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Speed-of-Sound Measurements in Liquid and Gaseous Air

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The speed of sound in air has been measured along isotherms for a "standard air" mixture ($0.7811\ N_2 + 0.2097\ O_2 + 0.0092\ Ar$) in the gas and liquid phases at pressures to 14 MPa. A cylindrical resonator was used in the vapor and supercritical gas phases, and a time-of-flight system was used for measurements of the liquid phase. Data were obtained for the liquid phase at 90, 100, 110, 120, and 130 K. Data were taken at 110, 120, 130, 135, 140, 150, 200, and 300 K in the vapor and supercritical gas phases. These experimental results were compared to a predictive computer model, namely, AIRPROPS.

KEY WORDS: air; cylindrical resonator; isotherms; liquified air; sound velocity; time-of-flight technique.

1. INTRODUCTION

The speed-of-sound measurements reported here are part of a comprehensive program to reduce the uncertainty in the thermophysical properties of air, especially at low temperatures. This research effort also includes experimental measurements of the heat capacity, pressure–volume–temperature (*PVT*), vapor–liquid equilibria, thermal conductivity, and viscosity. These speed-of-sound data have been used to improve the predictive model AIRPROPS [1–4]. This model is an equation of state developed jointly at the University of Idaho and the National Institute of Standards and Technology (NIST). The measurements reported here are compared to AIRPROPS 4.0 [1].

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2. EXPERIMENTAL

The measurements were taken with two separate experimental systems. Data were taken on isotherms at pressures to 14 MPa. The gas and supercritical data were taken with a cylindrical resonator previously used in measurements of natural gas [5]. The liquid-phase data were taken with a pulse-echo, or time-of-flight technique [6]. It was necessary to use this system for the liquid, because the resonant system does not operate efficiently in this region. The pulse technique works better in the liquid, because its transducers are a better match to the higher mechanical impedance of the liquid.

The low-density data were measured with a cylindrical resonant cavity operating at frequencies between 10 and 70 kHz. Longitudinal resonances were measured and the frequencies corrected for effects arising from viscous losses at the walls and for thermal-conduction losses at the walls and end surfaces. Temperatures were measured with a low-temperature capsule-type platinum resistance thermometer calibrated on the IPTS-1968 temperature scale. The total uncertainty in temperature is approximately 0.02 K at 100 K and 0.03 K at 300 K. Pressures were measured with a high-quality quartz-spiral bourdon gauge. The uncertainty in pressure is estimated to be 0.001 MPa.

Measurements at higher density were made with the pulse-echo technique, where the time taken for a round trip of the sound pulse is determined by the pulse repetition frequency necessary to produce constructive interference of the leading edge of the received signal. At the frequency of the quartz crystals, 10 MHz, the corrections due to viscous and thermal losses at the walls were negligible. The speed of sound is computed from the path length of the sound cell and the pulse repetition frequency, which is in the kilohertz range. The two quartz crystals are mounted on the ends of a cylinder made of a high-nickel steel. The ends of the cylinder were ground and polished to optical tolerances.

In the liquid-phase measurements the pressures were measured with an oil dead-weight gauge. The temperature was measured with a low-temperature capsule-type platinum resistance thermometer. We prepared our aim samples gravimetrically. The estimated uncertainty in the speed-of-sound measurements is less than 0.05% for both the liquid and the gas.

3. RESULTS

The experimental data for the vapor and supercritical gas are shown in Table I and graphically in Fig. 1. Table II and Fig. 2 show the data for

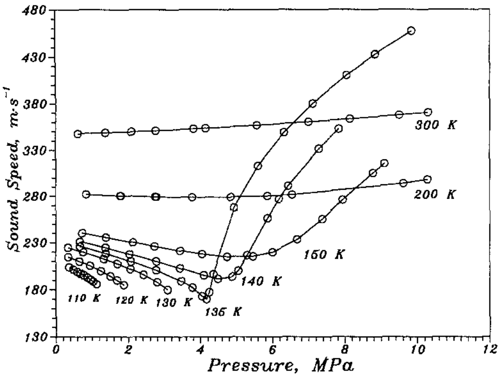

Fig. 1. Experimental speed-of-sound data along isotherms for the vapor and supercritical phases of air.

Table I. Experimental Speed of Sound for Gaseous Air with Comparisons to Values Computed from AIRPROPS 4.0 (Densities Are Also Computed from AIRPROPS 4.0)

Pressure (MPa)	Temperature (K)	Density (mol·L^{-1})	Speed of Sound (m·s^{-1})	$(W_{\text{exp}} - W_{\text{calc}})/W_{\text{exp}}$ (%)
0.357	110.00	0.414	203.88	0.14
0.476	110.00	0.565	201.54	0.22
0.584	110.00	0.708	199.24	0.22
0.677	110.00	0.837	197.23	0.27
0.770	110.00	0.972	195.13	0.32
0.870	110.00	1.125	192.77	0.35
0.956	110.00	1.264	190.57	0.30
1.028	110.00	1.386	188.60	0.27
1.124	110.00	1.559	185.87	0.25
0.345	120.00	0.361	214.68	−0.01
0.645	120.00	0.704	210.07	0.03
0.934	120.00	1.080	205.28	0.19
1.233	120.00	1.489	199.81	0.11
1.500	120.00	1.919	194.38	0.14
1.684	120.00	2.256	190.14	0.07
1.873	120.00	2.654	185.19	−0.06
0.338	130.00	0.323	224.79	0.00
0.759	130.00	0.759	219.78	−0.01
1.325	130.00	1.423	212.58	0.04

Table I. *(Continued)*

Pressure (MPa)	Temperature (K)	Density ($\mathrm{mol \cdot L^{-1}}$)	Speed of Sound ($\mathrm{m \cdot s^{-1}}$)	$(W_{\mathrm{exp}} - W_{\mathrm{calc}})/W_{\mathrm{exp}}$ (%)
1.690	130.00	1.915	207.50	0.10
2.047	130.00	2.466	202.02	0.06
2.415	130.00	3.142	195.80	0.10
2.795	130.00	4.037	188.13	−0.09
3.088	130.00	5.010	180.05	−0.69
0.667	135.00	0.631	226.15	−0.02
1.380	135.00	1.408	218.32	0.01
2.071	135.00	2.313	210.05	0.07
2.763	135.00	3.476	200.74	0.07
3.461	135.00	5.224	189.28	−0.22
3.774	135.00	6.522	182.35	−0.80
4.041	135.00	8.695	173.36	−2.16
4.169	135.00	10.787	170.23	−2.57
4.244	135.00	12.137	177.66	0.32
4.353	135.00	13.722	196.68	1.62
4.938	135.00	16.601	267.86	0.55
5.591	135.00	17.869	313.20	0.77
6.319	135.00	18.760	349.28	0.71
7.111	135.00	19.462	380.42	0.56
8.053	135.00	20.107	410.78	0.34
8.843	135.00	20.551	432.88	0.23
8.853	135.00	20.556	433.30	0.25
9.842	135.00	21.029	457.58	0.10
10.049	135.00	21.119	462.66	0.16
10.031	135.00	21.111	462.33	0.18
10.017	135.00	21.105	462.03	0.18
9.437	135.00	20.845	448.39	0.24
8.631	135.00	20.439	427.60	0.35
7.348	135.00	19.640	388.70	0.54
6.182	135.00	18.615	342.99	0.67
5.278	135.00	17.349	292.93	0.42
5.278	135.00	17.349	292.89	0.41
0.660	140.00	0.598	231.23	−0.03
1.369	140.00	1.323	224.59	0.04
2.036	140.00	2.114	217.86	0.03
2.773	140.00	3.174	210.11	0.05
3.422	140.00	4.379	202.94	0.02
4.083	140.00	6.129	195.47	−0.17
4.086	140.00	6.139	195.41	−0.20
4.479	140.00	7.739	191.90	−0.36
4.878	140.00	10.190	194.10	−0.21
5.042	140.00	11.338	200.18	0.54
5.303	140.00	13.001	216.61	1.11

Table I. *(Continued)*

Pressure (MPa)	Temperature (K)	Density ($mol \cdot L^{-1}$)	Speed of Sound ($m \cdot s^{-1}$)	$(W_{exp} - W_{calc})/W_{exp}$ (%)
5.854	140.00	15.168	256.37	0.50
5.859	140.00	15.182	256.72	0.48
6.181	140.00	15.964	277.12	0.58
6.433	140.00	16.454	291.33	0.66
7.290	140.00	17.679	331.84	0.74
7.834	140.00	18.249	353.09	0.68
0.724	150.00	0.608	240.39	−0.05
1.382	150.00	1.216	235.62	−0.03
2.128	150.00	1.985	230.39	0.04
2.725	150.00	2.681	226.12	0.01
3.439	150.00	3.638	221.36	0.03
4.047	150.00	4.596	217.87	0.08
4.742	150.00	5.918	215.09	0.04
5.461	150.00	7.629	215.37	0.08
6.003	150.00	9.168	219.84	0.06
6.681	150.00	11.183	233.53	0.14
7.371	150.00	12.986	255.50	0.20
7.946	150.00	14.169	276.19	0.07
8.773	150.00	15.460	305.37	0.19
9.087	150.00	15.860	315.76	0.24
0.840	200.00	0.515	281.92	−0.03
1.778	200.00	1.115	280.52	−0.03
1.802	200.00	1.131	280.48	−0.01
2.747	200.00	1.763	279.44	−0.02
2.786	200.00	1.789	279.44	−0.02
3.776	200.00	2.482	278.95	−0.05
4.843	200.00	3.263	279.26	−0.01
5.861	200.00	4.039	280.44	0.01
6.545	200.00	4.576	281.75	0.02
9.614	200.00	7.076	294.03	0.04
10.277	200.00	7.619	298.28	0.06
0.614	300.00	0.247	347.94	−0.02
1.369	300.00	0.551	348.99	0.00
2.086	300.00	0.841	350.08	0.02
2.761	300.00	1.114	351.22	0.01
3.808	300.00	1.539	353.16	0.02
4.146	300.00	1.676	353.86	0.02
5.563	300.00	2.252	356.99	0.00
6.994	300.00	2.831	360.63	0.01
8.138	300.00	3.292	363.83	0.01
9.498	300.00	3.837	368.08	0.05
10.292	300.00	4.152	370.76	0.07

Table II. Experimental Speed of Sound for Liquid Air with Comparisons to Values Computed from AIRPROPS 4.0 (Densities Are Also Computed from AIRPROPS 4.0)

Pressure (MPa)	Temperature (K)	Density ($\mathrm{mol \cdot L^{-1}}$)	Speed of Sound ($\mathrm{m \cdot s^{-1}}$)	$(W_{\mathrm{exp}} - W_{\mathrm{calc}})/W_{\mathrm{exp}}$ (%)
13.823	90.00	29.693	874.16	0.05
12.993	90.00	29.624	868.42	0.07
12.979	90.00	29.622	868.32	0.07
11.187	90.00	29.469	854.92	0.05
10.594	90.00	29.417	850.45	0.05
10.581	90.00	29.416	850.35	0.05
8.465	90.00	29.224	833.64	0.05
8.395	90.00	29.217	833.08	0.05
6.527	90.00	29.038	817.44	0.07
5.729	90.00	28.959	810.59	0.10
4.379	90.00	28.820	798.56	0.15
4.364	90.00	28.818	798.40	0.15
4.360	90.00	28.818	798.40	0.15
2.276	90.00	28.592	778.70	0.28
2.280	90.00	28.592	778.65	0.26
0.757	90.00	28.416	763.16	0.39
0.763	90.00	28.417	763.17	0.38
13.065	100.00	28.180	790.53	−0.24
12.425	100.00	28.112	785.10	−0.23
11.423	100.00	28.002	776.27	−0.22
9.785	100.00	27.815	760.73	−0.26
8.767	100.00	27.693	750.85	−0.25
7.273	100.00	27.506	735.44	−0.25
6.705	100.00	27.432	729.40	−0.23
5.040	100.00	27.205	710.71	−0.20
4.699	100.00	27.156	706.55	−0.21
3.190	100.00	26.931	688.01	−0.11
2.810	100.00	26.872	683.19	−0.07
1.268	100.00	26.618	662.21	0.08
1.115	100.00	26.591	659.88	0.09
0.830	100.00	26.541	655.71	0.12
0.769	100.00	26.530	654.90	0.14
13.592	110.00	26.714	718.28	−0.28
12.658	110.00	26.586	708.39	−0.31
12.649	110.00	26.585	708.28	−0.31
9.986	110.00	26.189	678.09	−0.36
8.312	110.00	25.914	657.09	−0.35
5.945	110.00	25.477	624.08	−0.26
4.289	110.00	25.128	598.05	−0.09
1.861	110.00	24.519	551.89	0.25
1.698	110.00	24.473	548.41	0.29

Table II. *(Continued)*

Pressure (MPa)	Temperature (K)	Density ($\text{mol} \cdot \text{L}^{-1}$)	Speed of Sound ($\text{m} \cdot \text{s}^{-1}$)	$(W_{\text{exp}} - W_{\text{calc}})/W_{\text{exp}}$ (%)
1.382	110.00	24.380	541.35	0.36
13.652	120.00	25.091	642.50	−0.26
12.864	120.00	24.947	632.54	−0.26
11.863	120.00	24.755	618.96	−0.30
9.942	120.00	24.350	591.30	−0.24
8.932	120.00	24.114	575.33	−0.19
7.904	120.00	23.854	557.66	−0.13
7.856	120.00	23.841	556.88	−0.11
7.627	120.00	23.779	552.66	−0.12
6.663	120.00	23.504	534.12	−0.05
5.173	120.00	23.015	501.64	0.15
3.893	120.00	22.505	468.45	0.44
2.413	120.00	21.729	418.85	0.99
13.416	130.00	23.262	564.19	−0.16
13.392	130.00	23.256	563.81	−0.16
11.347	130.00	22.702	530.09	−0.12
11.341	130.00	22.700	529.97	−0.12
9.185	130.00	21.985	487.88	0.04
9.177	130.00	21.982	487.69	0.04
7.270	130.00	21.158	441.24	0.28
7.267	130.00	21.156	441.18	0.29
5.847	130.00	20.317	396.49	0.60
5.845	130.00	20.315	396.40	0.61
5.748	130.00	20.246	392.70	0.59

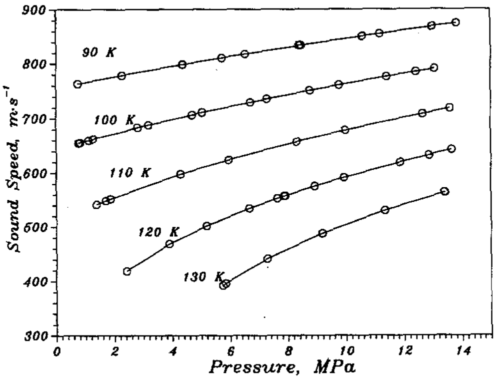

Fig. 2. Experimental speed-of-sound data along isotherms for liquid air.

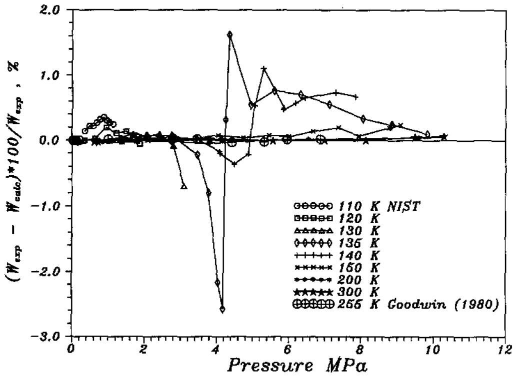

Fig. 3. Deviations of experimental speed-of-sound data from AIRPROPS 4.0 for the vapor and supercritical phases of air.

the liquid phase. Values of speed of sound were computed from AIRPROPS 4.0 [1]. The last column in the tables is the difference between the measured values and the computed values and is expressed as a percentage. The third column is the density computed from AIRPROPS 4.0.

The computed speed of sound agrees with the measured values within about ±0.1 % for the liquid phase. This agreement is also observed for the gas phase except for the 135, 140, and 150 K isotherms. The 135 K isotherm is closest to the critical temperature, and the nearness to the critical point explains the large departures at pressures near 5 MPa for

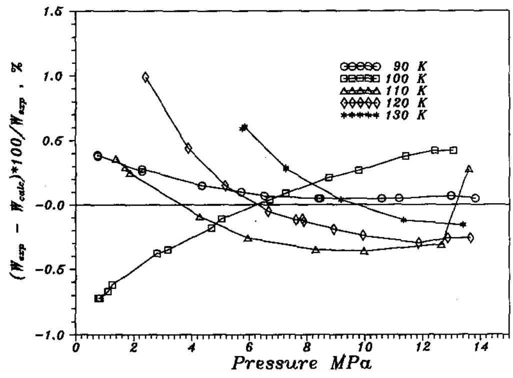

Fig. 4. Deviations of experimental speed-of-sound data from AIRPROPS 4.0 for liquid air.

the 135 K isotherm. The estimated uncertainty of the measured speed of sound is ±0.05% for all data except for the 135 K isotherm, where the uncertainty is larger due to the proximity of the critical point.

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