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Ultrasound attenuation dependence on air temperature in closed chambers

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Abstract

In the work attenuation regularities of acoustic signals, which propagate in closed chambers, are analysed. Due to this that in a closed chamber gases state parameters are interdependent, so change of one of the parameters results in corresponding changes of others. Usually the closed chambers are of constant volume or constant pressure, therefore influence of temperature variations on air parameters are analyzed for isobaric and isochoric processes. During theses processes the change of the temperature has the strongest influence on a relative humidity in air. The relative humidity achieves some percents when the temperature goes up and it increases up to 100% when the temperature decreases. Further decreasing of the temperature raises water vapor condensation and this result in a strong degradation of measurement conditions.

Influence of the frequency on the attenuation of acoustic signals also is evaluated. It was estimated that the attenuation of acoustic signals increases independently versus the frequency when the temperature goes up during the isobaric process. It was shown that the attenuation can increase or decrease depending on the frequency of acoustic signals when the temperature rise up during the isochoric process.

Keywords: attenuation of acoustic signals in air, relative humidity, isobaric process, isochoric process.

Introduction

Ultrasonic measurements are used frequently in solution of various research and industry tasks. Nowadays contactless air-coupled acoustic measurements have wide applications in nondestructive testing and evaluation of metallic and advanced composite material structures. It is necessary to achieve a high accuracy in the measurements due to this that the measurement results would be reliable. However, the total losses of air-coupled acoustic signals are much higher comparing them to the losses in acoustic contact or immersion measurements. Therefore in a number of cases, informative signals, received by air-coupled acoustic instrumentation, do not satisfy the defined measurement accuracy. A support of enough amplitude of acoustic (ultrasonic) signal that the required measurement accuracy would be achieved is one of the main tasks during the acoustic measurements in gases or air. Usually the following methods are used for increase of the signal to noise ratio: matching of acoustic impedances of piezoelectric transducers [1], signal processing [2, 3], increase of electric excitation voltage and gain [4, 5]. An attenuation of ultrasonic waves also must be evaluated for high accuracy air-coupled acoustic measurements [6,7].

However, the attenuation depends on a concentration of gases in air. The influence of the gases, which go to the composition of air, on the attenuation of the acoustic signals was investigated at the beginning of the last century [8]. Moreover, the attenuation of the acoustic waves depends on the surrounding medium temperature t, pressure p and frequency f of the acoustic signals. A relative humidity of air also has significant influence on the attenuation. The influence of the surrounding medium parameters on the attenuation can be estimated applying the ISO9613-1 standard [9]. Usually the temperature, the pressure and the humidity of air changes slowly in normal conditions, so it is enough to evaluate the influences of these parameters before the measurements when the measurements are carried out in the open air. If it is necessary, the changes of the parameters can be estimated easily during the measurements. Essentially another one situation is when the measurements are carried out in closed chambers, especially in the small ones. In the closed systems gas parameters are related by the ideal gas law:

$$pV = \frac{m}{\mu} RT ,$$

where m is the mass of the gasses, μ is the molar mass, R is the universal gas constant, V is the gas volume, T is the absolute temperature of gas, p is the gas pressure. During the measurements in these conditions, due to a change of one of the parameters (temperature, pressure or relative humidity), changes occur in others, which have influence on the attenuation, also. However, it is complicated to hold stable these parameters during a measurement process. For example, if the air temperature would be changed in the closed chamber, the air pressure and the relative humidity will change, also. In a number of cases, water vapor phase conversion can begin, too. The conversion would result in a strong degradation of the measurement conditions; therefore the measurement accuracy would be lost, also. So for the evaluation of the attenuation of the ultrasonic signals in air in the closed chambers, it is not enough to consider in analysis only the influences of the single parameters. In this case it is necessary to evaluate integrally the influences of the changed parameters on the ultrasonic attenuation in air. Due to this that in the closed chambers concentration of gases is stable, evaluation of the air parameters (pressure, temperature and relative humidity) before isolation of the space in a closed chamber for the measurements, it is possible to predict variations of the attenuation of the acoustic signals in air when one of the parameters is not stable or is changed artificially. This gives information about reliability of the acoustic measurements.

Theoretical investigation and calculation

A closed chamber with a constant volume V ($dV/d\tau=0$) and with a support constant pressure p ($dp/d\tau=0$) usually is used in measurements, where τ is the time. Therefore in this paper the attenuation of the acoustic signals versus air temperature T is analyzed at the following different conditions in the closed chamber: 1) the volume v of the chamber is constant, 2) the pressure p of air is constant in the chamber. Due to this that mass of a closed system does not vary, the first case corresponds to isochoric process, i.e. $p=p(T)$. The second case corresponds to isobaric process $V=V(T)$. Let's assume us that in the chamber the following initial air conditions are: the pressure $p=100$kPa, the temperature $t=20$°C, the relative humidity $\sigma_1=20\%$, $\sigma_2=40\%$ and $\sigma_3=60\%$. Changing the temperature during the isochoric process, the air pressure p varies proportionally: $p dv=\text{const}*T$, where T is the absolute temperature (Fig. 1).

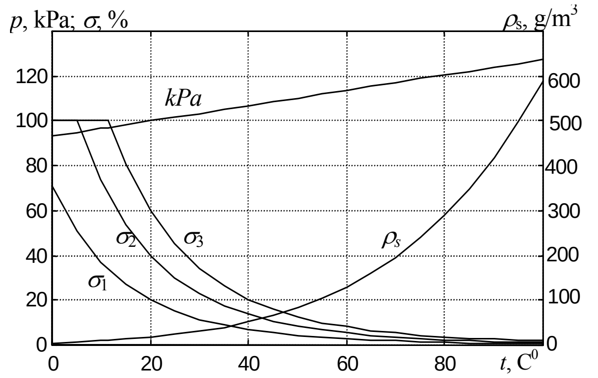


Fig. 1. **Dependences of the air pressure p, the density ρ_s of saturated water vapor and the relative humidity σ on the air temperature in the isohoric process. The initial relative humidity equales to $\sigma_1=20\%$, $\sigma_2=40\%$ and $\sigma_3=60\%$ at the air temperature of 20°C.**

In the chamber the density of water vapor ρ_g remains constant, because the system is closed. However, the density ρ_s of saturated water vapor has a strong dependence on the temperature. For example, the density ρ_s of the saturated water vapor is 17.2kg/m^3 at the temperature $t=20$°C and it becomes 290.1kg/m^3 at the temperature $t=80$°C (Fig. 1). Therefore, in the chamber of the constant volume the relative humidity of air $\sigma = \frac{\rho_g}{\rho_s}100\%$ has a strong dependence on variations of the temperature t (see Fig. 1).

The relative air humidity reduces and it achieves some percents when the temperature increases. The relative humidity increases and it tends to 100% when the temperature goes down. The results, presented in Fig. 1, show that the relative humidity of air, which initially has the relative humidity $\sigma_3=60\%$ at the temperature $t=20$°C, increases up to 100% at the temperature $t=11.5$°C. A reduction of the temperature below 11.5°C results in a condensation of water vapor and at this point density and gases concentration of air begin to change. Therefore, the ideal gas law can not be applied for estimation of air state. Moreover, everything what is inside of the chamber including and surfaces of ultrasonic transducers are covered by a thin layer of water condensate. Droplets of water condensate occur inside the entire of the closed chamber. Due to this increases the attenuation of ultrasonic signals and the measurement conditions degradate. Similar situation is observed with air having the initial temperature $t=20$°C and the relative humidity $\sigma_2=40\%$. In this case the relative humidity achieves 100% at the temperature $t=5.2$°C. When the relative humidity σ_1 is 20% at the temperature $t=20$°C, the relative humidity becomes a bit higher than 70% at the temperature $t=0$°C. The presented results show that the air parameters such as pressure, temperature and especially relative humidity must be evaluated before beginning of accurate acoustic measurements in the closed chambers. Knowing a temperature range, it is possible to predict a reliability of the measurements.

A similar situation to the presented isochoric process can be observed in an isobaric process, also. Due to a change of the temperature T, the gas pressure p does not vary, but the closed chamber volume V changes. The density of water vapor ρ_g will change respectively to the change of the volume, filled by air (Fig. 2). However, the density ρ_s of saturated water vapor will change due to the changes of the temperature T. The changes of these two parameters (ρ_s, ρ_g) will define variations of the relative humidity σ in air (Fig. 2). A comparison of the relative humidity curves of the isobaric process to the curves presented for the isochoric process when the initial conditions are the same, shows that the curves are similar. The results show that during the isobaric process the relative humidity in air changes faster with the temperature change; and the relative humidity of the 100% is achieved at a higher temperature than during the isochoric process. For example, air, which has the initial relative humidity 60% at the temperature $t=20$°C, achieves the relative humidity of the 100% at the temperature $t=12.0$°C. Below this temperature the ideal gas law can not be used for analysis of air state due to beginning of water vapor phase conversion, which also results in a strong deterioration of the measurement conditions.

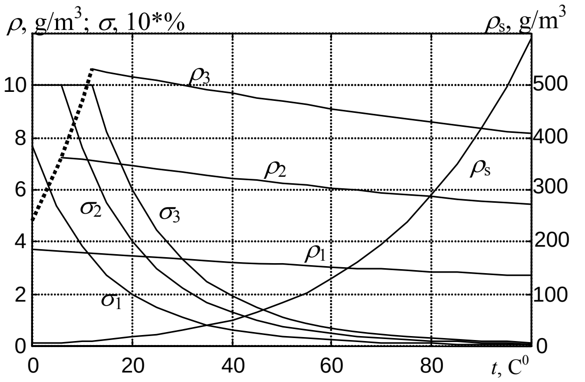
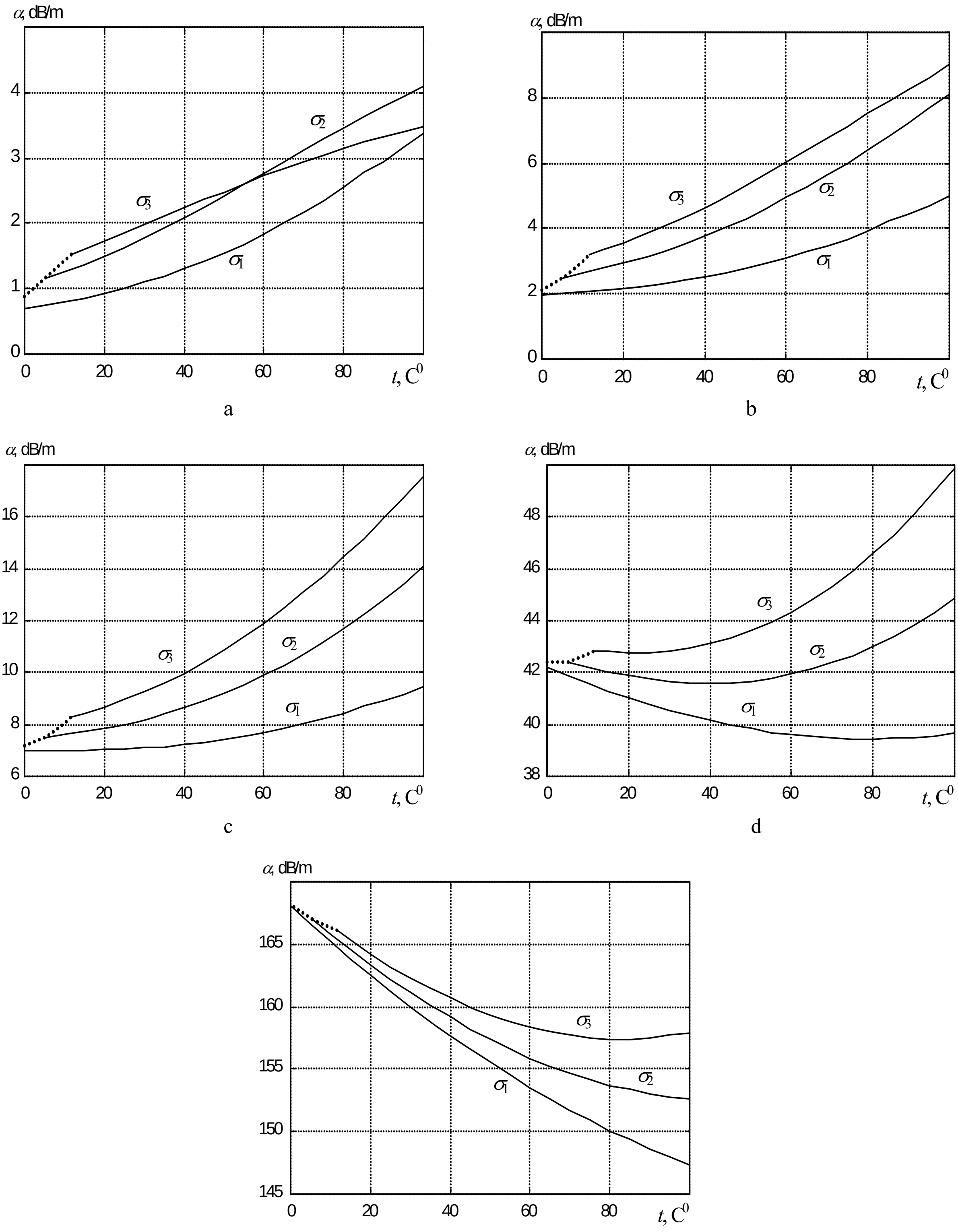


Fig. 2. **Dependences of the density ρ_s of saturated water vapor, the relative humidity σ and density ρ of water vapor corresponding to the σ on the air temperature in the isochoric process. The initial relative humidity equales to $\sigma_1=20\%$, $\sigma_2=40\%$ and $\sigma_3=60\%$ at the air temperature of 20°C. The dotted curve denotes the density of the saturated water vapour.**

When regularities of variations of the air parameters (pressure, temperature and relative humidity) versus the air temperature are known in closed chambers, it is possible to investigate the attenuation of acoustic signals dependence on the temperature at these conditions and to compare the obtained results to the attenuation estimated for the measurements in the open air [7]. The ISO9613-1 standard was used for the calculation of the attenuation of acoustic signals in both cases, which holds formulae for wider ranges (e.g. ultrasonic frequencies, lower pressure) and for other than pure tones [9]. The calculations were performed at the following frequencies of acoustic signals: 50 kHz, 100 kHz, 200 kHz, 500 kHz and 1 MHz.

The attenuation of acoustic signals is strongly influenced by a frequency of the signals during isochoric process in a closed chamber of constant volume at the varying temperature (Fig. 3). It is seen that at the central frequency *f*=200 kHz the attenuation increases when the temperature is going up (Fig. 3a, b, c). The results clearly show that the attenuation of the acoustic signal increases



a

b

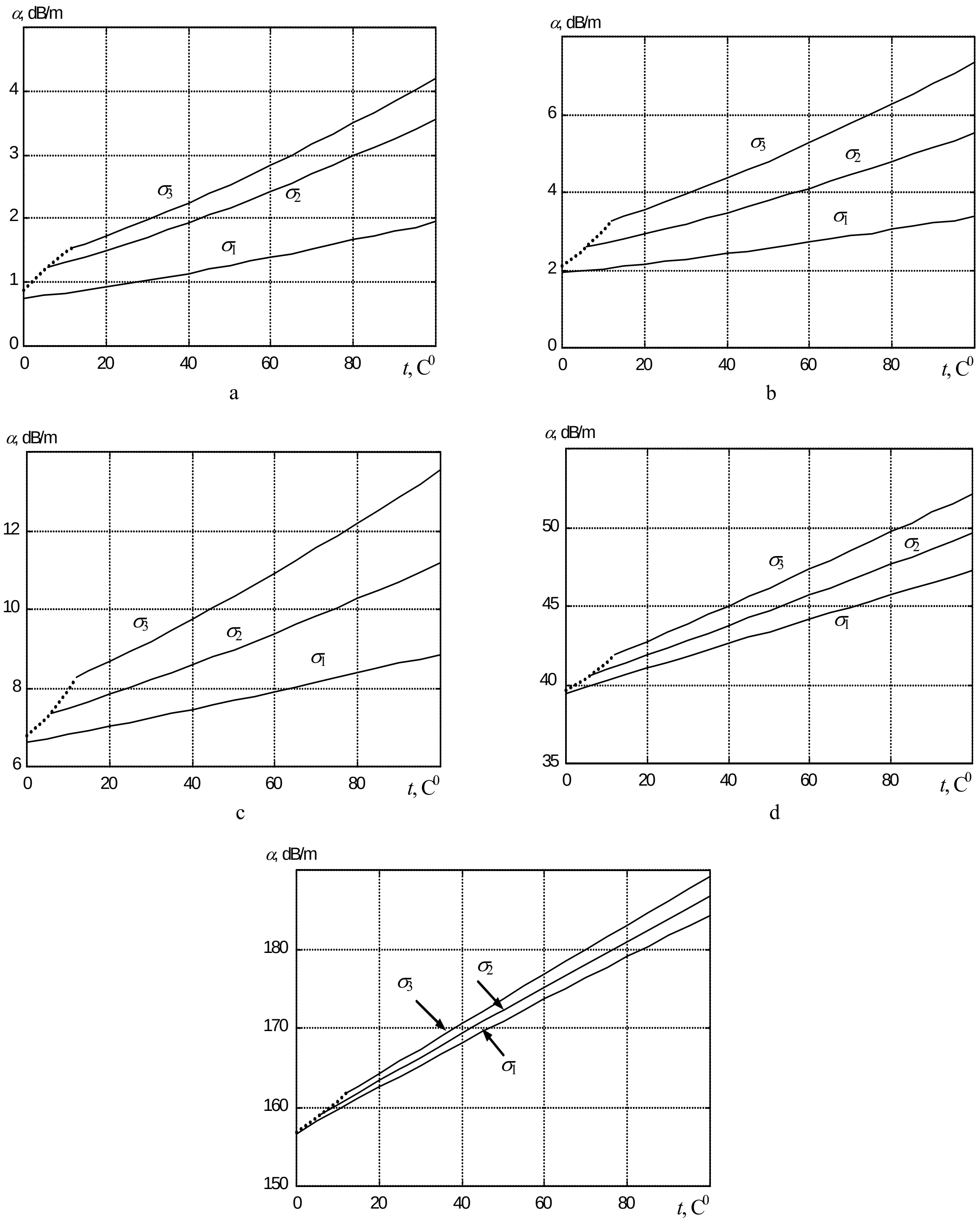
c

d

e

Fig. 3. **Attenuation of acoustic signals in air during isochoric process at the following frequencies: a – 50 kHz, b – 100 kHz, c – 200 kHz, d - 500 kHz and e – 1 MHz. The initial relative humidity equales to σ_1=20%, σ_2=40% and σ_3=60% at the air temperature of 20°C. The dotted curves denote the attenuation of the acoustic signals when the relative humidity is 100% in air.**

more sharply with the increase of the initial relative humidity in air. At the central frequency *f*=500 kHz, the attenuation behavior of the acoustic signals depends on the initial relative humidity in air. The attenuation increases when the temperature grows up and the initial relative humidity is 60%. It is seen that the attenuation increases faster at higher temperatures. The attenuation reduces when the initial relative humidity is 20% and the temperature is below 80°C. The attenuation increases slightly over the temperature of 80°C (Fig. 3d). When the initial relative humidity is 40%, the attenuation changes a little up to the temperature 60°C, but over it the attenuation starts to increase more significantly. When the central frequency of acoustic signals is *f*=1 MHz, the attenuation of the sound



a b c d e

Fig. 4. **Attenuation of acoustic signals in air during isobaric process at the following frequencies: a - 50 kHz, b - 100 kHz, c – 200 kHz, d – 500 kHz and e – 1 MHz. The initial relative humidity equales to σ_1=20%, σ_2=40% and σ_3=60% at the air temperature of 20°C. The dotted curves denote the attenuation of the acoustic signals when the relative humidity is 100% in air.**

signals reduces without dependence on the relative humidity in air in all range of the temperature (Fig. 3e).

During isobaric process the dependence of the attenuation of acoustic signals on the air temperature differs basically from the attenuation in the isochoric process (Fig. 4). During the isobaric process independently on the initial air parameters (pressure, temperature and relative humidity) in all frequency range, the attenuation of acoustic signals approximately increases linearly when the temperature rise up. Moreover, influence of the relative humidity on the attenuation of acoustic signals reduces with the increase of the frequency.

Conclusions

Comparison of the obtained attenuation results for the isochoric and isobaric processes to the attenuation of acoustic signals in the open air when the temperature goes up shows that there are essential differences.

The parameters are interdependent which describe air state in closed chambers. Therefore it is possible to predict their changes in advance and to evaluate their influences on the attenuation of acoustic signals. Especially the influence of relative humidity of air on the attenuation of acoustic signals must be evaluated during measurements in the closed chambers, because water vapor phase conversion can occur when the air temperature goes down. This results in a strong degradation of measurement conditions.

Polytrophic processes can occur in the real measurement situations. During these processes, a volume and pressure change when the temperature is unstable (for example aerodynamic balloon). Therefore isobaric and isochoric processes are the margin cases of the polytrophic process. So all other polytrophic processes with the variable pressure and volume when the temperature varies will take an intermediate state between the isochoric and isobaric processes. The obtained results show that change of the relative humidity is very similar to the cases of the isochoric and isobaric processes. Therefore, the variation of the relative humidity due to the change of the temperature during isobaric process can be used for evaluation of the relative humidity variations in any polytrophic process.

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Ultragarso slopinimo priklausomybė nuo uždarų talpų oro temperatūros

Reziumė

Nagrinėjami ultragarso signalų, sklindančių uždarų talpų ore, slopinimo ypatumai. Kadangi uždaros talpos dujų būsenos parametrai tarpusavyje glaudžiai susiję, tai kintant vienam parametrui atitinkamai kinta ir kiti. Uždaros talpos dažniausiai būna pastovaus tūrio arba pastovaus slėgio, todėl nagrinėjama temperatūros kitimo įtaka oro parametrams izobarinio ir izochorinio procesų metu. Tada temperatūros kitimas didžiausią įtaką turi santykiniam oro drėgniui. Temperatūrai kylant santykinis oro drėgnis sumažėja iki kelių procentų, o temperatūrai krintant sparčiai auga ir gali pasiekti 100 %. Toliau krintant temperatūrai prasideda ore esančių vandens garų kondensacija, dėl ko pablogėja ultragarsinių matavimų sąlygos. Be to, nustatyta, kad dažnis turi įtakos ultragarso signalų slopinimui. Izobarinio proceso metu ultragarso signalų slopinimas kylant temperatūrai didėja ir tai nepriklauso nuo dažnio. Izochorinio proceso metu ultragarso signalo slopinimas kylant temperatūrai gali didėti arba mažėti ir tai priklauso nuo dažnio

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