

## Velocity Properties of CO<sub>2</sub>-saturated Water and Methane-saturated Water at Temperatures up to 200 °C and Pressures up to 138 MPa

Min Sun\* and De-hua Han, Rock Physics Lab, University of Houston

### Summary

Within a wide range of temperatures (25°C up to 200°C) and pressures (10,000 psi to 20,000 psi), the velocities of CO<sub>2</sub>-saturated water and methane-saturated water were investigated and compared. Experimental results show that the effects of temperature and pressure on the velocities of CO<sub>2</sub>-saturated water and methane-saturated water are the same trends as on that of pure water. The effect of solubility generally decreases the velocity of saturated water, but only 1~3 % for the velocity of methane-saturated water and the difference is ignorable. A special temperature around 60°C reverses the velocity of CO<sub>2</sub>-saturated water from higher to lower than that of pure water with temperature increases. The different velocity slopes and solubility effects may separate velocity properties of CO<sub>2</sub>-saturated water from that of methane-saturated water.

### Introduction

Water, brine and methane are major components of hydrocarbon reservoirs and their behaviors have been investigated for many years. With CO<sub>2</sub> operation gets more attentions currently as climate change and industrial strategies, to better understand properties of H<sub>2</sub>O-CO<sub>2</sub>-CH<sub>4</sub> system under oil and reservoir conditions (up to 200°C and 20,000 psi) is important for us to detect or monitor fluids seismically in rock and fluid systems.

We have experimentally studied the velocities of water saturated with CO<sub>2</sub>, in the range of temperature from 23°C up to 150°C and pressure from 10,000 psi to 20,000psi, and the velocities of water saturated with methane in the range of temperature from 25°C up to 200°C and pressure from 10,000 psi to 20,000 psi. In this paper, we present the measured results, and discuss the effects of temperature, pressure and solubility on velocity of saturated water. These measurements are hoped to be helpful in understanding properties of real water in situ conditions and finding a clue to separate the velocity properties of CO<sub>2</sub>-saturated water from that of methane-saturated water.

### Experiments set up and procedures

The experiments were designed to measure velocities of water fully saturated with CO<sub>2</sub> (CO<sub>2</sub>-saturated water), and water fully saturated with methane (methane-saturated water) in high temperature and pressure conditions. The CO<sub>2</sub> with purity > 99.5% and methane with purity >

99.97% were obtained from commercial sources. The measurement system consists of test vessel, storage vessel, temperature control, pressure control and rocking equipments. The test vessel included two acoustic transducers (one on each side of the fluid-sample chamber), a pressure transducer and a thermal coupler connected to a pressure gauge and a digital temperature meter respectively to measure the pressure and temperature of the fluid sample. CO<sub>2</sub> or methane was held in the storage vessel. One side of the storage vessel was connected to the test vessel for providing CO<sub>2</sub> or methane and pressure. The temperature of the test vessel was provided by a flexible heater wrapped on the test vessel, and the temperature of the flexible heater was controlled by a digital temperature controller. The test vessel was set up on a rocking machine horizontally, which kept rocking during the saturating process (Fig.1).

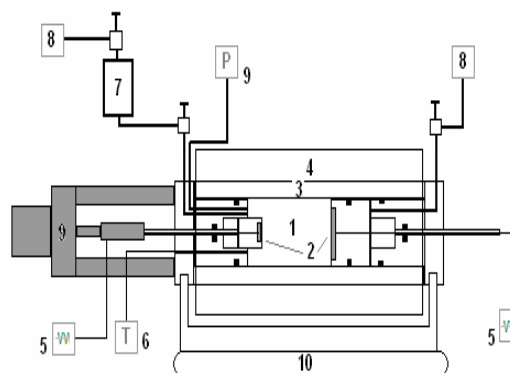


Fig.1 Schematic experimental setup used in the study.  
1. fluid sample; 2. transducers; 3. sample vessel;  
4. temperature controller; 5. scope; 6. temperature indicator; 7. storage vessel; 8. digital pump; 9. pressure gauge; 10. rocking machine.

After evacuating the sample chamber, 75% of the volume was filled with distilled water, and the remaining 25% of volume was left for CO<sub>2</sub> or methane. The horizontal orientation of the test system allowed the acoustic transducers of both sides to be merged into the fluid sample, and provided a larger contact surface between water and CO<sub>2</sub> or methane. At a given temperature, velocity of water fully saturated with CO<sub>2</sub> or methane was measured as a function of pressure. For each given point of

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the temperature and pressure, the rocking machine ran between 12 to 24 hours in order to allow water to be fully saturated with CO<sub>2</sub> or methane. The saturation time depends on temperature and pressure. High temperature and low pressure require more time to stabilize. Data were recorded when the fluid was at a stable condition of temperature, pressure and saturation.

### Results and discussions

#### Measured data

Velocities of CO<sub>2</sub>- and methane-saturated water were measured as a function of temperature and pressure in the designed ranges. The velocity data of CO<sub>2</sub>-saturated water spend from 34.48 MPa (5,000 psi) up to 103.44 MPa (15,000 psi), and temperature from 23° C ( 73.4° F) to 150° C (302°F). The velocity data of methane-saturated water cover a range from 68.96 MPa (10,000 psi) up to 137.92 MPa (20,000 psi), and 25° C ( 77°F) up to 200° C (392°F) (Fig.2.a).

The velocity data measured in 2001 indicate the velocity behaviors of methane-saturated water comparing to that of water undersaturated with methane (Fig.2.b). The sample of 'live' water saturated with methane was made by dissolving methane in water at a bubble point of 69 MPa (10,000 psi). At 69 MPa and room temperature, the solubility of methane in pure water was calculated around 0.3092 mol/kg. Since solubility is a function of temperature and pressure, water was fully saturated with methane within the indicated range on the solubility-pressure plot, where the solubility is lower than 0.3092 mol/kg. The rest of the area was undersaturated. The measured data show the influence of the three factors on the velocities - pressure, temperature and solubility. They are also the maximum influences in situ condition, since distilled water was used in the fluid

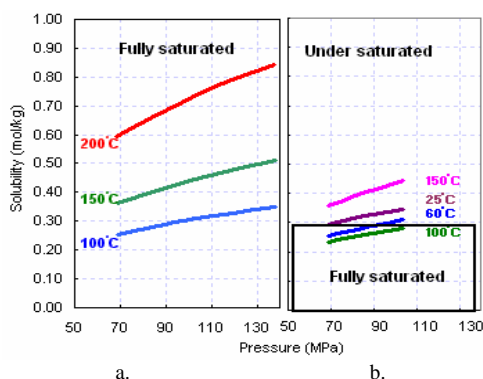


Fig.2 Methane solubility of the two sets of measured data. a. solubility of water fully saturated with methane in the high temperature and high pressure range; b. solubility of water saturated and undersaturated with methane.

samples, which has higher solubility for hydrocarbon gases than that of brines.

#### Calculated data

The IAPWS-IF97 Equations for water are used to calculate the properties of distilled water (Wagner and Kruse, 1998). The CO<sub>2</sub>'s solubility is obtained from Duan' model ( Duan, 2003), which gives results within or close to experimental uncertainty ( about 7%) in the temperature range from 0 to 263°C, and pressure from 0 to 200 MPa. The solubility of methane is calculated according to a new methane solubility correlation developed by Spivey et al (2004). The new correlation is valid in a wide range of temperatures from 0 to 300°C, and pressures from 1 to 200 MPa.

#### Pressure effect

The effects of pressure on velocities of CO<sub>2</sub>- and methane-saturated water at different temperatures are plotted in Fig. 3. Like the velocity of pure water, pressure's effect is almost linear positively within the measured range at the given temperatures. The velocity of CO<sub>2</sub>- and methane-saturated water increases with increasing pressure.

A difference between velocities of CO<sub>2</sub>- and methane-saturated water is the trends of the velocities with pressure

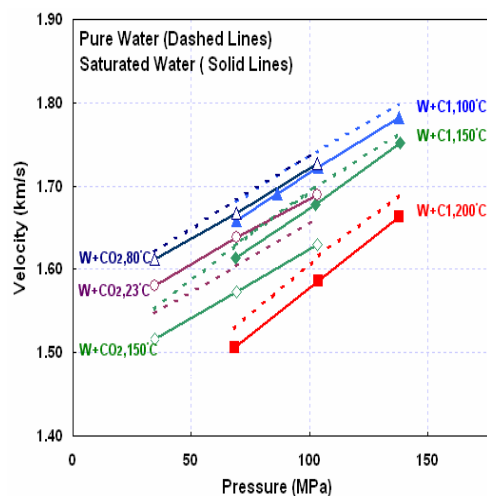


Fig.3 Velocities of CO<sub>2</sub>-saturated water, methane-saturated water, and pure water.

increases. Comparing the velocity slopes of the pure water, the velocity slope of CO<sub>2</sub>-saturated water becomes lower with pressure increases. But slopes of methane-saturated water tend to keep the same as that of pure water. Generally, dissolved gas will decrease the velocity of water. The different slopes of the gas (CO<sub>2</sub>/methane) fully saturated water may provide boundaries for velocities of

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H<sub>2</sub>O-CO<sub>2</sub>-CH<sub>4</sub> mixed system at the temperature range higher than 60°C. A velocity slop of pure water suggests a high boundary, and a velocity slop of CO<sub>2</sub>-saturated water can be a low boundary.

#### Temperature effect

The temperature effect on the velocity of CO<sub>2</sub>-saturated water is apparent (Fig.4). Comparing with the velocity of the pure water, the velocities of CO<sub>2</sub>-saturated water increase to their maximum range around 70°C and then decrease to a lower end with temperature increases from the room temperature up to 150°C. Within the measured temperature and pressure ranges, the maximum of the different velocity is around 90 m/s at the high temperature and high pressure end.

The measured data clearly show a special phenomenon. When temperature is below 60°C, the saturated CO<sub>2</sub> increases the velocity of CO<sub>2</sub>-saturated water with temperature decreases. But above 60°C, the saturated CO<sub>2</sub> begins to lower the saturated velocity. Comparing the velocity of pure water, the CO<sub>2</sub>-saturated velocity reverses around 60°C, which works like a “critical temperature”. This special phenomenon reveals the effect of solubility.

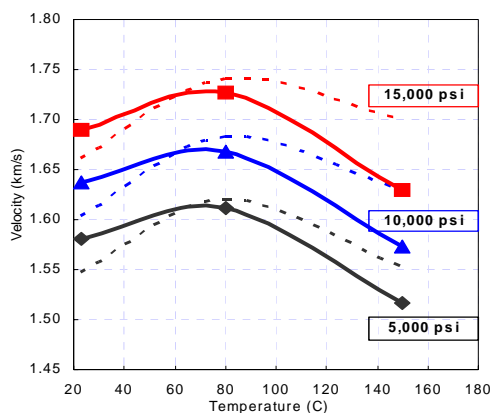


Fig. 4 Velocity of CO<sub>2</sub>-saturated water (solid lines) and velocity of pure water (dashed lines).

Measured velocities of methane-saturated water as a function of temperature are plotted on Fig.5. At the high temperature and pressure range, the velocities decrease a little with increasing temperature. Measured data in 2001 shown in the Fig.5.b indicate that the temperature effect on velocity of methane-saturated water is the same of pure water. The maximum velocity occurs around 80°C. With temperature increasing from the room temperature up to 200°C, velocity of methane-saturated water increases to its maximum range and then decreases to a lower end.

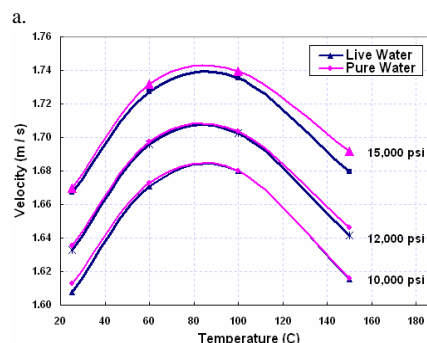
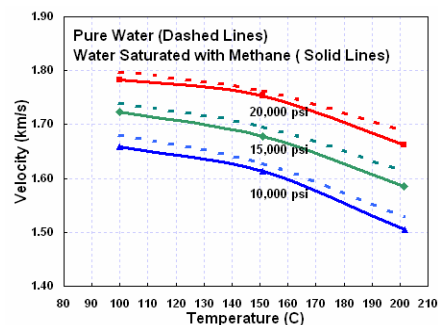


Fig.5 Velocity of methane-saturated water and velocity of pure water.

There are two differences between the effects of temperature on the velocities of CO<sub>2</sub>- and methane-saturated water. One is the range of the maximum velocity. For CO<sub>2</sub>-saturated water it appears around 70°C, but about 80°C for the methane-saturated water. The other is different strength of the effect. Above the “critical temperature”, the higher temperature the lower velocity, and the higher pressure also the higher velocity. The high temperature will significantly decrease the velocity of CO<sub>2</sub>-saturated water. The maximum difference between velocities of CO<sub>2</sub>-saturated water and pure water is two to three times of methane’s, which is only 1~3 % and can still be ignorable.

#### Solubility effect

Generally, dissolved gas causes velocity of saturated water to be lower than that of pure water, which is shown on above pressure and temperature effects. The special case that saturated CO<sub>2</sub> increases the velocity higher than that of pure water clearly discovers the solubility effect. But it is difficult to separate the effect of solubility from the effect of temperature and pressure since solubility is also a function of temperature and pressure. By comparing the velocity of CO<sub>2</sub>- and methane-saturated water, their solubility and bulk modulus, we can give some reasonable expressions.

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The solubilities of CO<sub>2</sub> and methane in distilled water are plotted in Fig.6. Fig.7 shows the correlations of the bulk modulus and temperature. The high velocity of CO<sub>2</sub>-saturated water below 60°C can be due to CO<sub>2</sub>'s high solubility and high modulus. With the temperature decreases to below 60°C, the bulk modulus of water decrease, but the bulk modulus of CO<sub>2</sub> increases significantly. Meanwhile, the solubility of CO<sub>2</sub> increases. Since acoustic velocity is a function of bulk modulus and density, the more CO<sub>2</sub> with higher bulk modulus dissolved in the water, the more the velocity of CO<sub>2</sub>-saturated water increases. Although additional density of the CO<sub>2</sub> will decrease the velocity, the dominant effect on the velocity of CO<sub>2</sub>-saturated water should come from bulk modulus of CO<sub>2</sub>. On the other hand, with temperature increases over 60°C, the lower CO<sub>2</sub> modulus decrease the velocities of CO<sub>2</sub>-saturated water, although solubility still increases beyond its lowest point as temperature increases.

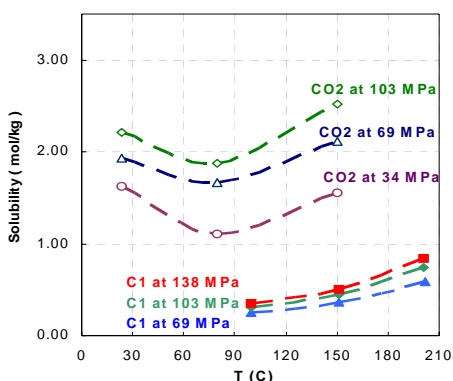


Fig.6 Solubility of CO<sub>2</sub> and methane in pure water as a function of temperature .

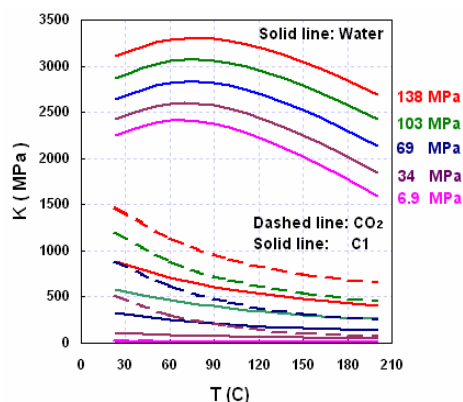


Fig.7 Bulk modulus of pure water, CO<sub>2</sub> and methane.

The bulk modulus of methane also increases when temperature is below 60°C, but they are much lower than that of CO<sub>2</sub>. The solubility and bulk modulus of methane are too low to increase the saturated velocity over that of pure water. The solubility effect also shows in Fig.5.b. The measured velocity of the ‘live’ water is only a little different from that of distilled water since the constant solubility is only 0.3092 mol/kg. The velocity of water undersaturated with methane is always lower than that of methane-saturated water.

### Conclusions

The velocities of CO<sub>2</sub>-saturated water and methane-saturated water were investigated and compared. Within a wide range of temperatures from 25°C up to 200°C and pressures from 10,000 psi to 20,000 psi, the experimental results show the following features.

1. The effects of temperature and pressure on velocities of CO<sub>2</sub>-saturated water and methane-saturated water are the same trends as on that of pure water.
2. The effect of methane's solubility decreases velocity of methane-saturated water by about 1 to 3 % and it is still ignorable. The solubility effect is even smaller on the velocity of undersaturated water.
3. There is a special temperature around 60°C for the velocity of CO<sub>2</sub>-saturated water. The effect of solubility increases CO<sub>2</sub>-saturated velocity when temperature is below it, otherwise decreases them with temperature increases.
4. The different velocity slop, degree of effect and the velocity reversed temperature may work as a guideline to separate CO<sub>2</sub>-saturated water from methane-saturated water.

### Acknowledgements

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**EDITED REFERENCES**

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