INTRODUCTION

Drilling is an activity inherent to oil and gas industry, as it is essential in the exploration and development of hydrocarbon reservoirs. Currently, increasing energy demand is driving drilling operation to deeper and harsher environments, and as a result, the safety is becoming increasingly challenging. When formation gas, which is often mostly supercritical methane, invades the annulus in a gas kick scenario during a drilling activity, it could expand and rapidly rise to the surface, creating an extremely hazardous situation that could lead to blowout and explosion. The occurrence of a kick is generally detected from the expansion and rise of the invading methane that causes pit gain and other anomalies. Unfortunately, some or all of the invading methane can dissolve in the mud at the higher pressures of the deeper portion in the wellbore. Dissolved methane will come out of solution at the lower pressures near the wellhead causing a dangerous delay in kick detection. This will significantly increase the risk of a blowout tragedy. Thus knowledge of methane solubility in mud is of major importance to early kick detection and well control operation in oil and gas drilling industry.

In recent years, growing attention has been paid to methane solubility research, since O’Brien first reported the effect of methane solubility on the well control operation. Generally, study of gas solubility includes two approaches: the experimental work and modeling research. During the

Abstract

Knowledge of methane dissolution behavior in drilling mud is of major importance to early kick detection and well control operation in oil and gas drilling industry. In this work, methane solubility experiments in water-based and oil-based muds were conducted over wide ranges of temperature and pressure conditions. The influences of mud compositions and methane phases were investigated accordingly. It is found that methane solubility in water-based mud is minimal and can be ignored. The data in oil-based mud were analyzed using different equation of state and mixing rules. Our results show that the combination of our novel binary interaction parameter equations, Peng-Robinson equation, and van der Waals mixing rule provides a very good representation of our data as well as those available in the literature. With the proposed model, the annulus methane solubility profile of a deepwater well in South China Sea was predicted, which provides a better understanding of the annulus flow behavior and further improve the safety of drilling operation.

KEYWORDS

annulus flow, equation of state, methane solubility, mixing rule, mud, phase equilibrium
In the last decades, some solubility data have been obtained under various temperature and pressure conditions. Matthews\(^7\) and O’Bryan\(^8\) measured the solubility of CH\(_4\), CO\(_2\), H\(_2\)S, and natural gas in diesel oil. Darwish reported methane solubility data in heavy n-paraffins at temperatures from 323 to 423 K and pressure up to 10.7 MPa.\(^9\) Silva, Monterio, and Ribeiro conducted methane solubility tests in different esters, and the experimental temperatures are 343.15 and 363.15 K.\(^10\)-\(^12\) Feng compared methane solubility in three base fluids (brine, mineral oil, and poly-alpha-olefin), showed that methane solubility in mineral oil and poly-alpha-olefin are much greater than that in brine.\(^13\) In the area of model development, Thomas applied equation of state (EoS) to predict the bubble point pressure of methane/diesel and methane/diesel-based mud.\(^14\) Srivastan used Soave-Redlich-Kwong (SRK) equation and Peng-Robinson (PR) equation to fit the solubility data of methane in hexane, decane, and dodecane.\(^15\) Berthezene applied a PR model to predict methane solubility in different base oils. A single binary interaction parameter (BIP) was fitted according to the experimental results.\(^16\) Bureau compared three different EoS models (PR, SRK, Elliott-Suresh-Donohue [ESD]) in the prediction of bubble point pressure of methane/ester mixture and recommended the ESD equation with BIP = 0 to best describe the phase behavior of methane/ester binary system.\(^17\) Kim used PR model to calculate the thermodynamic properties of methane/ester emulsion mixture according to the experimental results under high temperature and high pressure conditions.\(^18\)

However the majority of these studies are conducted with base oils or emulsions, only a very few cases regarding muds are presented in the literature. Actually, more solubility data and effective models for methane/mud mixture are still needed to improve the understanding of annulus flow behavior. In the present work, methane solubility in water-based mud and oil-based mud, both of which are widely used in deepwater drilling scenario in South China Sea, were measured at different conditions. Several factors were investigated to determine their influence on methane dissolution, including mud types, temperature/pressure, mud compositions, and methane phases. Then, these solubility data were analyzed using different EoS models (SRK, PR, Peng-Robinson-Stryjek-Vera 2 [PRSV2]) and mixing rules (van der Waals1 [vdW1], van der Waals2 [vdW2]) to find the most reliable thermodynamic models for methane/mud binary system. In addition, regression analysis was used with experimental data to develop association equations for BIPs. The accuracy of the models was evaluated by our data as well as those available in the literature. According to the proposed model, the distribution of annulus methane solubility and its influence to well control operation in a designed deepwater well in South China Sea was discussed.

### 2 | EXPERIMENTAL STUDY

#### 2.1 | Apparatus and procedures

The experimental apparatus used in this work, shown in Figure 2, includes two parts: the reaction system and the

**FIGURE 1** A typical annulus flow profile in the deepwater drilling operation

**FIGURE 2** Sketch of experimental apparatus
measurement system. The key equipment is the PVT cell, which has a 2000-mL chamber where the dissolution reaction is conducted. The maximum allowable working temperature and pressure of the PVT cell are 473.15 K and 100 MPa, respectively. Temperature was regulated using two temperature sensors and a heating resistance wire wound around the chamber. An automatic pump was connected to the PVT cell to maintain the chamber pressure by adjusting the amount of hydraulic oil in the chamber. The reaction chamber is capable of rotating with the shaft that increases the convection of gas and mud and accelerates gas dissolution rate.

Experiment is started with loading a known mass of mud into the PVT cell. Compressed methane is then injected into the chamber from the transition container until the chamber pressure reaches the injection pressure. After that, the chamber is sealed and begins to rotate to conduct the dissolution reaction. The temperature and pressure of the chamber are automatically maintained to the designed values during the reaction. When the mixture reaches equilibrium, the chamber is turned over and the saturated mud will come to the bottom of the chamber due to the gravity effect. At the same time, the rest of the free methane will slip out of the mud. The sample with dissolved gas is taken from the cell and flashed at ambient conditions. The out of dissolution gas is then collected at atmospheric pressure in a gasometer; the volume of which can be accurately read. The mud in separator is assumed to contain no more gas, and its volume is easy to get. The volume ratio of the collected gas and mud gives the gas solubility at the designed temperature and pressure conditions.

2.2 | Test programs

As mentioned earlier, the main purpose of this study is to understand methane dissolution behavior in mud. Therefore, the test items include the following aspects:

2.2.1 | Temperature and pressure conditions

The tests were conducted for three temperatures (303.15 K, 343.15 K, 393.15 K) and five pressures (10 MPa, 15 MPa, 30 MPa, 45 MPa, 60 MPa). These temperature and pressure conditions were decided upon based on a deepwater field case in South China Sea.

2.2.2 | Mud types

Two deepwater drilling muds in South China Sea were used in the experiments, a water-based and an oil-based mud. Their formulas are provided in Table 1.

2.2.3 | Mud compositions

For oil-based mud, oil/water ratio (OWR: 9:1, 8:2, 7:3) and the emulsifier content (3%, 4%, 5%) were varied to investigate the influence of the main compositions on gas solubility. Besides, mineral oil emulsion tests were also conducted, and comparisons were made between real muds and emulsions to study the effect of other components in mud.

2.2.4 | Methane phases

The critical temperature and pressure of methane are 190.55 K and 4.59 MPa, respectively. Methane solubility in oil-based mud was measured at five pressures (2 MPa, 3 MPa, 4 MPa, 5 MPa, 6 MPa) under ambient temperature, to investigate the dissolution difference between supercritical methane and vapor methane.

3 | MODELING APPROACH

Methane dissolution in mud is a vapor-liquid equilibrium issue; therefore, phase equilibrium theory is used to study this dissolution behavior. The chemical potential and fugacity of each component in the vapor phase is equal to that in the liquid phase when the vapor-liquid mixture reaches equilibrium. Hence:

\[ f^V_i = f^L_i \]  \hspace{1cm} (1)

where \( f^V_i \) and \( f^L_i \) represent the fugacity of component \( i \) in vapor and liquid phases, respectively (Pa).

Expressed in terms of fugacity coefficient, Equation 1 is rewritten as:

| Materials | Composition |
|-----------|-------------|
| Water-based mud | Water + 4% bentonite + 20% CaCl₂ + 0.4% HV-PAC + 3% SPNH + 0.5% XY-27 + 0.3% FA367 + 2% K₂SiO₃ + 0.2% KOH + 5% PEG-200 |
| Oil-based mud | 90% mineral oil + 3% emulsifier + 0.63% wetting agent + 2.9% CaO + 10% CaCl₂ brine (20% concentration) + 2% organic clay + 2.9% fluid loss agent |
| Gas | Methane 99.99% |

TABLE 1 Materials information
\[ \phi_i^V y_i = \phi_i^L x_i \quad (2) \]

where \( \phi_i^V \) and \( \phi_i^L \) are the fugacity coefficients of component \( i \) in vapor phase and liquid phase, respectively; \( y_i \) and \( x_i \) are the mole fractions of component \( i \) in vapor phase and liquid phase, respectively.

According to the definition of fugacity,\(^{19}\) it also can be written as:

\[ f = P \exp \left[ \frac{G(T,P) - G^{IG}(T,P)}{RT} \right] = P \exp \left[ \frac{1}{RT} \int_0^P (V - \frac{RT}{P}) \, dP \right] \quad (3) \]

where \( P \) is pressure (Pa); \( T \) is temperature (K); \( G \) represents the Gibbs free energy (J mol\(^{-1}\)); \( G^{IG} \) is the Gibbs free energy of ideal gas (J mol\(^{-1}\)); \( R \) is the gas constant (J K\(^{-1}\) mol\(^{-1}\)); and \( V \) is the molar volume (m\(^3\) mol\(^{-1}\)).

Therefore, the fugacity coefficient is given by:

\[ \ln \phi = \frac{G(T,P) - G^{IG}(T,P)}{RT} = \int_0^P (Z - 1) \, \frac{dP}{P} \quad (4) \]

where \( Z \) is the compressibility factor.

Combined with EoS that provides P-V-T relationship, Equations 2 and 4 can be solved to get the phase equilibrium properties. In this work, three widely used EoS models were taken into account, including SRK EoS\(^{20}\), PR EoS\(^{21}\) and PRSV2 EoS\(^{22}\). Their expressions are given by:

For SRK model:

\[ P = \frac{RT}{V - b} - \frac{a(T)}{V(V + b)} \quad (5) \]

For PR and PRSV2 models:

\[ P = \frac{RT}{V - b} - \frac{a(T)}{V(V + b) + b(V - b)} \quad (6) \]

where \( a \) and \( b \) are pure component parameters. For different models, \( a \) and \( b \) have different expressions. Detailed information can be found in the literatures. Note that the expression of PRSV2 model is the same as the PR model, the difference between the two models lies in the representation of the parameter \( a \).

In order to extend these EoS models to mixtures, mixing rules must be introduced to calculate mixture parameters \( a_m \)

**FIGURE 3** Calculation scheme to determine BIPs in vapor-liquid equilibrium system
and \( b_m \). Two classical van der Waals mixing rules were applied in this study to associate with these EoS models: the vdW1 and vdW2 mixing rules.\(^{23-25}\)

The vdW1 mixing rule contains one BIP \((k_{ij})\), and the \(a_m/b_m\) can be expressed as:

\[
a_m = \sum_i \sum_j x_i x_j \sqrt{a_i a_j (1 - k_{ij})}
\tag{7}
\]

In Equations 7 and 8, \(x_i\) and \(x_j\) are the mole fractions of component \(i\) and \(j\); \(a_i\) and \(a_j\) are the interaction-related parameters of component \(i\) and \(j\); \(b_i\) is the volume-related parameter of component \(i\).

The vdW2 mixing rule introduces two BIPs \((k_{ij}, l_{ij})\) that are given by:

\[
a_m = \sum_i \sum_j x_i x_j \sqrt{a_i a_j (1 - k_{ij})} \tag{9}
\]

### TABLE 2  Methane solubility in oil-based muds with different OWR (m\(^3\)/m\(^3\))

| Exp. conditions | T (K) | OWR | 15 | 30 | 60 |
|-----------------|-------|-----|----|----|----|
|                 | 303.15| 9:1 | 53.600 | 120.265 | 315.735 |
|                 |       | 8:2 | 47.365 | 110.550 | 214.815 |
|                 |       | 7:3 | 40.375 | 78.685 | 173.855 |
|                 | 343.15| 9:1 | 56.925 | 109.960 | 383.900 |
|                 |       | 8:2 | 50.265 | 101.385 | 281.160 |
|                 |       | 7:3 | 44.250 | 76.635 | 196.530 |

### TABLE 3  Methane solubility in oil-based muds with different emulsifier content (m\(^3\)/m\(^3\))

| Exp. conditions | T (K) | Emulsifier cont. (%) | P (MPa) |
|-----------------|-------|----------------------|---------|
|                 | 303.15| 3                    | 15  | 30 | 60 |
|                 |       | 4                    | 53.600 | 120.265 | 315.735 |
|                 |       | 5                    | 54.460 | 118.240 | 322.600 |
|                 | 343.15| 3                    | 56.925 | 109.960 | 383.900 |
|                 |       | 4                    | 57.580 | 125.915 | 398.235 |
|                 |       | 5                    | 62.820 | 123.680 | 348.325 |

### TABLE 4  Methane solubility in real muds and emulsions at 343.15 K (m\(^3\)/m\(^3\))

| Solvents        | OWR | \(P\) (MPa) |
|-----------------|-----|-------------|
|                 | 15  | 30 | 60 |
| Oil-based mud   | 9:1 | 56.925 | 109.960 | 383.900 |
| Mineral oil emulsion | 62.840 | 134.325 | 399.170 |
| Oil-based mud   | 8:2 | 50.265 | 101.385 | 281.160 |
| Mineral oil emulsion | 54.745 | 121.900 | 304.850 |

### FIGURE 4  Distribution of methane solubility under different temperature and pressure conditions in water-based mud

### FIGURE 5  Distribution of methane solubility under different temperature and pressure conditions in oil-based mud

### FIGURE 6  Solubility of supercritical methane and vapor methane in oil-based mud
where $b_j$ is the volume-related parameter of component $j$.

The BIPs are adjustable for different materials and conditions. Generally, regression analysis of experimental data is the most effective way to determine these parameters. 26,27

The calculation scheme is represented in Figure 3. After getting the values of BIPs, phase equilibrium properties of methane/mud binary system can be calculated with these thermodynamic models.

4 | RESULTS AND DISCUSSION

4.1 | Effects of temperature and pressure

Figure 4 displays solubility data of methane in water-based mud under different temperature and pressure conditions. These data suggest that the methane solubility in water-based mud is so small that the dissolution behavior is unlikely to have any influence on annulus flow behavior. The distribution of methane solubility under different conditions indicates that gas solubility increases with pressure, and it appears to be insensitive to temperature at low pressures. However, at high pressures, gas solubility increases with the temperature, and the higher the pressure, the greater the influence of temperature is observed.

Methane solubility in oil-based mud at different temperatures and pressures are shown in Figure 5. In general, solubility in oil-based mud is much greater, often 10-100 times, than that in water-based mud. Such a large solubility will cause a significant impact on the annulus transient flow. The influences of temperature and pressure on methane solubility are similar to those in water-based mud. Methane solubility in oil-based mud increases with pressure, and the higher the pressure, the greater is the solubility increment. At low pressures, temperature has little influence on the dissolution. But at high pressures, solubility increases with the temperature.

4.2 | Effects of mud compositions

Table 2 provides methane solubility data in oil-based muds with different OWR. As the data show, OWR of mud does have an influence on gas dissolution, especially at high pressure conditions. Methane solubility increases with OWR of mud, and the difference broadens with increased pressure. Besides, similar tendency can be observed in terms of the influence of temperature and pressure on gas dissolution in oil-based muds with different OWR.

| TABLE 5 | Binary interaction parameters of different equation of state models and mixing rules for methane/oil-based mud mixture |
| OWR | $T$ (K) | SRK + vdW1 | SRK + vdW2 | PR + vdW1 | PR + vdW2 | PR + vdW1 | PR + vdW2 | PRSV2 + vdW1 | PRSV2 + vdW2 |
|---|---|---|---|---|---|---|---|---|---|
| 9:1 | 303.15 | 0.117 | 0.519 | 0.708 | 0.204 | 0.511 | 0.523 | 0.248 | 0.548 | 0.559 |
| | 343.15 | 0.117 | 0.519 | 0.708 | 0.204 | 0.511 | 0.523 | 0.248 | 0.548 | 0.559 |
| | 393.15 | 0.117 | 0.519 | 0.708 | 0.204 | 0.511 | 0.523 | 0.248 | 0.548 | 0.559 |
| 8:2 | 303.15 | 0.097 | 0.640 | 0.803 | 0.195 | 0.660 | 0.667 | 0.240 | 0.639 | 0.703 |
| | 343.15 | 0.097 | 0.640 | 0.803 | 0.195 | 0.660 | 0.667 | 0.240 | 0.639 | 0.703 |
| | 393.15 | 0.097 | 0.640 | 0.803 | 0.195 | 0.660 | 0.667 | 0.240 | 0.639 | 0.703 |
| 7:3 | 303.15 | 0.072 | 0.687 | 0.748 | 0.183 | 0.716 | 0.768 | 0.230 | 0.747 | 0.794 |
| | 343.15 | 0.072 | 0.687 | 0.748 | 0.183 | 0.716 | 0.768 | 0.230 | 0.747 | 0.794 |
| | 393.15 | 0.072 | 0.687 | 0.748 | 0.183 | 0.716 | 0.768 | 0.230 | 0.747 | 0.794 |

| TABLE 6 | Deviations of phase equilibrium coefficient with different EoS models and mixing rules for methane/oil-based mud mixture |
| OWR | $T$ (K) | SRK + vdW1 | SRK + vdW2 | PR + vdW1 | PR + vdW2 | PR + vdW1 | PR + vdW2 | PR + vdW1 | PR + vdW2 |
|---|---|---|---|---|---|---|---|---|---|
| 9:1 | 303.15 | 34.643 | 1.870 | 31.947 | 0.086 | 37.493 | 0.010 | 37.493 | 0.010 |
| | 343.15 | 25.833 | 2.440 | 24.604 | 2.380 | 37.143 | 3.325 | 37.143 | 3.325 |
| | 393.15 | 16.657 | 0.144 | 19.383 | 0.053 | 44.628 | 0.911 | 44.628 | 0.911 |
| 8:2 | 303.15 | 53.483 | 2.154 | 53.740 | 1.524 | 57.651 | 2.005 | 57.651 | 2.005 |
| | 343.15 | 41.148 | 3.778 | 42.961 | 1.506 | 55.505 | 2.029 | 55.505 | 2.029 |
| | 393.15 | 28.545 | 4.628 | 28.754 | 4.743 | 91.145 | 5.331 | 91.145 | 5.331 |

Note. AARD$_\%$ is the average absolute relative deviation of phase equilibrium coefficient.
The influence of emulsifier content in oil-based mud on gas dissolution is shown in Table 3. The data indicate that the emulsifier content has a slight impact on gas solubility. In addition to being small, the impact of emulsifier content appears irregular and is hard to predict. Actually, the emulsifier content will affect the degree of dispersion of oil and water in mud, and its effect varies to muds with different OWR. In general, it is a very complex process. Based on the experimental results, the influence of emulsifier content will be ignored in this study.

Table 4 shows the difference in methane solubility between oil-based muds and mineral oil emulsions. The comparisons were conducted at 343.15 K, and two OWRs were used in experiments. It can be seen that the methane solubility in oil-based mud is smaller than that in mineral oil emulsion under the same conditions. In other words, the existence of those components beside base fluids and emulsifier in the mud will decrease the methane solubility of mud.

### 4.3 Effect of methane phases

Solubility of vapor methane and supercritical methane in oil-based mud are represented in Figure 6. According to the solubility curve, no significant difference of solubility between the two phases of methane can be observed. In other words, the effect of methane phase transition from supercritical to vapor in the annulus near the wellhead can be ignored when calculate methane solubility in mud.

### 4.4 Comparison of different models

Different combinations of EoS models and mixing rules were tested to determine the most reliable thermodynamic model for methane/mud mixture. Because of minimal dissolution of methane in water-based mud, no modeling study for this system was conducted. Therefore, only the oil-based mud will be discussed in this part.

Table 5 lists the calculated results of BIPs with different EoS model and mixing rule combinations for methane/oil-based mud binary system. The results suggest that pressure has no influence on BIPs. The main factors that determine BIPs are temperature and OWR. The deviations of the phase equilibrium coefficient for these matching are provided in Table 6. It is obvious that the combinations of vDW1 mixing rule with all EoS models are much less accurate than those of the combinations with vDW2 mixing rule. In other words, vDW1 mixing rule is not suitable for modeling methane/oil-based mud mixture. On the other hand, very good agreement can be observed for each EoS model and vDW2 mixing rule with data. This may be caused by the size difference between methane molecule and hydrocarbon molecule in oil-based mud, which is corrected in the vDW2 mixing rule by an extra BIP. In addition, the accuracy of PR model with vDW2 mixing rule is slightly better than the two other models. It is also observed from Table 5 that BIPs of PR model with vDW2 mixing rule relates more smoothly with temperature and OWR.

Based on these results, methane solubility in oil-based mud was further examined with different EoS models combined with vDW2 mixing rule. The results were presented...
in Figures 7-9. Comparing the three EoS models at different conditions, it is found that the PR model has a better fit with solubility data than the other two models. It can be seen that most of the predictions of PR model show very good agreement with experimental data. However, there also exist a few points with high deviations. There are two possible explanations for these high deviation points; that the model is deficient, or the data represent experimental error. We note that, compared with adjacent points, the deviations at points (9:1, 343.15 K, 30 MPa) in Figure 7b and (8:2, 303.15 K, 60 MPa) in Figure 8a are abnormal for all of the three EoS models. We conclude therefore, that these deviations are unlikely to be caused by model problem, these are more like experimental errors.

**Figure 8** The fitting results of methane solubility in oil‐based mud (OWR 8:2) with different EoS models and vdW2 mixing rule: (A) 303.15 K and (B) 343.15 K

**Figure 9** The fitting results of methane solubility in oil‐based mud (OWR 7:3) with different EoS models and vdW2 mixing rule: (A) 303.15 K and (B) 343.15 K

| Coeff. | $a_0$ $(b_0)$ | $a_1$ $(b_1)$ | $a_2$ $(b_2)/K^{-1}$ | $a_3$ $(b_3)/K^{-1}$ | $a_4$ $(b_4)$ | $a_5$ $(b_5)/K^{-2}$ |
|--------|---------------|---------------|----------------------|----------------------|---------------|----------------------|
| $k_{ij}$ | 2.20885       | 6.55179       | −0.01933             | −0.00613             | −3.57500      | 3.08426E−05          |
| $l_{ij}$ | 2.83713       | 0.81284       | −0.00989             | −0.00725             | 0.10000       | 2.02222E−05          |
According to these fitting results, the combination of PR model and vdW2 mixing rule is recommended to model phase behavior of methane/oil-based mud binary system. More BIPs under different conditions may be needed before extended application of the optimized model. To facilitate use of the model, mathematical expressions were developed to relate the BIPs with temperature and OWR based on the existing data. Note that those high deviation points discussed earlier and are likely experimental errors, were not used in the development of these expressions. After much studies, the following two polynomial equations for BIPs were developed,

\[
k_{ij} = a_0 + a_1 r + a_2 T + a_3 r T + a_4 r^2 + a_5 T^2 \quad (11)
\]

\[
l_{ij} = b_0 + b_1 r + b_2 T + b_3 r T + b_4 r^2 + b_5 T^2 \quad (12)
\]

In Equations 11 and 12 \( r \) is OWR, expressed as 0.9, 0.8, or 0.7 according to the OWR; \( T \) is temperature (K); \( a_0 \) to \( a_5 \) are the coefficients of the associated equation for \( k_{ij} \); and \( b_0 \) to \( b_5 \) are the coefficients of the associated equation for \( l_{ij} \). The values of these coefficients are listed in Table 7.

Table 8 provides the predicted BIPs by the developed association equations. It can be seen that the association accuracy is really good for both BIPs. Using these equations, further calculations of methane solubility in oil-based mud were conducted by PR EoS and vdW2 mixing rule. Excellent agreement between the results of the proposed model and the experimental data in this work is presented in Figure 10. We also evaluated the capacity of the proposed model to calculate methane solubility in extra oil-based mud. Experimental data for methane solubility in mentor oil-based mud\(^7\) were accurately predicted by our proposed model. Figure 11 displays a comparison between the results of our model and the experimental data in the literature. Figures 10 and 11 show that the agreement between calculated and experimental values is excellent for the given systems, further validating the reliability and accuracy of the proposed model.

5 | METHANE SOLUBILITY MODEL: FIELD APPLICATION

We offer a field application of methane solubility model developed in this work. A designed deepwater well (C1) in South China Sea was used to calculate methane solubility profile in the wellbore, assuming that a gas kick occurred at the bottom hole with a formation pressure of 60 MPa.
Table 9 lists the basic parameters of C1 well. Figure 12 displays the drilling mud transient temperature in annulus and drilling pipe. With the distribution of transient temperature, methane solubility at various depths can be calculated by the proposed models. Note that the following calculations are conducted as undetected kick calculates to the surface.

Figure 13 shows methane solubility profile in the wellbore during the kick process. The saturated solubility was calculated by the presented thermodynamic model, and the actual solubility is obtained by coupling of formation production rate and annulus flow characteristics. As can be seen, even though the saturated solubility decreases with drilling fluid flowing upward in the annulus, it is still much greater than the actual solubility in the majority of wellbore section. When the saturated solubility is equal to the actual solubility at some depth near the wellhead, methane will come out of solution, causing a complex multiphase flow in the wellbore. Figure 14 displays the comparisons of annulus gas holdup with and without the consideration of methane solubility in oil-based drilling mud condition during the kick process.

Table 9

| Parameter                      | Value      |
|--------------------------------|------------|
| Well depth (m)                 | 4500       |
| Wellbore size (mm)             | 311.1      |
| Water depth (m)                | 1500       |
| Drill pipe size (mm)           | 127        |
| Surface temperature (K)        | 293.15     |
| Geothermal gradient (K m⁻¹)    | 0.03       |
| Flow rate (L s⁻¹)              | 60         |
| Drilling mud density (g cm⁻³)  | 1.23       |
the bottom hole to the area near wellhead. After the dissolved gas starting to come out of solution, the annulus gas holdup will increase dramatically in a very short well section.

Annulus flow behavior is the most essential part to the kick detection and well control operation. With the knowledge of annulus gas holdup, we can calculate the most concerned engineering parameters. Figure 15 shows the responses of pit gain during kick process. It can be seen that with the consideration of solubility, the pit gain response is smaller than that of without solubility at the same time. This is because the volume expansion caused by free gas is larger than that caused by dissolved gas. Assuming that the critical pit gain to reliably detect a kick is 1.6 m³ (10 bbl), then it will take about 30 minutes to detect a kick in this case under the condition of without solubility. However, it needs about 50 minutes to detect a kick with the consideration of solubility. As mentioned before, it would be much better to detect a kick as early as possible. Therefore, in the case of kick detection design in oil-based mud, the determination of critical pit gain value should take the influence of gas solubility into account. Figure 16 shows the bottom hole pressure behavior during the kick process. The influx gas solubility also has a great influence on the wellbore pressure. Compared with no gas solubility, the bottom hole pressure drops much slower under the condition of with solubility. Obviously, it will take much more time to detect a kick through the monitoring of bottom hole pressure in oil-based mud.

6 | CONCLUSIONS

New methane solubility data have been obtained in water-based and oil-based muds under various temperature and pressure conditions. Methane solubility in water-based mud is much smaller than that in oil-based mud. It was found that methane solubility increases with pressure and that solubility is insensitive to temperature when the pressure is low. However, at high pressures, solubility increases with the temperature. Oil/water ratio (OWR) is also a key factor that determines methane solubility in oil-based mud. Generally, the higher the OWR, the greater is the solubility. In addition, investigations regarding emulsifier content and methane phases indicated that they have insignificant impact on gas dissolution process in oil-based mud. The comparisons between real muds and emulsions indicate that the existence of other components in mud decreases the methane solubility of mud.

Different combinations of EoS models and mixing rules were tested in view of the experimental data of methane solubility in oil-based mud. Results suggest that the PR EoS and vdW2 mixing rule is the most reliable combination to model the phase equilibrium of methane/oil-based mud binary system. For further application of the optimized thermodynamic model, association equations for BIPs were developed using the experimental data. A good agreement was obtained with the proposed equations and our data as well as those available in the literature. Based on the developed models in this work, the annulus methane solubility profile and its influence on well control in a deepwater well were discussed, which enable a better understanding of the annulus flow behavior during deepwater kick scenario.

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