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"CALCULATING THE VELOCITY OF SOUND IN REAL PURE COMPONENT GASES AND MIXTURES OF REAL GASES"

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INTRODUCTION

The velocity of sound in real gases and real gas mixtures is an important physical property. It is required for the design of pulsation dampeners for compressors and the calculation of throat velocities in supersonic nozzles (Sherwood, 1962). The velocity of sound is used for locating hydrate freezes and other obstructions in gas pipe lines (Whiting and Ackerberg, 1978), and in testing pipe lines for leaks (Hough, 1988). It also is required for the study of vibrations in high speed, high pressure, gas compressors (Dunskus, 1969).

If consideration is limited to infinitesimal, low frequency sound waves, the equations of motion lead to the wave equation (Whiting and Ackerberg, 1978):

$$\frac{\partial^2 v_x}{\partial t^2} = c^2 \frac{\partial^2 v_x}{\partial X^2} \qquad (1)$$

In Equation 1 the speed of sound, c, is given by:

$$c^2 = \left(\frac{\partial P}{\partial \rho}\right)_S \tag{2}$$

The assumptions made in developing Equation 2 are:

a. The fluid medium is a continuum.
b. Changes in pressure are small so that changes in pressure are proportional to changes in density.
c. Viscous effects are negligible.
d. The velocity of flow of medium is small as compared to the velocity of sound.
e. Heat conduction is neglected in all directions.
f. The absorption coefficient in the medium is small (the frequency has to be low).

For an ideal gas the speed of sound can be computed from:

$$c^2 = C_p \, RT/C_v \, M \tag{3}$$

In many cases calculations along an isentropic path as required in Equation (2) are not convenient. Equation 2 can be rewritten as:

$$c^2 = (C_p/C_v) \left(\frac{\partial P}{\partial \rho}\right)_T \tag{4}$$

CALCULATING SONIC VELOCITY

Squire (1961) used the identity:

$$\left(\frac{\partial P}{\partial \rho}\right)_S = \frac{P}{\rho} \left(\frac{\partial h}{\partial u}\right)_S \tag{5}$$

He then assumed that:

$$\left(\frac{\partial h}{\partial u}\right)_S \approx \frac{h}{u} \tag{6}$$

With this simplification Equation 2 becomes:

$$c^2 = (CF)^2 ZRT \left(\frac{h}{h - ZRT}\right) \tag{7}$$

Where:

$$CF = 31.81 \frac{\text{meters}}{\text{second}} \left(\frac{\text{gram}}{\text{liter - atm}}\right)^{0.5}$$

Squire obtained $\Delta H/T_c$ and Z from generalized plots representing each as a function of reduced temperature and reduced pressure.

Sherwood (1962) used the specific volume form of Equation 2 for his calculations of the velocity of sound:

$$c^2 = -v^2 \left(\frac{\partial P}{\partial v}\right)_s = \frac{aRT\,(C_p/C_v)\,Z^2}{Z - P_r \left(\frac{\partial Z}{\partial P_r}\right)_{T_r}} \tag{8}$$

where:

$$aR = (8308/m) \text{ sq. m./ sec}^2\text{K}$$

Sherwood defined the terms in Equation 8 so that the Pitzer and Curl (1958) tables for compressibility factor and the isothermal effect of pressure on enthalpy could be used to calculate them. The terms defined by Sherwood are:

$$C_p = C_p^o + \Delta C_p \tag{9}$$

$$C_v = C_p - (C_p - C_v) \tag{10}$$

$$\Delta C_p = \frac{\partial}{\partial T_r} \left(\frac{H - H^o}{T_c}\right) P_r \tag{11}$$

$$C_p - C_v = \frac{R\left[Z + T_v \left(\frac{\partial Z}{\partial T_r}\right) p_r\right]^2}{Z - P_r \left(\frac{\partial Z}{\partial P_r}\right) T_r} \qquad (12)$$

Sherwood used the Pitzer and Curl tables to develop tables of c^2/aRT (C_o/C_v), $\triangle C_p$ and (C_p/C_v) as function of reduced temperature and reduced pressure. These three tables provide the necessary values for computation of the velocity of sound in real gases using Equation 8.

Macchi (1974) also used the Pitzer and Curl tables for compressibility factor and enthalpy correction. He used the equation of Vennix and Kobayashi (1969) for methane and the equation of Vukalovick and Altunin (1968) for CO_2 to fit the compressibility factor tables of Pitzer and Curl. These were then manipulated mathematically to give the necessary terms for evaluating the speed of sound using Equation 8. Macchi presented tables of his calculated values for $Z^{(o)}$ and $Z^{(1)}$ to be used in the calculations. His procedure is limited to the calculation of velocity of sound in pure gases for reduced temperatures between 0.8 and 4 and reduced pressures between 0 and 8.

Whiting and Ackerberg (1978) also used the specific volume form of the speed of sound equation as shown in Equation 8. Their values of compressibility factor and heat capacity correction were obtained from the tables presented by Lee and Kesler (1975). Whiting and Ackerberg suggested two different mixing rules be used. Those suggested by Lee and Kesler (1975) were suggested for pressures between 50 and 300 atmospheres. For pressures above 300 atmospheres Amagat's Law was recommended for the mixing rule.

Thomas, Hankinson and Phillips (1970) used a form of the Benedict Webb Rubin Equation of State to calculate to necessary terms in Equation 8 and evaluate the velocity of sound from the specific volume form of the equation. The pseudo reduced form of the Benedict Webb Rubin Equation is:

$$P_{pr} = \frac{T_{pr}}{V_{pr}} + (B_{o_r} T_{pr} - A_{o_r} - C_{o_r}/T_{pr}^2)/V_{pr}^2 \qquad (13)$$

$$+ (b_r T_{pr} - a_r)/V_{pr}^3 + a_r\alpha_r/V_{pr}^6$$

$$+ [c_r (1 - \gamma_r/V_{pr}^2) e^{-\gamma_r/V_{pr}^2}]/V_{pr}^3 T_{pr}^2$$

The pseudo reduced volume is defined as:

$$V_{pr} = \frac{V}{\frac{RT_{pc}}{P_{pc}}} \tag{14}$$

and is related to T_{pr}, P_{pr} and gas compressibility factor, z, by:

$$V_{pr} = \frac{ZT_{pr}}{P_{pr}} \tag{15}$$

The difference in heat capacity was expressed as:

$$C_p - C_v = -T \left(\frac{\partial P}{\partial T}\right)_v^2 / \left(\frac{\partial P}{\partial v}\right)_T \tag{16}$$

The partial differentials on the right hand side of Equation 16 were evaluated from Equation 13 and the heat capacity at constant volume was obtained by differentiating the internal energy form of the Benedict-Webb-Rubin Equation. The pseudo critical pressure, the pseudo critical temperature, and the ideal gas state heat capacity for natural gas mixtures were obtained from equations fitted as a function of the specific gravity of the natural gas. This means that the work of Thomas, Hankinson and Phillips is restricted in application to natural gas mixtures and that the only composition parameter used in their calculations is the specific gravity of the natural gas mixture.

SONIC VELOCITY FROM AN EQUATION OF STATE

All of the terms in the specific volume form of the equation for the velocity of sound in gases can be developed from an equation of state. If this is done then the calculation procedure becomes general and should be applicable to pure components and gas mixtures over a wide range of temperature and pressure conditions. The form of the equation most suitable per use is Equation 4 which, when written in specific volume form, is:

$$c^2 = -v^2 \left(\frac{C_p}{C_v}\right) \left(\frac{\partial P}{\partial v}\right)_T (CF)^2 \qquad (17)$$

where:

CF = conversion factor to m/sec
= (1.033 x 9.8 10/m)

The Peng-Robinson (1976) equation of state was selected. After appropriate manipulation of the basic Peng-Robinson Equations expressions suitable for use in calculating the velocity of sound can be developed. The equations to be used in calculations for single component gases are shown in Table 1 and those for gas mixtures are shown in Table 2.

CALCULATION RESULTS

Calculations were carried out to compare the results obtained when using the equations in Table 1 with the limited amount of experimental data available on velocity of sound in pure component gases.

Measurements of the velocity of sound in methane have been made by Nierode et al. (1970) and also by Gammon and Douslin (1976). Table 3 shows a comparison of their experimental measurements with the values calculated from the Peng-Robinson Equations. The average absolute error of the calculated values from the Gammon and Douslin data is 2.58. The overall average absolute percentage deviation from the data of Nierode, et al. is 0.62 percent. The calculated values are much closer to the values of Nierode, et al. except that all are slightly lower than the experimental values.

Table 4 shows a comparison of the calculated sonic velocity in ethylene with the values measured by Herget (1940) and Jahangiri et al. (1986). Most of the values measured by Herget are in the region of the critical, which makes the good agreement between the calculated and experimental values somewhat surprising. The reason for the large errors at extremely low pressure, and at 65 atmospheres is unclear.

The velocity of sound in pure isobutane in the vicinity of the critical region was measured by Sengers, Kamar-Parsi and Sengers (1983). Table 5 shows the comparison between calculated and experimentally determined values. The agreement between the two sets of values is very good, particularly when consideration is given to the fact that the measurements are near the critical for isobutane.

Table 6 shows a comparison of calculated and experimental values for three pure components where measurements were reported by Nierode, et al. (1970). The agreement between experimental and calculated values for carbon tetrafluoride is very good. The agreement for Difluorodichloromethane is not so good, and the values for Argon are even further apart. One would think that the equation of state would hold better for Argon than for Difluorodichloromethane, but that appears not to be the case for velocity of sound calculations.

The velocity of sound in nitrogen has been measured by Nierode, et al. (1970) and Hodge (1937) with a single value reported by Rostafinski (1959). The comparison is shown in Table 7. As would be expected the calculated and experimental values of the velocity of sound in nitrogen are in excellent agreement.

The velocity of sound comparison for carbon dioxide is shown in Table 8. The experimental determinations have been reported by Hodge (1937) and by Herget (1940). The measurements by Herget are in the region of the critical for carbon dioxide and show large errors. The error of the calculated values from the experimental ones reported by Hodge show smaller deviations.

Table 9 shows a comparison of calculated velocity of sound with the experimental values reported by Hodge (1937) for hydrogen. The agreement is good with all deviations being less than 5%.

Only very limited experiment data are available for measurements of velocity of sound in mixtures. Nierode, et al. (1970) made measurements on binary mixtures containing argon, nitrogen, carbon tetrafluoride, and methane. Their measurements for mixtures containing argon are shown in Table 10 and those for binary mixtures containing methane are shown in Table 11. In both cases there is excellent agreement between the values calculated using the Peng-Robinson properties and the experimental measurements.

Rostafinski (1959) and Hodge (1937) report measurements on the velocity of sound in air. While air is a multicomponent gas mixture for the purpose of calculating the velocity of sound using the Peng-Robinson equations air was assumed to be a binary mixture containing 79% nitrogen and 21% oxygen. The comparison of values calculated on this basis with experimental measurements from the two literature sources is shown in Table 12. In all cases there is excellent agreement between the calculated and experimentally measured values.

CONCLUSION

The velocity of sound in pure component real gases and mixtures of real gases can be reliably calculated using properties from an equation of state. The Peng-Robinson Equation used in this paper gave excellent reproduction of experimental measurements for both pure components and gas mixtures.

There are no experimental measurements available for multi-component gases. However there is every reason to believe that reliable estimates of the velocity of sound in multicomponent mixtures can be made with properties calculated from an equation of state which yields good values for gas mixture properties such as density and enthalpy.

NOMENCLATURE

C	=	Velocity of sound, meters/second
C_p	=	Heat capacity at constant pressure, cal/gram mol K
C^o_p	=	Ideal gas state heat capacity at constant pressure, cal/gram mol K
C^o_v	=	Ideal gas state heat capacity at constant volume, cal/gram mol K
C_v	=	Heat capacity at constant volume, cal/gram mol K
H	=	Molar enthalpy, cal/gram mol
h	=	Specific enthalpy, cal/gram
M	=	Molecular weight
P	=	Absolute pressure, atmospheres
P_c	=	Critical pressure, atmospheres
P_r	=	Reduced pressure, P/P_c
R	=	Universal gas constant, 82.06 atm cm^3/gram mol K
RC	=	Universal gas constant, 1.987 atm cm/gram mol K
S	=	Entropy, cal/gram mol K
T	=	Absolute temperature, K
T_c	=	Critical temperature, K
T_r	=	Reduced temperature, T/Tc
U	=	Molar internal energy, cal/gram mol
u	=	Specific internal energy, cal/gram
v	=	Specific volume, cm^3/gram
v_x	=	Velocity in x direction, meter/second
V	=	Molar volume, cm^3/gram mol
y	=	composition of component in gas phase, mol fraction
Z	=	Compressiblility factor
Z_m	=	Compressibility factor for mixture

GREEK LETTERS

ρ	=	Density, gram/cm^3
ω	=	Acentric factor

SUBSCRIPTS

i , j	=	One component in a mixture
m	=	Mixture property
pc	=	Pseudo critical value
pr	=	Pseudo reduced value

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TABLE 1

Equations for Calculating the Velocity of Sound in Single Component Gases

$$\left(\frac{\partial V}{\partial T}\right)_P = - \frac{\left(\frac{\partial P}{\partial T}\right)_V}{\left(\frac{\partial P}{\partial V}\right)_T}$$

$$\left(\frac{\partial P}{\partial V}\right)_T = - \frac{RT}{(V-b)^2} + \frac{a(T_c)\alpha}{2\sqrt{2}\, b} \left\{\frac{1}{[V+b(1-\sqrt{2})]^2} - \frac{1}{[V+b(1+\sqrt{2})]^2}\right\}$$

$$\left(\frac{\partial P}{\partial T}\right)_V = \frac{R}{(V-b)} + \frac{a(T_c)\ [1+K\ (1-T_r^{1/2})]}{[V\ (V+b) + b\ (V-b)]} \left(\frac{K\ T_r^{1/2}}{T}\right)$$

$$C_P = C_P^o + \frac{a(T_c)\ (1+K)}{2\sqrt{2}\, b} \left\{\alpha^{1/2} \left[\frac{2\sqrt{2}\, b \left(\frac{\partial V}{\partial T}\right)_P}{(V+b_1)\ (V+b_2)}\right] - \left[\ln\left(\frac{V+b_1}{V+b_2}\right) \left(\frac{KT_r^{1/2}}{\partial T}\right)\right]\right\} + P \left(\frac{\partial V}{\partial T}\right)_p - R$$

$$C_v = C_v^o - \frac{a(T_c)}{2\sqrt{2}\, b} (1+K) \left[\ln \left(\frac{V+b_1}{V+b_2}\right)\right] \left[\frac{K\ T_r^{1/2}}{2T}\right]$$

TABLE 2

Equations for Calculating the Velocity of Sound in Mixtures of Real Gases

$$\left(\frac{\partial V_m}{\partial T}\right)_P = - \frac{\left(\frac{\partial P}{\partial T}\right)_{V_m}}{\left(\frac{\partial P}{\partial V_m}\right)_T}$$

$$\left(\frac{\partial P}{\partial V_m}\right)_T = - \frac{RT}{(V_m - b_m)} + \frac{A_m(T)}{2\sqrt{2}\, b_m} \left[\frac{1}{(V_m + b_{m_1})^2} - \frac{1}{(V_m + b_{m_2})^2}\right]$$

$$\left(\frac{\partial P}{\partial T}\right)_{V_m} = \frac{R}{(V_m - b_m)} + \frac{\Sigma\Sigma y_i y_j (a_i a_j \alpha_i \alpha_j)^{1/2} [K_j (Tr_j/\alpha_j)^{1/2} + K_i (Tr_i/\alpha_i)^{1/2}]}{2T\,[V_m(V_m + b_m) + b_m (V_m - b_m)]}$$

$$C_{p_m} = C_{p_m}^{o} + \frac{1}{2\sqrt{2}\, b_m} \left\{(cc^*)\left[\frac{2\sqrt{2}\, b_m \left(\frac{\partial V_m}{\partial T}\right)_P}{(V_m + b_{m_1})(V_m + b_{m_2})}\right] + \left[\ln\left(\frac{V_m + b_{m_1}}{V_m + b_{m_2}}\right)\right]\left(\frac{\partial (cc^*)}{\partial T}\right)_P \right\} + P\left(\frac{\partial V_m}{\partial T}\right)_P - R$$

TABLE 2, Cont'd.

$$C_{v_m} = C^{o}_{v_m} + \left[\left(\frac{1}{2\sqrt{2}\, b_m}\right) \ln \left(\frac{V_m + b_{m_1}}{V_m + b_{m_2}}\right)\right] \left(\frac{\partial (cc^*)}{2T}\right)_{V_m}$$

$$(cc^*) = \sum\sum_{ij} y_i y_j (a_i a_j \alpha_i \alpha_j)^{1/2} \left\{1 + \frac{1}{2}\left[K_j \left(\frac{T_{r_j}}{\alpha_j}\right)^{1/2} + K_i \left(\frac{T_{r_i}}{\alpha_i}\right)^{1/2}\right]\right\}$$

$$\left(\frac{\partial (cc^*)}{\partial T}\right)_P = \left(-\frac{1}{4T}\right) \sum\sum_{ij} y_i y_j (a_i a_j \alpha_i \alpha_j)^{1/2} \left\{K_j \left(\frac{T_{r_j}}{\alpha_j}\right)^{1/2} + K_i \left(\frac{T_{r_i}}{\alpha_i}\right)^{1/2} + 2K_i K_j \left(\frac{T_{r_i} T_{r_j}}{\alpha_i \alpha_j}\right)^{1/2}\right]$$

$\left(\frac{\partial (cc^*)}{\partial T}\right)_{V_m} = \left(\frac{\partial (cc^*)}{\partial T}\right)_{\rho}$ because (cc^*) is function of T only

TABLE 2, Cont'd.

$$V_m = Z_m \, RT/P$$

$$Z_m^3 - (1-B_m) \, Z_m^2 + (A_m - 3 B_m^2 - 2B_m) \, Z_m - (A_m B_m - B_m^2 - B_m^3) = 0$$

Where: $b_{m_1} = b_m \, (1-\sqrt{2})$; $b_{m_2} = b_m \, (1 + \sqrt{2})$

$$a_m(T) = \sum_{ij} \sum y_i y_j \, (a_i a_j \alpha_i \alpha_j)^{1/2}$$

$$a_i = 0.45724 \left(\frac{R^2 T_{c_i}^{\,2}}{P_{c_i}}\right) ; \; b_i = 0.07780 \, \frac{RT_{c_i}}{P_{c_i}} \; ; \{\text{Similar for j}$$

$$\alpha_i = \left[1 + K_i \, (1-T_{r_i}^{\,1/2})\right]^2$$

$$K_i = 0.37464 + 1.54226 \, \omega - 0.26992 \, \omega_i^2 \qquad \{\text{Similar for j}$$

$$b_m = \sum_i y_i b_i$$

TABLE 3
Velocity of Sound in Methane

Pressure atm.	Temperature K	Velocity of Sound meters/second		
		Experimental	Peng-Robinson	
			Calculated	% error
Nierode et al., 1970				
242.73	323.15	574.3	549.3	−4.35
103.54	298.15	444.6	441.1	−0.79
159.67	273.15	478.4	472.0	−1.34
126.48	248.15	430.9	435.8	1.14
7.72	193.05	353.2	359.9	1.90
15.43	193.05	340.6	346.7	1.79
36.43	193.05	298.3	310.7	4.16
7.61	190.05	350.5	357.5	2.00
15.18	190.50	337.6	344.1	1.93
21.75	190.50	325.3	332.2	2.12
27.24	190.50	314.0	322.0	2.55
31.84	190.50	303.2	313.6	3.43
38.51	190.50	284.7	203.0	6.08
Gammon and Douslin, 1976				
10.00	294.26	443.1	441.6	−0.34
20.00	294.26	440.3	437.4	−0.66
30.00	294.26	437.5	434.0	−0.80
50.00	294.26	434.5	429.7	−1.10
70.00	294.26	434.8	429.3	−1.26
10.00	273.15	426.7	426.2	−0.12
20.00	273.15	422.3	421.0	−0.31
30.00	273.15	428.4	416.1	−0.55
50.00	273.15	412.6	410.0	−0.63
70.00	273.15	410.6	409.0	−0.39

TABLE 4
Velocity of Sound in Ethylene

Pressure atm.	Temperature K	Velocity of Sound meters/second		
		Experimental	Peng-Robinson	
			Calculated	% error
Jahangiri et al., 1986				
1.	300.00	331.0	329.6	−0.42
	400.00	384.0	373.2	−0.21
	350.00	353.0	352.1	−0.25
59.21	300.00	249.0	257.9	3.56
	400.00	351.0	346.8	−1.20
	450.00	381.0	377.0	−1.05
	350.00	313.0	309.2	−1.21
0.0033	110.00	208.0	235.8	13.37
0.27	150.00	241.0	255.2	5.89
4.5	200.00	262.0	266.8	1.83
23.0	250.00	249.0	248.1	−0.36
Herget, 1949				
35.27	282.85	265.3	260.6	−1.77
58.48	282.85	348.5	349.2	0.20
35.68	291.85	276.8	271.1	−2.06
71.77	291.85	335.4	341.5	1.82
35.74	296.15	281.6	275.9	−2.02
59.50	296.15	274.1	256.0	−6.60
65.00	296.15	242.1	276.6	14.25

TABLE 5
Velocity of Sound in Iso-Butane

Pressure atm.	Temperature K	Velocity of Sound meters/second		
		Experimental	Peng-Robinson	
			Calculated	% error
Sengers, Kamgar – Parsi, and Sengers, 1983				
34.15	405.00	210.1	121.7	1.33
35.79	407.80	99.0	120.8	22.02
63.48	438.00	200.3	204.0	1.85
46.76	438.00	154.3	159.8	3.56
56.02	430.00	186.2	191.6	2.90
43.83	430.00	186.2	191.6	3.28
38.00	410.00	139.3	152.6	9.55
36.20	410.00	125.3	126.8	1.20
40.06	420.00	136.1	139.3	2.35
46.85	420.00	166.1	174.3	4.94
38.15	415.00	130.7	133.1	1.84
42.37	415.00	154.2	164.3	6.55

TABLE 6
Velocity of Sound by Nierode et al. (1970)

Pressure atm.	Temperature K	Velocity of Sound meters/second		
		Experimental	Peng-Robinson	
			Calculated	% error
Carbon Tetrafluoride				
10.00	273.15	168.1	166.8	−0.77
20.00	273.15	162.3	160.6	−1.05
30.00	273.15	157.0	155.2	−1.15
45.00	273.15	150.4	149.7	−0.47
60.00	273.15	174.5	149.3	1.22
10.00	294.26	175.6	174.2	−0.80
20.00	294.26	171.3	169.6	−0.99
30.00	294.26	167.5	165.8	−1.01
45.00	294.26	163.1	161.9	−0.74
60.00	294.26	160.8	161.1	0.19
Difluorodichloromethane				
10.00	388.71	160.0	159.5	−0.31
20.00	388.71	145.1	144.9	−0.14
30.00	388.71	130.0	128.2	−1.38
40.00	388.71	125.4	108.0	−13.88
45.00	388.71	134.0	129.0	−3.73
50.00	388.71	146.3	154.7	5.74
60.00	388.71	170.7	183.7	7.62
Argon				
1.0	273.15	317.3	314.8	−0.79
10.00	273.15	336.2	307.6	−8.51
20.00	273.15	337.5	307.8	−8.80
30.00	273.15	339.4	308.3	−9.16
45.00	273.15	342.7	309.5	−9.69
60.00	273.15	347.2	311.3	−10.34

TABLE 7
Velocity of Sound in Nitrogen

Pressure atm.	Temperature K	Velocity of Sound meters/second		
		Experimental	Peng-Robinson	
			Calculated	% error
Nierode et al., 1970				
10.00	273.15	338.2	337.1	−0.33
20.00	273.15	339.4	338.0	−0.41
30.00	273.15	341.2	339.3	−0.56
45.00	273.15	344.4	341.8	−0.75
60.00	273.15	348.4	345.0	−0.98
Rostafinski, 1959				
100.00	255.37	350.5	344.4	−1.74
Hodge, 1937				
1.0	300.15	343.4	353.0	−0.11
10.00	300.15	354.6	354.0	−0.17
50.00	300.15	363.2	360.8	−0.66
70.00	300.15	369.0	365.6	−0.92
100.00	300.15	379.4	374.3	−1.34

TABLE 8
Velocity of Sound in Carbon Dioxide

Pressure atm.	Temperature K	Velocity of Sound meters/second		
		Experimental	Peng-Robinson	
			Calculated	% error
Hodge, 1937				
1.00	300.15	270.1	269.3	− .30
10.00	300.15	262.2	261.7	− .19
50.00	300.15	223.2	226.4	1.43
60.00	300.15	208.8	218.1	4.45
Herget, 1940				
20.59	301.15	255.3	253.2	−0.82
57.79	301.15	214.2	221.0	3.17
65.12	301.15	199.3	216.7	8.73
70.00	301.15	242.8	297.1	22.36
26.03	303.15	257.9	249.8	−3.14
71.62	303.15	177.4	271.5	53.04
21.41	306.15	258.2	255.4	−1.08
72.30	306.15	197.3	222.8	12.92
37.65	311.15	247.7	246.2	−0.61
53.90	311.15	232.3	234.7	1.03
63.22	311.15	224.3	229.7	2.41
71.83	311.15	212.3	226.5	6.69

TABLE 9
Velocity of Sound in Hydrogen

Pressure atm.	Temperature K	Velocity of Sound meters/second		
		Experimental	Peng-Robinson	
			Calculated	% error
Hodge, 1937				
1.00	273.15	1199.5	1258.6	4.93
10.00	273.15	1207.2	1263.3	4.61
50.00	273.15	1240.6	1287.3	3.76
100.00	273.15	1281.4	1323.0	3.25

TABLE 10
Velocity of Sound in Binary Mixtures Containing Argon by Nierode et al.

Pressure atm.	Temperature K	Velocity of Sound meters/second		
		Experimental	Peng-Robinson	
			Calculated	% error
Argon – Nitrogen 25.39 mol % Argon				
1.	273.15	325.0	324.9	−0.06
10.	273.15	325.9	325.1	−0.24
30.	273.15	327.8	326.8	−0.31
50.	273.15	331.6	329.7	−0.57
70.	273.15	336.3	333.8	−0.74
48.70 mol % Argon				
1.	273.15	317.0	316.7	−0.09
10.	273.15	317.6	316.9	−0.22
30.	273.15	319.1	318.1	−0.31
50.	273.15	321.7	320.6	−0.34
70.	273.15	325.6	324.2	−0.43
70.22 mol % Argon				
1.	273.15	311.7	311.4	−0.10
10.	273.15	312.0	311.4	−0.19
30.	273.15	313.1	312.4	−0.22
50.	273.15	315.5	314.5	−0.32
70.	273.15	318.9	317.7	−0.38
Argon - Carbon Tetrafluoride 46.10 mol % Argon				
1.	273.15	207.9	207.6	−0.14
10.	273.15	205.7	204.5	−0.58
30.	273.15	201.5	199.1	−1.19
50.	273.15	198.9	196.5	−1.21
70.	273.15	199.2	197.3	−0.95

TABLE 11
Velocity of Sound in Binary Mixtures Containing Methane by Nierode et al.

Pressure atm.	Temperature K	Velocity of Sound meters/second		
		Experimental	Peng-Robinson	
			Calculated	% error
Methane – Carbon Tetrafluoride 29.78 mol % Methane				
1.	273.15	236.5	236.5	0.00
10.	273.15	232.8	231.3	−0.64
30.	273.15	228.6	221.8	−0.97
50.	273.15	220.0	216.1	−1.77
70.	273.15	219.5	216.1	−1.55
Methane – Nitrogen 53.33 mol % Methane				
1.	273.15	376.2	376.8	0.16
10.	273.15	375.5	374.9	−0.16
30.	273.15	374.7	372.4	−0.61
50.	273.15	376.3	372.6	−0.98
70.	273.15	379.7	375.4	−1.13

TABLE 12
Velocity of Sound in Air

Pressure atm.	Temperature K	Velocity of Sound meters/second		
		Experimental	Peng-Robinson	
			Calculated	% error
Rostafinski, 1959				
1.	293.15	344.1	343.6	−0.15
1.	373.15	385.9	387.3	0.36
1.	273.15	552.9	549.4	−0.63
1.	1273.15	700.1	698.6	−0.21
25.0	273.15	331.9	332.8	0.27
50.0	273.15	334.7	336.1	0.42
100.0	273.15	350.5	348.2	−0.66
Hodge, 1937				
1.	300.15	347.9	347.7	−0.06
10.	300.15	349.0	348.3	−0.20
30.	300.15	352.2	350.6	−0.45
50.	300.15	356.4	353.8	−0.73
70.	300.15	361.5	358.0	0.97
100.	300.15	370.3	365.7	−1.24