mm, thickness 1.5 mm) and two ceramic transducers glued to the rod with salol. A sample of the liquid, the phase transition of which was being studied, was injected with a syringe through the upper surface of the cell, after which this surface was isolated from the external environment (covered). Heat transfer through the side walls of the cell was also prevented by the poor thermal conductivity of Teflon, so that the liquid was in contact only with the upper surface of the silicon. The nature of the phase transition of liquid into ice was controlled by the change in temperature ΔT of the test sample as the sample cooled.

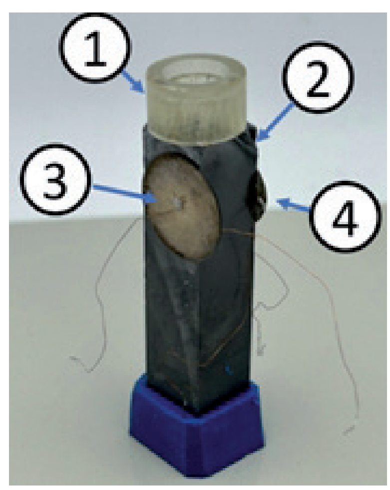
The sample, together with the rod and transducers, cooled to a temperature below the phase transition temperature, was probed at a certain distance from the silicon end with a bulk acoustic wave with known sensitivity to temperature. The change in liquid temperature ΔT during the ice formation process (if any) was transmitted practically unchanged to the internal regions of the silicon rod due to its high temperature conductivity, which led to a change in the speed ΔV and phase $\Delta\varphi$ of the probing acoustic wave. The value of ΔT was determined from the known relation [12]

$$\Delta T = (1/\mathrm{TC}V)\,(\Delta V/V) = (1/\mathrm{TC}V)(\Delta\varphi/\varphi), \quad (1)$$

where TCV is the temperature coefficient of the velocityof the probing wave in silicon, close to the temperature coefficient of delay of the wave TCD (known), V, φ are the velocity and phase of this wave (known), ΔV, $\Delta\varphi$ are changes in velocity and phase, which are measured using a network analyzer KEYSIGHT E5061B in phase mode.



a



b

Fig. 3. *Schematic representation (a) and photograph (b) of an experimental sample for non-contact study of exo-($\Delta T > 0$), endo-($\Delta T < 0$) and iso-($\Delta T = 0$)thermal processes accompanying liquid-ice phase transitions-liquid. 1 – test sample, 2 – silicon rod, 3 – emitter, 4 – receiver.*

To account for temperature changes in the adhesions between the transducers and the rod, as well as in transducers that are pressed piezoceramics, similar measurements were previously carried out without the test sample and the values of the output signals with and without the test liquids were subtracted. Distilled water was used as the test liquid. Salol was used to glue ceramic converters to a silicon rod. The measurement accuracy, which was mainly determined by the quality of the acoustic contact (bonding) between the piezoelectric transducers and the silicon rod, is estimated to be ±1°C.

Fig. 4 shows the measurement results. The experiment used ceramic transducers of longitudinal body waves at 10 MHz with a wavelength $\lambda = V_L/f = 0.85$ mm. Since the length of the rod in the direction of wave propagation was $L = 10$ mm, the total phase shift between the transducers was $\varphi_0 = 360°(L/\lambda) = 360°(10\ \text{mm}/0.85\ \text{mm}) = 4235°$.

The measurement procedure was as follows. At the first stage, the temperature delay coefficient TC*D* of a longitudinal acoustic wave was measured in a silicon rod with ceramic transducers and gluing in the absence of a test liquid: when the sample was cooled,

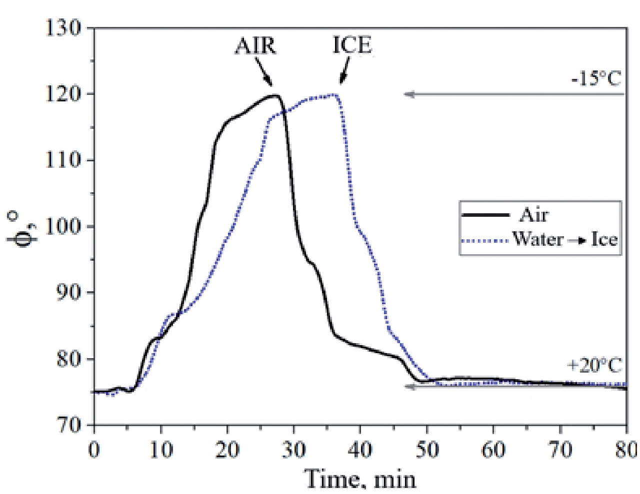


Fig. 4. *Phase responses of longitudinal acoustic waves measured in air (black line) and during the water-ice phase transition (blue dashed line).*

for example, from $T = +20°$C to $T = -15°$C, the phase change was $\Delta\varphi = 53.1°$ (Fig. 4, solid line). Therefore, the TC*D* of the rod with ceramic converters and gluing was equal to $(1/\Delta T)(\Delta\varphi/\varphi_0) = (1/35°\text{C})(51.13°/4235°) = +345$ ppm/°C. For comparison, the same coefficient for longitudinal BAW in silicon without converters and gluing is an order of magnitude lower and amounts to only +32.7 ppm/°C [13].

At the second stage, a similar change in the phase of the wave was measured when a rod with water on its upper surface was cooled. Water was transformed into ice, which gave an additional change in phase $\Delta\varphi$ by –0.16° compared to a clean rod (Fig. 4, dotted line). Hence, the additional temperature change associated with the water-ice phase transition is $\Delta T = (1/\text{TC}D)(\Delta\varphi/\varphi_0) = (1/345\text{ppm}/°\text{C})(-0.16°/4235°) = -0.1°$C or the value, close to zero ($\Delta T \approx 0°$C) – the water-ice phase transition, as it should be, is isothermal [11].

Thus, non-contact studies of thermal processes accompanying liquid-ice and ice-liquid phase transitions under conditions of thermal contact of the object under study only with the measuring element are possible using volumetric acoustic waves. The measurement accuracy is low (±1°C) and is mainly determined by the quality of the acoustic contact of the piezoelectric transducers with the silicon rod and thermal losses. To minimize the bonding effect, measurements with pure silicon should be carried out immediately before testing each liquid, and to minimize thermal loss, piezoelectric transducers should be located in close proximity to the interface with the substance being tested. Approbation of the methodology has shown that the phase transition process for distilled water, as it should be, is isothermal ($\Delta T \approx 0°$C), However, small values of the accompanying temperature variations ΔT are determined with low accuracy ±1°C.

More reliable measurements of ΔT using the developed method are possible only for phase transitions that are accompanied by more significant temperature changes $|\Delta T| \geq 5$°C.

4. CONCLUSION

The propagation of longitudinal bulk acoustic waves in liquids with much less attenuation than in gaseous media makes it possible to record the excess or fall of the liquid level relative to a given value.

Temperature changes in the velocity of the bulk acoustic wave probing the silicon rod in depth make it possible to record the nature of the thermal processes accompanying the phase transition on the surface of the rod. The disadvantage of using bulkacoustic waves to detect liquid-ice phase transitions is the need to take into account temperature changes in electromechanical transducers and gluing the transducers to a liquid cell.

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