CO_2 Velocity Measurements and Models for Temperatures down to -10 °C and up to 200 °C and Pressures up to 100 MPa

Min Sun and De-hua Han, Rock Physics Lab, University of Houston*
Micheal Batzle, Colorado School of Mines

Summary

Studies concerning how CO_2 velocity is affected by a wide range of temperatures and pressures are important in understanding CO_2 behavior in fluid and rock systems. Three laboratory experiments were carried out to investigate the effect of temperature and pressure on CO_2 velocity for the range $-10\,^{\circ}C \le T \le 200\,^{\circ}C$ and $7\ MPa \le P \le 100\ MPa$. The results show that CO_2 velocity increases as pressure increases and as temperature decreases in the temperature ranges of $-10\,^{\circ}C \le T \le 20\,^{\circ}C$ and $25\,^{\circ}C \le T \le 200\,^{\circ}C$. Near the critical point (31°C and 7.4 MPa), CO_2 velocity is very sensitive to temperature and pressure change. CO_2 velocity models were developed to better match the experimental data.

Introduction

Recently, carbon dioxide has been considered as an important agent in global warming that has occurred due to rising temperature of the earth. The increased concentrations of CO_2 in the atmosphere have been associated with human activity. Extensive studies on the properties of CO_2 have been undertaken both experimentally and theoretically in order to find ways to minimize its impact on the environment. Consequently, CO_2 sequestration, injection and storage are increasingly becoming the climate change and industrial strategies of oil companies. In oil and reservoir conditions, temperature and pressure are higher up to 200 °C and 100 MPa. At lower temperature, one way to combat climate change is to store CO_2 in to the deep ocean around 3000 meters where temperature and pressure are about 6.9 °C and 40 MPa. Pipeline conditions are usually in the ranges of temperature -20 to 50°C and pressure 5 to 25 MPa (Folas et al., 2007). To understand the properties of CO_2 at a wide range of temperature and pressure is crucial for CO_2 operations. Theoretically, many equations of state are unable to predict the thermodynamic properties of CO_2 accurately over the entire range of temperature and pressure required for CO_2 operations (Batzle,1998). Laboratory measurements of acoustic properties of CO_2 are rarely available beyond 40 MPa.

In the Rock Physics Laboratory (RPL), University of Houston, the CO_2 velocity has been measured over a wide range of temperature from $-10\,^{\circ}$C to 200°C and pressure from 7 MPa up to 100 MPa. Models were built to fit the measured data.

Experiments

Considering different behaviors of CO_2 velocity in the wide range of temperature and pressure, we separated the interested region to the three parts:

a. the low temperature and high pressure range: $-10\,^{\circ}C \le T \le 20\,^{\circ}C$ and $20\,MPa \le P \le 100\,MPa$.
b. the high temperature and high pressure range: $25\,^{\circ}C \le T \le 200\,^{\circ}C$ and $20\,MPa \le P \le 100\,MPa$.
c. the low pressure range: $7\,MPa < P < 20\,MPa$.

Correspondently, three experiments were performed.

Measurement results and discussions

Since the CO_2 is a fluid in the measured range, we can use the following definition of the compressional velocity to understand its properties (McCain, 1990),

$$V_p = \sqrt{\frac{K}{\rho}},$$

where K is bulk moduli and ρ is density.

<u>Velocity properties in the low temperature and high pressure range</u>

The measured velocities within the low temperature and high pressure range $-10\,^{\circ}C \le T \le 20\,^{\circ}C$ and $20\,MPa \le P \le 100\,MPa$ are plotted in Fig.1. The compressional velocity increases as pressure increases at a given temperature, but it decreases as temperature increases at a given pressure. Because CO_2 is liquid below the critical temperature 31°C and above the critical pressure 7.4 MPa, the bulk modulus increases faster than density with increasing pressure. At a given pressure, increasing temperature will increase pressure. But in order to keep the constant pressure, releasing the pressure will decrease the bulk modulus faster than the density, and then the velocity decreases. The effects of the temperature and pressure become more pronounced as the pressure decreases to below 40 MPa, since the CO_2 liquid is approaching to the critical point and the phase boundary of liquid and gas.

CO_2 Velocity Measurements and Models

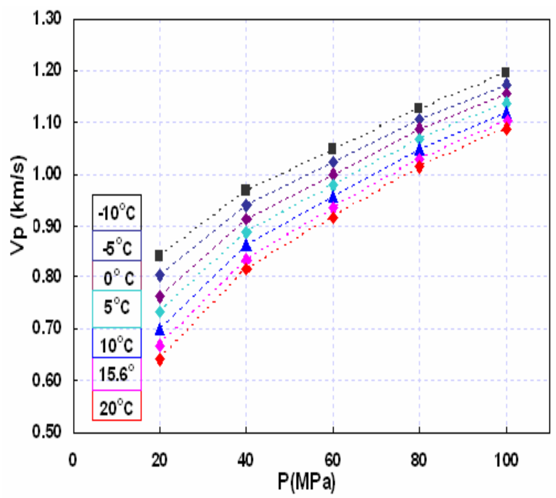

Fig.1 Measured velocities of CO_2 as a function of pressure P for different temperatures from 20 °C down to -10 °C.

Velocity properties in the high temperature and high pressure range

Like in the low temperature range, the CO_2 velocity increases as pressure increases at a given temperature, and it decreases as temperature increases at a given pressure (Fig.2). But the temperature effect becomes complicated. A small increase in temperature causes a large decrease in the velocity when temperature is lower. Higher temperature has less effect to decrease velocity than that of lower temperature. For example, when the pressure is around 40MPa, the temperature increases 25°C from 25°C to 50°C, the velocity decreases several times comparing to the temperature increases from 150°C to 200°C, where the velocity doesn't lower much by the temperature increases.

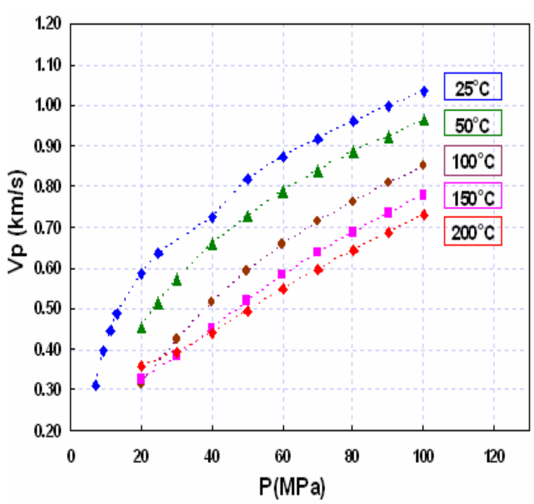

Fig.2 Measured velocities of CO_2 as a function of pressure P for different temperatures from 25 °C up to 200 °C.

With the temperature increases over the critical temperature (31°C), CO_2 is supercritical fluid. Because the properties of the supercritical fluid are more like "gas" at the low pressure range, the effects become greater as the pressure decreases to below 40 MPa. Generally, the compressional velocity in the CO_2 gas phase decreases as pressure increases because density increases faster than the bulk modulus. But in the supercritical fluid phase, the velocity also increases as pressure increases because the bulk modulus also increases fast with a given temperature. When the pressure increases over 20 MPa, the bulk modulus increase faster than the density, therefore, the velocity continues to increase with pressure increases.

Velocity properties around the CO_2 critical point

The velocity properties around the CO_2 critical point (31° C and 7.4 MPa) are very sensitive to temperature and pressure change. There are liquid phase, gas phase, liquid/gas phase boundary and supercritical fluid in the region. Even within the range of pressure up to 40 MPa, the temperature and pressure effects are still complicated. Fig. 3 shows the measured data around the critical point, the temperature from 25°C to 45°C and pressure from 7 MPa to 13 MPa.

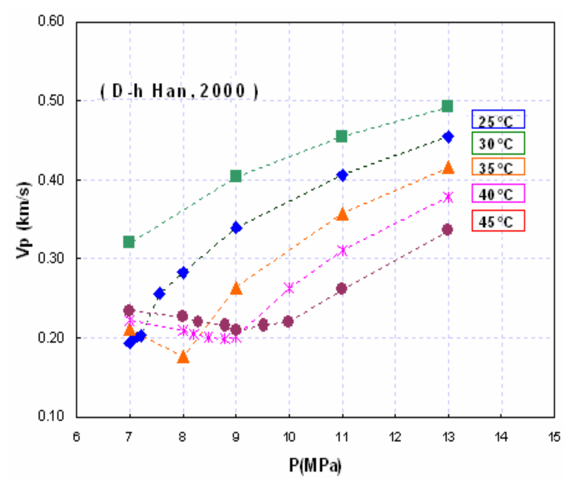

Fig.3 Measured velocities of CO_2 as a function of pressure P for the range near the CO_2 critical point.

With the pressure above the critical point from 7.4 to 13 MPa and the temperature bellows the critical point, the CO_2 is in the liquid phase. The velocity increases with pressure increases. Above the supercritical temperature (31° C), the CO_2 is the supercritical fluid. The velocity decreases to a certain point first, and then increases as the pressure increases. The turn point of the velocity shows the property of the supercritical fluid changed from like "gas" when the pressure is lower, to like "liquid" with pressure increases.

CO_2 Velocity Measurements and Models

Empirical Models

Empirical models have been developed to fit the experimental data and to describe the effects of temperature and pressure on CO_2 velocity.

Model for the low temperature and high pressure range

Based on the experimental result, the following polynomial model is suitable to describe CO_2 velocity as a function of temperature and pressure for this range,

$$V_p = a + bT + cT^2 + dP + eP^2 + fTP \,,$$

where

a = 0.61571 b = -0.00709 c = 0.00002
d = 0.00833 e = -0.00003 f = 0.00004.

The result of comparing the calculated CO_2 velocities with the measured data shown in Fig. 4, indicates that the model is correct to evaluate the CO_2 velocity at the range of temperature and pressure, $-10\,^{\circ}C \le T \le 20\,^{\circ}C$ and $20\,MPa \le P \le 100\,MPa$.

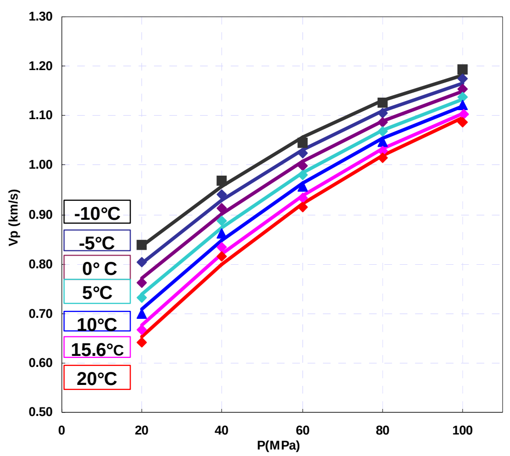

Fig.4 Calculated (solid lines) and measured velocities of CO_2 as a function of pressure P for different low temperatures from 20 °C down to -10 °C.

Model for the high temperature and high pressure range

The measured data show that the CO_2 velocities of the high temperature range are more likely extended from those of the low pressure area. We can use the following model to better match the measured data within the two regions, the high temperature and high pressure range, and the low pressure range,

$$V_p = (1 - W_f)V_{lp} + W_f V_{hp} \,,$$

where

$$W_f = \frac{W_{f1} + |W_{f1}|}{2(0.5 + |W_{f1}|)}$$

$$V_{lp} = 150 + 120T_{pr} - [9 + 175(1.5 - T_{pr})^2]P_{pr}$$

$$V_{hp} = 45 + 600(a - T_{pr})^3 + 246|P_{pr} - S_{hp}|^{0.44}$$

$$W_{f1} = (P_{pr} + 7.661 - bT_{pr})^9$$

$$P_{pr} = \frac{P}{7.386} + 4.20831\frac{T^{1.43}}{(c - T)(1 + 1.249P)}$$

$$T_{pr} = \frac{1}{304.21}[T_{abs} - d(304.21 - T_{abs})]$$

$$T_{abs} = T + 273.15$$

The parameters for the high temperature and high pressure range are

a = 1.71 b = 7.789 c = 312 d = 0.

In Fig.5, comparing the computed CO_2 velocity with the measured data shows that the model can be used to predicate CO_2 velocity at a wide range of temperatures (from 25°C to 200°C) and pressures (from 20 MPa to 100 MPa).

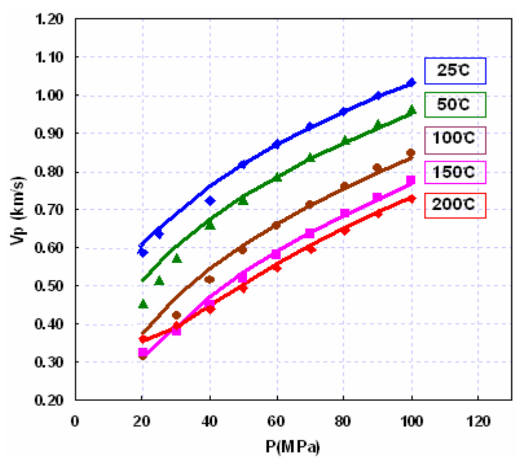

Fig.5 Calculated (solid lines) and measured velocities of CO_2 as a function of pressure P for different temperatures from 25 °C up to 200 °C.

Model for the low pressure range

Since the low pressure range from 7 to 20 MPa includes the CO_2 critical point, the velocity is very sensitive to temperature and pressure change. The model for the high temperature and high pressure range can be used to predict the its behavior with the parameters,

a = 1.66 b= 6.405 c = 30000 d = 40.

CO_2 Velocity Measurements and Models

The result shown in the Fig.6 indicates they are matched, but the more libratory data are needed to correct the model, especially near the critical point.
Comparing the measured CO_2 velocities with calculated by the model and by Span & Wagner's equation of state (EOS)

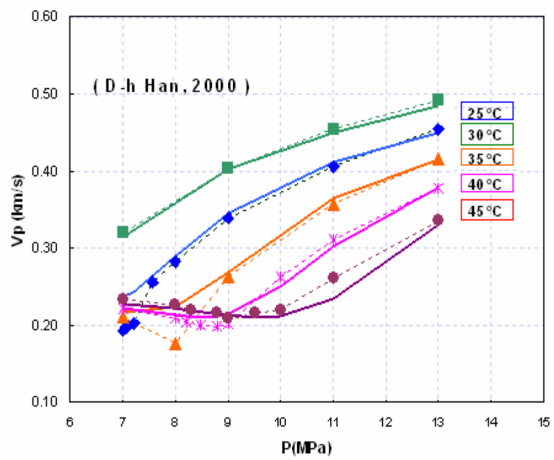

Fig.6 Calculated (solid lines) and Measured (dashed lines) velocities of CO_2 as a function of pressure P for the range near the CO_2 critical point.

(Span and Wagner, 1996) is shown in Fig.7 and Fig.8. The EOS equation for carbon dioxide is able to describe almost all reliable measured data within their experimental uncertainty, and is valid in the wider fluid region from the triple-point temperature to 1100K at pressures up to 800 MPa. The equation is accurate but contains many terms. Some of the terms are complex exponential which become difficult for computation. Our model with less terms and simple exponentials is simpler and easer to use. Fig.8 shows that the model is less accurate than Span and Wagner's in the lower pressure regions but more of a match to the measured data as pressure increases.

Conclusions

Laboratory experiments were carried out to study the effects of temperature and pressure on CO_2 velocity for a wide range of temperatures and pressures, $-10^\circ C \le T \le 200^\circ C$ and $7\,MPa \le P \le 100\,MPa$. Clearly, CO_2 velocity increased as pressure increased and temperature decreased at the ranges of $-10^\circ C \le T \le 20^\circ C$, $20\,MPa \le P \le 100\,MPa$ and $25^\circ C \le T \le 200^\circ C$, $20 MPa \le P \le 100 MPa$. When pressure bellows to 20 MPa, CO_2 velocity is vary sensitive to temperature and pressure change. The CO_2 velocity models have been developed to match the experimental data and describe the relationships of CO_2 velocity with temperature and pressure. However, more laboratory data are needed to limit the bias of the experimental data and to correct the models.

Acknowledgments

This research has been supported by the "Fluids/DHI" consortium, which is sponsored by industry and collaborated between University of Houston and Colorado School of Mines.

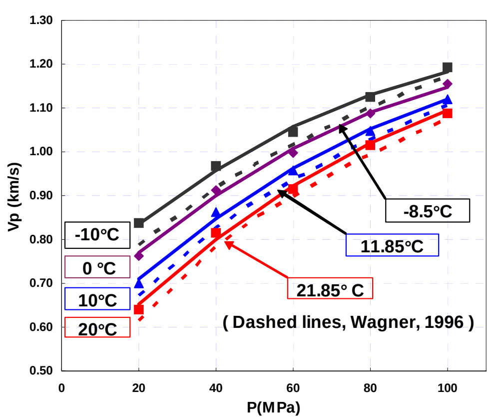

Fig.7 Comparing the calculated (solid lines) and measured velocities with the calculated velocities (dashed lines) by Span and Wagner for the low temperature and high pressure range.

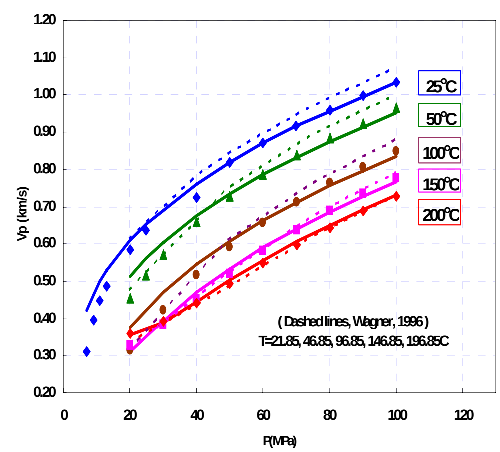

Fig.8 Comparing the calculated (solid lines) and measured velocities with the calculated velocities (dashed lines) by Span and Wagner for the high temperature and high pressure range.

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2009 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Batzle, M., R. Christiansen, and D. Han, 1998, Reservoir recovery processes and geophysics: The Leading Edge, **10**, 1444–1447.

Folas, G. K., E. W. Froyna, J. Lovland, G. M. Kontogeorgis, and E. Solbraa, 2007, Data and predition of water content of high pressure nitrogen, methane and natural gas: Fluid Phase Equilibria, **252**, 162–174.

McCain, Jr., W. D., 1990, The properties of petroleum fluids, 2nd ed.: PennWell Publishing Company.

Span, R., and W. Wagner, 1996, A new equation of state for carbon dioxide covering the fluid region from the triple temperature to 1100 K at pressures up to 800 MPa: Journal of Physical and Chemical Reference Data, **25**, 1509–1596.