Acoustic velocities in super-critical hydrocarbon fluids and their relations to PVT data

Wu Xiangyang[1], Ge Hongkui[2] and Dehua Han[3]

[1] Institute of Geology and Geophysics, CAS, Beijing 100101, China
[2] Department of Petroleum Engineering, University of Petroleum of China (East China), Shandong 257061, China
[3] Houston Advanced Research Center, The Woodlands, TX 77381, USA

E-mail: xywu@mail.c-geos.ac.cn and xywu@vip.163.com

Abstract
Measurements on acoustic velocities and densities of a set of super-critical hydrocarbon fluids were taken at temperature up to 100 °C and pressure up to 70 MPa. The results showed that the velocities and densities of these hydrocarbon fluids above bubble points depend almost linearly on temperature and pressure. Dissolved gases can greatly change these fluid properties. Isothermal compressional wave velocity was introduced to correlate acoustic velocity data with PVT data through the heat capacity ratio γ. No obvious effects of gas on the relation of the acoustic and isothermal velocities was found, and the ratio γ for the super-critical hydrocarbon systems studied ranged between 1.1 and 1.4.

1. Introduction

Natural hydrocarbon fluids are mixtures of compounds. Their existing phases depend on the composition of the fluid as well as pressure and temperature. At the super-critical pressure and temperature, these hydrocarbon fluids can dissolve all gases and form a single phase. As pressure is reduced to below bubble points, the fluids are separated into gas and liquid phases. Within the two-phase region, the proportion of the liquid in the gas or gas saturation of oil will change with the P–T condition. In the Earth's surface, liquid oil is considered to be gas-free. Oils with gases dissolved in them are called live oils, while oils without gases are called dead oils. The focus of this study was on the acoustic velocity in super-critical live oils above bubble points. Also the correlation of acoustic velocity with isothermal compressional wave velocity was studied. For this purpose, the experimental studies on the densities of these super-critical live oils were included.
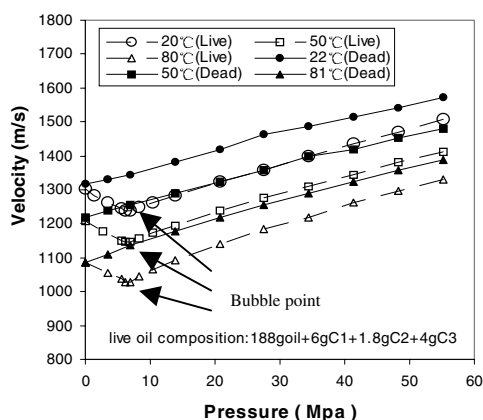
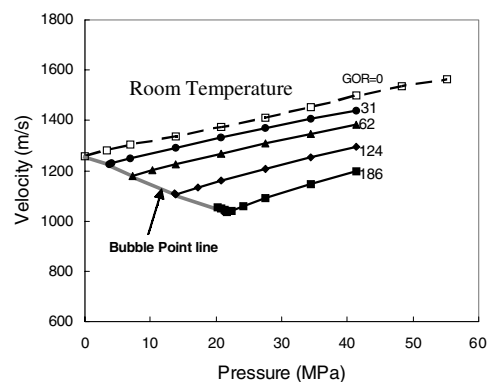**Figure 1.** Measured velocities in number 7 live oil and dead oil.

Figure 2. Measured velocities in sample number 8 with different GORs.

2. Measurement of acoustic velocities in super-critical hydrocarbon fluids

38 live oil samples were recombined above the bubble point pressure with dead oils and different amounts of various gases (mainly methane). With the pulse transmission method, acoustic velocity measurements were made on these super-critical fluids at temperatures up to 100 °C and pressures up to 70 MPa. For a comparative purposes, velocity tests were also made on the corresponding dead oils. Typically, velocities in liquid live oils decreased with decreasing pressure above bubble points, but increased with decreasing pressure below bubble points (figure 1), while velocities in dead oils only decreased monotonically with decreasing pressure. This velocity reversal in live oils should be due to the decrease in gas solubility (or GOR, gas–oil ratio) since some gases have come out of the live oils below the bubble point pressure. Dissolved gases had great effects on the velocities of super-critical live oils. Figure 2 shows that the more gas the live oil has dissolved in it, the lower its velocity is; the fastest velocity is in dead oil. The dependence of velocities of super-critical live oils on temperature T and pressure P in this experimental condition can described very well by

$$V_p = A - BT + CP + DTP, \tag{1}$$

where A, B, C, D are composition-dependent coefficients.

Equation (1) was used to describe the behaviours of velocities in pure substances and dead oils [1, 2] and in live oils [3].

3. Measurements of densities of super-critical hydrocarbon fluids

Densities of 24 live oils were measured under super-critical pressures and temperatures corresponding to the velocity tests. The density of one dead oil was also measured for comparative purposes. The test method was the constant-mass volume expansion technique which is usually used in fluid P–V–T tests. The typical behaviours of densities of live oils as a function of pressure and temperature are shown in figure 3. Above bubble points, the density increases almost linearly with increasing pressure and decreases with increasing temperature. But some slight nonlinearly was observed near the bubble points. As pressure reduced to below bubble points, the density showed a drastic drop. Figure 4 shows the effects of dissolved gases on live oil density in super-critical conditions. It illustrates that the more gas dissolved in the oil, the lower the density.
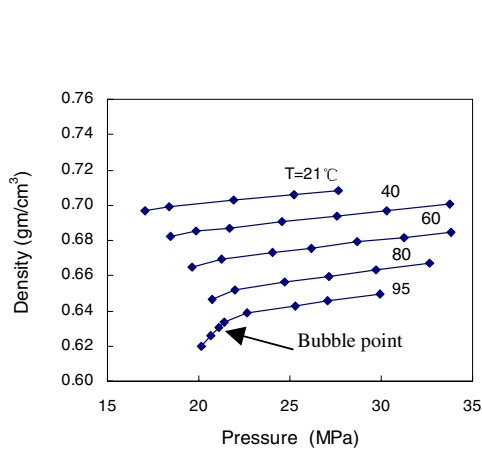
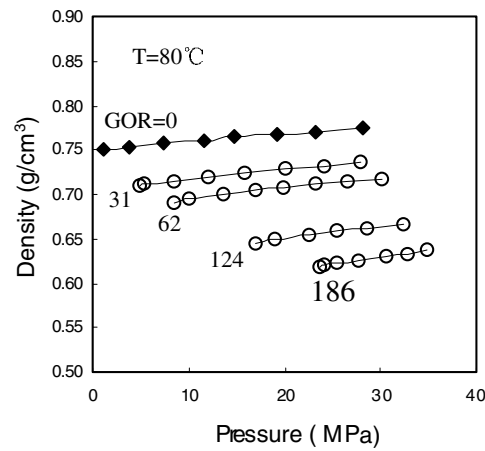**Figure 3.** Measured densities of live oil sample number 11.

Figure 4. Measured densities of sample number 8 with different GORs.
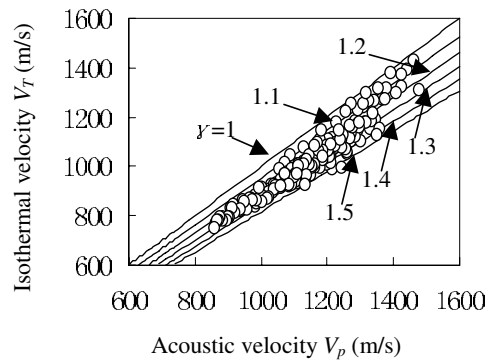

Figure 5. Measured acoustic velocity versus isothermal compressional wave velocity. Solid curves are drawn using equation (3).

4. Discussion of the relation of the acoustic velocity to the isothermal compressional wave velocity obtained from PVT data

Acoustic velocities in fluids are pure thermodynamic quantities; if the equation of state (EOS) is precise enough, one can derive $P-V-T$ properties of the fluids by acoustic velocity measurements. Since usually acoustic velocity measurements are very simple and can also provide more precise information than $P-V-T$ tests do, it should be useful to estimate the $P-V-T$ properties of fluids from acoustic velocity data. But the process of acoustic wave propagation in a fluid is adiabatic, since the acoustic wave passes so rapidly through the fluid; in contrast, the properties of a fluid (such as compressibility β_T) obtained from $P-V-T$ measurement are often isothermal values. For comparison of adiabatic acoustic velocities with the isothermal coefficient of the fluids, an isothermal compressional velocity V_T is introduced:

$$V_T = \sqrt{\frac{1}{\rho \beta_T}},\tag{2}$$

where ρ is the density of the fluid. Theoretically the acoustic velocity V_P is correlated with the isothermal compressional velocity through γ, the ratio of heat capacity at constant pressure to heat capacity at constant volume; e.g.,

$$V_P^2 = \gamma V_T^2. \tag{3}$$

It is obvious that the ratio γ is a key parameter for conversion between the adiabatic properties and the isothermal ones. Theoretically the ratio γ can be derived from the other thermodynamic properties of thermal expansion α, density ρ, constant-pressure heat capacity C_P as well as compressibility β_T:

$$\frac{1}{\gamma} = 1 - \frac{\alpha T}{\rho \beta_T C_P}. \tag{4}$$

But these thermodynamic properties are not easy to ascertain for a real complex hydrocarbon system. For evaluation of the ratio γ of the super-critical hydrocarbon systems of this study, the direct calculation of the ratio γ is made using the experimental data according to equations (2) and (3). The isothermal compressional velocities were obtained from density data via

$$V_T = \sqrt{\left(\frac{\partial P}{\partial \rho}\right)} \approx \sqrt{\left(\frac{P_2 - P_1}{\rho_2 - \rho_1}\right)}, \tag{5}$$

where P is pressure, ρ is density, and the subscripts 1 and 2 denote the two neighbouring test points. Figure 5 shows an experimental relation of acoustic velocity with isothermal compressional velocity. The theoretical curves of equation (3) with different ratios γ are also shown in the same figure. Comparing the experimental and theoretical results, it is found that most data lay within a narrow band which was described with the ratio γ ranging over 1.1–1.4; no obvious effects of gases were observed.

5. Conclusions

According to the experimental data, the behaviours of velocities and densities of super-critical hydrocarbon fluids above bubble points depend almost linearly on temperature and pressure. Dissolved gases can greatly change these fluid properties, but there are no obvious effects of gas on the relation of acoustic velocity to isothermal compressional velocity; the ratio γ for the super-critical hydrocarbon systems studied ranges between 1.1 and 1.4.

Acknowledgment

References

[1] Wang Z, Nur A and Batzle M 1988 Acoustic velocities in petroleum oils *Proc. 63rd Soc. Petroleum Engineers Technical Conf. on Formation and Evaluative Research in Geology* pp 571–85
[2] Wang Z 1988 Wave velocities in hydrocarbons and hydrocarbon saturated rocks—with applications to EOR monitoring *PhD Thesis* Stanford University, CA
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