A new model of foam resistance factor based on NMR experiments

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1. Summary

- A new foam flow resistance model was established by measuring water saturation during foam flooding using nuclear magnetic resonance visualization experiments (Fig.1).
- Developed a new foam flooding flow calculation program to compute pressure, gas saturation, and water saturation changes in one-dimensional rock cores.

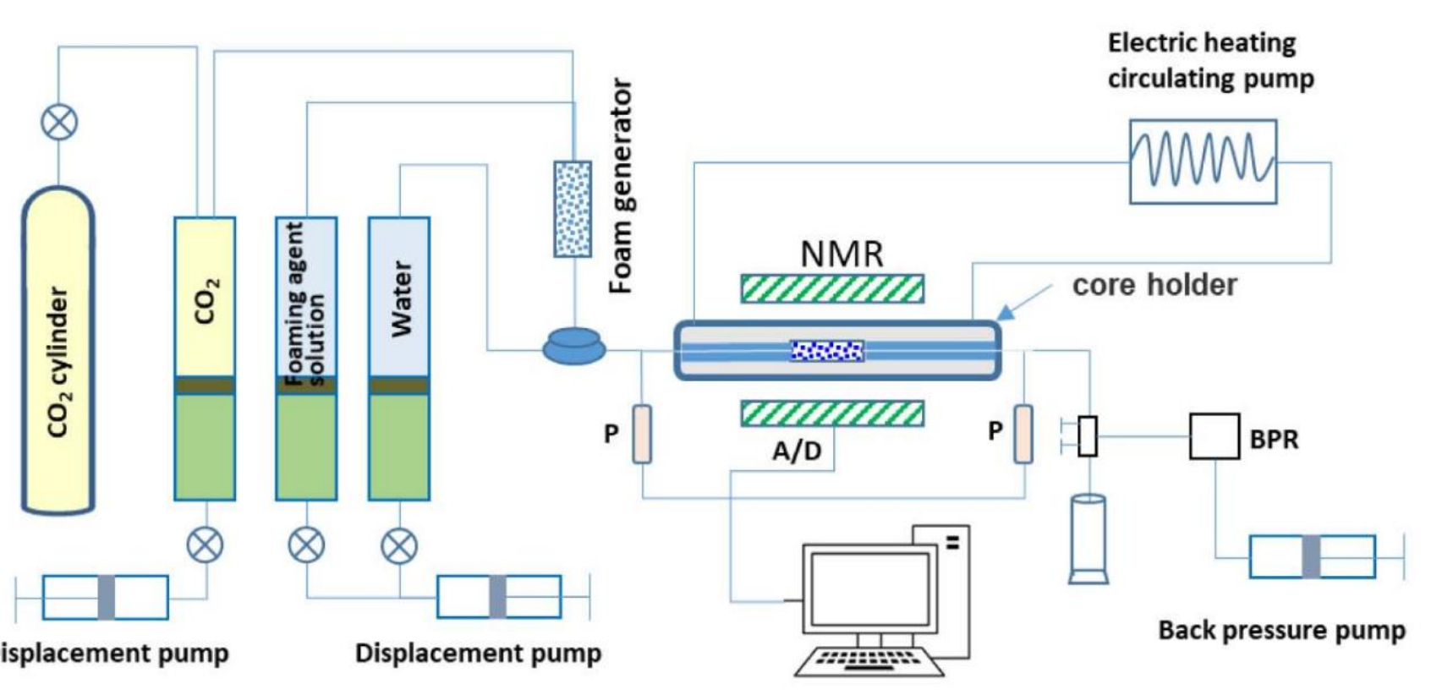

Fig. 1. Experimental process.

2. Introduction

- Foam flooding can improve the development effect of water flooding or chemical flooding by increasing the flow resistance.
- The conventional models for calculating flow resistance are mostly based on empirical formulas, which cannot be characterized in empirical formula.
- Based on the critical capillary force theory, the foam system is stable when it reaches the critical water saturation, but the current experimental methods are difficult to accurately measure the critical water saturation, and cannot establish a flow resistance calculation model considering the foam flow theory.

3. New Model of Foam Resistance Factor

- When the water saturation decreases to about 0.6, the resistance factor increases rapidly, and the water saturation is the rising pressure water saturation of foam (S_{wf}).
- When the liquid saturation decreases to around 0.38, the resistance factor gradually stabilizes, and effective sealing is formed in the rock core. At this time, the water saturation is the critical saturation (S_w^*).
- A new flow resistance model (Eqs.1 to 5) that can characterize the theory of foam formation and collapse is established, and the parameters of the new model are determined through the experimental results.

$$k_{rg}^f = \frac{k_{rg}^0\left(S_w\right)}{FM} \tag{1}$$

$$FM = \begin{cases} 1+\dfrac{(R\text{-}1)\left(S_{wf}-S_w\right)}{S_{wf}-S_w{}^*} & S_w{}^* < S_w < S_{wf} \\ 1 & S_w > S_{wf} \end{cases} \tag{2}$$

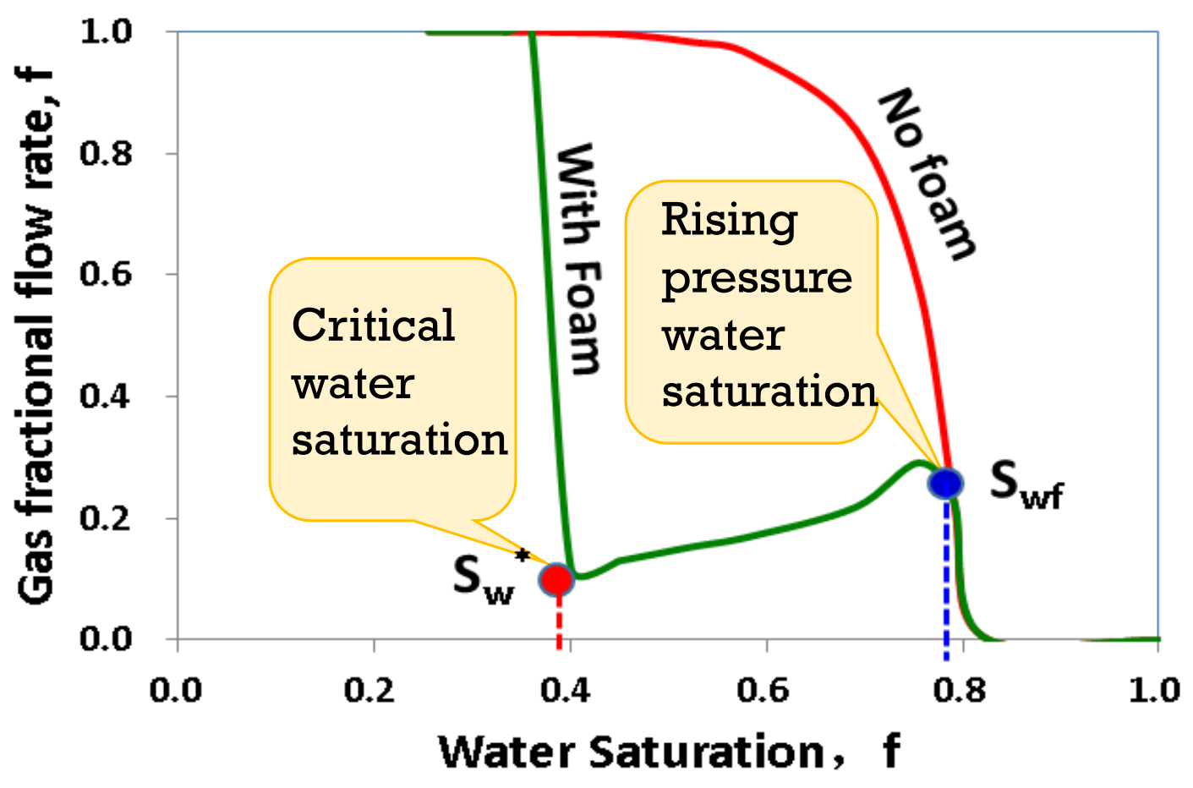

Fig. 2. Foam diversion curve.

- Critical water saturation:

$$S_w^* = a-(1-S_{w0}^*)\left(\frac{k}{k_{\max}}\right)^b \qquad k<k_{\max} \tag{3}$$

- Resistance factor:

$$R = 1+R_0\left(\frac{u_w}{u_{w\max}}\right)^m\left(\frac{u_g}{u_{g\max}}\right)^n\left(\frac{w_s}{w_{s\max}}\right)^p\left(\frac{k}{k_{\max}}\right)^q \qquad u_w<u_{w\max}、u_g<u_{g\max}、w_s<w_{s\max}、k<k_{\max} \tag{4}$$

- Rising pressure water saturation:

$$S_{wf} = c-(1-S_{wf0})\left(\left(\frac{k}{k_{\max}}\right)^d+\left(\frac{R_{gl}}{R_{gl\max}}\right)^e\right) \qquad k<k_{\max}、R_{gl}<R_{gl\max} \tag{5}$$

4. Numerical Simulation

- Numerical simulation model for one-dimensional two-phase foam flooding.
- Gas component:

$$\frac{\partial}{\partial x}\left(\frac{kk_{rg}}{B_g\mu_g}\frac{\partial p_g}{\partial x}\right)+q_{gv} = \frac{\partial}{\partial t}\left(\frac{\phi s_g}{B_g}\right) \tag{6}$$

- Water component:

$$\frac{\partial}{\partial x}\left(\frac{kk_{rw}}{B_w\mu_w}\frac{\partial p_w}{\partial x}\right)+q_{wv} = \frac{\partial}{\partial t}\left(\frac{\phi s_w}{B_w}\right) \tag{7}$$

- Foaming agent component:

$$C\left(\frac{\partial v_w}{\partial x}+\phi\frac{\partial S_w}{\partial t}\right)+v_w\frac{\partial C}{\partial x}+\phi S_w\frac{\partial C}{\partial t}=0 \tag{8}$$

- Auxiliary equation:

$$s_w+s_g=1 \qquad p_{cgw}=p_c-p_w=0 \tag{9}$$

5. Results

5.1 Factors influencing the foam resistance factor model

- Based on the diversion model and resistance factor model, and referring to the phase permeation, the impact of different parameters such as permeation velocity, surfactant concentration, permeability, and gas-liquid ratio on gas phase diversion can be calculated.
- Permeation velocity primarily influences the maximum resistance factor (Fig.3a), surfactant concentration mainly affects the maximum resistance factor (Fig.3b), permeability mainly impacts the onset pressure saturation (Fig.3c), and gas-liquid ratio mainly influences the onset pressure saturation (Fig.3d).

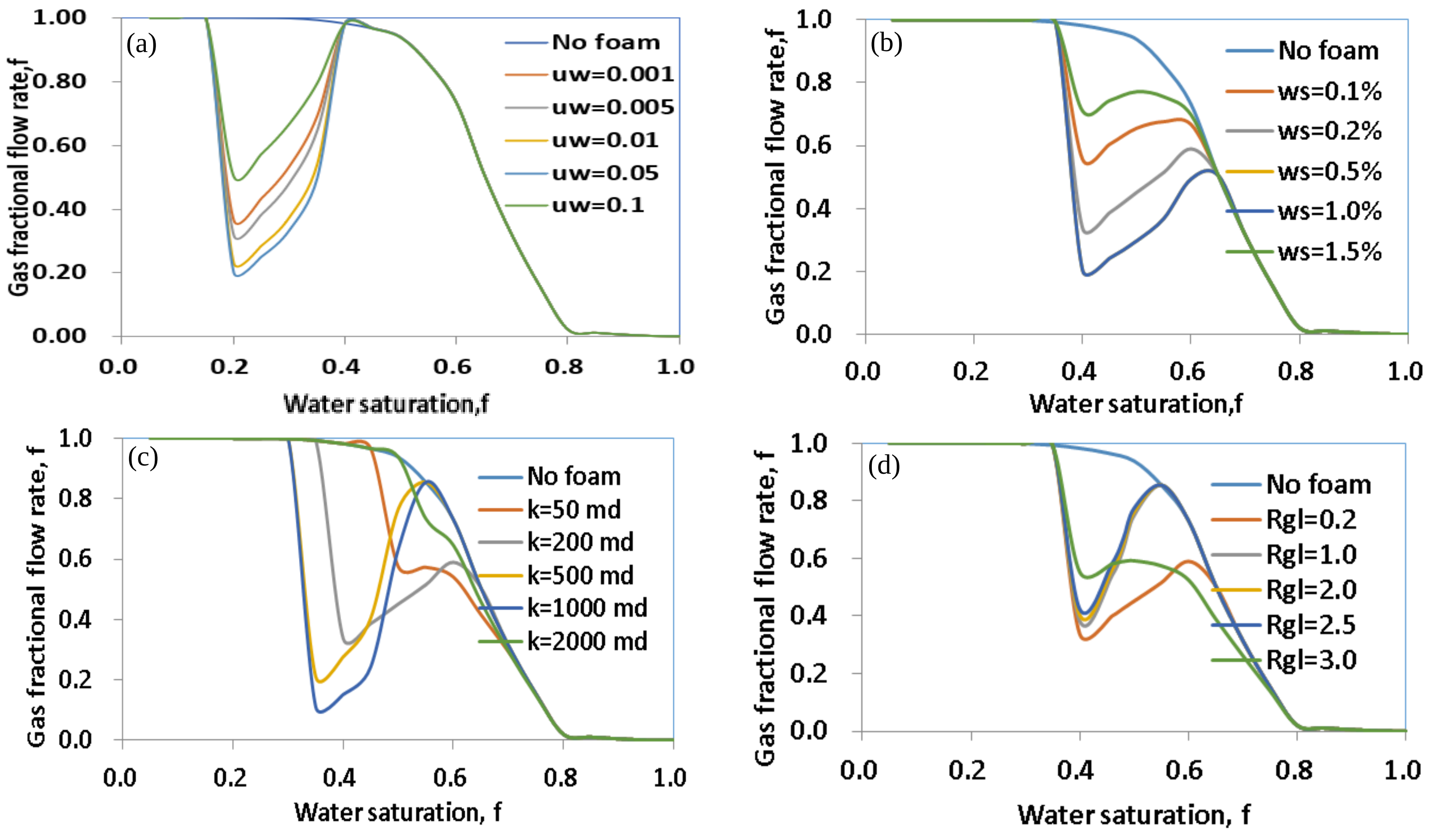

Fig. 3. Analysis of factors influencing the resistance factor model. (a) Permeation velocity, (b) surfactant concentration, (c) permeability, (d) gas-liquid ratio.

5.2 Validation results of the numerical simulation model

- The liquid and gas production curves calculated by the program closely align with the results from commercial software, confirming the program's validity and reliability (Figs. 4a to 4c).
- The foam flooding flow calculation program can calculate one-dimensional core pressure, gas and water saturation and other parameters change. Compared with the results of online nuclear magnetic resonance experiments, the fitting accuracy can reach 96%. The new model realizes the accurate calculation of the evolution mechanism of foam and the plugging effect of foam in the seepage process of foam.

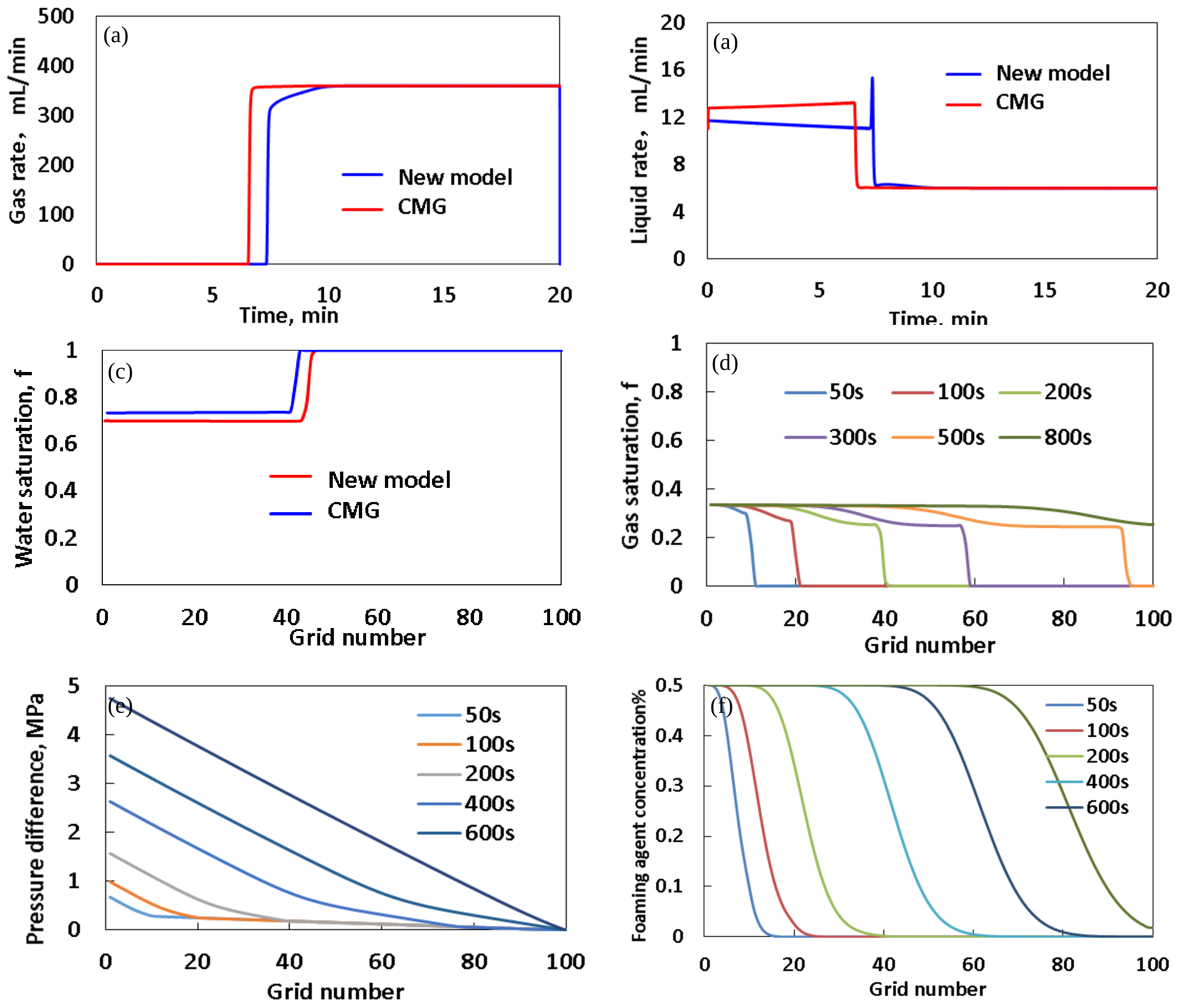

Fig. 4. Calculation results of the one-dimensional two-phase foam flooding model. (a) Gas rate, (b)liquid rate, (c) water saturation, (d) gas saturation, (e) pressure difference, (f) Foaming agent concentration.

6. Conclusion

- A novel foam resistance factor calculation model has been developed, taking into account variations in water saturation, and discussed the influencing factors of foam resistance factor.
- A one-dimensional two-phase numerical simulation model for foam flooding, considering the foam resistance factor, has been developed, with simulation results matching experimental data.

References

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