Research Article

A Prediction Model for Sustained Casing Pressure under the Effect of Gas Migration Variety

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Sustained casing pressure (SCP) is a challenge in the well integrity management in oil and gas fields around the world. The flow state of leaked gas will change when migrated up annulus protective fluid. To show the influence of gas migration on casing pressure recovery, a prediction model of SCP based on Reynolds number of bubbles was established. The casing pressure prediction of typical wells and the sensitivity analysis of casing pressure are performed. The results show that the casing pressure recovery time decreases with the increase of cement permeability. However, larger cement permeability has little effect on the casing pressure after stabilization. Increasing the height of annulus protective fluid reduces the stable casing pressure value and shortens the casing pressure recovery time. Compared with the existing models, the results show that the time of casing pressure recovery will be shortened by the change of gas migration, and the effect of bubbles \(Re < 1\) on SCP will be greater. The new model can be used to detect and treat the SCP problem caused by small Reynolds number gas leakage.

1. Introduction

Sustained casing pressure of annulars cannot be bled to zero, or it will build back up to original pressure [1]. SCP will bring both risks to the safe production of wells and the cost of pressure relief [2]. In recent years, SCP has become a common phenomenon threatening the safety of injection and production wells. According to statistics, over 43% of wells in the outer continental shelf of the Gulf of Mexico (GOM) in the United States have been reported with SCP [3]. In Tarim Oilfield of China, there are over 93% SCP in high-pressure gas wells, and the maximum casing pressure even exceeds 50 MPa [4]. The Norwegian Institute of Technology (SINTEF) tracked and analyzed 217 production wells in 10 years and found that SCP increased from 1.7% to 25.5% [5, 6]. SCP problem poses a severe challenge to the safety of oil and gas wells, which is a common problem and safety problem faced by the world petroleum industry.

The main causes of SCP are divided into three categories: (1) Gas lift, annulus detection and thermal recovery may cause SCP; (2) The top of the annulus is the gas cap. The volume expansion of the gas in the gas cap is caused by the change of temperature, which leads to SCP; and (3) Gas leakage can cause SCP [7]. After wellhead pressure relief, SCP expansion effect caused by operation can be eliminated. Casing leakage failure can be eliminated by replacing the casing string, but the loss of the cement sheath is permanent. At present, the research on SCP focuses on the derivation of the mathematical model. Pressure calculation models for cement sheath loss are divided into two categories:

(1) The movement of gas in annulus protective fluid is neglected, and only the gas channeling in the cement annulus and gathering at the gas cap are considered. Xu and Wojtanowicz [8] establish a casing pressure prediction model by using the hydrostatic column pressure balance equation without considering the migration of a cross-flow gas in annular protective fluid, then [9] combined with the variation of the viscosity and the deviation factor of the leaked gas under different pressures, and the pressure prediction model was further improved. Rocha-Valadez et al.
[10] based on the XU model, through fitting the field measured data with killing well, completed the acquisition of cement permeability, annulus protective hydraulic shrinkage coefficient, and other parameters which cannot be easily measured and calculated. Huerta et al. [11] transform the effective permeability of the cement sheath into equivalent geometry of discrete leakage path and determine the leakage rate of the gas in the annulus through the transport model. However, these models did not consider the same process of gas migration in annulus protective fluid and only apply to the case of cement slurry returning to the ground.

(2) It considers the gas channeling in the cement annulus and the change of the gas channeling in the annulus protective fluid. This kind of model is suitable for the condition that cement slurry does not return to the ground. After the leakage gas enters the annulus protective fluid, its motion state changes constantly and reaches the equilibrium state of zero resultant force in the process. At this point, the rising velocity is called the terminal velocity [12]. Xu and Wojtanowicz [13] calculated the rising velocity of the gas through the drift flow model; on this basis, Zhu et al. [14] realize the pressure prediction of annulus A in CO₂ injection wells combined with the phase transformation law of CO₂. However, in their study, the effect of Reynolds number of bubbles on gas terminal velocity was neglected. Yunjian et al. [15] neglected the liquid velocity and assumed that the bubbly flow of channeling gas in annulus protective fluid. The one-dimensional Navier–Stokes (N–S) equation was used to establish the gas force balance equation. The annulus fluid was regarded as non-Newtonian fluid to predict the pressure value. The staggered grid and the semi-implicit difference method were used to solve the SCP prediction model. However, there are obvious differences in the motion law of bubbles under different Reynolds numbers. This model cannot distinguish the rising velocity of bubbles with different Reynolds numbers. Uncertainty of the terminal rising velocity of bubbles will affect the accuracy of casing pressure prediction.

In this paper, considering the correlation between initial bubble radius and Reynolds number of bubbles, a casing pressure prediction model for calculating different Reynolds number bubbles was established for cement not returning to the ground. Based on the Reynolds number of bubbles, this paper considers two models: the large Reynolds number bubble rising velocity model and small Reynolds number bubble rising velocity model. Based on these models, casing pressure of an example well is predicted. Then, sensitivity analysis of casing pressure prediction is made by changing calculation parameters. The prediction results show that cement permeability and annular fluid height are the key parameters affecting casing pressure recovery. Compared with the XU model, the flow rate of gas at both ends of annulus protective fluid calculated by the new model is different, which indicates that the velocity of gas in annulus protective fluid will change. Computation and comparison of case wells are carried out; it is shown that the variation degree of gas is different under the variable Reynolds number. There is a greater difference between them when the Reynolds number of gas bubbles is lower. It is explained that the variation of gas in annular protective fluid cannot be ignored. This further indicates that it is important to consider the Reynolds number of gas bubbles for exploring the law of gas migration in annulus protective fluid and detecting and controlling the casing pressure in situ.

2. Initial Bubble Force Analysis

After separating from the surface of cement, gas flows into the gas cap by migration in annulus protective fluid and causes an increase in casing pressure, as shown in Figure 1.

In the process of detaching from the surface of the cement sheath, the force acting on a bubble is affected by the following:

(1) Buoyancy: upward force produced by the difference in gas-liquid density.

\[ F_j = V_b \left( \rho_b - \rho_g \right) g \]

where \( V_b \) is the initial bubble volume, \( \rho_b \) is the initial bubble density, \( \rho_g \) is the annulus protective fluid density, \( \rho_b \) is the gas density, kg/m³; and \( g \) is the gravitational acceleration, 9.8 m/s².

(2) Surface tension: inhibits bubble growth and maintains bubble shape.

\[ F_s = \pi d_0 \sigma \cos \theta \]

where \( d_0 \) is the cement pore diameter, m; \( \sigma \) is the surface tension coefficient of annulus protective fluid and gas, N/m; and \( \theta \) is the angle of the bubble growth direction and vertical direction at the hole of the cement sheath, °.

(3) Viscous resistance: gas entering the annulus through the cement pore needs to break through the interfacial tension between gas and liquid, thus forming bubbles in annulus protective fluid and expanding constantly. In the process of bubble expansion, the annulus protective fluid around the bubble will produce slight flow, which will produce resistance to the bubble. If the bubble and the cement sheath do not separate, the Stokes resistance formula is applied (Wang and Su [16]).

\[ F_{vis} = 3 \pi d_0 \mu_1 v_b \]

where \( v_b \) is the growth rate of bubble radius, m/s and \( \mu_1 \) is the viscosity of annular protective fluid, Pa·s.

(4) Inertia resistance: the gas enters the annular protective fluid from the cement to form bubbles, which expand at a corresponding rate, causing a change in momentum.
temperature, $K$; $\mu_g$ is the gas viscosity, Pa-s; $T_f$ is the formation temperature, $K$; $L_f$ is the length of cement, m; and $P_{sc}$ is the standard condition pressure, Pa.

In vertical wells, the direction of bubble growth on the surface of the cement sheath is vertical. In practice, the pore size distribution on the surface of the cement sheath is nonuniform. For convenience of calculation, the pore radius $r_0$ on the surface of the cement sheath can be approximately expressed as follows [18]:

$$r_0 = \frac{1}{2}d_0 = \frac{\phi D_p}{6(1 - \phi)}$$  \hspace{1cm} (7)

The surface tension of the bubble is as follows:

$$F_s = \frac{\sigma \pi \phi D_p}{3(1 - \phi)}$$  \hspace{1cm} (8)

where $\phi$ is the porosity of the cement sheath, dimensionless, and $D_p$ is cement particle diameter, m.

Inertia force and viscous drag also hinder the growth of bubbles. According to the balance of resultant forces acting on bubbles during separation, it can be expressed as

$$\frac{4}{3} \pi r_b^3 (\rho_l - \rho_g) g = \frac{d(Mv_b)}{dt_b} + 6 \pi r_b \mu_l v_b + \frac{\sigma \pi \phi D_p}{3(1 - \phi)}$$ \hspace{1cm} (9)

The expansion of inertial force is as follows:

$$\frac{d(Mv_b)}{dt_b} = M \frac{dv_b}{dt_b} + v_b \frac{dM}{dt_b}$$ \hspace{1cm} (10)

where

$$\frac{dM}{dt_b} = \frac{dM}{dt_b} \cdot \frac{dV_b}{dt_b} = \left( \rho_g + \frac{11}{16} \rho_l \right) \cdot q_g$$ \hspace{1cm} (11)

The growth rate of bubble radius $v_b$ can be expressed as

$$v_b = \frac{dr_b}{dt_b} = \frac{dV_b}{dt_b} = \frac{dV_b}{dt_b} = \frac{q_g}{4\pi r_b^2}$$ \hspace{1cm} (12)

Equation (12) derives the radius of bubbles $r_b$:

$$\frac{dv_b}{dr_b} = -\frac{q_g}{2\pi r_b}$$ \hspace{1cm} (13)

The relationship between bubble radius growth rate $v_b$ and expansion time $t_b$ is expressed as follows:

$$\frac{dv_b}{dt_b} = \frac{dr_b}{dt_b} = \frac{dV_b}{dt_b} = \frac{dV_b}{dt_b} = \frac{q_g}{4\pi r_b^2}$$ \hspace{1cm} (14)

Using equations (6), (9), (11), (12), and (14), we have

$$\frac{4}{3} \pi r_b^3 (\rho_l - \rho_g) g = \left( \rho_g + \frac{11}{16} \rho_l \right) \cdot q_g^2 + \frac{3 \pi \mu_l}{2r_b} + \frac{\sigma \pi \phi D_p}{3(1 - \phi)}$$ \hspace{1cm} (15)

With the leakage rate of gas (from the cement sheath into annulus protective fluid), the initial bubble radius can be calculated by simulating when the bubbles leave cement. Then, the Reynolds number of bubbles can be calculated, and gas rising velocity model calculated.
3. Bubble Rising Velocity Model Based on Reynolds Number

After the bubbles break away from the cement surface, they rise along the annulus protective fluid under the action of buoyancy. The initial size and rising velocity of bubbles in the annulus affect the distribution ratio and flow state of gas-liquid two-phase in the annulus and ultimately act on the Reynolds number. In general, bubbles in fluids can be classified into many types. The Reynolds number describes the shape of bubbles:

$$\text{Re} = \frac{\rho v d_b}{\mu}.$$  (16)

Leal [19] summarized a large number of experimental results and gave the shapes in different Reynolds number ranges. When Re < 1, the inertia force of bubbles is small, but the surface tension and viscous resistance are large, and the bubbles are spherical; when Re < 1000, the bubbles are enlarged by inertia force, and the bubbles are flattened into ellipsoids; when Re > 1000, the bubble deformation is further intensified, and the bottom of the spherical bubbles is depressed into caps or skirts.

3.1. Bubble Rising Velocity Model with Small Reynolds Number. When the Reynolds number of bubbles is small, the rising velocity of bubbles is relatively slow, and the morphology of bubbles hardly changes during the rising process. It can be seen as a sphere [20]. Rising bubbles are affected by buoyancy, gravity, and viscous drag, as shown in Figure 2.

When Reynolds number is small (<1), creeping flow theory is used to calculate the bubble motion resistance. Where $C_D$ is the drag coefficient, which is equal to 24/Re [21].

The resultant forces of small Reynolds number bubbles in the rising process of annulus protective fluid are as follows:

$$F_{\text{tot}} = F_f - F_g - F_D \sin \alpha.$$  (17)

Small Reynolds number bubbles rise slowly in annulus protective fluid, and their migration path can be regarded as a straight line, i.e., $\alpha = 90$ degrees. The force formula of small bubbles can be expressed as follows:

$$F_{\text{tot}} = \frac{4}{3} \pi r_b^3 (\rho_1 - \rho_b) g - \frac{4}{3} \pi r_b^3 \rho_b g - \frac{1}{2} C_D \pi r_b^2 \rho_b v_t^2.$$.  (18)

The rising acceleration of a small Reynolds number bubble is

$$a = \frac{(4/3) \pi r_b^3 (\rho_1 - \rho_b) g - (4/3) \pi r_b^3 \rho_b g - (1/2) C_D \pi r_b^2 \rho_b v_t^2}{m_g}.  \quad (19)$$

When $a = 0$, the bubble reaches its terminal velocity in annulus protective fluid:

$$v_t = \sqrt{\frac{2 \rho_b g D}{3C_D \rho_l}}.$$  (20)

3.2. Bubble Rising Velocity Model with Large Reynolds Number. When the Reynolds number of bubbles is large, the shape of bubbles will change obviously during annular transport. Under the same flow conditions, the larger the Reynolds number of bubbles, the more obvious the deformation. Because the bubble shape acts directly on the rising velocity during the rising process, there are many bubbles in the annulus protective fluid, and the deformation law is complex, it is difficult to accurately establish the calculation model describing the rising velocity of large Reynolds number bubbles by the mechanical method. The approximate calculation is made by using the model of rising velocity of large bubbles given by Collins [22]:

$$v_t = 0.652 \sqrt{g r_b}.  \quad (21)$$

4. SCP Prediction Model

After reaching the terminal velocity, the bubbles continue to rise along the annulus protective fluid. When the bubbles move to the upper interface of annulus protective fluid, the bubbles burst and the pressure in the annulus rises when the gas in the bubbles is injected into the gas cap. In practice, the bubbles that cause the pressure do not migrate as individual ones but in the form of swarm bubbles. Sun and Zhu [23] presented a computational model for the relationship between the velocity of a single bubble and swarm bubbles in a non-Newtonian fluid. The value of $a_1$, $a_3$, and $a_4$ can be obtained [23].
where \( v_{t,w} \) is the swarm bubble terminal velocity, m/s; \( v_{t,s} \) is the single bubble terminal velocity, m/s; \( \alpha \) is the gas holdup; and \( n \) is the power law index.

The terminal velocity of a swarm bubble is

\[
v_{t,w} = \frac{2r_b \rho_g g}{3C_D \rho_i} \left(1 - s^{-1}\right) \left[ n(19 - 2n - 8n^2) \right] \left[ 3(1 - s^{-1}) 8(1 - n) a_1 + 2(1 + 2n) a_3 - 12(1 - n) a_4 \right] \left[ 3(1 - s^{-1}) 8(1 - n) a_1 + 2(1 + 2n) a_3 - 12(1 - n) a_4 \right]^{1/n}, \tag{23}
\]

\[
v_{t,w} = 0.652 \sqrt{(\rho_g \rho_b)} \cdot \left(1 - s^{-1}\right) \left[ n(19 - 2n - 8n^2) \right] \left[ 3(1 - s^{-1}) 8(1 - n) a_1 + 2(1 + 2n) a_3 - 12(1 - n) a_4 \right] \left[ 3(1 - s^{-1}) 8(1 - n) a_1 + 2(1 + 2n) a_3 - 12(1 - n) a_4 \right]^{1/n}. \tag{24}
\]

Initially, the gas flowing from the formation has not entered the gas cap, and the wellhead pressure does not rise at this time. Because the formation pressure is greater than the interface pressure of cement, gas enters annulus protective fluid from formation in the form of swarm bubbles and eventually migrates to the gas cap. The SCP can be calculated as \[8\]

\[
P_t = \frac{1}{2} \left( P_t - V_m V_{m-1} - \left( P_t - \frac{V_{m-1}}{C_m V_{m-1}} \right)^2 \right) \left( \frac{P_t - \frac{V_{m-1}}{C_m V_{m-1}}}{P_t - \frac{V_{m-1}}{C_m V_{m-1}}} \right)^2 + \frac{4T_{w,b} \sum_{i=1}^{n} (P_t - \frac{V_{m-1}}{C_m V_{m-1}}) \cdot AV_{t,w}}{C_m V_{m-1} T_{w,b}}, \tag{25}
\]

where \( v_{t,w} \) is the velocity of gas considering the Reynolds number, which is different from the previous velocity \( V_t \).

The solution process of the new model is shown in Figure 3. At the beginning of each time step, \( q_c \) can be calculated by equation (6), where the value of \( P_c \) is obtained at the previous time step. Using equation (15), we can get the initial bubble radius \( r_b \). At this time, the model for calculating \( v_{t,w} \) needs to be selected according to the Reynolds number of the initial bubbles. If Reynolds number is less than 1, velocity can be calculated by equation (23). Otherwise, equation (24) is needed. After the SCP is obtained from equation (25), one step time calculation is completed.

Iterative calculation is used for the aforementioned process. And, verification can be determined whether there is pressure difference between the upper and lower ends of the cement sheath after obtaining the SCP value \( P_t \) of the last time step. Because of the previous \( P_n, P_t, \) and \( P_t \) will increase until \( P_t = P_t \) is terminated. This is the basis for verifying whether iterative calculation is needed or not.

5. Example Calculation and Analysis

5.1. Analysis of SCP in Well 23 and Well 24. Using the same calculation parameters as given in Xu and Wojtanowicz [8] to carry out the calculation of this model, the parameters involved and the wellbore structure are shown in Table 1 and Figures 4 and 5.

Table 2 gives the data of Reynolds number from the beginning to the end of calculation for two wells. The initial Reynolds number of #23 leaked gases is 0.5521, which decreases with the increase of time. A small Reynolds number bubble casing pressure calculation model is applied; #23 Model.

The calculation model of pressure in the annulus of the bubble with large Reynolds number is applied.

Figures 6 and 7 show the calculation results of two case wells. Apparently, the upper and lower flow of the annular protective fluid decreases continuously, and the decline rate of the leakage flow reduces constantly. Meanwhile, the upper flow in the annular protective fluid is greater than the lower flow. That is caused by reducing pressure difference between the gas cap and the formation with the continuous rise of casing pressure. In the early stage, the rising velocity of the bubble is accelerated, and it generates a higher upper leakage flow in the annular protective fluid. According to the aforementioned comparisons, larger rise of bubble velocity is caused by the lower Reynolds number, but it has little effect on the leakage flow.

The new model is applied to predict the #23 and #24 casing pressure. The XU SCP calculation model is compared, and the results are shown in Figures 8 and 9. Given the migration state change of the leaking gas in the annular protective fluid, the new model obtains a larger casing pressure, and the time to reach the maximum casing pressure is shorter. In #24, the calculation result difference between the new model and XU model is smaller, but the difference in #23 is larger. Compared with the XU model, the new model has better matching effect with well history data, which indicate that the new model can be applied to calculate annular pressure considering gas migration in annular protective fluid.

5.2. Effect of Well Parameters on SCP Buildup. Figure 10 shows the casing pressure recovery curve when the cement permeability changes. According to the figure, the early stage
of pressure recovery is sensitive to the size of the permeability, and a small change in the permeability may cause a large fluctuation in the casing pressure value. When the cement permeability increases, the casing pressure at the wellhead is higher, and the time to reach the maximum SCP value is faster in the same time, but the change of the cement permeability has no effect on the maximum casing pressure. With larger permeability of the cement sheath, the deviation of the annular pressure value between the new model and XU model decreases. The cement with low permeability allows the gas to obtain a lower leakage flow and also makes the initial bubble Reynolds number smaller. This makes it easier for the bubbles to change their motion state during the rising process, resulting in that the leakage at the annular protective liquid-gas cap interface increases. As a result, the SCP value has a higher rate of increase compared with the

Table 1: Well parameters.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Units</th>
<th>#23</th>
<th>#24</th>
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<tr>
<td>$T_{wb}$</td>
<td>K</td>
<td>319</td>
<td>306</td>
</tr>
<tr>
<td>$T_f$</td>
<td>K</td>
<td>350</td>
<td>324</td>
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<td>288</td>
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<td>0.25268</td>
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<td>m</td>
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<tr>
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<td>1.5e−5</td>
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<td>$\mu_l$</td>
<td>Pa·s</td>
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<td>0.056</td>
</tr>
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<td>$\rho_l$</td>
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</tr>
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<td>$\epsilon_m$</td>
<td>Pa⁻¹</td>
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<td>$Z$</td>
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</table>
high permeability cement well. This also explains why the accuracy of the new model has been improved more obviously in the calculation of #23 than in #24.

The casing pressure under different cement permeability is compared and calculated for #23. When the cement permeability is higher than 0.007 mD, the bubble’s Reynolds number is greater than 1, corresponding to the calculation model of the large bubble SCP, and the deviation value with the XU model at this time is 3.2%. When the permeability is increased again, the deviation values of the two do not change much, indicating that when the Reynolds number of the bubble reaches a certain value, the motion state tends to be stable during the closed annular rising process.

Figure 11 shows the relationship between the casing pressure and the pressure recovery time at three annular protective fluid heights. Figure 11 indicates that reducing the height of the annular protective fluid can effectively slow the rising velocity of the casing pressure, so that it reaches the maximum SCP value over a wide time range; however, hydraulic pressure provided by annular protective fluid decreases as the height of annular protective fluid decreases, which results in an increase in the maximum SCP value. During the practical on-site construction process, the injection height of the annular protective fluid properly designed can reduce the casing pressure, while delaying the time for the operating well to reach the maximum SCP value. By comparing with the model of XU, the new model predicts higher casing pressure, and the deviation of the two shows an upward trend with the decrease of the annular protective.
When the height of annulus protective fluid decreases, the length of cement increases. At this time, the gas flow into annulus protective fluid decreases and results in lower Reynolds number of initial gas bubbles. Therefore, the lower the annulus protective fluid height, the greater the deviation value. This result also proves that the motion state of the bubble with low Reynolds number is more likely to change in the annular protective fluid.

However, the premise of the model established in this paper is that the annulus protective fluid is needed above the cement sheath. In this case, the annular pressure rise can be predicted based on the Reynolds number of the initial bubbles. If annulus protective fluid does not exist, that means cement needs to return to the ground, the SCP calculated by the new model will generate a large error, which is the limitation of the new model. Obviously, some factors affecting SCP have not been considered in this paper and need further study. Our further research will propose a more comprehensive approach to improve the model.

6. Conclusion

(1) In this paper, considering the gas migration in annulus protective fluid, a model of annulus pressure based on Reynolds number is established.

(2) Reynolds number of initial bubbles affects the variation of the gas in annulus protective fluid. If Reynolds number of initial bubbles is greater than 1, the gas migration state changes slightly. Otherwise, the gas changes obviously.

(3) As the permeability of the cement sheath decreases, the Reynolds number of initial gas bubbles decreases. In this case, the deviation value of SCP calculated by the new model and the XU model increases significantly. The influence of Reynolds number of initial bubbles on annular pressure cannot be ignored.

(4) Reducing the height of annulus protective fluid effectively slows down the rate of early annulus pressure rise, but increases the maximum pressure value, which is likely to cause casing failure.

Data Availability

The data used to support the findings of this study have not been made available because the manuscript submitted is a study about mathematical models. The formulas cited in the paper are listed in the references. Meanwhile, the calculation methods and parameters are in the flowcharts and tables, so there are no more data to be provided.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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