EXPERIMENTAL INVESTIGATION OF THE SOUND SPEED DISPERSION IN MOIST CARBON DIOXIDE VAPOR

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Systematic experimental data are obtained in the ranges of pressure 43-70 bar, degree of dryness 0.55-1.0, frequency 1.5-13 kHz, and effective drop diameter 6-50 μm.

Many papers during the past 10-15 years have been devoted to experimental investigations of the sound speed in two-phase mixtures. However, up to now there have nevertheless been no systematic data on the sound speed dispersion for at least a narrow range of two-phase states for any substance.

Such a situation can be explained by the comparatively large number of independent parameters that affect the acoustic properties of two-phase media: in addition to the thermal parameters, it is still necessary to take account of the vapor content, the wave frequency, and the drop or bubble size. In order to investigate the multiparametric dependence for just one value of the pressure, an enormous number of experimental points must be obtained by varying the three remaining independent parameters in sufficient detail.

Moreover, obtaining each experimental point is fraught with additional difficulties as compared with measurements in single-phase media since the vapor content and the size of the disperse particles must be measured simultaneously with the measurement of the sound speed. Each of these problems is complex and requires independent investigations and methodological developments.

In the majority of known experimental papers, e.g., [1, 2], the dependence of the velocity of perturbation propagation on just the vapor content was investigated and the dependences on the wave frequency and dispersed particle size were ignored (these parameters were simply not measured). The exceptions are several papers (e.g., [3, 4]) in which the sound speed dispersion was studied, however, the measurements were made only at atmospheric pressure.

We developed a new express method to obtain systematic experimental data about the sound speed dispersion within a reasonable time interval. Mainly it consists of phase lags at different frequencies determined from the spectrum analysis of two acoustic pulses, one of which has passed through the moist vapor being investigated, while the other has passed through a standard medium without dispersion but with a known speed of sound.

Spectrum analysis of the pulses is accomplished by using the Fourier integral transform [5]. In conformity with the equality

$$s(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty}S(\omega)\exp(i\omega t)\,d\omega \tag{1}$$

a pulse of arbitrary shape s(t) is equivalent to the superposition of an infinite number of harmonic oscillations that form a continuous spectrum. The Fourier transform of the pulse is hence defined by the expression

$$S(\omega)=\int_{-\infty}^{\infty}s(t)\exp(-i\omega t)\,dt. \tag{2}$$

As is known, a pulse that has passed through some medium is generally deformed by absorbing information about the properties of the medium. If there is an acoustic pulse

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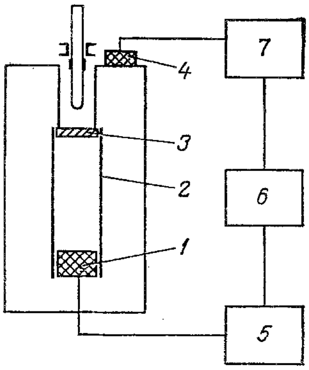

Fig. 1

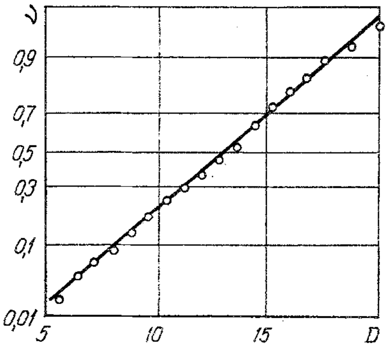

Fig. 2

Fig. 1. Instrument block diagram: 1) detector—piezotransducer; 2) waveguide; 3) emitter; 4) trigger piezotransducer; 5) SI-15 oscilloscope; 6) delayed-pulse generator G5-4B; 7) trigger signal amplifier.

Fig. 2. Integrated distribution function of the drop diameter in a normal probability scale for one of the experiments. D, μm.

y(t) at the entrance to the medium, then the output pulse s(t) can be determined by using a convolution integral of the input signal with the weight function h(t), that is a function of the system response to a unit pulse:

$$s(t) = \int_{-\infty}^{\infty} h(u)\, y(t-u)\, du. \tag{3}$$

Since a convolution in the time domain is equivalent to a product of the Fourier transforms S(ω), Y(ω), H(ω), and the corresponding functions s(t), y(t), h(t) in the frequency domain [5], there exists a simple relation

$$S(\omega) = Y(\omega) H(\omega). \tag{4}$$

The Fourier transform H(ω) is a complex frequency characteristic of the medium and contains information about the phase delay and the attenuation of each harmonic component of the pulse in the medium, i.e., about the acoustic properties of the medium.

If the moist vapor under investigation and the standard medium are probed by identical acoustic pulses y(t), then as follows from (4), the ratio between the frequency characteristics of these two medium will be equal to the ratio between the Fourier transforms of the pulses which have passed through. Denoting the function referring to the standard medium by 0, we obtain an expression to determine the frequency characteristic of the moist vapor

$$H(\omega) = H_0(\omega) S(\omega)/S_0(\omega). \tag{5}$$

All the functions in relationship (5) are complex. Representing each in the form $|A(\omega)|\exp[i\varphi(\omega)]$, we find that the difference between the phase lags of the harmonic wave in the moist vapor and in the standard medium equals the difference between the phases of the corresponding harmonic components of the pulses that have passed through the moist vapor and the standard medium, respectively. Let us note that the ratio of the amplitude spectral densities of the pulses that have passed through $|S(\omega)|/|S_0(\omega)|$ also permits determination of the attenuation of the harmonic wave in the moist vapor, caused by relaxation of the interphasal microprocesses.

We therefore obtain an expression to determine the difference in the time delays in the investigated and standard media for any fixed frequency f_j:

$$\Delta t(f_j) = [\varphi(f_j) - \varphi_0(f_j)]/2\pi f_j. \tag{6}$$

The sound speed in the moist vapor is determined from the evident formula

$$a(f_j) = l/[l/a_G + \Delta t(f_j)]. \tag{7}$$

TABLE 1. Speed of Sound (a, m/sec) in Moist Carbon Dioxide Vapor

f, kHz	T, °K								
	281,3	284,7	284,7	285,4	285,5	287,3	287,3	287,3	288,0
	x								
	0,86	0,77	0,87	0,80	0,74	0,98	0,70	0,82	0,75
	D_e, μm								
	15,8	11,6	10,8	11,1	12,0	5,6	12,4	10,2	11,1
1,6	201	194	196	193	190	204	188	191	187
1,8	202	193	196	193	191	204	189	191	187
2,0	202	194	196	194	192	204	190	192	188
2,2	203	195	197	195	194	204	191	193	190
2,4	203	196	198	196	195	204	193	195	192
2,6	203	198	199	197	197	204	195	196	194
2,8	204	199	200	199	198	204	196	198	195
3,2	204	201	201	200	200	204	198	200	197
3,6	205	202	202	201	201	204	199	201	199
4,0	205	202	203	202	202	204	199	202	199
4,4	205	203	203	202	202	204	200	202	200
4,8	206	203	203	203	202	205	200	203	200
5,2	206	204	204	203	202	205	200	203	201
5,6	206	204	205	204	203	205	201	204	201
6,0	206	205	206	205	204	205	201	205	202
7,0	206	—	—	—	—	204	—	—	203
8,0	—	205	204	204	204	—	201	—	—
9,0	206	205	204	204	204	203	201	204	202
10,0	206	205	205	204	204	203	201	204	202
11,0	206	204	204	204	204	203	201	204	202
12,0	206	204	203	203	203	203	200	203	202
13,0	206	204	203	202	203	—	200	203	202

f, kHz	T, °K								
	291,4	291,5	292,7	293,1	295,3	295,3	295,3	296,2	296,7
	x								
	0,75	0,66	0,90	0,68	0,98	0,91	0,55	0,94	0,81
	D_e, μm								
	8,4	11,8	6,7	11,0	9,9	31,8	9,9	6,9	8,8
1,6	175	183	181	182	194	194	160	185	182
1,8	176	184	182	183	194	194	164	186	183
2,0	177	185	183	184	194	194	167	187	184
2,2	178	186	185	185	194	193	169	187	185
2,4	180	188	187	187	193	193	172	188	185
2,6	182	190	188	189	193	193	175	189	186
2,8	184	191	190	190	194	193	178	190	187
3,2	188	193	192	191	194	193	182	190	188
3,6	191	195	193	192	194	193	184	191	189
4,0	192	195	193	193	194	193	186	191	189
4,4	192	196	194	193	194	193	188	191	189
4,8	193	196	194	193	194	193	190	191	189
5,2	194	196	195	193	194	193	191	191	189
5,6	195	197	195	193	194	193	191	191	188
6,0	196	197	196	193	194	193	191	191	188
7,0	—	198	196	194	194	193	191	191	189
8,0	196	198	195	—	195	194	191	191	190
9,0	195	198	195	195	195	194	191	191	191
10,0	197	198	195	195	195	194	191	191	191
11,0	197	198	194	195	195	194	191	191	191
12,0	197	197	194	195	195	194	191	191	191
13,0	197	197	194	196	195	194	191	191	192

To diminish the influence of inaccuracy in measuring the spacing between the emitter and detector on the final result, it is expedient to represent (7) as

$$a(f_j) = a_0 + \Delta a(f_j), \tag{8}$$

$$\Delta a(f_j) = -a_0^2 \Delta t(f_j) / [a_0 \Delta t(f_j) + l]. \tag{9}$$

The phase spectra of the pulses were analyzed by using the relationship [5]

$$\varphi(\omega) = \operatorname{arctg}\left[\int_{-\infty}^{\infty} s(t)\sin\omega t dt \Big/ \int_{-\infty}^{\infty} s(t)\cos\omega t dt\right]. \qquad (10)$$

Numerical integration was performed according to the Simpson quadrature formula. The nonuniformity of the time scale was hence taken into account because of curvature of the S1-15 oscilloscope screen on which the electrical analogs of the acoustic pulses taken were recorded (and photographed). The oscilloscope scale was calibrated directly before each experiment.

The measurement block diagram is displayed in Fig. 1. Acoustic-pulse probing of the moist vapor and the standard medium is performed alternately in the measuring chamber. Saturated or slightly overheated vapor of the same substance (carbon dioxide in this case) is used as the standard. Values of the speed of sound in the standard medium were taken from the experimental results of Novikov and Trelin [6], obtained with high accuracy (less than 0.25% error).

The electrical analog of the pulse taken is delivered from the detector—transducer 1 to the input of the oscilloscope operating in the single trigger mode. The oscilloscope sweep is triggered by a pulse from the generator G5-4B that assures a fixed pulse delay. The generator itself is triggered by an amplified signal from the piezoceramic 4 glued near the emitter 3 at the time of sound pulse emission.

The emitter is a circular, 3-mm-thick steel plate clamped stiffly at the edges. Oscillations are excited in the plate by a steel hammer that slides in a bronze bearing. To achieve identity of the pulses being emitted, the rubbing surfaces of the hammer and bearing surfaces were carefully polished.

The problem of obtaining identical acoustic pulses with a sufficiently broad frequency band in the audio range where the zone of developed dispersion for drop diameters greater than 5 μm is solved in selecting the emitter type and construction. The emitter thickness was selected by tending to diminish the influence of a change in the state of the medium in the chamber on the natural frequencies. Moreover, the coincidence frequency for the chosen emitting plate thickness is below the natural frequency band, whereupon the plate oscillations attenuate rapidly [5], i.e., the pulse is of comparatively moderate duration (around 500 μsec). This permits raising the accuracy of the oscillograms by applying a sweep of moderate duration.

A TsTS-19 piezoceramic was the sound pulse detector. The practical identity of the detector frequency characteristics in the standard and investigated media is assured by the nonresonant operation mode.

To exclude phase distortion because of nonplanar wave propagation, the measuring volume is separated from the remaining space in the chamber by a thin-walled Duralumin waveguide 2 of 20-mm diameter. As is known [7], only plane waves are propagated in the guide under the condition

$$d < 1.22\lambda. \qquad (11)$$

Condition (11) was satisfied in our experiments for frequencies up to 13 kHz.

Primary processing of the oscillograms of the pulses received was performed on the instrument microscope BMI-1. Around 150 pulse ordinates were determined per oscillogram, where the measurement of each ordinate was repeated five times. All the subsequent processing, including the evaluation of the spectral densities and phase spectra of the Fourier integral transform and the determination of the frequency dependence of the sound speed in the long run was performed by using an electronic computer.

A feature of this method is the possibility of obtaining a large volume of information in a comparatively short time: the frequency dependence of the speed of sound is determined in a broad frequency range as a result of processing just one experiment.

A method [8] based on the occurrence of a supercooled vapor condensation shock in the space of the measuring chamber was used to obtain the moist vapor. Supercooling of the vapor in the chamber was achieved by expansion during escape into the water-cooled condenser. The condensation shock occurred approximately a second after the beginning of the expansion and was determined by the characteristic breakpoint in the record of the vapor temperature, as well as visually through the inspection window of the chamber.

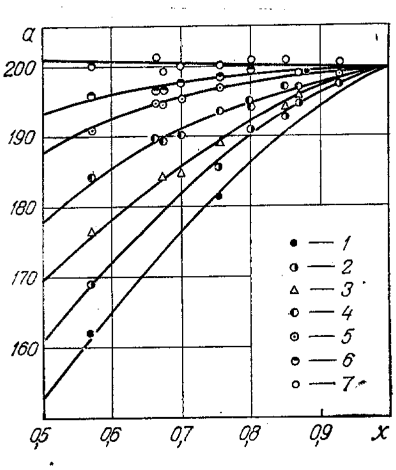

Fig. 3. Speed of sound, m/sec, in moist carbon dioxide vapor at $T = 290°K$; 1) $\varkappa = 8 \cdot 10^{-7}$ m^2/sec; 2) $1.1 \cdot 10^{-6}$; 3) $1.5 \cdot 10^{-6}$; 4) $2 \cdot 10^{-6}$; 5) $3 \cdot 10^{-6}$; 6) $4 \cdot 10^{-6}$; 7) $\varkappa = 10^{-5}$ m^2/sec; curves according to the theory in [10-12].

The pressure drop between the chamber and the condenser diminished considerably up to the time of moist vapor formation, and the flux velocity of the moist vapor in the measuring space became negligible, less than 1 mm/sec as a rule. The rate of change of the moist vapor temperature after the condensation shock is also quite small, less than 0.1 °K/sec. Consequently, and because of the large interphasal surface, the expansion of the moist vapor occurs practically in equilibrium. The equilibrium is confirmed by the results of measuring the temperature and pressure of the moist vapor, which correspond to the phase equilibrium curve within the limits of measurement error (0.06°K and 0.03 MPa).

The degree of dryness in the equilibrium states is easily computed if the density and temperature of the moist vapor are known. To determine the density of the moist vapor at the time it is being probed by the acoustic pulses, we used a method [8] based on the regularities of escape from an unfilled space.

The dispersion of the moist vapor obtained depends on the supercooling being achieved, i.e., on the initial escape velocity. This latter can be varied by changing the initial parameters of the vapor and the temperature of the cooling water in the condenser.

The distribution function of the drop diameter was determined by using microphotography and subsequent statistical processing of the photographs on the instrument microscope BMI-1. The integrated drop distribution function is presented in Fig. 2 in a normal probability scale (results of processing the microphotograph obtained in one of the experiments). The good approximation of the experimental points by a straight line indicates that the distribution was almost normal. An analogous form of the distribution function was observed in all the experiments, where as is seen from Fig. 2, the spectra of the drop diameters were comparatively narrow ($\sigma/D_b \approx 0.1$-0.2).

The effective drop diameter [9] was determined from the experimental distribution function

$$D_e = \left[\int_0^\infty f(D) D^3 dD \Big/ \int_0^\infty f(D) D dD\right]^{1/2}, \tag{12}$$

$$f(D) = dv/dD, \tag{13}$$

from which we obtain

$$D_e = \left[\int_0^\infty D^3 dv \Big/ \int_0^\infty D dv\right]^{1/2}. \tag{14}$$

The effective diameter is one of the reference parameters of the results of measuring the speed of sound since, as is shown in [9], it uniquely characterizes the influence of dispersion on the acoustic properties of a two-phase medium.

Measurements were performed in moist carbon dioxide vapor (with not more than a 0.2% nitrogen impurity) in the ranges of pressure 43-70 bar, the degree of dryness 0.55-1.0, frequency 1.5-13 kHz, and effective drop diameter 6-50 μm. About 5000 experimental points were obtained for a sufficiently detailed description of the dependence of the speed of sound on the listed parameters. Part of the data obtained is presented in Table 1. The maximum probable error with the errors in measuring all the reference parameters taken into account is 1%, with the exception of the frequency range below 2 kHz, where the error can reach 1.5-2%.

Experimental and theoretical results from relaxation theory [10-12] at $T = 290°K$ are compared in Fig. 3. The points denote results obtained in different experiments at temperatures that differed from 290°K by not more than 0.2-0.3°K. The deviation of the experimental points from the theoretical curves does not exceed 1%. Analogous results are also obtained for other temperatures in the range investigated.

NOTATION

a, speed of sound in the moist vapor; a_0, speed of sound in the standard medium; d, diameter of the waveguide; D, diameter of the drops; D_b, most probable drop diameter; D_e^2, effective drop diameter; f(D), probability density of the drop-diameter distribution; f_j, frequency of the j-th harmonic component of the pulse; l, spacing between emitter and detector; t, time; Δt, difference between the delayed times in the investigated and standard media; T, temperature; x, degree of dryness; $\varkappa = \omega D_e^2$, frequency-dispersion parameter; λ, wavelength; ν, relative integral number of drops; σ, standard deviation; φ, phase; and ω, circular frequency.

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