Numerical Investigation on the Mechanism of Multicomponent Boiling in Porous Media Using LBM at Pore Scale

Da Zhang, Sufen Li, Yan Li, Ning Mei, Hang Pu and Si Jiao

Abstract

In this study, the boiling of seawater containing non-condensable gas (NCG) in porous media was simulated using the pseudopotential multiphase multicomponent lattice Boltzmann model at pore-scale. The porosity of porous media is 0.37. In addition, the effects of wettability, NCG concentration, and capillary number (CN) on the variations in the gas volume and fluid temperature were numerically investigated. The simulation results show that increasing wettability and CN can effectively suppress the increase of gas volume in equilibrium, while gas volume is not sensitive to changes in NCG concentration. Besides, a decrease in wettability can effectively reduce the average fluid temperature, whereas an increase in the NCG concentration and CN can increase the average temperature of the fluid in the equilibrium state although the effect is limited. The decrease in wettability, concentration of NCG and CN can effectively inhibit the temperature rise of the fluid, but this effect is limited.

Keywords: Multicomponent boiling flow; Seawater; Non-condensable gas; Lattice Boltzmann; Porous media.

1. Introduction

In recent years, seafloor hydrothermal has attracted increasing attention as a new energy source that is rich in thermal energy and minerals. The causes of submarine hydrothermal fluid are basically, seen in Fig. 1, as follows: Firstly, cold seawater penetrates the cracks in infiltration area. Then, the seawater is heated and reacts with the high-temperature surrounding rocks, causing gradual leaching of metal elements and resulting in the formation of metal-rich, acidic, and reductive hydrothermal fluid. The final state of the hydrothermal solution is determined by many factors. In addition to the temperature and pressure in the seabed reaction zone, porous rock structure, and wettability of the rocks, NCG concentrations and patterns of fluid-flow and heat transfer also exert tremendous effects.[2-4] In the hydrothermal reaction zone, for example, when the single-phase acidic hydrothermal liquid flows through the high-temperature heat source, the hydrothermal liquid will boil and separate into a denser brine phase and a lower density vapour phase.[5] In order to understand the circulation mode of the seabed hydrothermal fluid, a key problem must be solved, i.e. the mechanism of heat and mass transfer of hydrothermal fluid with phase transition in porous rock media, such as bubble behaviour, phase distribution, liquid–vapour non-condensable gas (NCG) activity, and temperature variation at the pore-scale.

Fig. 1 Schematic diagram of the hydrothermal formation.

Many experimental studies have investigated the boiling problem in a porous medium. In heat-pipe application, several novel designs such as heat pipes with bi-porous medium,[6] those with a honeycomb shape,[7] and those with a big chimney for vapour vents[8] with good heat-transfer performance have
been proposed. In addition, Wang et al.\cite{9} reported that the porous honeycomb plate could both enhance the critical heat flux and reduce surface superheat area at various flow rates. Chen et al.\cite{10} proposed a porous interconnected microchannel under the condition of higher mass flux or inlet subcooling, which showed better two-phase heat-transfer performance, such as higher heat-transfer coefficients, lower pressure drop, and suppression of two-phase fluids instability. In addition, in the application of heat dissipation of highly integrated micro-devices, Moghaddam et al.\cite{11} found that copper foam with 30 ppi (90% porosity) exhibited substantial heat-transfer enhancement in the boiling of water. Ji et al.\cite{12} experimentally investigated pool boiling in foam-coated tubes and exhibited that a higher heat-transfer coefficient was achieved in porous medium with high porosity and small thickness. In contrast to the extensive experimental studies, there are few numerical investigations on boiling heat transfer of porous metals due to the difficulty that arises from movement, irregular phase interfaces, and implementation of fluid-solid coupling in the physical boundary of complex porous media. To avoid these problems, almost all of the previous numerical studies applied the method of representative elementary volume. Based on the local thermal-equilibrium assumption, Benard et al.\cite{13} proposed a model of phase transitions in porous media. Nevertheless, it was soon proven inaccurate in dealing with the temperature difference, especially in a two-phase region.\cite{14} Xin et al.\cite{15} have recently developed a modified two-phase phase change model by considering the local thermal non-equilibrium. Although these numerical methods can partly reveal the heat- and mass-transfer mechanisms, some significant features such as the detailed porous morphology, liquid–vapour interface information description, fluid velocity, and temperature field at the pore-scale are ignored. Fortunately, according to minimal lattice formulations of the kinetic Boltzmann equation, the lattice Boltzmann method (LBM) has emerged and exhibited great ability in modelling complex fluid systems.\cite{16-19} In addition, the pseudopotential LBM has been successfully applied in the study of the phase-change problem in a multiphase flow\cite{20-21} due to its precise capture of the phase interface during movement. In recent years, Gong and Cheng\cite{22} have proposed an improved liquid–vapour phase-change LBM model of a single component, which could greatly deal with a series of phase-transition problems, including boiling,\cite{23} condensation,\cite{24} and phase change in porous media.\cite{25} Furthermore, combined with the multiphase multicomponent (MCMP) pseudopotential model,\cite{9} the Gong and Cheng’s model can be used in the simulation of multicomponent phase-change phenomenon.\cite{24}

In the present study, the MCMP model and the model by Gong and Cheng are adopted to investigate the heat- and mass-transfer mechanisms of submarine hydrothermal mixture in a porous rock medium. In previous studies, the focus of research related to phase change of multiphase flow was often focused on improving the heat transfer performance and preventing the "dryout" phenomenon caused by excessive wall temperature. However, there are few studies studied the impact of NCG on boiling process in porous rock medium,\cite{25,26} Besides, the bubble morphology and its stress analysis are often overlooked, which may play important roles in multiphase flow patterns in porous rock.\cite{27} To further investigate the flow and heat transfer mechanisms, the present study is interested in the influence of various factors, including porous structure, solid wettability, capillary number (CN), and NCG concentration, on hydrothermal activities such as bubble behaviour and change in the fluid temperature. Additionally, the weights of the factors that affect the hydrothermal activity are numerically investigated.

2. Numerical Modelling

2.1 MCMP pseudopotential LBM model

The MCMP pseudopotential model,\cite{16} which governs the evolution of the density distribution, can be expressed as follows:

\[ f_i^\sigma(x + e_i \delta_x t + \delta_t) - f_i^\sigma(x, t) = \frac{-1}{\tau} \left( f_i^{\sigma(eq)}(x, t) \right) + \Delta f_i(x, t), \]

where \( f_i^\sigma \) is the density-distribution function of component \( \sigma \) at spatial position \( x \) and time \( t \), \( \delta_x \) and \( \delta_t \) are the lattice spacing and time step, respectively. \( f_i^{\sigma(eq)} \) is the density equilibrium distribution function, and \( \Delta f_i(x, t) \) is the external force scheme based on the exact difference method.\cite{29} For a two-dimensional nine-velocity (D2Q9) model, discrete velocities \( e_i \) are defined as:

\[ e_i = \begin{cases} (0,0) & i = 0 \\ \left( \cos \left( \frac{(i-1)\pi}{2} \right), \cos \left( \frac{(i-1)\pi}{2} \right) \right) c, & i = 1 - 4 \\ \sqrt{2} \left( \cos \left( \frac{(i-5)\pi}{2} + \frac{\pi}{4} \right), \sin \left( \frac{(i-5)\pi}{2} + \frac{\pi}{4} \right) \right) c, & i = 5 - 8 \end{cases} \]

where \( c \) is the lattice speed, which is equal to \( \delta_x / \delta_t \). \( \tau^\sigma \) is the dimensionless relaxation time of component \( \sigma \), determined by dimensionless kinematic viscosity \( \nu^* \) of the fluids of component \( \sigma \) as:

\[ \tau^\sigma = \frac{\nu^*}{c_s^2} + 0.5 \]

where \( \nu^* \) can be obtained by dimensionless treatment of kinematic viscosity \( \nu \) and \( c_s^2 \), which related to the lattice sound velocity with the value of 1/3.

The equilibrium distribution function of the D2Q9 lattice model is

\[ f_i^{\sigma(eq)}(x, t) = \omega_i \rho_\sigma \left[ 1 + \frac{e_i u_\sigma}{c_s^2} + \frac{(e_i u_\sigma)^2}{2 c_s^4} - \frac{u_\sigma^2}{2 c_s^2} \right] \]

where weight factors \( \omega_i \) are given by

\[ \omega_i = \begin{cases} \frac{1}{9} & i = 0 \\ \frac{1}{9} & i = 1 - 4, \\ \frac{1}{36} & i = 5 - 8 \end{cases} \]

where \( \rho_\sigma \) and \( u_\sigma \) are the macroscopic density and velocity of component \( \sigma \), respectively, which can be calculated from
\[
\rho_\sigma = \sum f_i^\sigma, \rho_\sigma u_\sigma = \sum \mathbf{v}_i f_i^\sigma + \frac{\delta}{2} F^\sigma
\]  
(6)

Force term \( F^\sigma \) in Eq. (6) represents the total force acting on component \( \sigma \) and consists of four parts:

\[
F^\sigma = F_{\text{int}}^\sigma + F_{\text{int}}^{\sigma \prime} + F_{\text{ads}} + F_b
\]  
(7)

where \( F_{\text{int}}^\sigma \) and \( F_{\text{int}}^{\sigma \prime} \) are the forces interacting on component \( \sigma \) with its surrounding components \( \sigma \) and \( \sigma' \), respectively. \( F_{\text{ads}} \) represents the fluid–solid interaction force. \( F_b \) is the external body force, which can be expressed as:

\[
F_b^\sigma = \rho_\sigma g
\]  
(8)

where \( g \) is the gravity acceleration per unit mass.

The MCMP system considers both intra- \( (F_{\text{int}}^\sigma) \) and inter- \( (F_{\text{int}}^{\sigma \prime}) \) molecular forces interacting on each component, which can be defined as

\[
F_{\text{int}}^\sigma(x, t) = -\psi^\sigma(x, t) \sum G_{\text{int}}^\sigma \sum \omega_i \psi^\sigma(x + \delta_i \mathbf{t}, t) \mathbf{e}_i,
\]

\[
F_{\text{int}}^{\sigma \prime}(x, t) = -\psi^{\sigma \prime}(x, t) \sum G_{\text{int}}^{\sigma \prime} \sum \omega_i \psi^{\sigma \prime}(x + \delta_i \mathbf{t}, t) \mathbf{e}_i,
\]

where \( G_{\text{int}}^\sigma \) is a parameter that is usually negative for an attraction force and controls the interaction forces between these two different components. Besides, its value is set at 0.25 in the current study to separate the different phases and obtain stable two-phase interface zones (the details of determining \( G \) are listed in Table 1). Additionally, \( \psi^\sigma(x, t) \) donates the interaction potential between different fluid particles.

Similar to the fluid–fluid interaction force, \( F_{\text{ads}} \), which determines the contact angle, characterizes the magnitude of the interaction force between the fluid of component \( \sigma \) and the solid and can be expressed as:

\[
F_{\text{ads}}(x) = -G \psi(x) \sum g_{\text{ss}}(x) s(x + \delta_i \mathbf{t}) \cdot \mathbf{e}_i \delta_i
\]  
(11)

where \( g_{\text{ss}} \) is the fluid-solid force strength, and \( s(x) \) is a indicator function that distinguishes the fluid or solid. The wettability of the wall, i.e. contact angle, can be adjusted by setting the wall density. \( \psi_{ss}(x) \) is the potential for interaction on the wall lattice node, which is determined by the wall density \( \rho_w \). It should be noticed that \( \rho_w \) is not the actual density of the wall; it is a simulation parameter for adjustment of the contact angle.

The Peng–Robinson equation of state (EOS) is used to describe the pressure, temperature, and density of the seawater and vapour, as:

\[
p = \frac{\rho RT}{1 - \frac{\rho \alpha \varepsilon(T)}{1 + 2b \rho - b^2 \rho^2}} - \frac{a \rho \varepsilon(T)}{1 + 2b \rho - b^2 \rho^2}
\]  
(12)

with \( a = 0.45724 \frac{R^2 T_c^2 \varepsilon(T)}{p_c}, \) \( b = 0.0778 \frac{R T_c}{p_c}, \) and \( R = 1, \)

\[\varepsilon(T) = \left[1 + \frac{0.37464 + 1.54226 \omega - 0.26992 \omega^2}{\sqrt{T_c}}\right]^2 \]

where \( T_c \) and \( p_c \) are the critical temperature and critical pressure of the seawater, respectively, and \( \omega \) is the centric factor. In addition to the seawater, NCG is considered as an ideal fluid, which means that there are no interaction forces exist among the fluids of NCG. Therefore, an ideal gas equation is used, as:

\[
P = \rho RT
\]  
(14)

### 2.2 Thermal phase-change model

Similar to the density evolution distribution function, the temperature field is obtained using the temperature-distribution function. By neglecting the viscous heating dissipation of fluid, the evolution equation of the temperature distribution functions of the components (\( \alpha \text{str} \)) can be expressed as:

\[
g_i^\sigma (x + \mathbf{e}_i \delta_i, t + \delta_t) - g_i^\sigma (x, t) = -\frac{1}{T_c} \left( g_i^\sigma (x + e_1 \delta_1, t) + \delta_t \omega_i \phi_i \right)
\]  
(15)

where \( g_i(x, t) \) is the temperature distribution function with a discrete velocity of \( \mathbf{e}_i \) at position \( x \) and time \( t \). \( e_i \) is expressed in Eq. (2). \( \iota \) is the lattice time step, and \( g_i^\sigma (x, t) \) is the equilibrium temperature distribution function, which is expressed as follows:

\[
g_i^\sigma (x, t) = \omega_i T [1 + \frac{e_i u_{r}}{c_i^2} + \frac{(e_i u_{r})^2}{2c_i^2} - \frac{u_i^2}{2c_i^2}]
\]  
(16)

where \( u_r \) is the real velocity of the fluid, which is expressed as follows:

\[
u_{r} = \sum e_i f_i + \frac{\delta_t}{2} F
\]  
(17)

Non-dimensional relaxation time \( \tau \), which is related to dimensionless thermal diffusivity \( \alpha^* \) as follows:

\[
\alpha^* = \frac{c_2^2}{c_2^4} (\tau_i - \frac{\delta_t}{2})
\]  
(18)

where \( \alpha^* \) can be obtained from the dimensionless treatment of thermal diffusivity \( \alpha \).

The phase-change source term can be determined as follows:

\[
\phi = T \left[1 - \frac{1}{\rho c_v} \frac{\partial \rho}{\partial T} \right] \nabla \cdot u
\]  
(19)

where \( c_v \) is the specific heat at a constant volume of component \( \sigma \).

Macro temperature \( T \) can be calculated from the average temperature of the two component \( \sigma \) and \( \sigma' \):

\[
T = \frac{1}{\rho c_v} \sum \rho \sigma c_v \sigma T_{\sigma}
\]  
(20)

with

\[
T_{\sigma} = \sum g_i^\sigma.
\]  
(21)

More information and relevant validations of the LB phase-change model can be found in our previous work.\textsuperscript{[1]}

### 2.3 Computational domain and boundary conditions

A 2D computational domain with an 842 × 255 mesh system is shown in Fig. 2, and the porous rock medium with a porosity (\( \varepsilon \)) of 39% is placed in the simulation domain. The inlet and outlet of the computational domain are set as velocity and full development boundaries (\( \nabla p = 0 \)), respectively, and the other two boundaries are the solid boundaries.\textsuperscript{[3]}

Considering the actual hydrothermal environment at a depth of 1330 meters under seawater, the computational domain is initially filled with saturated seawater mixture and NCG, and the temperature is set as 0.86 Tc, where Tc is the critical temperature of the seawater.\textsuperscript{[1]}

For the temperature field, six discontinuous heating points (\( q \)), each with a width (\( L \)) of four lattice units, are located at the bottom wall to simulate seafloor rocks with uneven high temperature. Since the heat flux of the heating point is much higher than that in the other places at the bottom wall, so the thermal boundary condition is set as follows: the nucleation points are set by a constant temperature.
boundary condition, whereas the others places are adiabatic. Besides, the similar temperature boundary treatment can also be found in.\cite{35} The temperature of the porous structures is assumed to have a linear distribution along the positive direction of the y axis. For convenient implementation of the numerical study, the homogeneous porous structure is composed of 14 solid square blocks, marked with yellow colour. In order to ensure the accuracy of the phase change process, the distance ($H$) between blocks is set equal to $1.5l_0$, where $l_0$ is a typical characteristic scale, (i.e. capillary length)\cite{36} expressed as:

$$l_0 = \sqrt{\frac{\gamma}{(\rho_l-\rho_v)g}}$$ (22)

where $\gamma$ is the surface tension. In addition, more details about the simulation parameters are listed in Table 1.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic length</td>
<td>$1 \times 10^{-4}$ m</td>
</tr>
<tr>
<td>Characteristic time</td>
<td>$1 \times 10^{-4}$ s</td>
</tr>
<tr>
<td>Characteristic mass</td>
<td>$1 \times 10^{-10}$ kg/m$^3$</td>
</tr>
<tr>
<td>Saturated sea density</td>
<td>591.37 kg/m$^3$</td>
</tr>
<tr>
<td>Saturated gas density</td>
<td>58 kg/m$^3$</td>
</tr>
<tr>
<td>Kinematic viscosity of fluid</td>
<td>$5 \times 10^{-5}$ m$^2$/s</td>
</tr>
<tr>
<td>Radius of heat source</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Salinity</td>
<td>40 g/kg</td>
</tr>
<tr>
<td>Gravity force</td>
<td>10 m/s$^2$</td>
</tr>
<tr>
<td>Pr</td>
<td>0.8</td>
</tr>
<tr>
<td>$G_{11}^{\text{int}}$</td>
<td>-0.25</td>
</tr>
<tr>
<td>$G_{12}^{\text{int}}$</td>
<td>-0.000025</td>
</tr>
</tbody>
</table>

3. Results and discussion
3.1 Boiling behaviour in porous media
As an efficient heat transport mode, the phase separation phenomenon caused by the boiling phase change in the enclosed narrow space is an essential heat transfer mechanism when local hot spots are imposed into the hydrothermal reaction zone of porous rock media. Generally, thermodynamic performance (e.g. thermal conductivity and temperature uniformity) is accepted to be largely determined by the vapour–liquid two-phase flow and boiling phase change inside an enclosed narrow space.\cite{37} To provide further insight into the vapour-liquid thermodynamic behaviours that occur in the evaporation section with the action of local heat flux, the flow regimes of the two-phase mixture with phase-transition are discussed in detail next.

Initially, as shown in Fig. 3(a) and Fig. 4(a), the pore spaces in the porous media are filled with liquid seawater mixture consisting of liquid seawater and soluble NCG. The flow and temperature boundaries are set as same as Sec. 2.3. Under the effect of high temperature of the discontinuous heat sources, the boiling phenomena begin near the heat sources and result in a decrease in fluid density followed by the condensable component. Then, shown in Fig. 3(b) and Fig. 4(b), with the formation of buoyant bubbles around the solid walls, the NCG concentration increases significantly in the gas region, especially near the top area of the vapour bubbles, because gas has lesser repulsion to NCG than liquid fluid due to the relatively large density difference. Besides, the relative high temperature at the top of the buoyant bubbles leads to the

\[\text{Fig. 2 Schematic of the computational domain and boundary conditions.}\]

\[\text{Fig. 3 (a)–(d) Density distribution of water.}\]
Finally, when the slow layer of thermal resistance near the gas source, as shown in Fig. 4(c), film boiling continues to occur, and the buoyant bubbles continue to grow, and the gas–liquid interface contacts the solids of the porous rock media. Under the capillary force (CF), a small amount of gas can rise along the fluid-solid surface of solid porous media and enter the pores along the y-direction. Nevertheless, it cannot fill the pores because of the effect of surface tension between the gas and the non-wettability solid wall. In addition, the phase transition behaviour can be seen at the surface of the porous solids close to the upper surface of the solid porous media due to its high temperature, which exceeds the boiling-point temperature of the seawater mixture. To further explain the flow and deformation mechanism of the buoyant bubbles, the stress state of a bubble is plotted in Fig. 5. The bubble behaviours, e.g. bubble confinement in the pores, bubble split, and escape, are governed by the forces being imposed on it. Besides, there are six different forces involved in the bubble flow process, which are buoyant force \( F_b \), evaporation momentum force \( F_m \), surface tension force \( F_r \), contact pressure force \( F_p \), repulsion force of NCG \( F_{NCG} \), and drag force \( F_d \). In this study, most gas phases are confined in the horizontal pore channels near the bottom surface, which can be seen in Fig. 3(c). This is because the buoyant force acting on it cannot overcome the joint interaction strength of the surface-tension, contact-pressure, and drag forces in the y direction. Simultaneously, NCG is mainly concentrated in the bubbles near the bottom heat source, as shown in Fig. 4(c).

This phenomenon may lead to a layer of thermal resistance near the gas-liquid interface that slows down the heat- and mass-transfer performance of the mixture fluids around the nucleate bubbles. Finally, when the multicomponent multiphase fluid system reaches equilibrium, the pore channels near the bottom along the x direction are completely covered by the gas phase, forming a stable gas-transport channel, as shown in Fig. 3(d). Moreover, the other gas phases are discontinuously and randomly distributed in the other pore channels. Notice that, there are no gas exhibit in the pore channels close to the upper surface, which may be because the CF plays a leading role in the gas movement patterns and the relatively lower temperature above the region inhibits occurrence of the phase transition. However, seen in Fig.4(d), the distribution of NCG is different from that of the water vapour, and it is still mainly distributed in the bubble core domain due to the uneven temperature distribution of the gas phase.

Additionally, the dominant heat transfer mechanism of this phenomenon is the film boiling, which has a relatively low heat transfer coefficient compared with the nucleate boiling and transition. The temperature variations and heat transfer mechanism of the fluids are determined by the proportion of gas and liquid. So, gas-phase volume is one of the research focuses in our research. In the following sections, the influence of the different effect factors, including the wall wettability, NCG concentration, and CN, on the heat- and mass transfer behaviour of the two phase flow is numerically discussed.

![Fig. 4](a)–(d) Density distribution of NCG.

**Fig. 4** (a)–(d) Density distribution of NCG.

**Fig. 5** Schematic diagram of the bubble force.

**Fig. 5** Schematic diagram of the bubble force.

**Fig. 6** Gas-volume variations as a function of time in porous media (\( \varepsilon = 0.376 \)) at different static contact angles.

**Fig. 6** Gas-volume variations as a function of time in porous media (\( \varepsilon = 0.376 \)) at different static contact angles.

### 3.2 Effect of wettability

In this section, the effect of wettability on the boiling behaviour and heat transfer in porous rock media are presented. The bubble volume variations as a function of time in the porous media with different solid wettability, presented by contact angles, are shown in Fig. 6. Under three wettability conditions (\( \theta = 72^\circ, 90^\circ, 108^\circ \)), the gas volumes all rapidly increase (from \( t = 0 \) to \( t = 5000 \)) due to the occurrence of the nucleate boiling phenomenon. When the wettability is non-wetting (\( \theta = 108^\circ \)), the variation in the gas volume shows the most maximum growth rate since the heat flux of the hydrophobic surface is higher than that of the hydrophilic surface, which means that the heat transfer and gasification...
efficiency of the hydrophilic surface is better.\textsuperscript{23,24} In addition, compared with a hydrophilic surface, a hydrophobic surface can decrease the bubble detaching period, which further accelerates the gas growth. Interestingly, an intense fluctuation in the volume variation (from $t = 1500$ to $t = 2500$) with a non-wetting condition ($\theta = 108^\circ$) is observed, which is different from that under neutral-wetting ($\theta = 90^\circ$) and wetting ($\theta = 72^\circ$) conditions. The reason may be because that, the buoyant bubble has a relatively higher rising speed and more violent bubble oscillation when it detaches from the hydrophobic surface.\textsuperscript{25} When the gas volume reaches the equilibrium state (after $t = 7500$), the gas volume with the non-wetting condition ($\theta = 108^\circ$) is more than that with the other two conditions ($\theta = 72^\circ, 90^\circ$), because the bubbles acquire a larger contact pressure force and an increased drag force. Thus, the gas-solid contact areas are enlarged significantly, and the gas pressure is strengthened, which then result in the increased gas volume.

For the thermodynamic field, shown in Fig. 7, the related change in the average temperature of fluids during the phase change process in the porous media. Similar to the trend of the gas volume change, the average temperature of the fluids increases with time and subsequently tends to be stable. However, the time ($t = 3500$) for the temperature to reach equilibrium state is earlier than that for the volume. The reason may be because that, after time $t = 3500$, the main heat transfer mechanism of the film boiling has been stably formed, \textit{i.e.} a stable temperature field has been formed, whereas the buoyant bubbles condense due to the relatively low temperature near the upper wall, resulting in the continuous transformation of the phase state and volume decrease. When the temperature reaches steady state, the average temperature of the fluid decreases with the increase in wettability. Because the contact angle decreasing leads to a higher gas–liquid ratio (see Fig. 6), the pressure of the fluid can be increased effectively. Thus, the saturation temperature of the seawater under the corresponding pressure is increased.

**Fig. 7** Change in the average temperature of fluids as a function of time in porous media ($\epsilon = 0.376$) at different static contact angles.

To investigate the effect of the heterogeneous components, \textit{i.e.} NCG, of seawater mixture on the hydrothermal activity, numerical simulations of the two-phase boiling flow in regular porous rock media are carried out with different NCG concentrations. The variations in the gas volume with time under different NCG concentrations are shown in Fig. 8. The gas volumes first rapidly increase over time (from $t = 0$ to $t = 1500$) due to the occurrence of nucleate boiling, then slightly decrease (from $t = 1500$ to $t = 1800$) due to the buoyant bubbles detaching from the bottom solid surface (transition boiling). Subsequently, the gas volumes rapidly increase again (from $t = 1800$ to $t = 3500$) due to the bubble rewriting\textsuperscript{34} and finally get a slow growth phenomenon, \textit{i.e.} film boiling. It should be noticed that, the increase in the NCG concentration has a weak inhibitory effect on the gas growth, as shown in the locally enlarged drawing in Fig. 8. The reasons may be the following: When phase separation occurs, NCG gathers at the gas–liquid interface and form a layer of resistance to the heat and mass transfer\textsuperscript{116,120} and the resistance could be enhanced with the increase in the NCG concentration. In addition, the increase in the NCG concentration can effectively reduce the bubble detaching diameter,\textsuperscript{35,37} which can further reduce the gas growth rate. In addition to the gas volume variations, the related average temperature of the seawater in the porous rock media is considered to analyse the heat transfer mechanism. As shown in Fig. 9, the average temperature of the fluids is not sensitive to the change in the NCG concentration. When the temperature change tends to be stable ($t > 3000$), increasing the NCG concentration in the confined pores space can elevate the total pressure of the seawater mixture. The fluid temperature in the corresponding saturated state correspondingly increases, which can be seen in the locally enlarged drawing in Fig. 9. In addition, the average temperature of the fluid in the steady state exhibits a weak
downward trend. This is caused by the condensation of the low temperature liquid near the gas-solids contact interface when the high-temperature gas rises.

Fig. 9 Change in the average temperature of fluids as a function of time in porous media under different NCG concentrations.

Furthermore, we also note that the average temperature of the fluid mixture at equilibrium state exceeds the critical temperature of the pure seawater fluid \( T_c = 0.0729 \). Besides, the fluid state is still in a non-critical state because the pressure is lower than its critical pressure \( P=0.05957 \).

Fig. 10 Change in the gas volume of fluids as a function of time in porous media under different CN values.

3. 4 Effect of CN

In order to simulate the boiling flow in porous rock media, a lateral force \( F_l \), which is used to drive the fluid in the horizontal direction, is incorporated in total force \( F_\sigma \) described in Eq. (7) and can be expressed as:

\[
F_l = CF/\sigma,
\]

where \( CF \) is the capillary force. In this study, to explore the effect of the Reynolds (Re) number on the phase change behaviour and heat transfer at the pore-scale, three different Re numbers (Re = 0, 1 \times 10^{-3}, and 2 \times 10^{-3}) are adopted in the simulation by applying different horizontal force \( F_l \) along the \( x \)-direction. As shown in Fig. 10, the gas volume in the porous rock media firstly rapidly increase as time increases in the liquid–gas phase transition process due to the nucleate boiling occurrence. For all investigated CN, the calculated gas volume trends are almost the same as those before the occurrence of the bubble detaching since the phase transition behaviour of the seawater is the same due to the nucleate boiling process. Then, the average temperature of the fluid mixture slightly decreases due to the occurrence of the bubble detaching. Besides, as the bubbles reposition and grow, the gas volumes consistently increase. Finally, the gas volume tends to stabilise because stable boiling, i.e. film boiling, is reached. It can also be clearly observed that, the enlargement of CN can distinctly reduce the gas volume because the gas volume which mainly depends on the boiling behaviour, which is determined by the heat flux between the fluid and heat sources. Thus, a larger lateral force can promote the boiling state from transition boiling to film boiling, which could lead to a smaller gas volume. Furthermore, the gas volume in the pore channel is reduced because of the enhancement of the CF caused by the enlargement of the drag force along the \( x \)-direction. However, seen in Fig. 11, the average temperature of fluid is not sensitive to the change in CN. This is because an increase in CN increases the sensible heat transfer intensity (mainly referred to as convective heat transfer) between the bottom heat source and surrounding fluid while the equilibrium of the main heat-transfer mode refers to film boiling, the CN effect on the average temperature of the fluid is limited.

Fig. 11 Change in the average temperature of fluids as a function of time in porous media under different CN values.

4. Conclusion

In this study, the MCMP LBM was applied to investigate seawater boiling flow with the presence of an NCG in porous rock media. In addition, the effects of wettability, NCG concentration, and CN on the variations in the gas volume and
the fluid average temperature were numerically discussed. The main conclusions of the study are as follows.

1. The average temperature of the fluid and volume of the gas phase obviously decrease in the equilibrium state with the increase in the porous wettability.

2. When boiling occurs, NCG condenses into the gas phase to create a thermal resistance, which weakens the heat-and mass-transfer rates in the phase change process. Additionally, the increase in the NCG concentration only weakly affects the average temperature of the fluid in equilibrium state and slightly affects the volume of the gas phase.

3. The increase in CN distinctively reduces the volume of the gas phase in the equilibrium state, whereas the variations in the average temperature of fluids are not sensitive to the change in CN.

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Conflict of Interest
There are no conflicts to declare.

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