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Original Paper

An integral method for calculation of capillary pressure based on centrifuge data of tight sandstone

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A B S T R A C T

The traditional Hassler-Brunner (HB) interpretation method of centrifuge capillary pressure is widely used in materials, soil, biotechnology, and especially in the petroleum industry. However, the assumptions of the traditional method cannot be simultaneously satisfied, the traditional method has been known to lead significant errors in some cases. In this paper, a new double integral method is proposed to evaluate the centrifuge capillary pressure of long tight sandstone samples. Both the changes of capillary length and interface of wetting phase and non-wetting phase fluids are considered by the new integral method, thus the average pressure and saturation derived from the proposed double integral method is more sufficient in theoretic foundation and clearer on physical meaning. By comparing with the measured capillary pressure of long tight sandstone core samples from porous plate, the capillary pressure calculated from traditional HB method is obviously smaller than the measured value, and the discrepancy increases with the decreasing core porosity. However, the average capillary pressure obtained by the proposed double integral method is remarkably consistent with the measured value. The findings of this study can help for better understanding of distribution of wetting phase fluid and average centrifuge capillary pressure in the core during centrifugal process.

1. Introduction

Capillary pressure curves are widely used in the materials, soil, and environmental sciences, and especially in the petroleum industry (Vavra et al., 1992; Hosseinzadeh et al., 2020; Liu and Yang, 2020). In hydrocarbon reservoir, the capillary pressure curve is actually a relationship curve between capillary pressure of reservoir rock and the wetting-phase saturation (Shao et al., 2016). The capillary pressure curve can be used to directly determine the irreducible water saturation, rock wettability, permeability (Zhao et al., 2020), pore size distribution (Liao et al., 2020), and it can also be used to study the oil recovery, initial static fluid distribution, and water flood performance in reservoirs (Masalmeh, 2003; Wu et al., 2017; Aghaeifar et al., 2019; Rücker et al., 2020; Su et al., 2020). All these petrophysical parameters are crucial for reservoir evaluation and simulation.

In the laboratory, the capillary pressure curve can be measured by either mercury injection (Gong et al., 2015), porous plate (Li et al., 2016), or centrifuge methods (Sarris et al., 2019). The mercury injection method is rapid and can reach very high capillary pressure, but it is destructive for the core and cannot be used to determine the irreducible wetting phase saturation. The porous plate method is considered the most direct and accurate method which can use reservoir conditions and fluids easily (Falode and Manuel, 2014). However, weeks or months may be required to complete a measurement, and the application of the porous plate method is usually limited by the maximum withstand pressure value of the porous plate. As a common compromise, the centrifuge method uses reservoir fluids and decreases the equilibrium time by using high centrifugal forces (Chen and Balcom, 2005). Although the centrifuge method for measuring capillary pressure has been used throughout the oil industry for more than 70 years (Hassler and Brunner, 1945), questions about its validity continue. The most important questions concern inversion algorithms of the centrifuge equation and the outlet boundary condition of capillary pressure. Actually, the fundamental centrifuge equation, which is a

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Nomenclature

a_c	= centrifuge acceleration, m/s^2
D	= diameter of a cylindrical core, m
D_p	= diameter of capillary in core sample, m
g	= acceleration of gravity, m/s^2
l_i	= length of ith capillary of core sample, m
L	= length of a cylindrical core, m
ΔL	= length of air in the capillary of core sample, m
P_{nw}	= non-wetting phase pressure, MPa
P_w	= wetting phase pressure, MPa
P_c^i	= capillary pressure of ith capillary during the drainage experiment, MPa
P_{cav}^i	= average capillary pressure of ith capillary during the drainage experiment, MPa
p_c	= capillary pressure of core sample, MPa
p_{cav}	= average capillary pressure of core sample, MPa
$P_c(r_1)$	= capillary pressure at the inlet end face of core sample, MPa
$P_c(r_2)$	= capillary pressure at the outlet end face of core sample, MPa
r_1	= distance from the axis of rotation to the inlet end face of core sample, m
r_2	= distance from the axis of rotation to the outlet end face of core sample, m
R_t	= pore-throat radius, m
R	= distance from the axis of rotation to the center of the core, m
$\bar{S}$	= average saturation of wetting phase fluid, %
$S_W(r)$	= saturation of wetting phase fluid at centrifugal radius r, %
S_{w_nmr}	= water saturation derived from NMR method, %
S_{w_g}	= water saturation derived from porous plate method, %
$S(P_c)$	= fundamental centrifuge equation of P_c
T_2	= transverse relaxation time of NMR, ms
θ	= contact angle of water and oil, rad
ρ	= density of liquid, g/cm^3
ρ_o	= density of oil, g/cm^3
ρ_w	= density of water, g/cm^3
$\Delta\rho$	= density difference between non-wetting and wetting fluids, g/cm^3
σ	= interfacial tension between oil and water
ω	= angular velocity, rad/s
Φ	= porosity of core sample, %

Volterra integral equation, is known to be ill-conditioned. Many researchers have proposed numerous approximate solutions for the centrifuge equation. As the earliest solution of centrifuge equation, the Hassler and Brunner's solution has been used by oil industry frequently. They assumed that the pressure field in the core is linear and the gravity effect is negligible. These assumptions can be accepted only for short and narrow samples rotated far from the rotation axis (O'Meara et al., 1992; O'Meara et al., 1992; Chen, 1999). However, these assumptions cannot be simultaneously satisfied, their method is known to lead to significant errors in the interpretation of centrifuge capillary pressure. Many other researchers have proposed different algorithms and numerical schemes to calculate the centrifuge capillary pressure (Subbey and Nordtvedt, 2002; Green et al., 2008; Nazari, 2015). However, most solutions address simplified forms of the ill-conditioned centrifuge equation, and the results obtained from each solution can be significantly different depend on the applied implementation scheme. Considering frequent use of the centrifuge experiment data in the oil industry, an accurate and effective technique for determining the centrifuge capillary pressure is still demanded.

In this paper, a simple and accurate double integral method is proposed for calculating the centrifuge capillary pressure of tight sandstone. Unlike the traditional methods, this new method not only considers the length change of different capillary, but also considers the interface change of wetting phase and non-wetting phase fluids. It can provide an average capillary pressure of core sample rather than solve the centrifuge equation and estimate the capillary pressure at the inlet flow face like the traditional methods did. Compared with the calculated capillary pressure from traditional methods, the average capillary pressure derived from the proposed double integral method is more sufficient in theoretic foundation and clearer on physical meaning.

To verify the validity of the proposed double integral method, centrifuge experiment data sets of four long tight sandstone core samples are obtained at several rotation speeds. The centrifuge capillary pressure curves of these cores are calculated by the proposed double integral method and traditional method respectively. By comparing with the available data of capillary pressure curves from the porous plate method, the advantages and limitations of the proposed double integral method are discussed in this paper. The remainder of this paper is organized as follows. First, the theory of centrifuge capillary pressure is presented in Section 2. Then, the principles of the new double integral method are described in Section 3. The advantages and limitations of the new method are discussed based on the centrifuge data of tight sandstone core samples in Section 4. The summaries are given in Section 5.

2. Theory of centrifuge capillary pressure

For single phase fluid, the hydrostatic pressure gradient on the elevation z can be represented as follow:

$$\frac{dP}{dz} = \rho g. \tag{1}$$

where ρ and g are the density of the liquid and the acceleration of gravity, respectively.

For an oil-water system in oil reservoir, if water is the wetting phase and oil is the non-wetting phase, the capillary pressure P_c is defined as the difference between the non-wetting phase pressure P_{nw} and the wetting phase pressure P_w (Donaldson et al., 1991):

$$P_c = P_{nw} - P_w. \tag{2}$$

The capillary pressure P_c is related to the height of the fluid above the oil-water contact in the reservoir, and the pressure gradient can be represented as follow:

$$\frac{dP_c}{dz} = (\rho_o - \rho_w)g. \tag{3}$$

where ρ_o and ρ_w are the densities of oil and water, respectively.

Usually, the pore-throat shape of reservoir rock can be described as a cylindrical capillary tube, then the capillary pressure can be described as (Zhang et al., 2017):

$$P_c = 2\sigma \cos\theta / R_t. \tag{4}$$

where R_t is the pore-throat radius, θ is the contact angle, and σ is the interfacial tension between oil and water. The capillary pressure can be converted directly into a pore-throat size using Equation (4) (Nabawy et al., 2009).

Centrifuge experiment is one of the most effective methods to evaluate the capillary pressure of reservoir rock. As illustrated in Fig. 1, a cylindrical core sample, which initially saturated with a wetting fluid (usually water) and confined in a special core holder, is spun at different rotational speeds. r_1 and r_2 are the distances from the axis of centrifuge rotor to the inlet end face and the outlet end face of core sample, respectively. The non-wetting fluid (usually air or oil) which contained in core holder replaces the wetting fluid from the core during the centrifuge experiment. After reaching equilibrium at each speed, which means the centrifugal conquer the capillary pressure, the initially saturated wetting fluid will be gradually displaced by the non-wetting fluid, and the average wetting fluid saturation remaining in the core could be measured.

The capillary pressure distribution and the water saturation distribution along the length of the core sample are illustrated in Fig. 2. The capillary pressure along the length of core sample varies from a maximum value $P_c(r_1)$, at the inlet end face, to zero at the outlet end face. On the contrary, the water saturation along the length of core sample varies from a minimum value at the inlet end face, to a maximum value at the outlet end face. The centrifuge capillary pressure curve has been widely used to describe the relationship between the capillary pressure and water saturation, especially at the inlet end face. Even though many attempts have been made to construct the centrifuge capillary pressure curve, the solution method of local water saturation and capillary is still a challenge in the application of centrifuge capillary pressure.

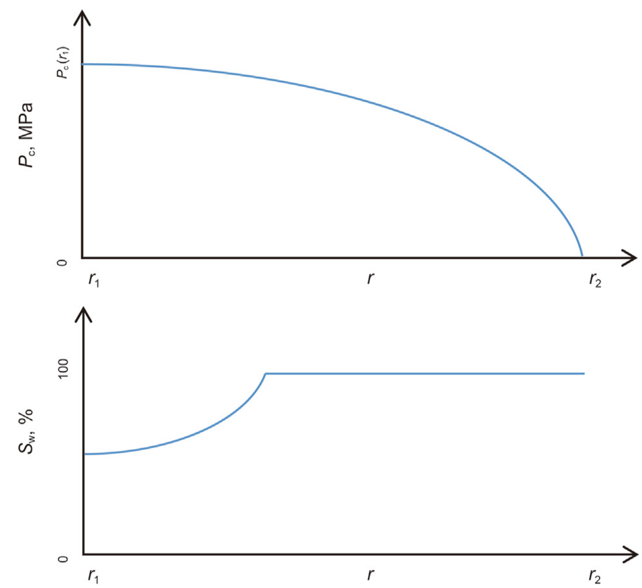

Fig. 2. Local saturation and capillary pressure along the core during the drainage centrifuge experiment.

3. Principles for determining centrifuge capillary pressure

3.1. Hassler and Brunner's method

Modern centrifuge techniques are primarily based on the pioneer work by Hassler and Brunner in 1945. The traditional Hassler and Brunner (HB) interpretation method of centrifuge capillary pressure is based on several assumptions: (1) nonlinearity of the centrifuge field, over the length of a core sample, is not significant; (2) gravity has no effect on the water saturation distribution in the centrifuge process; (3) the capillary pressure is zero and water saturation is 100% at the outlet end face of the core sample. Based on the assumptions of HB method, the capillary pressure and water saturation distribution along the core are illustrated in Fig. 3. In their model, water saturation along the length of core varies from a low level at the inlet end face, where the capillary pressure is a maximum, to a maximum water saturation of 100% at the outlet end face, where the capillary pressure is zero.

In the centrifuge experiment, the angular velocity ω at each step is maintained constant until no water separate from core sample, and the cylindrical core is subjected to an acceleration $a_c = \omega^2 r$. The core holder becomes horizontal at high enough angular

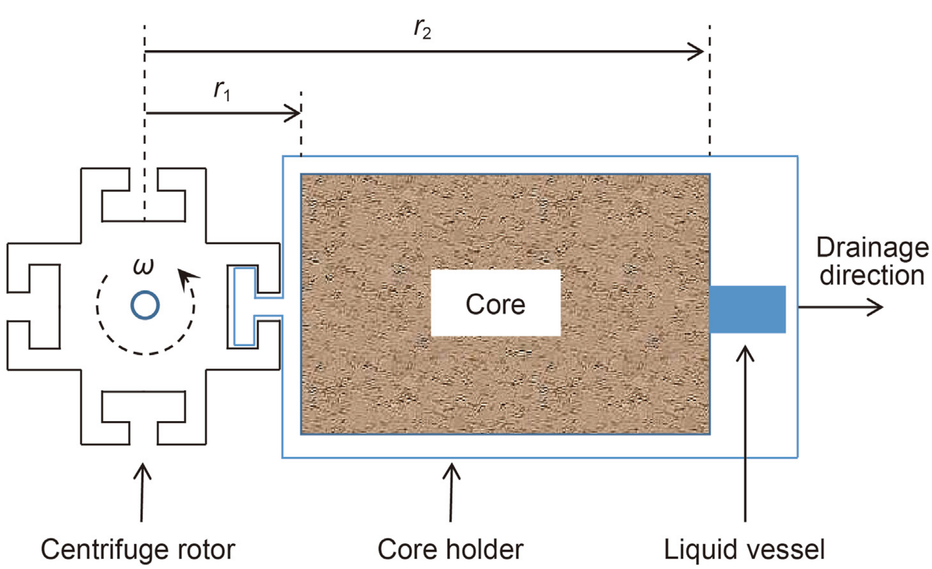

Fig. 1. Diagram of conventional core model based on centrifuge experiment.

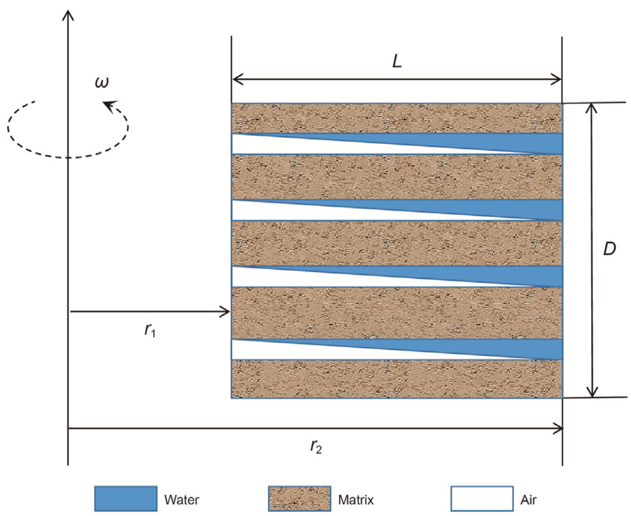

Fig. 3. Diagram of Hassler and Brunner's core model based on centrifuge experiment.

velocity, and the gravity effect can be negligible, then the gravity acceleration g in Equation (3) is replaced by centrifuge acceleration a_c:

$$\frac{dP}{dr} = \Delta\rho a_c, \tag{5}$$

where $\Delta\rho$ is the density difference between non-wetting fluid and wetting fluid.

Applying Darcy's law at hydrostatic equilibrium and using Hassler-Brunner boundary condition, the capillary pressure at the centrifuge radius r, where $r_1<r<r_2$, is simple integration of the differential Equation (5):

$$P_c(r) = \int_r^{r_2} \Delta\rho\omega^2 r dr = \frac{1}{2}\Delta\rho\omega^2\left(r_2^2 - r^2\right), \tag{6}$$

For a continuous wetting phase, the capillary pressure at the inlet end face is:

$$P_c(r_1) = \frac{1}{2}\Delta\rho\omega^2\left(r_2^2 - r_1^2\right), \tag{7}$$

When a core is placed in a core holder of the centrifuge, the distance from the axis of centrifuge rotor to the outlet end face, r_2, is a constant, but the distance from the axis of centrifuge rotor to the inlet end face, r_1, which depends on the length of the core, is a variable. For a cylindrical core of length L subjected to a centrifuge, Equation (7) can be rewritten as:

$$P_c(r_1) = \Delta\rho\omega^2 RL. \tag{8}$$

where R is the distance from the axis of centrifuge rotor to the center of the core, $R = (r_2 + r_1)/2$.

As illustrated in Fig. 2, the capillary pressure distribution is related to the water saturation distribution along the length of the core. The measured average saturation of wetting phase fluid, $\overline{S}$, at each step can be expressed as an integral of the point saturation, $S_W(r)$, over r.

$$\overline{S} = \frac{\int_{r_1}^{r_2} S_W(r)dr}{r_2 - r_1}, \tag{9}$$

Most of the solution procedures given in the literature started by transforming the variable of integration in Equation (9) from distance, r, to capillary pressure, P_c, by using Equation (6). Thus, Equation (9) can be rewritten by changing the integration variable $P_c(r_1)$ and $P_c(r_2) = 0$, which yields an integral equation (Christiansen, 1992):

$$\overline{S} = \frac{r_2 + r_1}{2r_2 P_c(r_1)} \int_0^{P_c(r_1)} \frac{S(P_c)}{\sqrt{1 - BP_c/P_c(r_1)}} dP_c, \tag{10}$$

where $B = 1 - r_1^2/r_2^2$.

Equation (10) is known as the fundamental centrifuge equation, which is a Volterra equation, cannot be directly solved from the unknown function $S(P_c)$. As pointed out by HB method, for short core that $r_1/r_2 \approx 1$, the variation of capillary pressure gradient along the core can be neglected, the effect of gravity is negligible at the high centrifuge speed, then the saturation at the inlet end can be calculated by an approximation (App and Mohanty, 2002):

$$S(P_c(r_1)) = \overline{S} + P_c(r_1)\frac{d\overline{S}}{dP_c(r_1)}. \tag{11}$$

In the HB method, the value of $P_c(r_1)$ at each rotational speed is calculated by Equation (8), and the saturation at the inlet end face, $S(P_c(r_1))$, is derived by Equation (11). Then the obtained values of $P_c(r_1)$ and $S(P_c(r_1))$ from several rotation speeds can be converted to the traditional centrifuge capillary pressure curve.

However, these assumptions of HB method cannot be simultaneously satisfied. When the length of core sample is not short enough, the nonlinearity of the centrifuge field in the core sample cannot be negligible, and the approximation of the saturation at the inlet in Equation (11) is not strictly accurate. Besides, when the rotation speed is low, the capillary pressure is also low, then the gravity effect cannot be neglected. In addition, this method aims at providing an expression between water saturation and capillary pressure at the inlet end face of core sample, which means the length of capillary should be always equal to the length of core sample during the centrifuge process, and it obviously conflicts with the physical phenomenon of oil-water interface changes in the actual centrifugal process. Therefore, in the interpretation of centrifuge capillary pressure of long and tight core sample, the application of HB method may lead to significant errors, and a new accurate and effective method is still needed.

3.2. Double integral method

Many attempts have been made to improve the approximate solution of centrifuge equation in Equation (10). The traditional HB solution is one of the earliest solution being used by oil industry widely. However, this method usually leads to significant errors when the assumptions of it cannot be simultaneously satisfied. Several researchers have questioned the validity of centrifuge equation itself, and there is still some controversy over the use of the boundary condition given by centrifuge equation. However, implement of those solutions requires different algorithms and numerical schemes, and the results obtained from each solution can be significantly different depending on the applied implementation scheme. All these traditional solutions try to solve the ill-conditioned Volterra equation and address simplified forms of Equation (10). In the application of these solutions, the length of the wetting phase fluid in the capillaries, which denote the change of oil-water interface position, is remain unchanged during the centrifuge experiment as shown in Fig. 3. In other words, saturation is the only variable in traditional methods.

Actually, as a typical porous medium, the pore network of natural rock is composed of pores of different size and location, the simple capillary models proposed from the above traditional methods cannot characterize the pore structure of the core accurately. Besides, in the drainage centrifuge experiment, the capillary pressure in different capillary is different at the same centrifuge rotation speed. Thus, when the capillary pressure reaches mechanical equilibrium at each specified rotation speed, not only the water saturation, but also the locations of water-air interface change in different capillary. Obviously, the capillary model used by the traditional methods is not strict.

Considering the properties of local capillary pressure in different pores, we introduce a simplified capillary model as shown in Fig. 4. In the new capillary model, two main assumptions are adopted to calculate the centrifuge capillary pressure: (1) the lengths of different capillary are not equal, and the maximum length of capillary is equal to the length of core; (2) the radii of different capillary are not equal, thus the water-air interfaces in different capillary are different in the same rotation speed. Based on above assumptions, not only the length and radius of capillary, but also the change of water-oil interface in the centrifuge process have been considered in the new capillary model. Theoretically, the new model is more suitable to describe the distribution of water and air in the core during centrifugal process than the traditional capillary model of HB method.

Based on the new capillary model, this paper aims at providing an effective expression between average water saturation and average capillary pressure of core sample, the former can be directly measured by many methods, while the latter need to be calculated based on our assumptions. To get an accurate solution of average capillary pressure, a double integral method is introduced to balance the effects of water-air interface and dimension size of different capillary. For the ith capillary in the model of Fig. 4, the position of water-air interface, which depends on the ratio of centrifuge force to capillary pressure, can change from the inlet end face to the outlet end face of the capillary. When the capillary is full saturated with water, the capillary pressure at the inlet end face of capillary can be calculated from Equation (8):

$$P_c^i = \Delta\rho\omega^2 R_i l_i, \tag{12}$$

where l_i is the length of i th capillary, $R_i = (r_2^i + r_1^i)/2$ is the distance from the axis of centrifuge rotor to the center of the ith capillary,

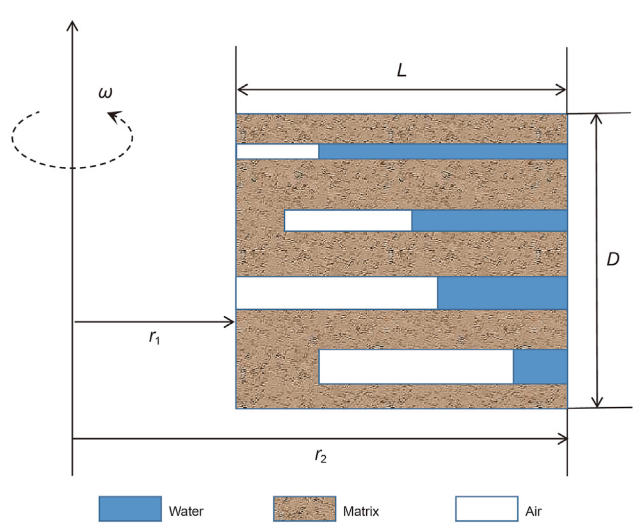

Fig. 4. Diagram of new core model based on centrifuge experiment.

r_2^i and r_1^i are the distances from the axis of centrifuge rotor to the outlet end face and inlet end face of the ith capillary, respectively.

To simplify the calculation of average capillary pressure of each capillary, the position of outlet end face of each capillary is assumed to be the same with the outlet end face of core, that means the r_1^i used in the expression of R_i can be substituted by the inlet end face r_1.

Considering the actual physical phenomenon of drainage centrifuge experiment, the capillary pressure of water-air system in a core sample can be described as:

$$P_c^i = \Delta\rho\omega^2\left(R + \frac{L - l_i}{2} + \frac{\Delta L}{2}\right)(l_i - \Delta L), \tag{13}$$

where R is the distance from the axis of centrifuge rotor to the center of the core, L is the length of the core, $l_i - \Delta L$ and ΔL are the lengths of water and air in the ith capillary, respectively.

For a single capillary, the ratio of centrifuge force to capillary pressure cannot be determined in advance, thus the position of water-air interface may change from the inlet end face to the outlet end face of the capillary. In the new integral method, the first integral is used to calculate the average capillary pressure of a single capillary under a specified centrifuge speed:

$$P_{cav}^i = \frac{\Delta\rho\omega^2}{l_i}\int_0^{l_i}\left(R + \frac{L - l_i}{2} + \frac{\Delta L}{2}\right)(l_i - \Delta L)d\Delta L, \tag{14}$$

After considering the effect of water-air interface position in a single capillary, the effect of the length of different capillary is also considered in the new integral method. When the outlet end face of capillary is fixed as illustrated in Fig. 4, the centrifuge force only depends on the distance from the axis of centrifuge rotor to the water-air interface, thus the tortuosity of capillary is not considered in our method, and the maximum length of single capillary is equal to the length of core sample. For the whole pore network in the core, the average capillary of all capillaries can be calculated by the second integral of Equation (14):

$$P_{cav} = \frac{\Delta\rho\omega^2}{L}\int_0^{L}\frac{1}{l_i}\int_0^{l_i}\left(R + \frac{L - l_i}{2} + \frac{\Delta L}{2}\right)(l_i - \Delta L)d\Delta L dl_i, \tag{15}$$

By simplification and substitution, Equation (15) can be rewritten as:

$$P_{cav} = \Delta\rho\omega^2\left(\frac{RL}{4} + \frac{5L^2}{72}\right). \tag{16}$$

In the double integral method, the value of P_{cav} at each rotational speed is calculated by Equation (16), and the average water saturation, $\overline{S}(P_{cav})$, is measured by NMR or other methods. Then the obtained values of P_{cav} and $\overline{S}(P_{cav})$ from several rotation speeds can be converted to a new average centrifuge capillary pressure curve.

Compared with the calculated capillary pressure $P_c(r_1)$ of traditional HB method, the calculated average capillary pressure P_{cav} by the proposed double integral method is more sufficient in theoretic foundation and clearer on physical meaning. In addition, the average capillary pressure P_{cav} can be directly calculated from Equation (16) without need to solve the fundamental centrifuge equation, thus the double integral method is theoretically more robust and efficient than the traditional HB method.

Table 1
Physical properties of four tight sandstone core samples.

No.	Diameter, cm	Length, cm	Porosity, %	Permeability, mD
1	2.503	4.765	4.6	0.191
2	2.501	5.391	5.4	0.204
3	2.507	4.735	5.9	0.227
4	2.504	4.805	7.0	0.215

4. Capillary pressure curves from centrifuge method and porous plate method

In this paper, four cylindrical tight sandstone samples, which from an oilfield located in northwestern China, are employed for the centrifuge capillary experiment. As shown in Table 1, the porosity of these core samples distributes between 4.6% and 7.0%, and the relevant permeability distributes between 0.191 mD to 0.227 mD, all these samples can be classified as tight sandstone undoubtedly.

To perform the centrifuge experiment of these core samples, a high speed refrigerated centrifuge (GL-25M) was used. It can provide maximum rotate speed of 12000 rpm with ±50 rpm error, the distance from axis of the centrifuge rotor to the outlet end face of core holder is 9 cm, and the temperature in the core holder can be set between −20 and 40 °C. In the centrifuge experiment, the rotation speed is set as 500, 3000, 5000, 7000, 9000 rpm gradually, and the centrifuge time at each rotate speed is fixed at 1 h to reduce the effects of the experiment environment.

For the centrifuge experiment of tight sandstone, the amount of water displaced from the core sample is very small and susceptible to evaporation, it is a trouble for the traditional measurements. In this work, the residual water in the pore space, which is rarely affected by evaporation, is precisely measured by NMR core analyzer (MicroMR02-050v, Niumag). As shown in Fig. 5, the small pore, which corresponds to small T_2 value, and the big pore, which corresponds to large T_2 value, can be clearly classified from the spectra of transverse relaxation time T_2 of saturated cores. By comparing the spectra of T_2 at different rotation speeds in centrifuge experiment, the change of fluid distribution in different pores can be clearly observed. When the rotation speed is low, the amplitude of large T_2 value drops slightly, it means that part of the movable water, which is mainly from the large pore, has been centrifuge out the pore space. As the rotation speed increase, the movable water in the large pore and small pore has been centrifuge out the pore space gradually, and the amplitude of large T_2 value drops more significantly than the amplitude of small T_2 value. When the rotation speed reaches a certain high value, the amplitude of large T_2 value drops to a minimum value, and the amplitude of small T_2 value becomes drop significantly, it means that the movable water in both small pore and large pore has been absolutely centrifuge out the pore space, and part of the irreducible water in the small pore has also been centrifuge out the pore space due to the very large centrifuge force.

By combing the average capillary pressure calculated from Equation (16) and water saturation measured from NMR method, the average centrifuge capillary pressure curves of these tight sandstone core samples have been derived rapidly and simply. As illustrated in Fig. 6, both the capillary pressure curves from centrifuge method and porous plate method are demonstrated. The capillary pressure of the traditional HB method is obviously smaller

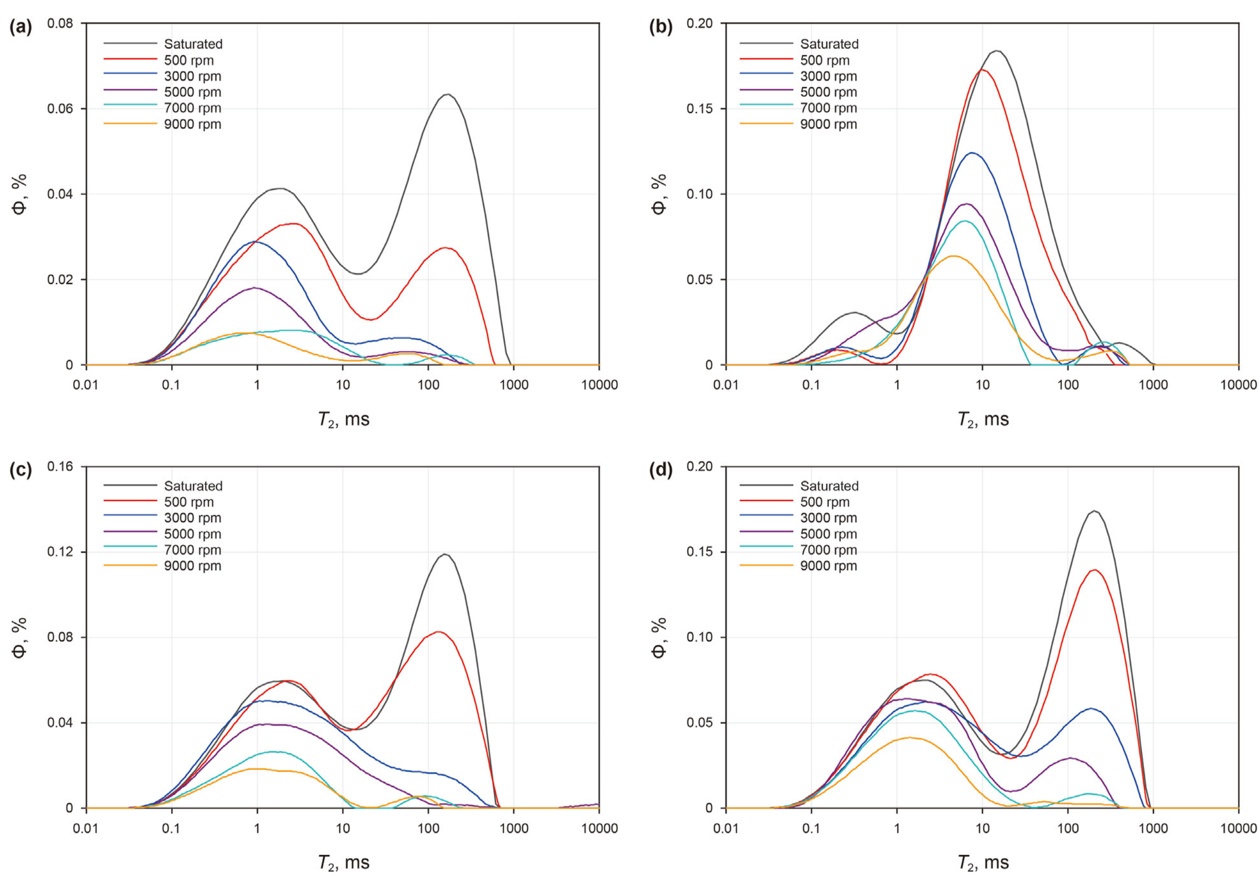

Fig. 5. T_2 spectra of tight sandstone core samples from different centrifugal speeds. (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4.

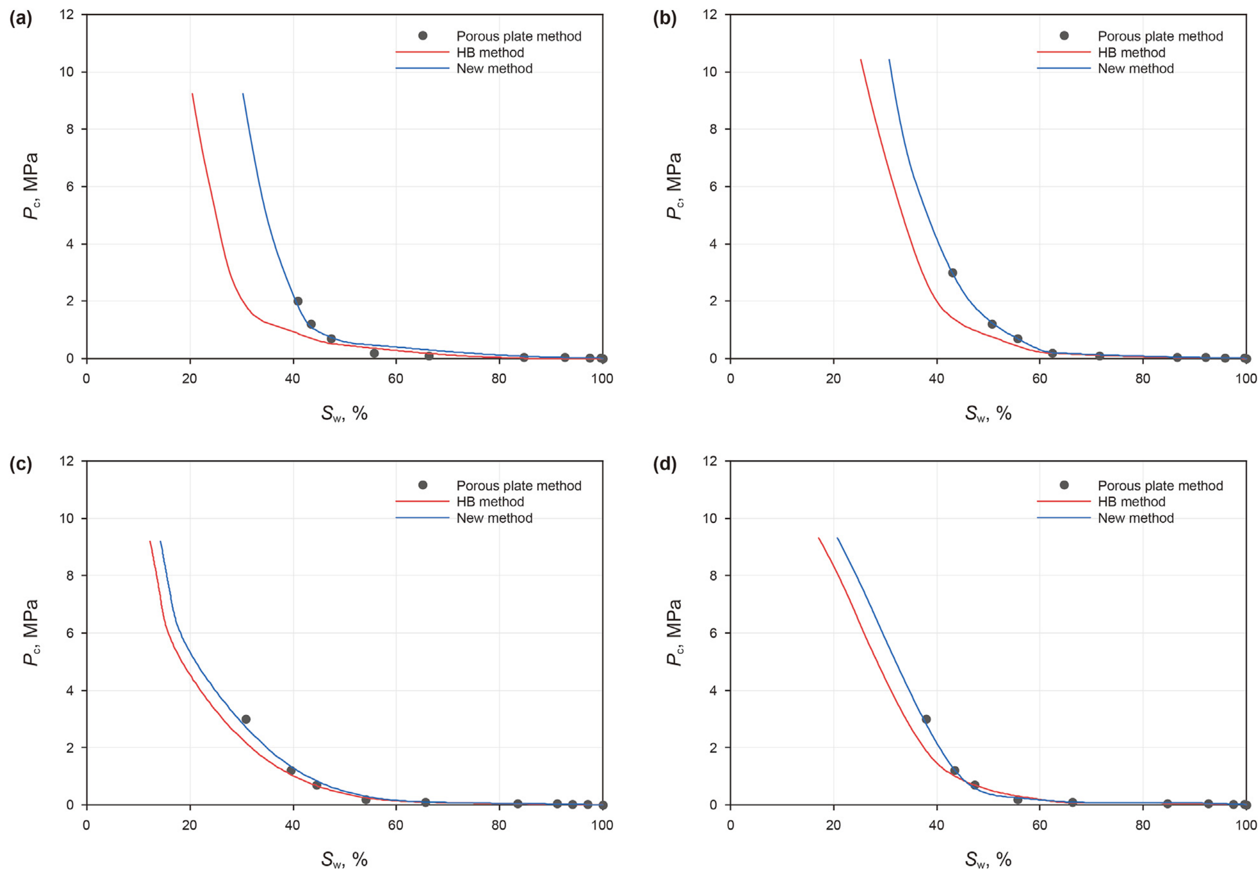

Fig. 6. Comparison of capillary pressure curves derived from centrifuge method and porous plate method. (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4.

than the pressure measured by porous plate method, while the capillary pressure of the new double integral method is remarkably consistent with pressure measured by porous plate method. As the porosity decreases from sample 4 to sample 1, the difference between the capillary pressure from the traditional HB method and the capillary pressure from the new double integral method becomes more and more obvious. The centrifuge capillary pressure measurement results demonstrate that the new double integral method is more suitable to evaluate the capillary pressure of long and tight sandstone core samples than the traditional HB method.

To further quantitatively analyze the limitations of the new double integral method, the crossplots of the values of water saturation derived from the porous plate method and the new double integral method are illustrated in Fig. 7. The maximum capillary pressure of the porous plate used in the measurement is 3 MPa, which means that the minimum water saturation determined from the capillary pressure curve is also limited at that capillary pressure. Thus, in Fig. 7, the values of water saturation from the new double integral method are obtained by interpolating the measured capillary pressure values in the centrifuge capillary pressure curves of the new double integral method.

As shown in Fig. 7, when the water saturation is high, which means the rotation speed is low, the water saturation from the new double integral method is slightly smaller than the measured water saturation from the porous plate method, is because the effect of gravity could not be neglected at the low rotation speed. As the water saturation decreases, the water saturation from the new double integral method is slightly larger than the measured water saturation from the porous plate method at some certain points, because the centrifuge time is not long enough at these points. When water saturation drops to a very low value, the water saturation from the new double integral method becomes consistent with the measured water saturation from the porous plate method, because the effects of gravity and centrifuge time could be ignored at the high centrifuge speed.

5. Summary and conclusions

In this paper, a simplified capillary model is introduced to characterize the wetting phase fluid distribution in the pore space during the centrifuge experiment. The new capillary model consists of capillaries with different length and radius, the interfaces of wetting phase fluid and non-wetting phase fluid and saturation of wetting phase fluid in different capillary of this model are different in the same rotation speed. Theoretically, the new model is more suitable to describe the distribution of wetting phase fluid in the core during centrifugal process than the capillary model of traditional HB method.

Based on the proposed new capillary model, a new double integral method is introduced to determine the average centrifuge capillary pressure of long core samples of tight sandstone. In the proposed double integral method, the interface change of wetting phase fluid and non-wetting phase fluid during the centrifuge experiment is considered, and the average capillary pressure of a single capillary is calculated by the first integral method. Besides, the effect of the capillary length of different capillary is also considered by the proposed double integral method, and the average capillary pressure of the core sample during the centrifuge experiment can be derived from the second integral method. Compared with the capillary pressure provided by traditional HB

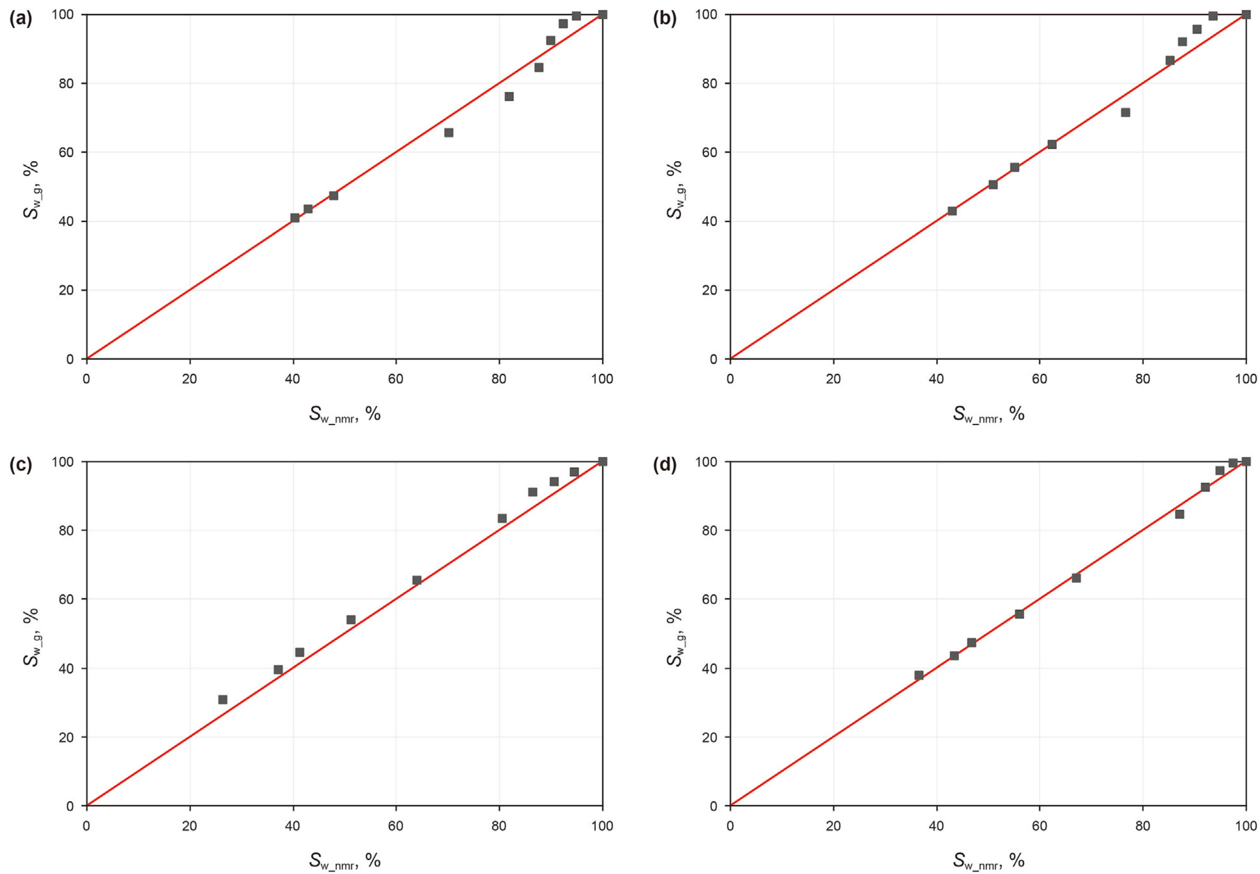

Fig. 7. Comparison of water saturation derived from NMR method and porous plate method. (a) Sample 1, (b) Sample 2, (c) Sample 3, (d) Sample 4.

method, the calculated average capillary pressure from the proposed double integral method is more sufficient in theoretic foundation and clearer on physical meaning.

The centrifuge experiment data sets of four classical long tight sandstone core samples are adopted to evaluate the validity of the new method. By comparing with the measured capillary pressure from porous plate, the capillary pressure calculated from traditional HB method is obviously smaller than the measured value, and the discrepancy between them increases with the decreasing porosity of core samples. However, the average capillary pressure obtained by the proposed double integral method is remarkably consistent with the measured value determined by porous plate method. There is no doubt that the proposed new double integral method can provide a capillary pressure with better accuracy than the traditional HB method for the long tight sandstone core samples.

In this paper, an effective and efficient new method for the evaluation of centrifuge capillary pressure of the tight sandstone core samples is introduced. Some limitations are also encountered in the application of the proposed new method, for example, when the rotation speed is not high enough, the capillary pressure calculated from the proposed method is still affected by the gravity and centrifuge time in some extents, and these impacts and limitations need to be further studied in future work.

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