

## Ultrasound attenuation dependence on air compression or expansion processes

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### Abstract:

In this work variation of ultrasonic attenuation coefficient is analyzed in terms of air compression or expansion processes. In closed spaces changing air volume, the ultrasound attenuation coefficient depends on thermodynamic processes which occur during the air volume change. Two limiting cases are possible: 1) if the change of air volume is very slow or intensive heat exchange occurs between the system and surrounding environments, so the system stays in a thermodynamic equilibrium; therefore an isothermal process occurs; 2) if the change of air volume is very fast or the working environment has a good thermal insulation, so the heat exchange between the system and the surrounding environment does not occur. In this case an adiabatic process is presented. The attenuation coefficient of ultrasound varies very differently depending on the process (isothermal or adiabatic) that occurs during the change of air volume. In particular, these differences occur when measurements are carried out in a frequency range above 500 kHz during air compression. Initial relative air humidity has high influence on the ultrasonic signals attenuation. Carrying out ultrasonic measurements in such systems, due to reliability of the measurements it is necessary to evaluate thermodynamic process and ultrasound attenuation variation during the process. Oversaturated water vapour may occur during the measurement process, therefore the measurement conditions become more complicated.

**Keywords:** attenuation of acoustic signals in air, relative humidity, isothermal process, adiabatic process

### Introduction

Development of new technologies causes a growing need to control various technological processes and their parameters. At the same time there is a requirement that control measurements would not affect technological processes themselves. This objective is particularly achieved by contactless ultrasonic measurements in water or other liquids. However, in recent years more and more such measurements have not satisfied these requirements. A number of technological processes increase when a product may come into contact with air only. Therefore, nowadays air-coupled ultrasonic measurement methods are under intensive development and improvement [1].

However, carrying out air-coupled ultrasonic measurements, ultrasonic signal losses, comparing with ultrasonic immersion measurements, increase significantly. The following two reasons determine the losses: 1 - high difference between acoustic impedances of environments and 2 - acoustical properties (attenuation) of air. Therefore, a support of required level of incoming ultrasonic signal amplitude is the main objective during air-coupled ultrasonic measurements. In order to achieve the objective of the air-coupled ultrasonic measurements, the following ways are applied:

- 1 - matching of acoustic impedances between piezoelectric transducers and air;
- 2 - use of high amplitude driving voltage for piezoelectric transducers and use of a high gain preamplifiers and amplifiers;
- 3 - selection of signal forming and signal processing methods;
- 4 - selection of optimal distance between piezoelectric transducer and test object.

The presented ways increases signal to noise ratio, but they do not guarantee the ultrasonic signal amplitude

stability. Changes in intrinsic air properties such as pressure, temperature and relative humidity have a strong influence on ultrasonic signal attenuation. Moreover, the attenuation has a strong dependence on the ultrasonic signal frequency.

### Theoretical investigation and calculation

ISO 9613-1 standard [2] can be used for estimation of ultrasonic signal attenuation under specific conditions. This standard is dedicated to acoustic signal attenuation in audio signal range. But the standard states that it can be applied for wider frequency range, including ultrasonic signal propagating in air. As can be seen from the algorithms presented in the standard, in air an attenuation coefficient  $\alpha$  is the non-linear function of temperature  $T$ , pressure  $p$ , relative humidity  $\sigma$  and acoustic signal frequency  $f$ , i.e.  $\alpha = \alpha(T, p, \sigma, f)$ . Moreover, these parameters are related to each other. Therefore, due to a change in one of the parameters, complex acoustic signal attenuation dependences are obtained for a given parameter [3]. Therefore, to ensure the incoming signal amplitude level it is necessary to evaluate parameters variations influence on the acoustic signal attenuation during the measurement. The situation becomes more complex when measurements are carried out in closed environments [4]. The relative humidity almost is unvarying during measurements in open environments. In closed spaces each macro parameters change of the space results in significant relative humidity changes. Therefore, during measurements in such environments, it is necessary to evaluate relative humidity influence on measurement results [5, 6, 7, 8].

Particularly difficult situation comes when air-coupled ultrasonic measurements are carried out in closed spaces and simultaneously air compression or expansion processes occur during the measurements [9]. Here, both, isothermal

and adiabatic processes, can take place, depending on the compression (expansion) process rate and working environment thermal insulation properties. If the compression (expansion) process is very slow or intensive heat exchange occurs between the working and surrounding environments, thermodynamic equilibrium is not disturbed; therefore an isothermal process occurs, during which the temperature does not change (Fig.1):

$$T_{\Delta U=0} = T_0 = const, \quad (1)$$

where  $T_0$  is the initial air temperature. If the compression (expansion) process is very fast or the working environment has a good thermal insulation, therefore the heat exchange between the working and surrounding environments does not occur. In this case an adiabatic process is presented during which temperature varies nonlinearly:

$$T_{Q=0} = T_0(V/V_0)^{1-\gamma}, \quad (2)$$

where  $V/V_0$  is the relative air volume change,  $\gamma$  is the adiabatic constant. In real case a polytropic process close to adiabatic occurs during air compression and this process breaks the thermodynamic equilibrium with a surrounding medium. After finishing of the process, a slow isochoric process begins due to heat leaking to a surrounding medium and therefore the system returns to the thermodynamic equilibrium. During all these processes, macro parameters of the system vary and they affect the attenuation of ultrasonic signals.

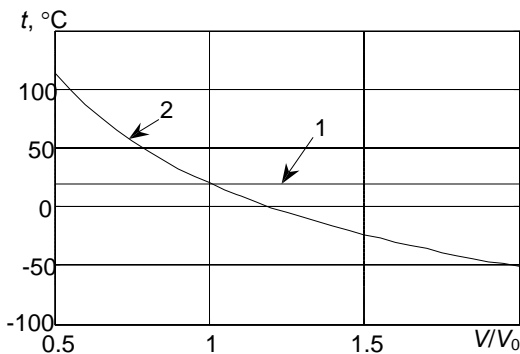


Fig. 1. Influence of air volume change on air temperature during isothermal (1) and adiabatic (2) processes

The attenuation of ultrasonic signals will be analyzed for limiting cases more in detail, i.e., when isothermal and adiabatic environment compressions occur. Let us assume the following initial conditions:  $V/V_0=1$ , air temperature  $T_0$  is 20°C, pressure  $p_0=100$  kPa, relative air humidity  $\sigma_0$  is 20%, 40% and 60%. The surrounding medium pressure varies during these processes (isothermal and adiabatic) and the variations (Fig.2) are given by Eq. 3 and 4 for the isothermal and adiabatic processes, respectively:

$$p_{\Delta U=0} = p_0(V/V_0)^{-1}, \quad (3)$$

$$p_{Q=0} = p_0(V/V_0)^{-\gamma}. \quad (4)$$

Absolute air humidity variation is inversely proportional to the relative change in volume of air and it is independent of the ongoing process (Fig. 3). Temperatures, which vary in different ways during these processes, affect the relative air humidity, too. Therefore, the relative air

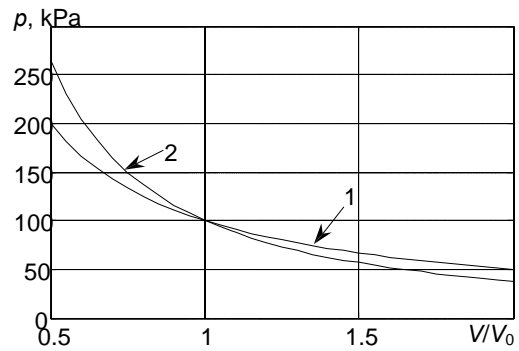


Fig. 2. Influence of air volume change on air pressure during isothermal (1) and adiabatic (2) processes

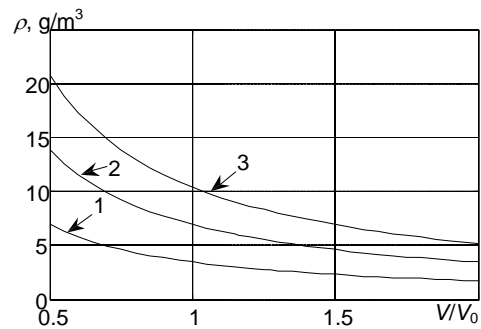


Fig. 3. Absolute air humidity variation due to air volume change when the initial relative air humidity is  $\sigma_1=20\%$ ,  $\sigma_2=40\%$  and  $\sigma_3=60\%$  and air temperature is 20°C

humidity variation is inversely proportional to the relative air volume change during isothermal air compression process (Fig. 4a). During adiabatic process the situation is opposite from the previous one. Depending on the initial air humidity, the relative air humidity increases up to 100% when the volume increases between 1.1÷1.3 times (Fig. 4b). According to the changes in these air parameters and applying ISO 9613-1 standard, peculiarities of ultrasonic signal attenuation in air are analyzed for isothermal and adiabatic processes. Ultrasonic signals of 50 kHz, 100 kHz, 200 kHz, 500 kHz and 1000 kHz were analyzed.

Results show that the attenuation coefficient does not change at low frequencies (around 50 kHz) when air the volume varies isothermally, however the attenuation coefficient has a strong dependence on the initial relative air humidity (Fig. 5a). The attenuation coefficient increases with increase of the relative air humidity. An increase of the ultrasonic signal frequency results in the attenuation coefficient dependence on the volume. The attenuation coefficient increases when air expands isothermally. The higher the frequency of acoustic signals, the more pronounced this transition and the dependence on volume changes becomes more linear (Fig. 5). The attenuation coefficient dependence on the initial air humidity decreases with increase of the ultrasonic signal frequency. The relative air humidity does not influence the ultrasonic signal attenuation coefficient variation when the ultrasonic signal frequency is above 500 kHz (Fig. 5).

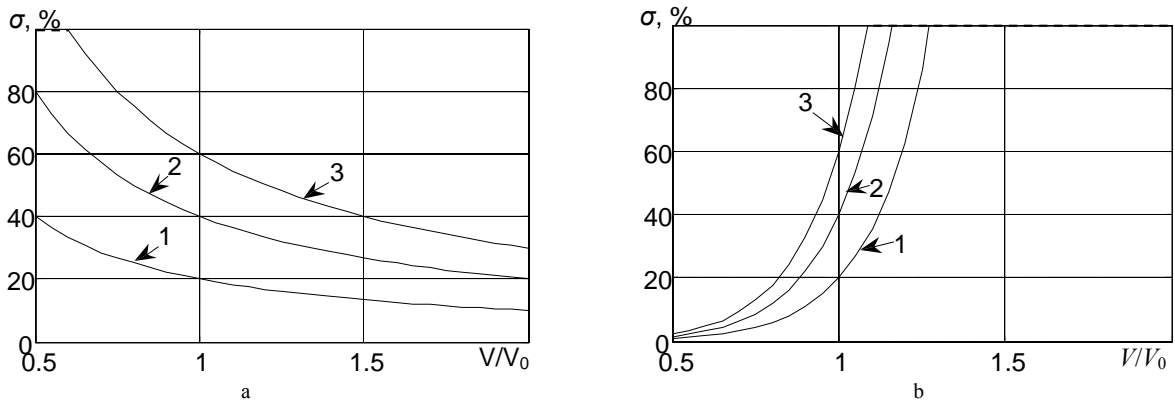


Fig. 4. Relative air humidity variation due to air volume change during isothermal (a) and adiabatic (b) processes. The initial relative air humidity is  $\sigma_1=20\%$ ,  $\sigma_2=40\%$  and  $\sigma_3=60\%$  and air temperature is  $20^\circ\text{C}$

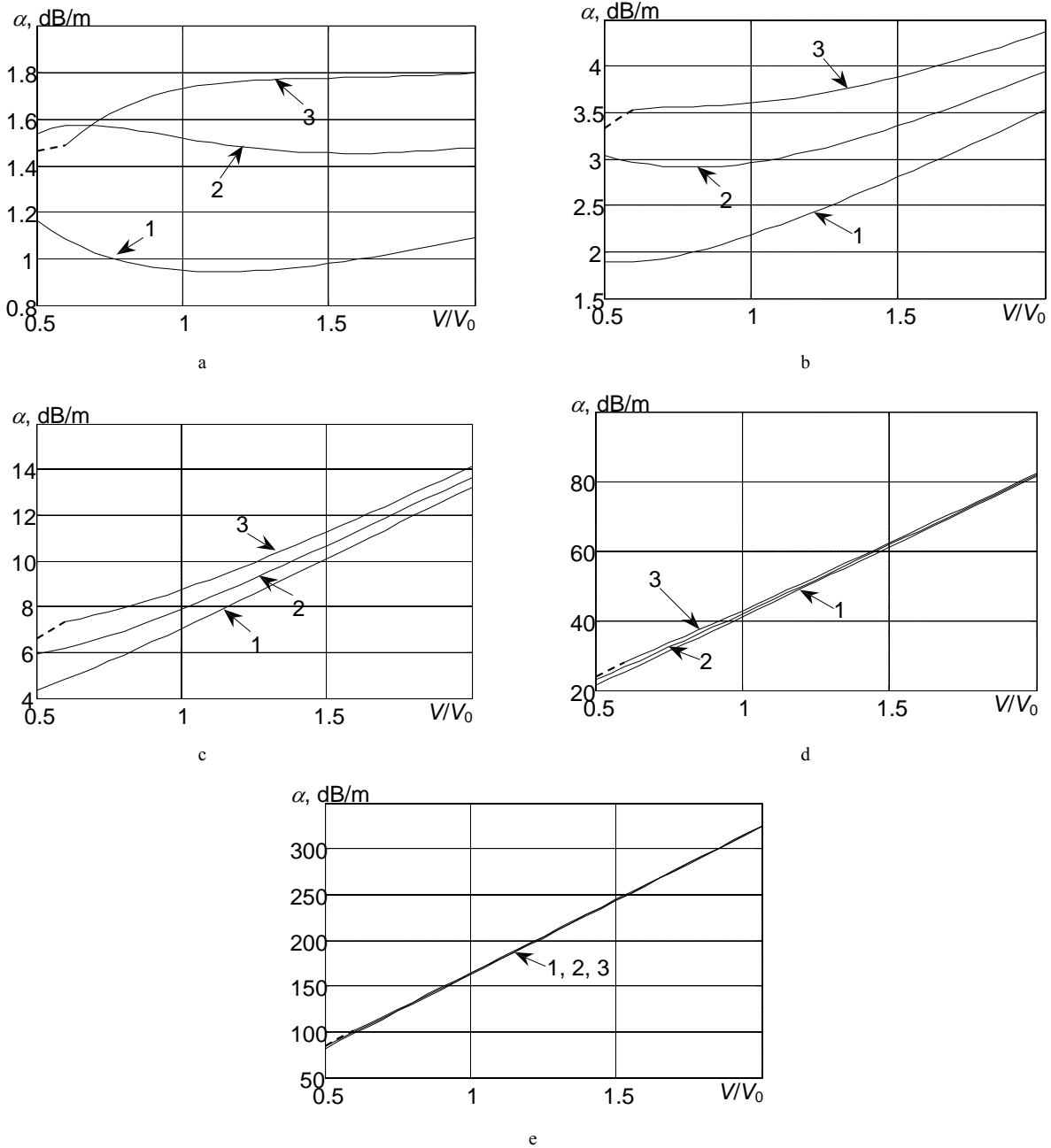


Fig. 5. Attenuation of acoustic signals in air during isothermal process at the following frequencies: a - 50 kHz; b - 100 kHz; c - 200 kHz; d - 500 kHz and e - 1 MHz. The initial relative air humidity is  $\sigma_1=20\%$ ,  $\sigma_2=40\%$  and  $\sigma_3=60\%$  when air temperature is  $20^\circ\text{C}$  and air pressure is 100 kPa

In air the attenuation coefficient varies in a different way during adiabatic process from the isothermal process. When air expands, the air temperature decreases and the relative air humidity increases very fast. Independently on the initial relative air humidity (usually it is >10%), air becomes oversaturated with water vapour (Fig. 6).

Therefore, the initial relative air humidity does not affect the ultrasound attenuation coefficient in air when air expands adiabatically. A theoretical curve, marked as the dashed curve in Fig. 6, represents this part of the process. After oversaturation a water vapour phase transitions occur. Small water droplets or frost tends to form in air and on piezoelectric transducers surfaces simultaneously.

Therefore the attenuation of ultrasonic signals increases more. The attenuation coefficient of ultrasound signal obtains complex nonlinear dependence when air is compressed adiabatically. The attenuation coefficient increases a few times when air volume is adiabatically compressed two times and ultrasonic signal frequency range is below 100 kHz. The attenuation coefficient of ultrasound signal in a frequency range up to 500 kHz is significantly affected by the relative air humidity during the adiabatic air compression. At the beginning the attenuation coefficient decreases and later it starts to grow quite rapidly (Fig. 6c) when the ultrasound signal frequency is around 200 kHz. In this range the relative air humidity has the

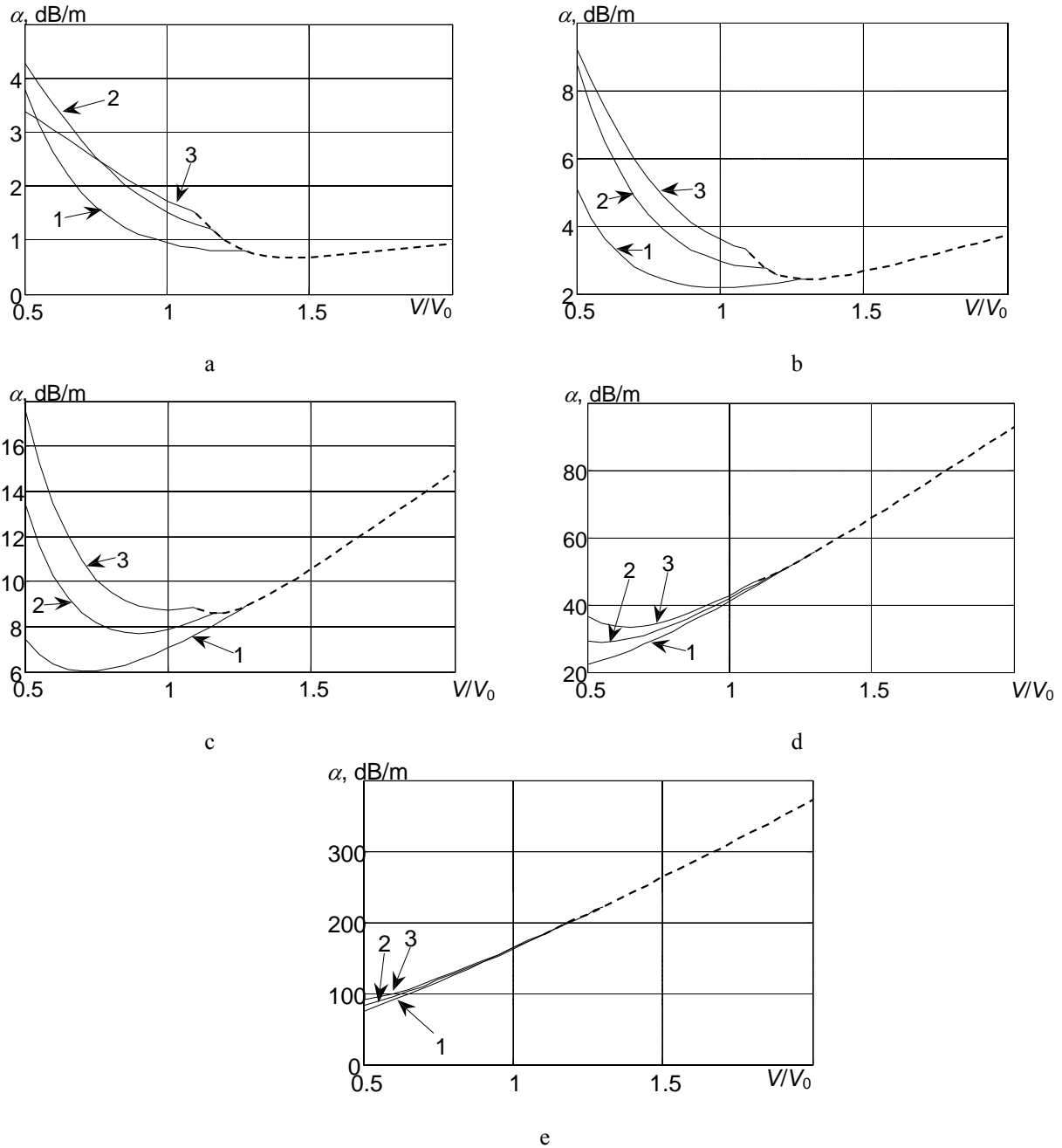


Fig. 6. Attenuation of ultrasonic signals in air during adiabatic process at the following frequencies: a - 50 kHz; b - 100 kHz; c - 200 kHz; d - 500 kHz and e - 1 MHz. The initial relative air humidity is  $\sigma_1=20\%$ ,  $\sigma_2=40\%$  and  $\sigma_3=60\%$  when air temperature is 20°C and air pressure is 100 kPa

strongest influence on the attenuation coefficient of acoustic signals. Going to the higher frequencies, the attenuation coefficient only decreases during adiabatic air compression and at frequencies above 1000 kHz the relative air humidity does not affect the attenuation coefficient.

## Conclusions

Attenuation coefficient of ultrasound depends on thermodynamic processes and variation of initial macro parameters in the system when air volume changes in closed spaces. Influence of these parameters on the attenuation coefficient of ultrasonic signals, as was shown above, occurs in different frequency ranges differently. Therefore carrying out measurements in such systems, due to reliability of the measurements it is necessary to evaluate thermodynamic process and ultrasound attenuation variation during the process. Moreover, it is necessary to evaluate possibility that oversaturated water vapour may occur during the measurement process, so measurement conditions would become even more complicated.

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## Ultragarso slopinimo priklausomybė nuo oro suspaudimo išsiplėtimo proceso

### Reziumė

Nagrinėjamas ultragarsinių signalų slopinimo koeficiento kitimas ore, kai jis suspaudžiamas arba leidžiama jam išsiplėsti. Uždarose erdvėse keičiant oro tūrį, ultragarso slopinimo koeficientas čia priklauso nuo tūrio kitimo metu vykstančių termodinaminių procesų. Galimi du ribiniai atvejai: 1) jei tūris kinta labai lėtai arba vyksta intensyvūs šilumos mainai tarp sistemos ir aplinkos, tai sistema išlaiko termodinaminę pusiausvyrą su aplinka ir vyksta izoterminis procesas; 2) jei tūris kinta labai greitai arba sistema labai gerai izoliuota nuo aplinkos, tuomet šilumos mainai su aplinka beveik nevyksta ir procesas yra adiabatinis. Pagal tai, ar tūrio kitimo metu vyksta izoterminis, ar adiabatinis procesas, ultragarsinių signalų slopinimo koeficientas kinta labai skirtingai. Ypač šie skirtumai pasireiškia suspaudimo metu, kai matavimai atliekami >500kHz dažnių diapazone. Šiame dažnių ruože didelę įtaką ultragarsinių signalų slopinimui turi ir pradinė santykinė oro drėgmė. Norint gauti patikimus tokiose sistemose atliekamų ultragarsinių matavimų rezultatus, reikia iš anksto nustatyti, kokio pobūdžio termodinaminis procesas vyks ir kaip jo metu kės ultragarsinių signalų slopinimas. Matavimų metu sistemoje gali atsirasti persotintųjų vandens garų. Tuomet matavimų sąlygos pasidaro dar sudėtingesnės.

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