EFFECT OF OPERATING CONDITIONS ON ACOUSTIC GAS METERING IN THE NIGER DELTA

Isehunwa, O. S. & Harry Y.

Department of Petroleum Engineering, University of Ibadan, Nigeria

ABSTRACT

This study investigated the relationship between velocity of sound and properties of natural gases under different equations of state and the operational implications on acoustic gas metering. The velocity of sound was related to the thermodynamic properties of natural gas using both the Soave-Redlich-Kwong (SRK) and Peng-Robinson (PR) equations of state and applied to 5 wet and 5 dry natural gas samples from the Niger Delta at different conditions of temperature and pressure. Predicted results were statistically analyzed and compared with experimental data. For wet gas, SRK and PR equations gave average absolute deviation (AAD) of 9.50% and 1.15% for velocity of sound respectively; while AAD of 0.943% and 7.021% were obtained for dry gas, using the SRK and PR equations respectively. Predictions of sonic velocity and gas properties using both SRK and PR tend to give higher accuracy at high pressures than at ambient pressures and temperatures suggesting that correction factors must be implemented for ambient metering of gases when acouistic meters are used.

Keywords: *Natural gas, acoustic gas metering, sonic velocity, Equations of state, Wet gas, Niger Delta.*

1. INTRODUCTION

Accurate estimation of gas volumes and properties is crucial in gas custody transfer operations, design of pipelines, gas liquefaction processes and storage facilities. However, difficulties in achieving accurate direct measurement of gas volumes and thermodynamic properties has made it imperative to design most gas meters to measure properties such as the velocity of sound which can be measured accurately and related to thermodynamic properties using appropriate equations of state.

The speed of sound in fluids is an important physical property commonly used for accurate measurements in modern gas flow meters, analyzers and in the design of combustion chambers. Sonic velocity is also applied to determine hydrates, lost pigs and other obstructions in pipelines and for estimating liquid levels in gas wells. The indirect route of estimating physical properties of gases using sonic velocity is particularly attractive because measurement of speed of sound can be undertaken rapidly and accurately over a wide range of temperatures and pressures by means of automated facilities. Using the velocity of sound is known to give higher accuracy than any other physical property and has proved to be remarkably successful for gases provided thata robust equation of state is used.

One of the earliest works on the acoustic velocity of gases by Sherwood (1962) deemonstarted the relationship of sonic velocity to other properties of gases. In 1967, Andsager and Knapp applied acoustic velocity to determine liquid levels in gas wells. Thomas et al (1970) predicted acoustic velocity using pseudocritical pressure and temperature with the Benedict-Webb-Rubin equation of state. In 1978, Wallace and Ackerberg worked on the estimation of acoustic velocities in gas mixtures. They established that acoustic velocity is not a function of temperature alone but also of pressure. Similarly, Ye, Laouretter, Alliez, Xans and Mantel (1992) have published the results of experiments carried out on the speed of sound in moderately systemic and asymmetric binary mixtures as a function of temperature and pressure. In 1993, Riazi and Mansoori used the Virial equation of state to relate velocity of sound to PVT properties of gases. In 1999, Burstein, Ingmann and Michlin developed a correlation between molecular weights, heating value and acoustic speed under variable natural gas compositions.

From literature, it is clear that a major challenge has been the choice of appropriate equations of state to estimate thermodynamic properties of gases from measured sonic velocities. The practical implications of the effect of operating pressures and temperatures on acoustic gas metering in the Niger Delta is the subject of this study.

2. PROBLEM FORMULATION

The speed of sound in a compressible fluid can be expressed mathematically as:

$$c = \left[\left(\frac{\partial p}{\partial \rho} \right)_s \right]^{1/2} \quad \dots\dots\dots\dots\dots\dots\dots (1)$$

Expressing equation (1) in terms of specific volume gives:

$$c = \left[-V^2 \left(\frac{\partial p}{\partial V} \right)_s \right]^{1/2} \quad \dots\dots\dots\dots\dots\dots\dots (2)$$

However, S, the entropy can be expressed as a function of temperature and pressure in the form:

$$dS = \left(\frac{\partial S}{\partial T} \right)_p dT + \left(\frac{\partial S}{\partial p} \right)_T dp \quad \dots\dots\dots\dots (3)$$

The terms on the right hand side of equation (3) can also be written as:

$$\left(\frac{\partial S}{\partial T} \right)_p = \frac{C_p}{T} \quad \dots\dots\dots\dots\dots\dots\dots\dots (4)$$

Equation (4) leads to:

$$\left(\frac{\partial p}{\partial V} \right)_s = \frac{C_p}{C_v} \left(\frac{\partial p}{\partial V} \right)_T \quad \dots\dots\dots\dots\dots (5)$$

Or,

$$\left(\frac{\partial p}{\partial V} \right)_s = k \left(\frac{\partial p}{\partial V} \right)_T \quad \dots\dots\dots\dots\dots (6)$$

Where,

$$k = C_p / C_v$$

However, for a real gas.

$$pV = zRT \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots (7)$$

And,

$$\left(\frac{\partial p}{\partial V} \right)_s = k \left[\frac{\left(\frac{p}{V} \right)}{1 - \frac{p}{z}\left(\frac{\partial z}{\partial p} \right)_T} \right] \quad \dots\dots\dots\dots\dots (8)$$

Combining equations (6), (7) and (8) yields:

$$c = \left[-V^2 \left(\frac{-\frac{p}{V}}{1 - \frac{p}{z}\left(\frac{\partial z}{\partial p} \right)_T} \right) k \right]^{1/2} \quad \dots\dots\dots (9)$$

Or,

$$c = \left[\frac{kzRT}{1 - \frac{p}{z}\left(\frac{\partial z}{\partial p} \right)_T} \right]^{1/2} \quad \dots\dots\dots\dots (10)$$

Equation (10) can also be expressed in terms of the isentropic expansion coefficient:

$$n = -\frac{V}{p}\left(\frac{\partial p}{\partial V} \right)_s \quad \dots\dots\dots\dots\dots\dots (11)$$

Hence,

$$c = \sqrt{nzRT} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots (12)$$

Including the gravitational constant g_c, to make for consistency of units, we have:

$$c = \sqrt{g_c nzRT} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (13)$$

Equation (14) can also be written in the form:

$$c = \left[g_c n \frac{p}{\rho} \right]^{1/2} \quad \dots\dots\dots\dots\dots\dots (15)$$

However, for wet gas, material balance of the liquid and gas phases yields:

$$\rho_{wg} = X_g \rho_g + (1 - X_g)\rho_l \quad\text{..............................(16)}$$

Therefore, substituting for wet gas density in equation (15) yields:

$$c = \sqrt{g_c n \frac{p}{\dfrac{\rho_{wg} - (1 - X_g)\rho_l}{X_g}}} \quad\text{...................(17)}$$

Equation (17) can be simplified and expressed as:

$$c = \left[\frac{g_c n X_g p}{\rho_g RT \left[\rho_{wg} - (1 - X_g)\rho_l\right]} \right]^{1/2} \quad\text{...............(18)}$$

Equation (18) represents a simple expression which can be used to relate the sonic velocity of a wet gas.

EQUATIONS OF STATE
The SRK equation of state is given as:

$$p = \frac{RT}{V - b} - \frac{a\alpha}{V(V + b)} \quad\text{...............................(19)}$$

Where,

$$\alpha = \left(1 + \left(0.48508 + 1.55171\omega - 0.15613\omega^2\right)\left(1 - T_r^{0.5}\right)\right)^2$$

$$a = \frac{\Omega_a R^2 T_c^2}{p_c} \quad and \quad b = \frac{\Omega_b RT_c}{p_c}$$

$$\Omega_a = 0.42747 \quad and \quad \Omega_b = 0.08664$$

On the other hand, the Peng and Robinson equation of state is given as:

$$p = \frac{RT}{(V - b)} - \frac{a(T)}{V(V + b) + b(V - b)} \quad\text{............................(20)}$$

Where,

$$a(T) = a(T_c)\left(1 + k\left(1 - T_r^{1/2}\right)^2\right)$$

Or,

$$a(T) = a(T_c), a(T_r, \omega)$$
$$b(T) = b(T_c)$$

$$a(T_c) = 0.45724 \frac{R^2 T_c^2}{p_c}$$

$$b = 0.07780 \frac{RT_c}{p_c}$$

For $\omega \prec 0.49$
$$k = 0.37464 + 1.5422\omega - 0.26992\omega^2$$
And for $\omega \succ 0.49$,
$$k = 0.379642 + 1.48503\omega - 0.164423\omega^2 + 0.016666\omega^3$$

Mixing Rule
For the critical points, Spencer and Danner mixing rule was used:

$$T_{cm} = \frac{\sum x_i (V_{ci} T_{ci})}{\sum x_i V_{ci}} \quad\text{...(21a)}$$

And,

$$P_{cm} = \frac{T_{cm}}{\sum x_i \left(\frac{T_{ci}}{P_{ci}} \right)} \dots\dots\dots(b)$$

$$\omega_n = \sum_{i=1} x_i \omega_i \dots\dots\dots(c)$$

The classical Van der Waals mixing rules were however used to estimate the equation of state mixture parameters:

$$b_m = \sum_i x_i b_i \dots\dots\dots(22a)$$

$$a_m = \sum_i \sum_j x_i x_j a_{ij} \dots\dots\dots(b)$$

$$a_{ij} = \sqrt{a_i a_j}\left(1 - k_{ij}\right) \dots\dots\dots(c)$$

k_{ij} is the binary interaction parameter. In this work,

$$k_{ij} = 0.$$

3. RESULTS AND DISCUSSION

Table 1 gives typical compositions of the wet and dry gas reservoir samples in the Niger Delta used in this study. These compositional data and the corresponding experimental values of velocity of sound were obtained from laboratory analyses undertaken by Shell Petroleum Development Company, Port Harcourt.

Figures 1- 6 show the predicted values of velocity of sound using SRK and PR equations at different operating conditions. The SRK equation generally performed better in dry gases while the wet gas samples show more accurate estimates using the PR EoS.

Table 2 reports the calculated average absolute deviation values for the velocity of sound for the wet and dry gas samples as predicted by the two equations of state. The mean AAD (%) were established on the basis of the number of points for a given mixture, by:

$$AAD\% = \frac{100}{n} \sum_{i=1} \left| \frac{C_{exp} - C_{EoS}}{C_{exp}} \right| \dots\dots\dots(4.1)$$

Where:

n = number of points

C_{exp} = experimental value

C_{EoS} = predicted value

The SRK and PR equations of state gave the AAD velocity of sound for wet gas samples of 9.495%, and 1.149% respectively, while for dry gas, the AAD velocity of sound was established as 0.943% and 7.021%, using the SRK and PR equations respectively.

Overall, these results confirm that both the PR and SRK equations of state can be used to predict acoustic velocity in gases with relatively high accuracy. However, in all cases, higher deviations from experimental values occurred at low pressures while convergence was achieved at high pressures. This has practical implications in terms of gas metering when acoustic meters are used.

TABLE 1: COMPOSITION OF TYPICAL NIGER DELTA RESERVOIR GAS SAMPLES

Component	WET GAS	DRY GAS
	Mole Fraction	Mole Fraction
C1	0.8387	0.9824
C2	0.0531	0.0039
C3	0.0272	0.0029
I-C4	0.0045	0.0006
N-C4	0.0082	0.0029
I-C5	0.0028	0.0010
N-C5	0.0027	0.0013
C6	0.0031	0.0010
C7+	0.0240	0.0003
N2	0.0009	0.0020
CO2	0.0348	0.0017

TABLE 2: AAD FOR VELOCITY OF SOUND

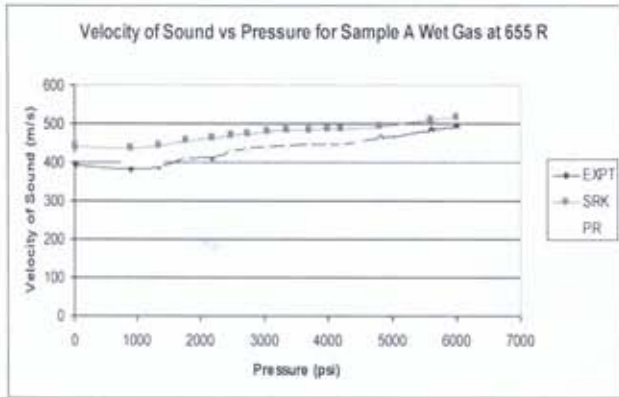| SAMPLE	NO. OF POINTS	AVERAGE ABSOLUTE DEVIATION (%)	
		SRK	PR
Wet Gas	45	9.495	1.149
Dry Gas	54	2.012	3.733

Fig. 1: Velocity of Sound for a Wet Gas sample at 655 °R
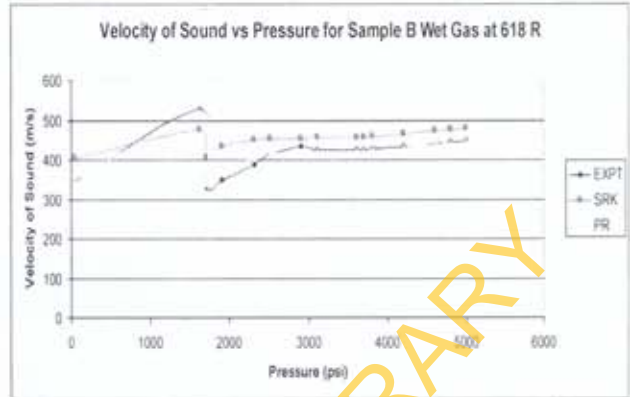

Fig. 2: Velocity of Sound for a Wet Gas sample at 618 °R
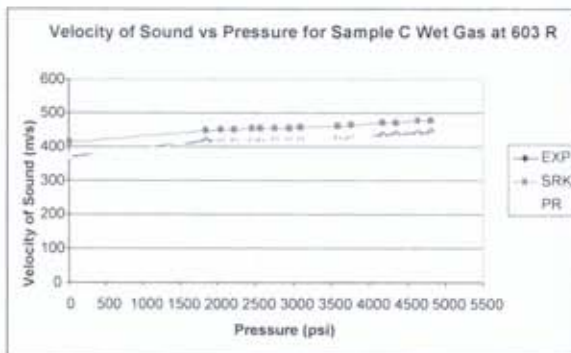

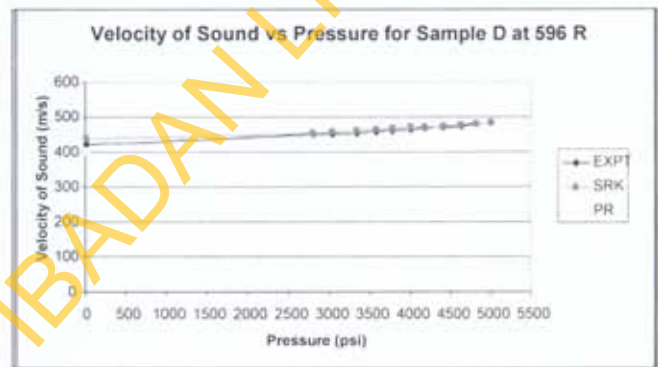Fig. 3: Velocity of Sound for a Wet Gas sample at 603 °R

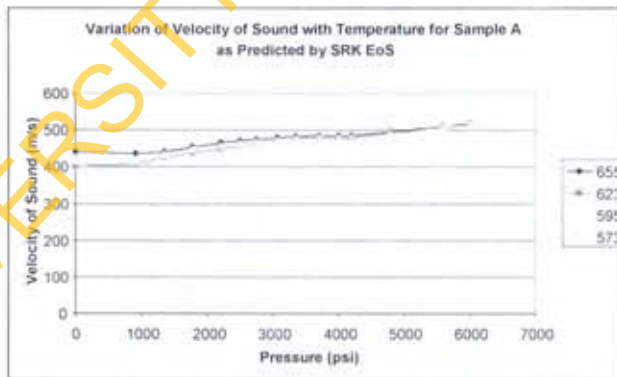Fig. 4: Velocity of Sound for a dry gas sample at 596 °R

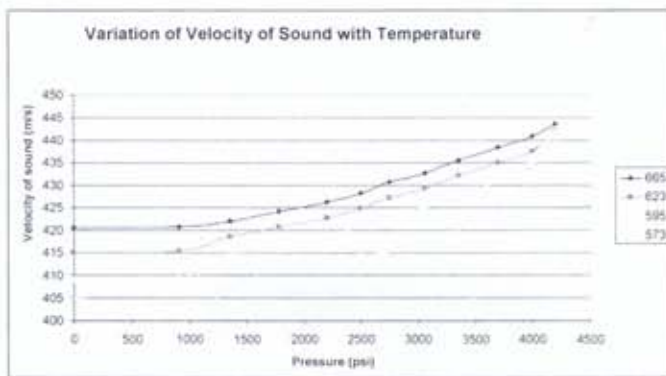Fig. 5: Variation of Velocity of Sound for a wet gas using SRK

Fig. 6: Variation of Velocity of Sound for a dry gas using PR

4. CONCLUSION

In conclusion, thermodynamic properties can be accurately determined from velocity of sound of dry and wet natural gases depending on the equations of state applied and the operating pressures and temperatures. In the Niger Delta, the PR EoS gives more accurate predictions for wet gases, while the SRK EoS proved better for dry gases. In both cases however, higher accuracy is achieved when metering at high pressures than at low pressures.

5. NOMENCLATURE

a, b	=	Parameter in the SRK and PR EoS
A, B, C	=	Coefficients of the cubic equation
AAD	=	Average Absolute Deviation
c	=	Velocity of sound
C_p	=	Specific Heat Constant Pressure
C_r	=	specific Heat Constant Volume
g_c	=	Gravitational constant
k	=	Compressibility coefficient
n	=	Isentropic expansion coefficient
p, P	=	Pressure
P_c	=	Critical Pressure
R	=	Universal Gas Constant
T	=	Temperature
T_c	=	Critical Temperature
T_r	=	Reduced temperature
V	=	(Molar) Volume
$V_{s,CEoS}$	=	Saturated liquid volume from EoS
$V_{s,exp}$	=	Experimental saturated liquid volume
X	=	Mole fraction
X_g	=	Gas slip
Z	=	Gas deviation factor
α	=	Thermal expansion coefficient
β_1, β_2	=	Constants in the SRK and PR EoS
ρ	=	Density

| ω | $=$ | Acentric factor |
| $\Omega_a, \Omega_b =$ | | SRK dimensionless parameters |

SUBSCRIPTS

c	$=$	Critical Property
g	$=$	Gas
l	$=$	Liquid
m	$=$	mixture
r	$=$	Reduced property
s	$=$	Adiabatic Property
wg	$=$	Wet Gas

6. ACKNOWLEDGEMENT

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