3d. Acoustic Properties of Gases

LEO L. BERANEK

Bolt Beranek and Newman Inc.

A number of the physical properties of a gas are important in determining its acoustic characteristics. These include density, pressure, temperature, specific heats, and coefficients of viscosity. These properties, and others, are presented and discussed below.

3d-1. Density. The density ρ_0 of a number of common gases at standard temperature and pressure is given in Table 3d-1. The density at any temperature and pressure can be obtained from the expression

$$\rho = \rho_0 \frac{P}{760} \frac{273.16}{T}$$

where P is the barometric pressure in millimeters of mercury, and T is the absolute temperature in kelvins.

3d-2. Atmospheric Pressure and Temperature. The atmospheric pressure and air temperatures, and consequently the air density, vary with elevation above the surface of the earth. Table 3d-2 gives the air pressure, temperature, density, and mean molecular weight as a function of altitude. This is the U.S. standard atmos-

TABLE 3d-1. DENSITY OF GASES ρ_0 AT 0°C, 1 ATM*

Gas	Formula	ρ_0, kg/m^3	ρ_0, lb/ft^3
Acetylene	C_2H_2	1.173	0.0732
Air	.....	1.2929	0.08072
Ammonia	NH_3	0.7710	0.0481
Argon	A	1.7837	0.1114
Carbon dioxide	CO_2	1.977	0.1234
Carbon monoxide	CO	1.250	0.0780
Chlorine	Cl_2	3.214	0.2006
Ethane (10°C)	C_2H_6	1.356	0.0846
Ethylene	C_2H_4	1.260	0.0786
Helium	He	0.1785	0.01114
Hydrogen	H_2	0.0899	0.00561
Hydrogen sulfide	H_2S	1.539	0.0961
Methane	CH_4	0.7168	0.0447
Neon	Ne	0.9003	0.0562
Nitric oxide (10°C)	NO	1.340	0.0836
Nitrogen	N_2	1.2506	0.0781
Nitrous oxide	N_2O	1.977	0.1234
Oxygen	O_2	1.429	0.0892
Propane	C_3H_8	2.009	0.1254
Sulfur dioxide	SO_2	2.927	0.1827
Steam (100°C)	H_2O	0.598	0.0373

* "Handbook of Chemistry and Physics," 48th ed.

phere used for the calibration of aeronautical instruments. The actual atmosphere differs from summer to winter.[1]

At 288.16 K (15.0°C) and at standard gravity of 9.80665 m/sec^2 a 0.760-m column of mercury exerts a pressure of 1.01325×10^5 newtons/m^2. This is the standard ICAO atmosphere. Other ICAO values are: density 1.225014 kg/m^3, kinematic viscosity 1.4607413×10^{-5} m^2/sec, mean free path 6.6317223×10^{-8} m, molecular weight 28.966 (dimensionless), sound speed 340.29205 m/sec, specific weight 12.013284 kg/(m^2-sec^2), coefficient of viscosity 1.7894285×10^{-5} kg/(m-sec).

3d-3. Specific Heat. For several common gases the values of C_p, the specific heat at constant pressure, and γ, the ratio of C_p to C_v, are given in Table 3d-3. C_v is the specific heat at constant volume. C_p is expressed in calories per g-°C.

3d-4. Viscosity. The coefficient of viscosity η of a number of gases is given in Table 3d-4. The units of η are dyne-seconds per square centimeter, or poises. For example, the coefficient of viscosity for air at 0°C is 1.708×10^{-4} poises (dyne-sec/cm^2).

The ratio η/ρ of viscosity to density occurs frequently and is known as the *kinematic viscosity coefficient*. It is usually designated by the letter ν and has the dimensions square centimeters per second in the cgs system.

For a plane acoustic wave propagating in an unbounded gas a small attenuation will occur because of viscosity. The attenuation factor is $e^{-\alpha_\eta x}$ for the pressure (or particle velocity), where

$$\alpha_\eta = \frac{2}{3}\frac{\eta}{\rho}\frac{\omega^2}{c^3} = \frac{2}{3}\nu\frac{\omega^2}{c^3} \qquad \text{nepers}$$

where c is the speed of sound, and ω the angular frequency of the wave.

---

[1] L. L. Beranek, "Acoustic Measurements," p. 42, John Wiley & Sons, Inc., New York, 1949.

Table 3d-2. U.S. Standard Atmosphere, 1962*

Altitude, km	Temp. T, K	Pressure P, newtons/m^2	Density ρ, kg/m^3	Molecular weight M
−5	320.676	1.77762 +5	1.9311 +0	28.964
−4	314.166	1.59598	1.7697	28.964
−3	307.659	1.42973	1.6189	28.964
−2	301.154	1.27783	1.4782	28.964
−1	294.651	1.13931	1.3470	28.964
0	288.150	1.01325	1.2250	28.964
0.5	284.900	9.54612 +4	1.1673	28.964
1.0	281.651	8.98762	1.1117	28.964
1.5	278.402	8.45596	1.0581	28.964
2	275.154	7.95014	1.0066	28.964
2.5	271.906	7.46017	9.5695 −1	28.964
3	268.659	7.01211	9.0925	28.964
4	262.166	6.16604	8.1935	28.964
5	255.676	5.40482	7.3643	28.964
6	249.187	4.72176	6.6011	28.964
7	242.700	4.11052	5.9002	28.964
8	236.215	3.56516	5.2579	28.964
9	229.733	3.08007	4.6706	28.964
10	223.252	2.64999	4.1351	28.964
15	216.650	1.21118	1.9475	28.964
20	216.650	5.52930 +3	8.8910 −2	28.964
25	221.552	2.54922	4.0084	28.964
30	226.509	1.19703	1.8410	28.964
40	250.350	2.87143 +2	3.9957 −3	28.964
50	270.650	7.97790 +1	1.0269	28.964
60	255.772	2.24606	3.0592 −4	28.964
70	219.700	5.52047 +0	8.7535 −5	28.964
80	180.65	1.0366	1.999	28.964
100	210.02	3.0075 −2	4.974 −7	28.964
150	892.79	5.0617 −4	1.836 −9	28.964
200	1235.95	1.3339	3.318 −10	28.964
250	1357.28	4.6706 −5	9.978 −11	28.964
300	1432.11	1.8838	3.585	28.961
400	1487.38	4.0304 −6	6.498 −12	27.97
500	1499.22	1.0957	1.577	26.86
600	1506.13	3.4502 −7	4.640 −13	26.06
700	1507.61	1.1918	1.537 −13	25.17

* See also Sec. 2k, and Tables 2k-4, and 3d-9. Data taken from "U.S. Standard Atmosphere, 1962," published by the U.S. Committee on Extension to the Standard Atmosphere (COESA), Washington, D.C., 1962.

Note. A one- or two-digit number (preceded by a plus or minus sign) following the initial entry indicates the power of 10 by which that entry and each succeeding entry of that column should be multiplied.

3d-5. Thermal Conductivity. The thermal conductivity κ of a number of gases is given in Table 3d-5. The units of κ are calories per centimeter-second-degree.

The quantity $\kappa/\rho C_v$ frequently appears in heat-conduction equations. It is often designated by the symbol α and is called the *thermal diffusivity.* In the cgs system the units of α are square centimeters per second. For air α = 0.27 cm^2/sec at 18°C and 760 mm of mercury.

TABLE 3d-3. SPECIFIC HEAT AT CONSTANT PRESSURE C_p AND THE RATIO γ OF C_p TO THE SPECIFIC HEAT AT CONSTANT VOLUME C_v*

[C_p (cal/g-deg); $\gamma = C_p/C_v$]

Gas	Temp., °C (atm)	C_p	Temp., °C (atm)	γ
Air	−120 (10)	0.2719	−118 (1)	1.415
	(20)	0.3221		
	(40)	0.4791		
	(70)	0.7771	− 78 (1)	1.408
	− 50 (10)	0.2440		
	(20)	0.2521		
	(40)	0.2741		
	(70)	0.3121		
	0 (1)	0.2398	0 (1)	1.403
	(20)	0.2484		
	(60)	0.2652	17 (1)	1.403
	50 (20)	0.2480		
	(100)	0.2719		
	(220)	0.2961		
	100 (1)	0.2404	100 (1)	1.401
	(20)	0.2471		
	(100)	0.2600	200 (1)	1.398
	(220)	0.2841		
	400 (1)	0.2430	400 (1)	1.393
	1000 (1)	0.2570	1000 (1)	1.365
	1400 (1)	0.2699	1400 (1)	1.341
	1800 (1)	0.2850	1800 (1)	1.316
Ammonia, NH_3	15 (1)	0.5232	15 (1)	1.310
Argon, Ar	15 (1)	0.1253	15 (1)	1.668
Carbon dioxide, CO_2	15 (1)	0.1989	15 (1)	1.304
Carbon monoxide, CO	15 (1)	0.2478	15 (1)	1.404
Chlorine, Cl_2	15 (1)	0.1149	15 (1)	1.355
Ethane, C_2H_6	15 (1)	0.3861	15 (1)	1.22
Ethylene, C_2H_4	15 (1)	0.3592	15 (1)	1.255
Helium, He	−180 (1)	1.25	−180 (1)	1.660
Hydrogen, H_2	15 (1)	3.389	15 (1)	1.410
Hydrogen sulfide, H_2S	15 (1)	0.2533	15 (1)	1.32
Methane, CH_4	15 (1)	0.5284	15 (1)	1.31
Neon, Ne	25 (1)	0.246	19 (1)	1.64
Nitric oxide, NO	15 (1)	0.2329	15 (1)	1.400
Nitrogen, N_2	15 (1)	0.2477	15 (1)	1.404
Nitrous oxide, N_2O	15 (1)	0.2004	15 (1)	1.303
Oxygen, O_2	15 (1)	0.2178	15 (1)	1.401
Propane, C_3H_8	....	......	16 (0.5)	1.13
Steam, H_2O	100 (1)	0.4820	100 (1)	1.324
Sulfur dioxide, SO_2	15 (1)	0.1516	15 (1)	1.29

---

* "Handbook of Chemistry and Physics," 41st ed.

A plane acoustic wave propagating in an unbounded gas will be attenuated slightly because of thermal conduction effects. The attenuation constant α_T is

$$\alpha_T = \frac{\kappa(\gamma - 1)\omega^2}{2\gamma\rho C_v c^3} \quad \text{nepers}$$

where $\kappa/\rho C_v$ is the thermal diffusivity, γ the ratio of specific heats, c the propagation speed, and ω the angular frequency of the wave.

Table 3d-4. Coefficient of Viscosity η for Different Gases as a Function of Temperature*

Gas	Formula	Temp., °C	Viscosity, micropoises (cgs)
Air	....	−104.0	113.0
		0	170.8
		18	182.7
		40	190.4
		54	195.8
		74	210.2
		229	263.8
		357	317.5
		409	341.3
		620	391.6
		810	441.9
		1034	490.6
Argon	Ar	0	209.6
		20	221.7
		100	269.5
		401	411.5
Carbon dioxide	CO_2	−60.0	106.1
		0	139.0
		20	148.0
		40	157.0
		104	188.9
		302	268.2
Carbon monoxide	CO	−191.5	56.1
		0	166
		15	172
		126.7	218.3
		276.9	271.4
Helium	He	−191.6	87.1
		0	186.0
		20	194.1
		100	228.1
		407	343.6
Hydrogen	H	−198.4	33.6
		0	83.5
		20.7	87.6
		129.4	108.6
		412	155.4
Neon	Ne	0	297.3
		20	311.1
		100	364.6
		429	545.4
Nitric oxide	NO	0	178
		20	187.6
		200	268.2
Nitrogen	N	−21.5	156.3
		10.9	170.7
		27.4	178.1
		490	337.4
Nitrous oxide	N_2O	0	135
		26.9	148.8
		126.9	194.3
Oxygen	O_2	0	189
		19.1	201.8
		127.7	256.8
		227.0	301.7
		402	369.3

* "Handbook of Chemistry and Physics," 48th ed.

TABLE 3d-5. THERMAL CONDUCTIVITY κ OF GASES AT 0°C*

Gas	Formula	Thermal conductivity κ at 0°C, cal/cm-sec-deg
Air	....	0.0576×10^{-3}
Argon	A	0.039×10^{-3}
Carbon dioxide	CO_2	0.034×10^{-3}
Carbon monoxide	CO	0.053×10^{-3}
Helium	He	0.343×10^{-3}
Hydrogen	H_2	0.419×10^{-3}
Neon	Ne	0.110×10^{-3}
Nitric oxide	NO	0.046×10^{-3}
Nitrogen	N	0.057×10^{-3}
Nitrous oxide	N_2O	0.036×10^{-3}
Oxygen	O_2	0.058×10^{-3}
Steam (100°C)	H_2O	0.055×10^{-3}

* Condon and Odishaw, "Handbook of Physics," p. 5-66, McGraw-Hill Book Co., New York, 1958.

3d-6. Speed (Velocity) of Propagation. The speed of sound for small sound amplitudes can be written exactly as[1]

$$c = \left[\frac{RT}{M}\left(f + \frac{gR}{hC_v^{\infty}}\right)\right]^{\frac{1}{2}}$$

where

$$f = -\frac{V^2}{RT}\left(\frac{\partial p}{\partial V}\right)_T$$

$$g = \left(\frac{V}{R}\frac{\partial p}{\partial T}\right)_v^2$$

$$h = \frac{C_v}{C_v^{\infty}} = 1 + \frac{T}{C_v^{\infty}}\int_V^{\infty}\left(\frac{\partial^2 p}{\partial T^2}\right)_v dV$$

C_v^{∞} is the specific heat for constant volume as the volume approaches infinity; M, the molecular weight of the gas, has been substituted for ρV; and R, the gas constant, puts the equation in a useful form. The quantities f, g, h are dimensionless and differ only slightly from unity as determined by the imperfection of the gas.

Thus, if the molecular weight, the specific heat, and the equation of state are known, the speed of sound under any conditions can be calculated.

For an ideal gas, where $PV = RT$ one can write

$$c = \left(\frac{RT\gamma}{M}\right)^{\frac{1}{2}} = \left(\frac{\gamma p}{\rho}\right)^{\frac{1}{2}}$$

where $\gamma = C_p/C_v$, and p is the ambient pressure.

The accepted value of c_0, the speed at standard conditions of temperature and pressure, for a number of gases is given in Table 3d-6.

The accepted value of the speed of sound in air, c, as calculated and checked on the average by several reported determinations, is[1]

$$c_0 = 331.45 \pm 0.05 \text{ m/sec}$$
$$c_0 = 1{,}087.42 \pm 0.16 \text{ fps}$$

---

[1] See Hardy, Telfair, and Pielemeier, *J. Acoust. Soc. Am.* **13**, 226 (1942).

TABLE 3d-6. SPEED (VELOCITY) OF SOUND IN GASES*

Gas	Formula	Speed, m/sec at 0°C	Speed, fps at 0°C
Air (dry)	.....	331.45	1,087.42
Ammonia	NH_3	415	1,362
Argon	A	319	1,047
Carbon dioxide	CO_2	259	850
Carbon monoxide	CO	338	1,189
Carbon disulfide	CS_2	189	606
Chlorine	Cl_2	206	676
Ethylene	C_2H_4	317	1,040
Helium	He	965	3,166
Hydrogen	H_2	1,284	4,213
Illuminating gas (coal)	.....	453	1,486
Methane	CH_4	430	1,411
Neon	Ne	435	1,427
Nitric oxide (10°C)	NO	324	1,063
Nitrogen	N_2	334	1,096
Nitrous oxide	N_2O	263	863
Oxygen	O_2	316	1,037
Steam (134°C)	H_2O	494	1,621
Sulfur dioxide	SO_2	213	699

* "Handbook of Chemistry and Physics," 48th ed.

under the conditions (1) audible frequency range, (2) temperature at 0°C, (3) 1 atm pressure, (4) 0.03 percent mole content of CO_2, (5) 0 percent water content. To calculate the speed of sound at various temperatures one can write

$$\begin{aligned} c &= \frac{R\gamma}{M}\left(273.16\right)^{\frac{1}{2}}\sqrt{\frac{T}{273.16}} \\ &= 331.45\sqrt{\frac{T}{273.16}} \quad \text{m/sec} \\ &= 331.45\sqrt{1+\frac{T°\text{C}}{273.16}} \doteq 331.45 + 0.6\,(T°\text{C})\ \text{m/sec}\left(\frac{T°C}{273} \ll 1\right) \end{aligned}$$

where T is the absolute temperature, and T°C is the temperature in degrees centigrade. If the gas is made up of a mixture of gases or if water vapor is present, the expression

$$c = \left[\frac{RT}{M}\left(1+\frac{R}{C_v}\right)\right]^{\frac{1}{2}}$$

can be used to calculate the velocity. The molecular weight M of the mixture can be calculated, or realizing that $RT/M = p/\rho$, the density of the mixture can be used.

In addition to correcting M (or ρ), it is necessary to correct C_v also. It is incorrect to take the weighted average of the ratios of the specific heats, γ. The weighted average of the specific heats themselves must be used.

For rough calculations of the variation with humidity or composition, a first approximation can be obtained by correcting for the density of the mixture.

Recent studies in molecular acoustics have yielded new values for the speed of sound at a wide range of temperatures, pressures, and frequencies. Some results are shown in Tables 3d-7 and 3d-8. Speeds of sound in helium and argon for a wide range of temperatures and pressures are shown in Figs. 3d-1 through 3d-5.

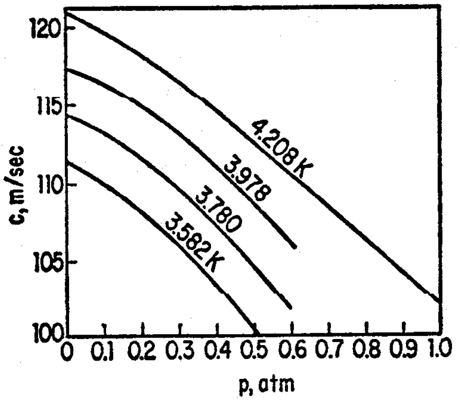


FIG. 3d-1. Speed of sound vs. static pressure in helium (gas) at 510 kHz. The parameter is absolute temperature. (*After van Itterbeek and Forrez.*)

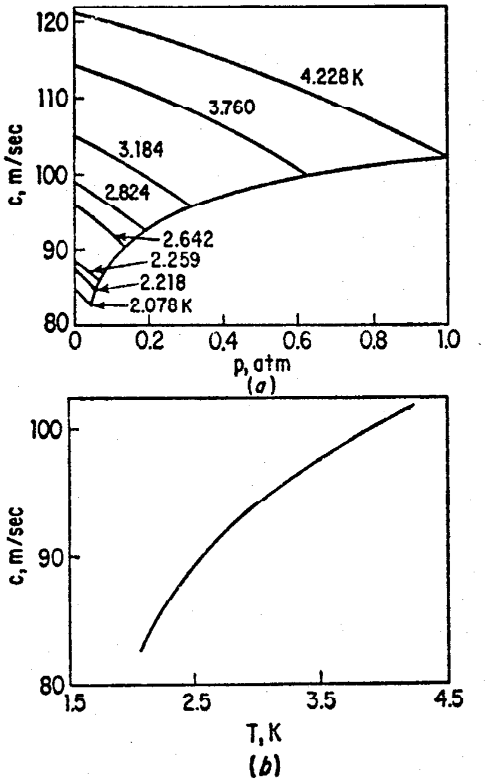


FIG. 3d-2. Speed of sound in helium (gas) at audio frequencies: (*a*) vs. static pressure with absolute temperature as parameter, and (*b*) vs. absolute temperature at vapor pressure. (*After van Itterbeek and de Laet.*)

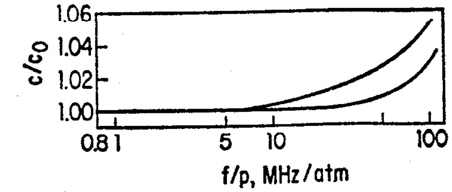


FIG. 3d-4. Relative speed of sound vs. ratio of frequency to static pressure in argon (gas) at 803.3 kHz. (*After van Itterbeek and Boyer.*)

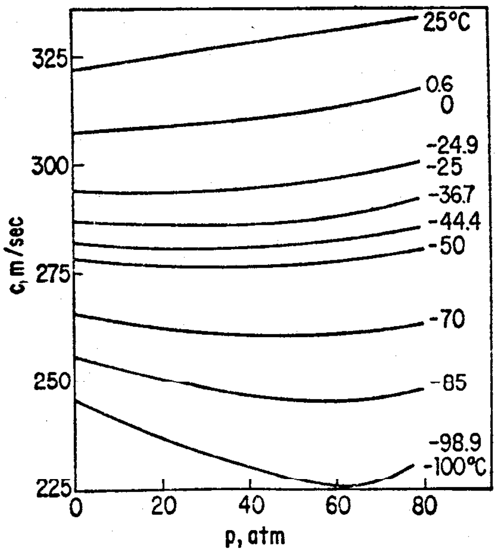


FIG. 3d-3. Speed of sound vs. static pressure in argon (gas). The parameter is temperature. (*After van Itterbeek.*)

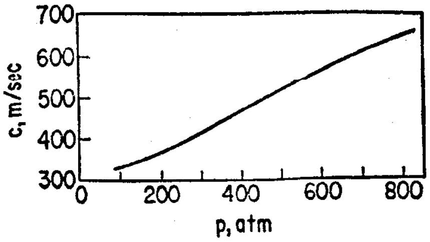


FIG. 3d-5. Speed of sound in argon (gas) vs. static pressure at 24°C and 600 to 900 kHz. (*After Lacam and Noury.*)

Table 3d-7. Speed of Sound in H_2, He, and N_2*

p, atm	H_2 at 0°C, m/sec (286 kHz)	He at 27°C, m/sec (286 kHz)	N_2 at 27°C	
			m/sec	kHz
1	1,200	946	353	286; 486
20	1,210	954	356	286; 486
40	1,232	963	361	286 ;486
60	1,249	972	366	286; 486
80	1,265	982	372	286; 486
100	1,281	...	379	286; 486
140	.....	...	390	900
200	.....	...	420	900
340	.....	...	496	900
480	.....	...	568	900
580	.....	...	621	900
780	.....	...	737	900
1,080	.....	...	884	900

* W. Schaafs, Landolt-Börnstein New Series, Group II, "Atomic and Molecular Physics," vol. 5, "Molecular Acoustics," Springer-Verlag New York Inc., New York, 1967.

Table 3d-8. Speed of Sound in CO_2, CO, N_2O, and SO_2 at 1 Atmosphere*

Gas	Frequency, kHz	T, °C	Speed, m/sec
CO_2...........	53–147	25	283
		100	313
		200	348
		500	430
CO............	8–27	1000	710
		1400	814
		1800	898
N_2O...........	94	19	273
		56	288
		128	316
SO_2............	111	20	222
		79	244
		124	260

* W. Schaafs, Landolt-Börnstein New Series, Group II, "Atomic and Molecular Physics," vol. 5, "Molecular Acoustics," Springer-Verlag New York Inc., New York, 1967.

3d-7. Altitude. The pressure, temperature, density, and mean molecular weight as functions of altitude in the atmosphere are given in Table 3d-2. Speed of sound, coefficient of viscosity, kinematic viscosity, and thermal conductivity as functions of altitude are given in Table 3d-9.

3d-8. Characteristic Impedance. The characteristic impedance is equal to the ratio of the sound pressure to the particle velocity in a plane wave traveling in an unbounded medium. It is equal to the density times the velocity of propagation,

TABLE 3d-9. U.S. STANDARD ATMOSPHERE, 1962*

Altitude, km	Sound speed c, m/sec	Coefficient of viscosity η, dyne-sec/cm²	Kinematic viscosity ν, cm²/sec	Thermal conductivity κ, cal/cm-sec-deg
−5	358.986	1.9422 −4	1.0058 −4	6.6545 −5
−4	355.324	1.9123	1.0806	6.5356
−3	351.625	1.8820	1.1625	6.4161
−2	347.888	1.8515	1.2525	6.2958
−1	344.111	1.8206	1.3516	6.1748
0	340.294	1.7894	1.4607	6.0530
0.5	338.370	1.7737	1.5195	5.9919
1.0	336.435	1.7579	1.5813	5.9305
1.5	334.489	1.7420	1.6463	5.8690
2.	332.532	1.7260	1.7147	5.8073
2.5	330.563	1.7099	1.7868	5.7454
3	328.583	1.6938	1.8628	5.6833
4	324.589	1.6612	2.0275	5.5586
5	320.545	1.6282	2.2110	5.4331
6	316.452	1.5949	2.4162	5.3068
7	312.306	1.5612	2.6461	5.1798
8	308.105	1.5271	2.9044	5.0520
9	303.848	1.4926	3.1957	4.9235
10	299.532	1.4577	3.5251	4.7942
15	295.069	1.4216	7.2995	4.6617
20	295.069	1.4216	1.5989	4.6617
25	298.389	1.4484	3.6135	4.7602
30	301.709	1.4753	8.0134	4.8593
40	317.189	1.6009	4.0067	5.3295
50	329.799	1.7037	1.6591	5.7214
60	320.606	1.6287	5.3241	5.4349
70	297.139	1.4389	1.6431	4.7230
80	269.44	1.216	6.085	3.925

* Data taken from: "U.S. Standard Atmosphere, 1962," published by the U.S. Committee on Extension to the Standard Atmosphere (COESA), Washington, D.C., 1962. For T, P, and ρ see Table 3d-2.

Note. A single-digit number (preceded by a plus or minus sign) following the initial entry indicates the power of 10 by which that entry and each succeeding entry of that column should be multiplied.

that is, ρc. The variation of ρc with temperature and pressure can be calculated from the expression

$$\rho c = \rho_0 c_0 \left(\frac{273.16}{T}\right)^{\frac{1}{2}} \frac{P}{760} \qquad \text{mks rayls}$$

where $\rho_0 c_0$ is the value at 0°C and 1 atm pressure. For air $\rho_0 c_0 = 428.5$ newton-sec/m³. Table 3d-10 contains values of $\rho_0 c_0$ for several common gases.

3d-9. Attenuation. In addition to the dispersion of sound due to wind, turbulence in the atmosphere, and temperature gradients, two properties of the medium combine to attenuate a wave which is propagated in free space. The first of these attenuations is caused by molecular absorption and dispersion in polyatomic gases involving an exchange of translational and vibrational energy between colliding molecules. The second is due to viscosity and heat conduction in the medium, discussed earlier in this section.

TABLE 3d-10. CHARACTERISTIC IMPEDANCE $\rho_0 c_0$ OF COMMON GASES AT 0°C (273.16 K) TEMPERATURE AND 0.760 M HG BAROMETRIC PRESSURE

Gas	Formula	$\rho_0 c_0$, newton-sec/m^3 at 0°C, 0.76 m Hg
Air	....	428.5
Argon	A	569
Carbon dioxide	CO_2	512
Carbon monoxide	CO	421
Helium	He	173.1
Hydrogen	H_2	114.1
Neon	Ne	385
Nitric oxide	NO	435
Nitrogen	N_2	421
Nitrous oxide	N_2O	518
Oxygen	O_2	453

Knudsen[1] says that "the attenuation of sound is greatly dependent upon location and weather conditions, that is, upon the humidity and temperature of the air. For the hot and relatively dry summer air of the desert, such as at Greenland Ranch, Inyo County, California, where the relative humidity may drop as low as 2.4 percent, the attenuation at 3,000 Hz is 0.14 dB/m, and at 10,000 Hz it is 0.48 dB/m."

Data on the absorption of audible sound in air are valuable because they are needed to calculate the reverberation time for high-frequency sound in rooms, for determining the amplification characteristics of public-address systems for use outdoors, and for predicting the range of effectiveness of apparatus for sound signaling and sound ranging in the atmosphere.

Kneser[2] treated analytically the problem of absorption and dispersion of sound by molecular collision and summarized his results in the form of a nomogram which has been reprinted along with comments by Pielemeier.[3] Recent data by Harris[4] show larger values for molecular absorption at most relative humidities than are yielded rom Kneser's nomogram.

The attenuation caused by heat conduction and viscosity of the air α_c is not known so accurately. The classical absorption due to these causes,[5] as discussed earlier, is given by

$$\alpha_c = \alpha_\eta + \alpha_T = \frac{\omega^2}{2\rho c^3}\left[\frac{4\eta}{3} + (\gamma - 1)\frac{\kappa}{C_p}\right] \qquad \text{nepers/m}$$

where $\omega/2\pi$ is the frequency in hertz, ρ is the density in kilograms per meter cubed, c is the speed of sound in meters per second, η is the coefficient of viscosity in mks

---

[1] V. O. Knudsen, The Propagation of Sound in the Atmosphere: Attenuation and Fluctuations, *J. Acoust. Soc. Am.* **18**, 90–96 (1946).

[2] H. O. Kneser, The Interpretation of the Anomalous Sound-absorption in Air and Oxygen in Terms of Molecular Collisions, *J. Acoust. Soc. Am.* **5**, 122–126 (1933); A Nomogram for Determination of the Sound Absorption Coefficient in Air, *Akust. Z.* **5**, 256–257 (1940) (in German).

[3] W. H. Pielemeier, Kneser's Sound Absorption Nomogram and Other Charts, *J. Acoust. Soc. Am.* **16**, 273–274 (1945).

[4] C. M. Harris, Absorption of Sound in Air versus Humidity and Temperature, *J. Acoust. Soc. Am.* **40**, 148–159 (1966).

[5] Lord Rayleigh, "Theory of Sound," The Macmillan Company, New York, 1929, and Dover Publication, Inc., New York, 1945.

units, γ is the ratio of specific heats, κ is the coefficient of thermal conductivity in mks units, and C_p is the specific heat at constant pressure in mks units. Measured values of α_c are as much as 40 to 50 percent higher than those calculated from the equation above.[1,2]

The total attenuation α_A due to both types of absorption is therefore

$$\alpha_A = \alpha_m + \alpha_c \qquad \text{nepers/m}$$

where α_m is the absorption in nepers/m arising from molecular resonance. To convert from nepers per meter to decibels per meter, multiply by 8.686.

Harris[3] has measured the total attenuation for a sound wave traveling through air having a carbon dioxide content of 300 parts per million (0.03 percent). The temperature, relative humidity, and frequency were varied over a wide range. The results are shown in Figs. 3d-6 and 3d-7*a* to *f*. In Fig. 3d-6, m is defined as the attenuation coefficient per meter as expressed in the equation $I = I_0e^{-mx}$, where I_0 is the sound intensity (in watts/m^2) at $x = 0$, and I is that at x. To convert from m to decibels per meter, multiply by 4.343.

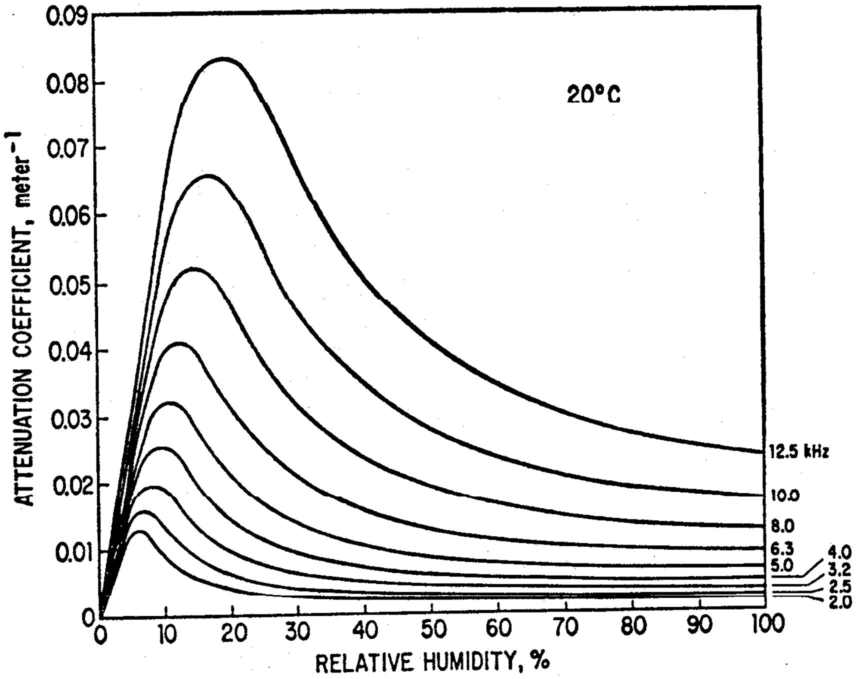


FIG. 3d-6. Values of the total attenuation coefficient m (in meters^{-1}) versus percent relative humidity for air at 20°C and normal atmospheric pressure for frequencies between 2,000 and 12,500 Hz at one-third-octave intervals. To convert to decibels per meter, multiply ordinate by 4.343. (*After Harris.*)

Harris[4] has also presented data on the absorption of sound in air at pressures in the range from 0.2 to 0.9 atm at 20°C. The results show that, at a given frequency,

---

[1] L. J. Sivian, High Frequency Absorption in Air and in Other Gases, *J. Acoust. Soc. Am.* **19,** 914–916 (1947).

[2] P. E. Krasnooshkin, On Supersonic Waves in Cylindrical Tubes and the Theory of the Acoustical Interferometer, *Phys. Rev.* **65,** 190 (1944). See also W. H. Pielemeier, Observed Classical Sound Absorption in Air, *J. Acoust. Soc. Am.* **17,** 24–28 (1945).

[3] C. M. Harris, Absorption of Sound in Air versus Humidity and Temperature, *Acoust. J. Soc. Am.* **40,** 148–159 (1966).

[4] C. M. Harris, On the Absorption of Sound in Humid Air at Reduced Pressures, *J. Acoust. Soc. Am.* **43,** 530–532 (1968).

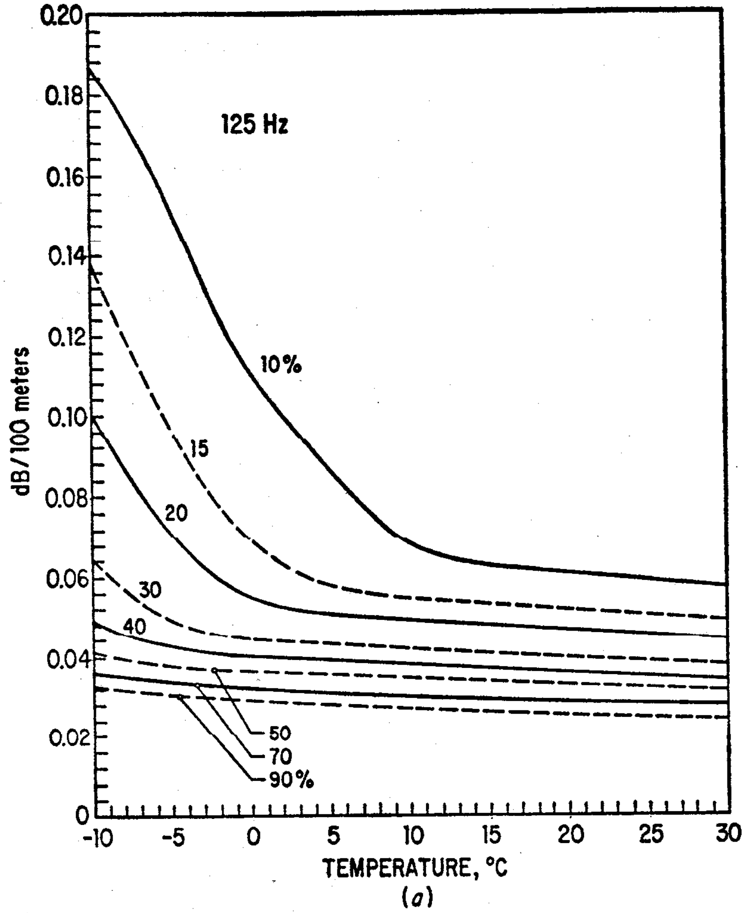


FIG. 3d-7. Attenuation of sound in air vs. temperature, at atmospheric pressure, for various values of relative humidity and frequency. The CO_2 content is 0.03 percent. (*After Harris.*)

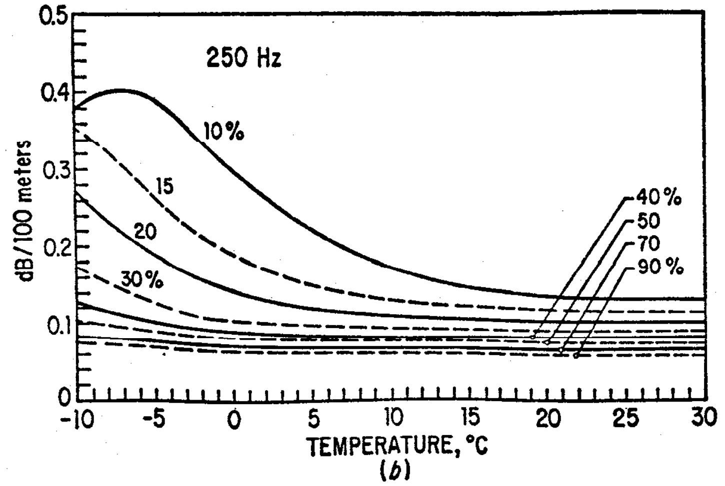
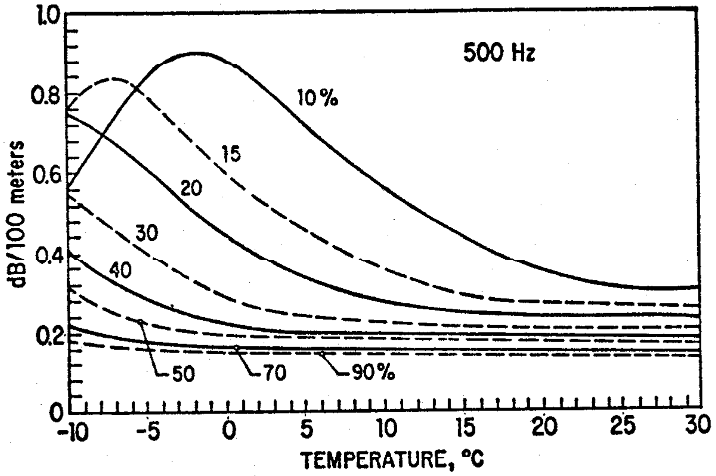
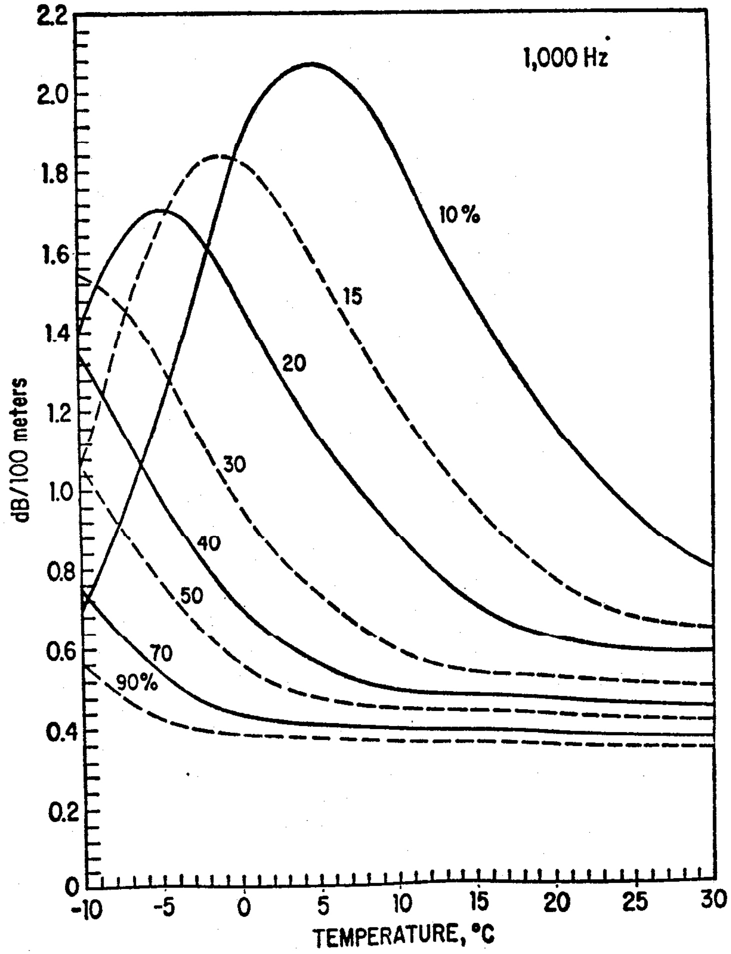


FIG. 3d-7. *Continued.*



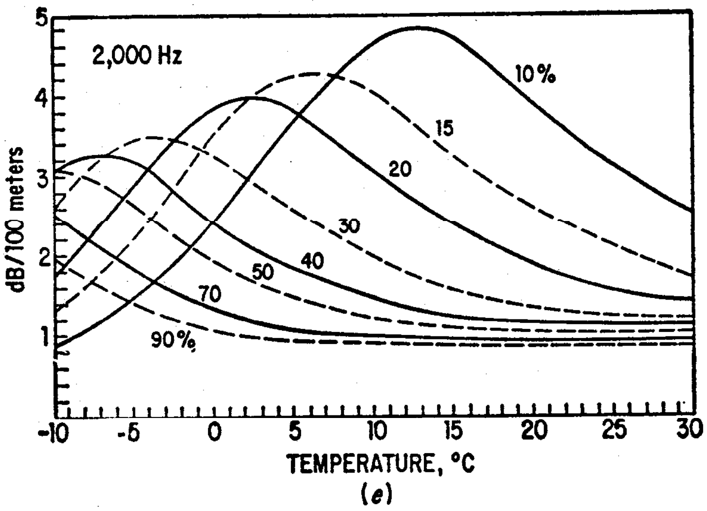
(c)

FIG. 3d-7. *Continued.*



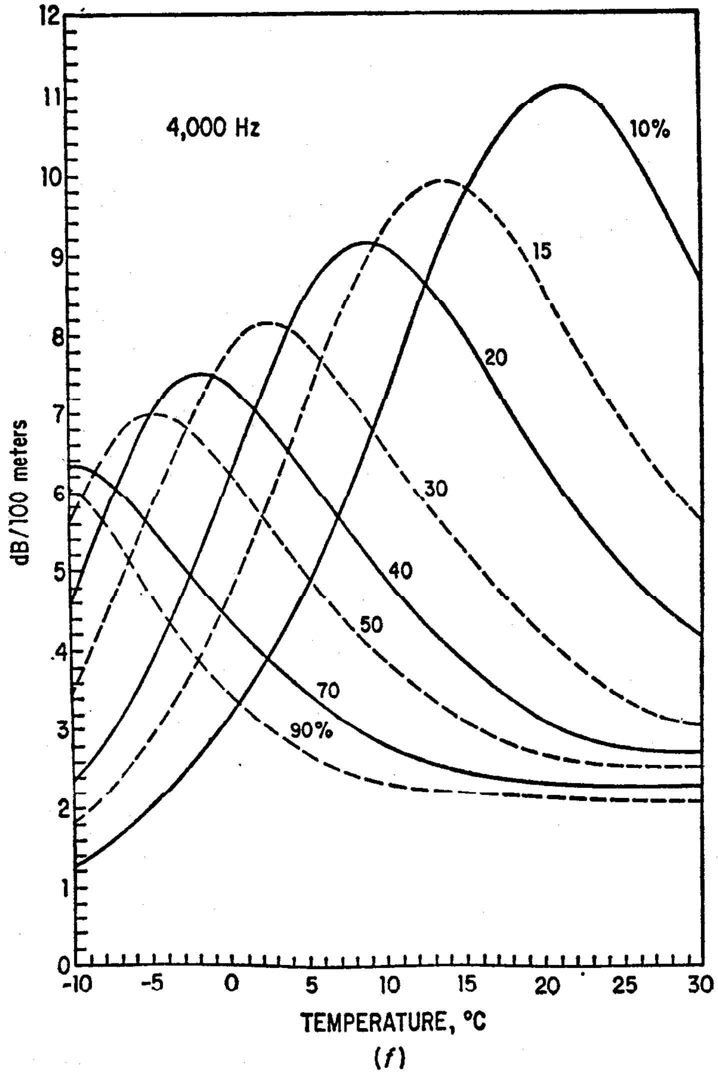
(d)

FIG. 3d-7. *Continued.*



(*e*)

FIG. 3d-7 (*Continued*)



(*f*)

FIG. 3d-7 (*Continued*)

a plot of molecular absorption versus humidity has a maximum value that is independent of pressure. Lowering the pressure shifts the peaks in the curves of absorption versus humidity to lower values of relative humidity. The relations among frequency of maximum absorption, relative humidity, and frequency are given in Fig. 3d-8.

Other studies of the molecular absorption process are reported by Monk,[1] Shields and Faughn,[2] Henderson and Herzfeld,[3] and Connelly.[4]

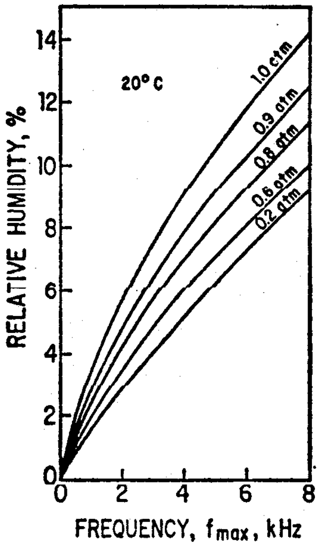


FIG. 3d-8. Frequency of maximum total absorption, $f_{\max}$, as a function of relative humidity. The parameter is atmospheric pressure. The temperature is 20°C.

Below 1,000 Hz the attenuation of sound in air is much less than above 1,500 Hz. Harris and Tempest[5] have measured attenuation coefficients for air in this frequency range. Their data for a range of moisture contents, temperatures, and barometric pressures are given in Fig. 3d-9*a* through *e*.

---

[1] R. G. Monk, Thermal Relaxation in Humid Air, *J. Acoust. Soc. Am.* **46**, 580–586 (1969).

[2] F. D. Shields and J. Faughn, Sound Velocity and Absorptions in Low-pressure Gases Confined to Tubes of Circular Cross Sections, *J. Acoust. Soc. Am.* **46**, 158–163 (1968).

[3] M. C. Henderson and K. P. Herzfeld, Effect of Water Vapor on the Napier Frequency of Oxygen and Air, *J. Acoust. Soc. Am.* **37**, 986–988 (1965).

[4] J. H. Connolly, Combined Effect of Shear Viscosity, Thermal Conduction, and Thermal Relaxation on Acoustic Propagation in Linear-molecular Ideal Gases, *J. Acoust. Soc. Am.* **36**, 2374–2381 (1964).

[5] C. M. Harris and W. Tempest, Absorption of Sound below 1000 Hz, *J. Acoust. Soc. Am.* **36**, 2390–2394 (1964).

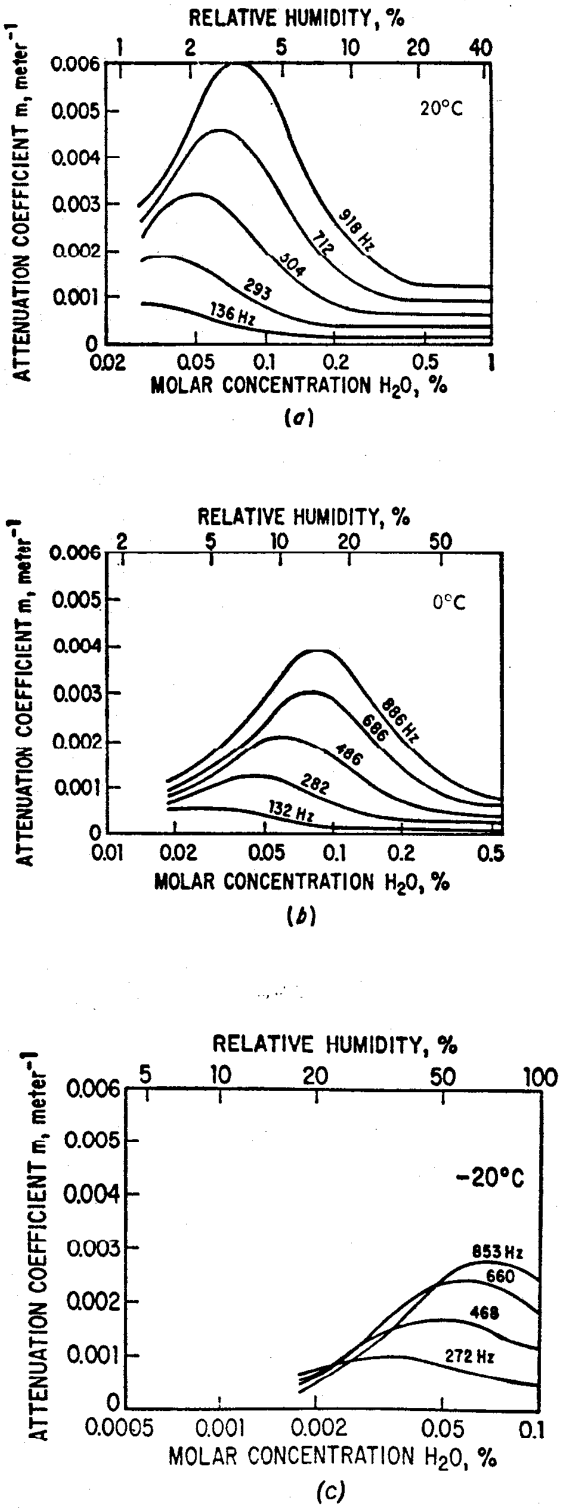
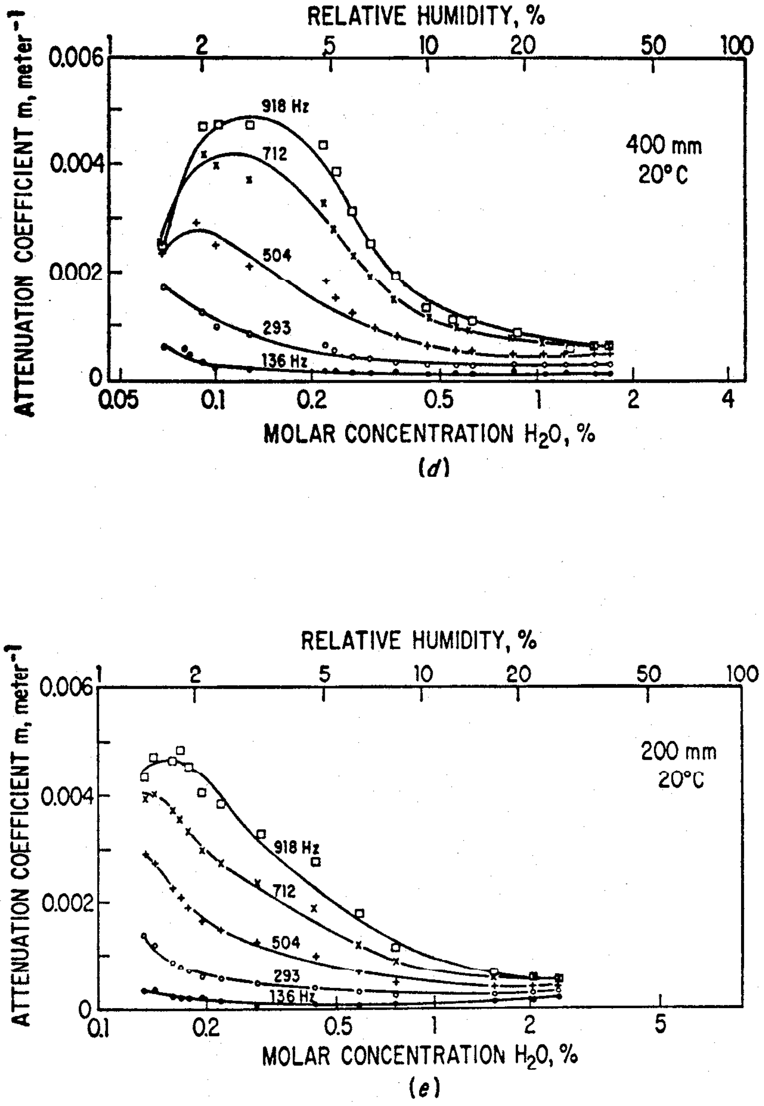


FIG. 3d-9. Attenuation coefficient m vs. percent relative humidity for air at various frequencies and temperatures. Pressure is atmospheric for (*a*), (*b*), and (*c*), and as shown on the graphs for (*d*) and (*e*). To convert to decibels per 100 meters, multiply ordinate by 434.



(*d*)

(*e*)

FIG. 3d-9. *Continued.*