EFFECT OF DISSOLUTION OF CO_2 AND CH_4 ON THE FLOW CURVE OF DRILLING FLUIDS

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ABSTRACT

When drilling a well, careful choice of drilling fluid is essential to allow, among others, for well stabilization and lubrication of the drill bit. The apparent viscosity of a drilling fluid is one of its major properties affecting the ability to be pumped and to transport particles. However, when the drilling fluid is circulated in a well, it may meet components that affect its properties. Here we investigate the case of a gas kick, i.e., fluid from the rock formation entering the wellbore, and evaluate how the reservoir fluid dissolution affects the apparent viscosity of the fluids.

The drilling fluid-reservoir fluid mixtures are prepared at high pressure (400 bar) in a 1L piston bottle, and the apparent viscosity is measured with a high-pressure Couette cell provided by Anton Paar. Several drilling fluids are tested, and as reservoir fluids we perform experiments with CO_2, CH_4, or a mix of both. The results show that reservoir fluid dissolution decreases the apparent viscosity of the fluids at given temperature and pressure conditions.

The experimental results will be used to calibrate numerical models in order to improve a well-control evaluation software.

INTRODUCTION

When drilling a well, careful choice of drilling fluid is essential to allow, among others, for well stabilization and lubrication of the drill bit. The apparent viscosity of a drilling fluid is one of its major properties affecting the ability to be pumped and to transport particles. However, when the drilling fluid is circulated in a well, it may meet different impurities that affect its functional properties. In oil and gas wells, gas kick, i.e., penetration of natural gas (mainly CH_4) into the well during drilling, poses a major risk for well safety, and may lead in worst case to blow out. Gas kicks are usually detected and remediated with the help of well control software.

The project "Well control for CO_2 wells", started in 2022, aims to integrate the performance prediction of CO_2 kick in software for well control. Key activity in the project is the generation of experimental data to calibrate a thermodynamical model on CO_2 solubility in drilling fluids and the effects on the density and apparent viscosity. The thermodynamical model is integrated to the software. The first results of the projects have already been published [1–5], including among others the solubility of CO_2 in drilling fluids and the effect on the density and the viscosity of the fluids. The risk of CO_2-hydrate formation in drilling fluids was also assessed.

In this paper, we focus on CO_2-CH_4 gas mixtures, to see how the solubility of each fluid component in the drilling fluid is affected by the presence of the other. Then, we evaluate the effect of the dissolution of the reservoir fluids on the density and the apparent viscosity of the drilling fluids.

MATERIALS AND METHODS

Materials

We have selected three commercial drilling fluids for the tests; two water-based drilling fluids (WBDF index 1 and 2) and one oil-based drilling fluid (OBDF). The exact composition of the fluids is not known, but the main characteristics of each drilling fluid are listed in **TABLE 1**. Note that the fluids are the same as used in previous publications[1–5].

TABLE 1: Drilling fluids used in this paper

Drilling fluid	**Base fluid**	**Density (g/L)**
WBDF1_factory	NaCl Brine	1160
WBDF1_field	NaCl Brine	1150
WBDF2	KCl Brine	1280
OBDF	Base oil	1480

Three different batches of water-based drilling fluids have been used in this study, all come from the same vendor. Water-based drilling fluids are typically made from a salt solution (brine), where polymer, particles and other additives are added to control the fluid properties (viscosity, density, fluid loss…). WBDF1_Factory and WBDF1_field are the same drilling fluid, i.e. have the same composition, but the former comes directly form the factory while the latter has been circulated in a well before it was shipped to us. WBDF1_field therefore contains additional particles and impurities from the well. WBDF2 has a different composition and is based on KCl brine.

We also performed experiments with one oil-based drilling fluids (OBDF). It is composed of a base oil, approximately 80%, and contains further on brine, emulsifiers, and diverse particles.

In this study, we have dissolved CO_2 and/or CH_4 into the drilling fluids. Pressurized CO_2 and CH_4 bottles are provided by Linde with a CO_2 purity higher than 99.7%, and a CH_4 purity of 99.5%. In this paper, we use the following conventions to indicate the amount of reservoir fluids in the OBDF-gas mixtures:

- The amount of reservoir fluids (CO_2 + CH_4) is given as a weight fraction of the total mixture, i.e., drilling fluid and gas.
- When both CO_2 and CH_4 are dissolved, we indicate the molar fraction of CH_4.

Solubility measurements

The drilling fluids – gas mixtures are prepared and homogenized at high pressure (up to 400 bar) as follows:

1- The drilling fluid is placed in a 1L Leutert piston bottle (see **FIGURE 1** (a)), called “mixing cylinder”. On the hydraulic side, the piston bottle is connected to a Vindum

VP-6K pump (Pump A), allowing to monitor the pressure in the mixing cylinder and the volume variations of the hydraulic fluid.

2- The reservoir fluids CO_2 or CH_4 are transferred first as gases from the respective CO_2 or CH_4 pressurized bottles to another piston bottle, called "gas cylinder", then from the gas cylinder to the mixing cylinder. This procedure allows us to accurately control the pressure and volume of gas transferred to the mixing cylinder at ambient temperature (23°C), and therefore the mass of gas.

3- The mixing cylinder is agitated for at least one night using a rolling steel ball and an oscillating platform at high pressure to homogenise the mixture and let CO_2 and/or CH_4 dissolve into the drilling fluid.

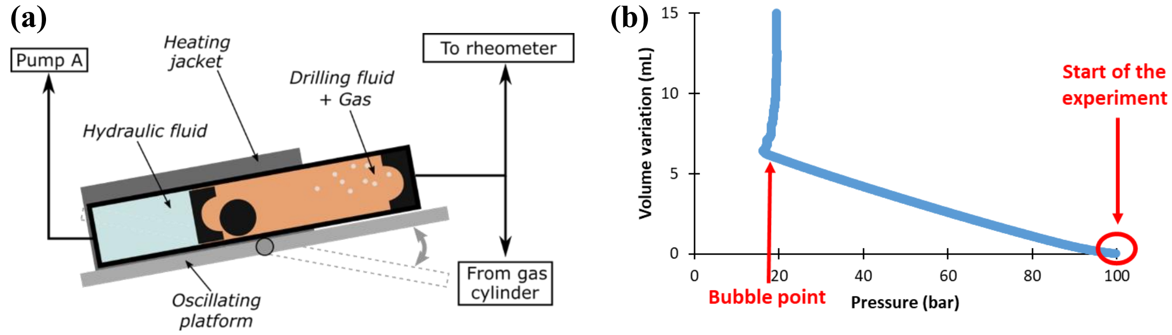

FIGURE 1: (a) Schematic of the mixing cylinder. (b) Illustration of the solubility measurement method. Drawings adapted from *Skogestad et al.*(2024)[1]

After the homogenization of the mixture, we perform solubility measurements. The hydraulic fluid is pumped out of the mixing cylinder at a constant rate (0.01 mL/min) to increase the volume of the of the drilling fluid – gas mixture, and the pressure is recorded. An example of obtained pressure-volume curve is shown in **FIGURE 1** (b): a clear change of slope appears, indicating a phase change in the mixture. The pressure when this happens is called the bubble point. The bubble point may reflect two physical phenomena:

- Release of dissolved CO_2 and/or CH_4 for the drilling fluid, i.e., apparition of gas bubbles
- Phase transition of undissolved CO_2 or CH_4, from liquid or supercritical to gas. This happens if the CO_2 or CH_4 is not fully dissolved in the drilling fluid. For CO_2 at ambient temperature, this transition occurs at 60 bar. It means for instance that if the CO_2 concentration in the fluids exceeds the maximal solubility of CO_2 (typically about 3% in water-based drilling fluids[2] and 15% in oil-based drilling[1]), we measure experimentally a bubble point at 60 bar.

The results of the solubility measurements are used to ensure that the density and rheology measurements, described in the next paragraphs, are performed only in the case where the gas is fully dissolved in the drilling fluids (gas content below the maximal solubility, pressure above the bubble point).

Density

The density of the drilling fluids - gas mixtures is assessed by analyzing the change of volume of the fluid in the mixing cylinder when gas is added, or temperature or pressure are modified. The volume of the fluid mixture is deduced from the volume variations of the hydraulic fluid, given by the pump, after correction for the compressibility of the hydraulic fluid. More details of the method can be found in Skogestad et al. (2024)[1].

We have observed that this method is accurate to determine volume variations, but not for measurement of absolute volume due to possible experimental artifacts such as bubbles in the hydraulic fluid. Therefore, in these experiments, we measure density variations from the reference density, i.e., the density of the drilling fluid at ambient temperature and without gas.

Rheology

Measurements are performed with a high-pressure cell (maximum pressure 1000 bar) from Anton Paar, placed in an Anton Paar MRC 102 rheometer. The high-pressure cell has been described in several publications[1,6,7], we will recall here the main points. The geometry is a Couette cell with a rotating cylinder of diameter 29 mm, giving a gap of 0.5 mm. To allow for high pressure inside the cell, it is closed on top, and the rotating cylinder is entrained by a magnet rotating outside the cell. Due to the high inertia of the magnet-cylinder system, the high-pressure cell has low relative accuracy at low torque values. The accuracy limit as defined by the shear stress value where system effects and repeatability are in the same range as the physical value, corresponds to about 5 Pa shear stress.

The cell has only one inlet, which is used for filling. Initially, a vacuum is made in the cell to remove air. Then, the cell is connected to the mixing cylinder; this leads to a pressure drop in the mixing cylinder. We always check that this drop does not lower the pressure below the bubble point, so that no gas bubbles are formed in the rheometer cell.

RESULTS AND DISCUSSION

Oil-based drilling fluid

Result of CO_2 solubility in the same OBDF have been published in Skogestad et al. (2024)[1], some measurements of CH_4 dissolution in two oil-based drilling fluids are presented in Torsvik et al. (2016)[6]. Here, we will focus on impact from mixtures of CO_2 and CH_4 exposed to the drilling fluids.

Solubility of CO_2 and CH_4 mixtures

Oil-based drilling fluids are mainly composed of base oil, where different components are added. This includes brine (here $CaCl_2$ brine), mass fraction typically between 15% and 40%, an emulsifier, and different types of particles such as clay, lime and barite. It has been shown before for both CO_2 and CH_4 at these fluids are more soluble in oil than in the brine, to such an extent that the dissolution of CO_2 and CH_4 into oil-based drilling fluids can be assumed to be only in the base oil.

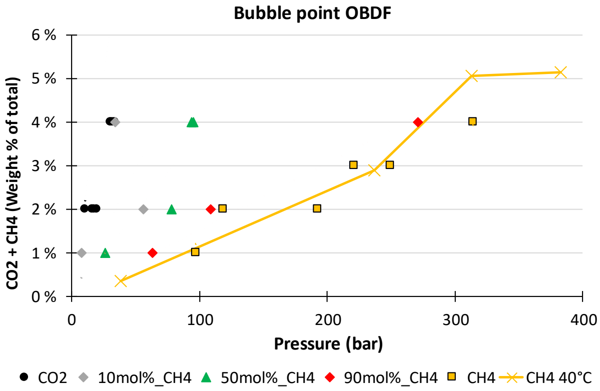

FIGURE 2: Bubble point curves of CO_2, CH_4, and CO_2-CH_4 mixtures in OBDF, at ambient temperature. The points "*CH4 40°C*" are taken for comparison from Torsvik at al. (2016)[6]. The points for CO_2 are from Skogestad et al (2024)[1]. The dotted lines indicate linear regression (passing by the origin) for each data series.

The solubility of CO_2 and CH_4 in OBDF is shown in **FIGURE 2**. We first note that bubble point with CH_4 dissolved is much larger than that for CO_2 for a given mass content, reflecting that the CO_2 solubility is much larger than the CH_4 solubility in the OBDF. The CO_2-CH_4 mixture bubble point curves are in between pure CO_2 and pure CH_4 curves. To better explain these results, we have plotted in **FIGURE 3**, the same bubble point results as a function of the concentration of (a) CH_4 content only and (b) CO_2 only. Here, we see that when plotting the data as a function of CH_4 content, most points collapse on one single curve. This shows that in experiments with CO_2-CH_4 mixtures, the resulting bubble point reflects the formation of CH_4 bubbles, thus the CH_4 bubble nucleation is not affected by the presence of dissolved CO_2. Only in the curve with 10 mol% CH_4, the measured bubble point seems larger than would be expected with CH_4 only. In this case, we see in **FIGURE 3** (b) that the measured bubble point is close to the bubble point of CO_2 only, showing that in this case, the bubble point probably reveals the apparition of CO_2 bubbles.

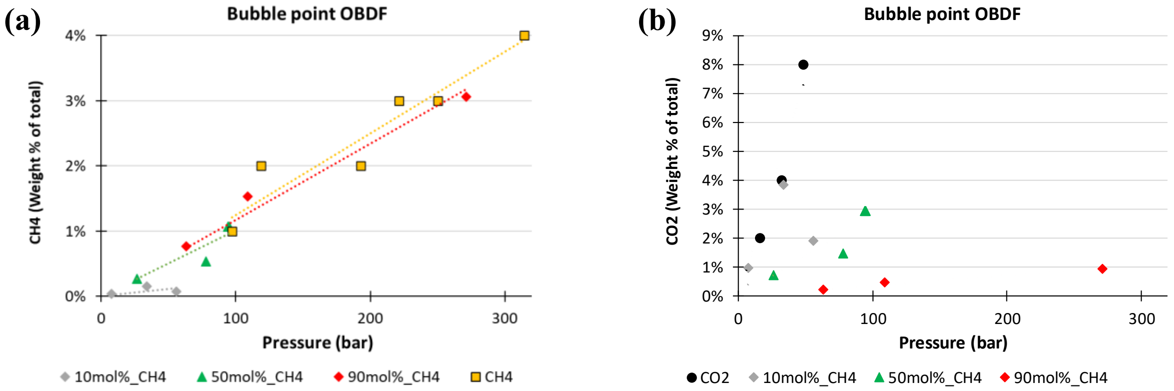

FIGURE 3: (a) Bubble point curves of CH_4 and CO_2-CH_4 mixtures, plotted as a function of the CH_4 content. (b) Bubble point curves of CO_2 and CO_2-CH_4 mixtures, plotted as a function of the CO_2 content. For both graphs, the doted lines indicate linear regression (passing by the origin) for each data series.

To summarize this part, the bubble point of CO_2-CH_4 mixtures seems to follow two distinct trends:

- With 50mol% CH_4 or more, the bubble point is equal to the bubble point of pure CH_4 and is unaffected by the presence of CO_2.
- With 10mol % CH_4, the bubble point aligns with the bubble point of CO_2.

Effect on drilling fluid density

The density of OBDF after gas dissolution has been measured at room temperature. The reference density at 400 bar and no dissolved gas is 1515 kg/m^3. The results are given in **FIGURE 4**. As reported before, CO_2 dissolution tends to decrease the OBDF density[1], by about 3% for 4% of CO_2 content. Our results show that CH_4 reduces even more the density, up to 15% for 4% of CH_4 content. CO_2-CH_4 mixes lead to intermediate values of density, with increasing density reduction with increasing CH_4 content.

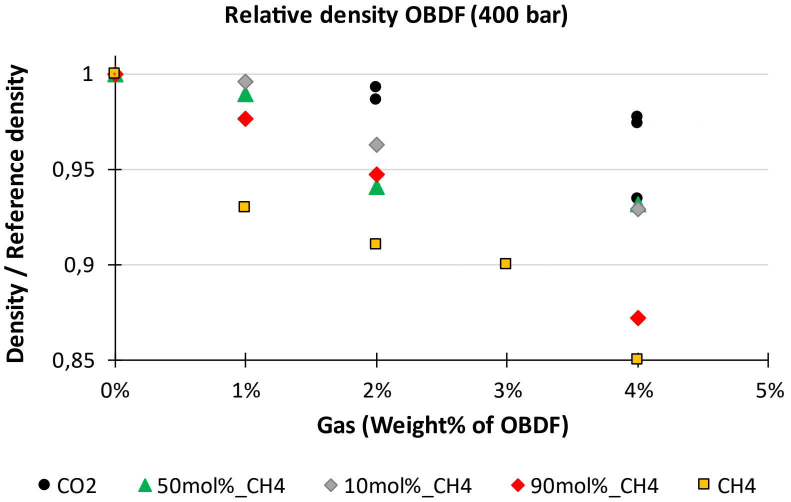

FIGURE 4: Effect of the dissolution of CO_2, CH_4 and CO_2-CH_4 mixtures on the density of OBDF, at room temperature. The points for CO_2 are from Skogestad et al (2014)[1].

Effect on rheological properties

A previous study[1] has investigated how the apparent viscosity of OBDF is affected by the pressure and temperature conditions, as well as the amount of dissolved CO_2. Results are illustrated in **FIGURE 5**. CO_2 dissolution in the oil-based drilling fluids strongly reduces the apparent viscosity; the flow curves are one order of magnitude lower when 8% CO_2 (by weight of the total mix) is dissolved. The results also showed that increasing the temperature decreased the apparent viscosity of the drilling fluids, this observation is valid with and without CO_2 dissolution. The same study showed that pressure conditions also slightly affect the flow curve: higher pressure leads to increased apparent viscosity (results not shown here). However, the effect of pressure is minor compared to the effect of temperature and CO_2 dissolution.

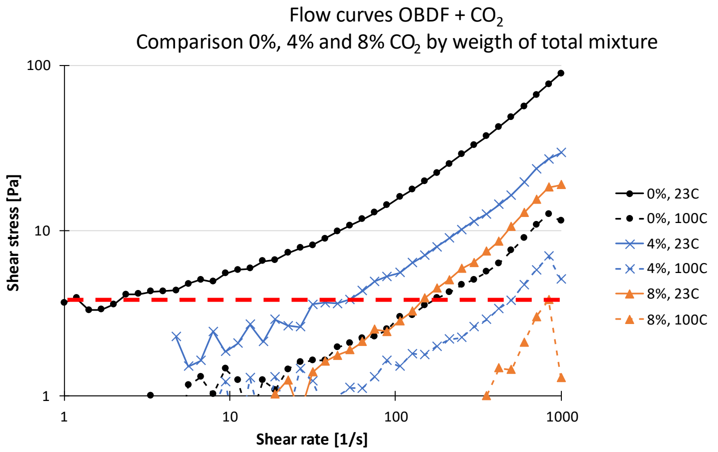

FIGURE 5: Effect of CO_2 loading and temperature on the rheological properties of OBDF. Gathering of all experimental results at 200 bar. Graph adapted from Skogestad et al. (2024)[1]. The red dotted line indicates the stress accuracy limit of the high pressure measuring cell.

Torsvik et al. (2016)[6] also showed that CH_4 dissolution reduces the apparent viscosity of oil-based drilling fluids. In **FIGURE 6**, we show the flow curves measured for different mixing proportions of CH_4 and CO_2. For both gas content (2% and 4% by weight), the apparent viscosity seems to decrease with the CH_4 content. This effect is minor compared to the points previously discussed, i.e., the impact of total gas content and temperature.

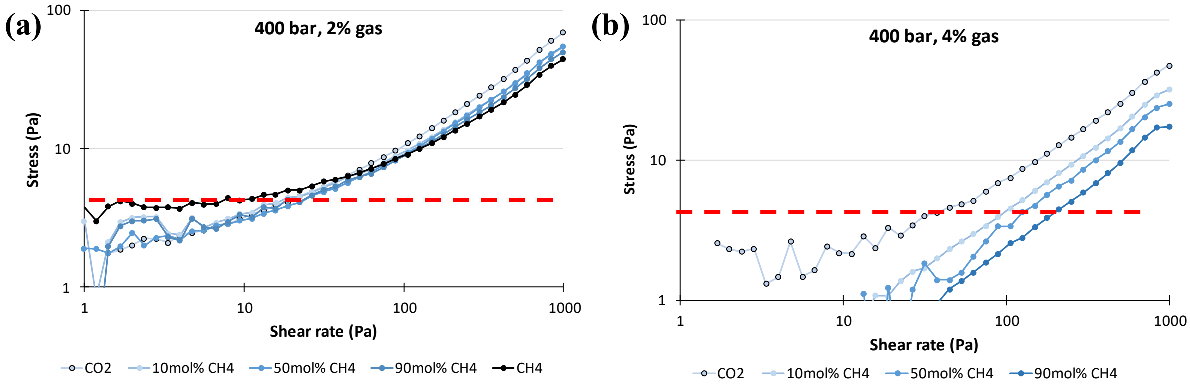

FIGURE 6: Effect of the dissolution of CO_2-CH_4 mixtures on the flow curves of OBDF, at 400 bar and room temperature, for different proportions of CH_4. The total mass fraction of gas is (a) 2% and (b) 4%. The red dotted lines indicate the shear stress accuracy limit of the high-pressure measuring cell.

Water-based drilling fluids

Results of solubility experiments of CO_2 in WBDF1_field and WBDF2 and density have been published before[2], at different temperatures. They showed that the solubility of CO_2 in the water-based drilling fluids is much lower than in oil-based fluids. The maximal solubility at ambient temperature (23°C) is about 3% CO_2 by weight of the total mixture for both drilling fluids under investigation; the bubble point is in this case close to 60 bar. Increasing the pressure further does not increase the solubility of CO_2.

Solubility curves of CO2 and CO2-CH4 mixtures

First, we compare in **FIGURE 7** the solubility curve of WBDF1_factory with the curve from WBDF1_field[2]. The solubility curves are similar for both batches of drilling fluid.

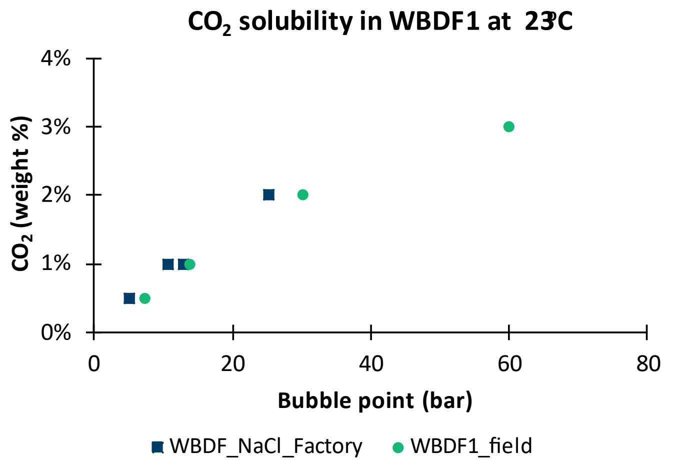

FIGURE 7: Bubble point curves of pure CO_2 in both batches of WBDF1. The data from WBDF1_field has already been published[2]

Next, we focus on solubility experiments for CO_2-CH_4 mixes in WBDF1_factory. In **FIGURE 8** (a), we show pressure -volume relations obtained from the solubility experiments at different total gas fractions, with 10mol% CH_4 in the gas. No distinct change of slope can be observed on these curves. On the contrary, the curves reveal a smooth change of slope as we reduce the pressure. This reflects that we cannot identify a bubble point. In some experiments, we observed small steps on the curves, However, when we repeated the tests (see for example the curves at 1% gas), we noted that these steps were not reproducible; we believe therefore that the steps are experimental artifacts, maybe particles hindering the smooth displacement of the piston in the mixing cylinder.

The absence of a distinct bubble point may indicate that CH_4 is never fully dissolved in WBDF1_factory. To confirm this hypothesis, we have plotted in **FIGURE 8** (b), the theoretical pressure-volume relation calculated with the assumption that no CH_4 is dissolved at all in the drilling fluids. The calculation method is as follows.

- We assume that the bubble point of CO_2 (about 20 bar for 1.9% CO_2) is not affected by the presence of the CH_4 phase.
- For pressure above the bubble point of CO_2,
    - We assume that there are two phases in the mixing cylinder: (1) the CH_4 phase and (2) the drilling fluid phase with dissolved CO_2. The mass of each of the phase is constant.
    - The density of the CH_4 phase at 23°C is taken from the NIST database. The density of the drilling fluid-CO_2 is experimental data[2].
    - The total volume is the sum of the volumes of the CH_4 and the drilling fluid (+ dissolved CO_2) phases
- For pressures below the bubble point of CO_2,
    - We assume that the relation between the mass of dissolved CO_2 and the pressure is linear (i.e., follows Henry's law)
    - The density of the CO_2 phase at 23°C is taken from the NIST database
    - The total volume is the sum of the volumes of the CH_4, CO2 and drilling fluid (+ dissolved CO_2) phases.

The resulting theoretical curve is compared with the experimental curve in **FIGURE 8** (b). We observe that the curves are quite similar to each other, with the increase of volume related mainly to the CH_4 phase. We can also note that the bubble point of CO_2 on the theoretical curve is characterized by a very small change of slope. Therefore, even if gas CO_2 is released during the experiments, we might not be able to see it on the experimental curve.

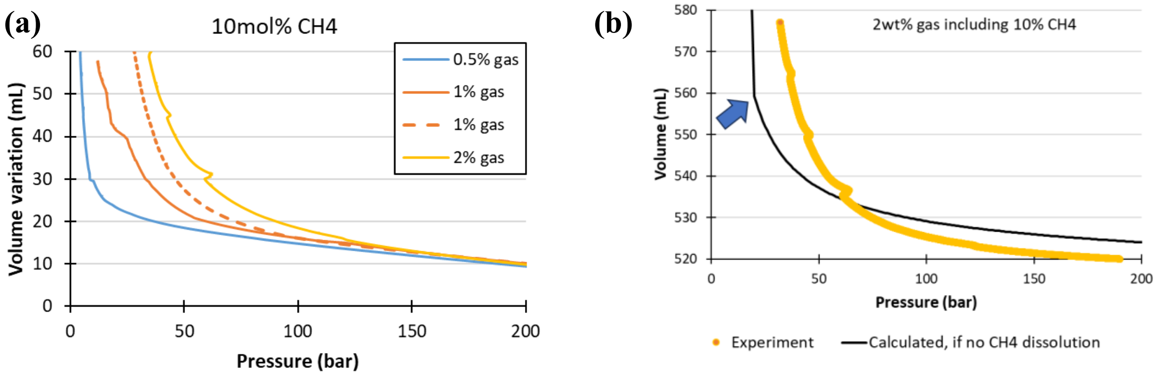

FIGURE 8: (a) Curves obtained during solubility measurements of CO_2-CH_4 mixtures in WBDF1_factory, the total gas constant varies between 0.5% and 2%, while the CH_4 molar fraction in the gas is kept constant (10%) (b) For the test with 2% gas, comparison of the experimental pressure-volume curve with a theoretical curve (see explanation in text). The blue arrow indicates the bubble point of CO_2 (25 bar).

Density and rheological properties

No density or rheological measurements have been performed with CO_2-CH_4 mixtures in water-based drilling fluids as no single phase system exists for this fluid mixture. The density results of drilling fluids with dissolved CO_2 have been already published, they show very little effect from CO_2 dissolution on the density of WBDF1_field and WBDF2.

In **FIGURE 9**, we observe the effect of CO_2 dissolution on the rheological properties of drilling fluids. For both WBDF1_field and WBDF2, the apparent viscosity is reduced when drilling fluid is subject to CO_2 dissolution. The impact from CO_2 is, however, much smaller for water-based drilling fluids than OBDF (see **FIGURE 6**).

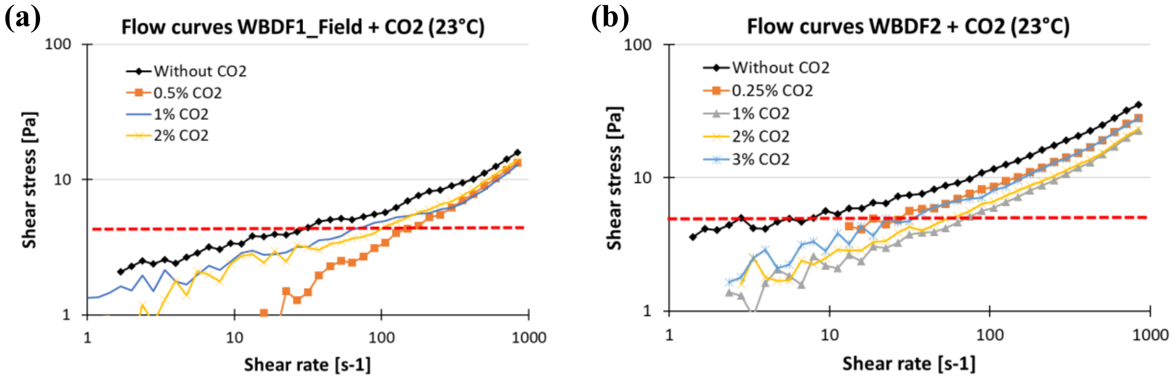

FIGURE 9: Effect of CO_2 dissolution on the flow curves of (a) WBDF1_field and (b) WBDF2. The red dotted lines indicate the stress accuracy limit of the high-pressure measuring cell.

CONCLUSIONS

In this paper we investigate the solubility of CH_4 and carbon dioxide in drilling fluids, and the effect of the dissolution on the density and apparent viscosity. The following observations have been made:

- The solubility of CO_2 is higher than CH_4 in oil-based drilling fluids. When CO_2-CH_4 mixtures are dissolved, the resulting bubble corresponds to the bubble point for CH_4 - drilling fluid for CH_4 ratio above 50mol% for the CO_2-CH_4 mixtures.
- In water-based fluids, CO_2 reveals lower solubility than in OBDF; while it was not possible to fully dissolve CH_4 in water-based drilling fluids at the concentration tested.
- Gas dissolution reduces the density of OBDF, and CH_4 has a larger density-reduction effect than CO_2.
- Gas dissolution reduces the apparent viscosity of all the drilling fluids. In OBDF, CH_4 reveal a larger viscosity-reduction effect than CO_2.

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