

Article

Effects of Variations in Water Table Orientation on LNAPL Migration Processes

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Abstract

Light non-aqueous phase liquids (LNAPLs) are significant groundwater contaminants whose migration in aquifers is governed by dynamic groundwater level fluctuations. This study establishes a multiphase flow coupling model integrating hydraulic, gaseous, LNAPL, and chemical fields, utilizing continuous multi-point water level data to quantify water table orientation variations. Key findings demonstrate that (1) LNAPL migration exhibits directional dependence on water table orientation: flatter gradients reduce migration rates, while steeper gradients accelerate movement. (2) Saturation dynamics correlate with gradient steepness, showing minimal variation under flattened gradients but significant fluctuations under steeper conditions. (3) Water table reorientation induces vertical mixing, homogenizing temperature distributions near the interface. (4) Dissolution and volatilization rates of LNAPLs decrease progressively with water table fluctuations. These results elucidate the critical role of hydraulic gradient dynamics in controlling multiphase transport mechanisms at LNAPL-contaminated sites, providing insights for predictive modeling and remediation strategies.

Keywords: light non-aqueous phase liquid (LNAPL); variations in water table orientation; multiphase flow coupling; LNAPL transport



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1. Introduction

Non-aqueous phase liquids (NAPLs) pose significant risks to soil–groundwater systems and human health due to their leakage during industrial processes, necessitating urgent investigation into their migration mechanisms for pollution control [1,2]. As critical contaminants, their subsurface transport behavior directly impacts the quantitative assessment and remediation strategies of petroleum pollutants [3,4].

NAPLs are typically categorized as light (LNAPLs) or dense (DNAPLs) based on their relative density to water. Field observations reveal that post-leakage LNAPLs exhibit complex phase behaviors: while residual fractions remain immobilized in soil matrices, mobile phases migrate vertically through capillary fringes and water table interfaces, forming contamination plumes and lens-shaped accumulations [5,6]. The current understanding of LNAPL transport dynamics in variably saturated zones has been advanced through multiphase flow studies. Kechavarzi et al. [7] demonstrated that LNAPL distribution involves

pore-trapped immobile phases and gravity-driven mobile phases, with volatilization contributing to vapor phase transport. Subsequent research by Siman-tiraki et al. [8] identified textural interfaces in layered soils as critical controls on plume migration paths, while Pan et al. [9] quantified reduced vertical migration rates at fine-coarse soil interfaces through capillary pressure differential analysis. Recent experimental–numerical work by Teng et al. [10] further established saturation-dependent flow regimes along inclined interfaces.

Numerical modeling has emerged as a pivotal tool for deciphering multiphase transport complexities in subsurface systems [11,12]. State-of-the-art simulations have successfully characterized three-phase flow dynamics in saturated–unsaturated zones, with validated models addressing NAPL transport under varying rainfall infiltration rates and groundwater velocities [13–16]. Particularly, COMSOL-based investigations by Amelie’s group [17,18] revealed DNAPL migration constraints in low-permeability silty clay, where convection–dispersion effects become negligible over decadal timescales, highlighting permeability coefficients and saturation–capillary pressure (S-P) relationships as dominant controls on longitudinal transport.

Despite these advancements, critical knowledge gaps persist regarding hydrological forcing effects on LNAPL transport. Current models inadequately address transient water table dynamics induced by rainfall events, particularly the impacts of water table orientation variations (distinct from periodic fluctuations) on capillary fringe interactions. Conventional hydraulic gradient assumptions fail to capture the coupled effects of terrain slope-induced gradients and water table tilt-derived driving forces [19,20]. This limitation raises unresolved questions: How do rainfall-induced hydraulic gradient alterations modify LNAPL redistribution mechanisms at water table–capillary fringe interfaces? What quantitative relationships exist between water table tilt angles and multiphase transport parameters in heterogeneous media?

To address these challenges, this study utilizes ANSYS FLUENT (2023 R1) multiphysics modeling framework to investigate water–air–LNAPL interactions under transient hydrological conditions. The methodology involves the integration of Laminar flow, Volume of Fluid (VOF), and User-Defined Functions (UDFs). The research focuses on three specific aspects: First, it examines the evolution patterns of saturation in porous media under diverse water table orientations. Second, it explores capillary-driven redistribution mechanisms. Third, it delves into the coupled hydrological–multiphase transport dynamics. The findings of this study not only enhance the fundamental understanding of LNAPL transport physics but also offer vital insights for optimizing pollution containment strategies and synergistic soil–groundwater remediation approaches, with the research scope primarily centering on simulating water–air–LNAPL interactions under transient hydrological conditions through the aforementioned multiphysics modeling framework and methodology.

2. Mathematical Model of LNAPL Migration Under Variations in Water Table Orientation

Figure 1 shows a conceptual model of the change in the direction of the diving surface, which is used to describe the migration of LNAPL in the aquifer, which is affected by the change in the direction of the diving surface. The blue solid triangle in the figure represents the measured water level of the three wells, and the initial diving surface direction is determined by the three water level gauges (as shown in the figure on the right). The triangular line represents the diving surface; The direction of groundwater movement is calculated from contours or based on hydraulic gradients. Through multi-point continuous water level data and regression analysis, the hydraulic gradient of the diving surface can be determined, and then the direction of groundwater movement can be determined. The

parallelogram represents the change of the direction of the diving surface under continuous time steps (t_0, t_1, t_2), and the red solid dots on the diving surface are the imaginary fluid points, which reflects the influence of the change of the direction of the diving surface on the migration of the particles. In the conceptual model, it is assumed that LNAPL will migrate after accumulation at the diving surface under the control of the hydraulic gradient and the direction of the diving surface.

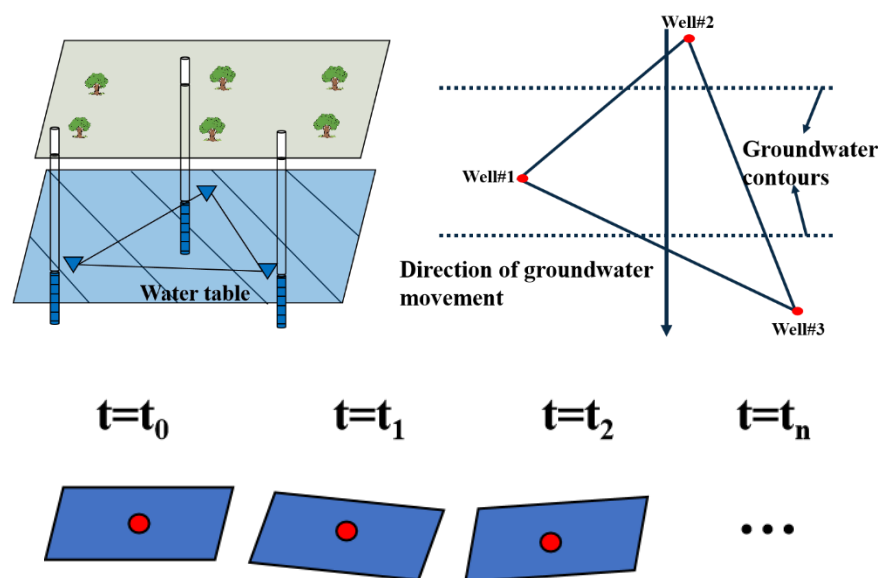


Figure 1. Conceptual model of variations in submerged surface orientation. The blue solid triangle represents the measured water level of the three wells, and the initial diving surface direction is determined by the three water level gauges (as shown in the figure on the right above). The triangular line represents the diving surface. The parallelogram represents the change of the direction of the diving surface under continuous time steps (t_0, t_1, t_2), and the red solid dots on the diving surface are the imaginary fluid points, which reflects the influence of the change of the direction of the diving surface on the migration of the particles.

2.1. Equation for Variations in Water Table Orientation

This study employs a model based on the continuous monitoring of dynamic water level data to determine variations in the water table orientation [19]. The migration path of a fluid particle is determined using Darcy's Law based on the hydraulic gradients in the x and y directions. First, the water table elevation (H) is obtained from water level data at multiple observation wells and regression methods at each time interval (Δt):

$$h(x, y)_i = A_i x + B_i y + C \quad (1)$$

where x and y are coordinates, A_i and B_i are the gradients in the x and y directions, respectively, C is a constant, and h_i is the elevation of the water table at point $(0,0)$ [L].

Given the water table elevation, the hydraulic gradients in the x and y directions at specified time intervals can be solved using the above equation. Under known aquifer parameters, assuming there is a fluid particle on the water table, the initial position of this particle at time step Δt can be defined as

$$x_{i=0} = x_{\text{initial}}, y_{i=0} = y_{\text{initial}} \quad (2)$$

The position of the fluid particle moving over time is

$$x_{i+1} = x_i + \Delta x_i, y_{i+1} = y_i + \Delta y_i \quad (3)$$

$$\Delta x_i = -\frac{KA_i}{\varphi}\Delta t_i, \Delta y_i = -\frac{KB_i}{\varphi}\Delta t_i \quad (4)$$

Here, Δt is the time step [T], K is the permeability [L/T], and φ is the effective porosity. Based on multi-point continuous monitoring of water levels, the water table at each time step can be determined through regression methods; the position and path of the fluid particle on the water table migrating with variations in the water table direction can be calculated using Darcy's Law.

2.2. Conservation of Momentum Equation

The migration process of LNAPL is modeled based on the conservation of momentum equation, with the following assumptions: (1) the suction of the soil matrix is caused by the water and LNAPL phases; and (2) LNAPL, water, and soil phases are incompressible, and variations in the structure of the porous medium can be neglected.

$$\frac{\partial(\varepsilon S_N \rho^N)}{\partial t} + \nabla \left[\varepsilon S_N \rho^N v^N \right] = -E_n^w - E_n^G \quad (5)$$

$$\frac{\partial \left(\frac{\varepsilon S_G P^G M}{RT} \right)}{\partial t} + \nabla \left[\frac{\varepsilon S_G P^G M v^G}{RT} \right] = E_n^G + E_{n/w}^G \quad (6)$$

where ε is the porosity of the porous medium; S_w , S_n , and S_G are the saturations of the water, LNAPL, and gas phases, respectively; ρ^w and ρ^n are the densities of the water and LNAPL phases (kg/m³); P^G is the gas phase pressure (Pa); M is the molar mass of the gas (kg/mol); R is the universal gas constant (J·mol⁻¹·K⁻¹); T is the temperature (K); v^w , v^N , and v^g are the velocities of the water, LNAPL, and gas phases (m/s); E_n^w represents the dissolved LNAPL phase; E_n^G represents the volatile LNAPL phase (kg/m³); $E_{n/w}^G$ represents the transformation of LNAPL from the liquid to the gas phase (kg/m³); and $E_{n/w}^s$ represents the transformation of LNAPL from the liquid to the solid phase (kg/m³).

The velocity of each phase (Darcy velocity, v^w , v^N , v^g) is calculated using multiphase Darcy's Law:

$$v^\alpha = \frac{kk_{ra}}{\varepsilon S_\alpha \mu_\alpha} (\nabla P^\alpha - \rho_\alpha g \nabla z) \quad (7)$$

where k is intrinsic permeability, k_{ra} is relative permeability; μ_α is dynamic viscosity (Pa s); P^α is the pressure of phase α ; g is acceleration due to gravity (m/s²); and α represents the Cartesian coordinate system (x, y, z).

The mass conservation of dissolved and volatile LNAPL phases on a representative volume scale is described by the transport equation 20:

$$\frac{\partial(\varepsilon S_W c_n^w)}{\partial t} + \nabla \left(v^W c_n^w \right) - \nabla \left(\varepsilon S_W D^W \nabla c_n^w \right) = E_n^w - E_{n/w}^G - E_{n/w}^s \quad (8)$$

$$\frac{\partial(\varepsilon S_G c_n^g)}{\partial t} + \nabla \left(v^G c_n^g \right) - \nabla \left(\varepsilon S_G D^G \nabla c_n^g \right) = E_n^G + E_{n/w}^G \quad (9)$$

where c_n^w is the concentration of dissolved LNAPL phase in the water phase (kg/m³); c_n^g is the concentration of LNAPL in the gas phase (kg/m³); and D^W and D^G are the hydrodynamic dispersion coefficients of LNAPL in the water and gas phases (m²/s). Hydrodynamic dispersion can be represented by Equation (11) 21:

$$D^\alpha = \tau_\alpha D_{\alpha l}^q \left| \sigma_{ij} \right| + \left[\alpha_T |U_\alpha| \sigma_{ij} + (\alpha_L - \alpha_T) \frac{U_{\alpha i} U_{\alpha j}}{|U_\alpha|} \right] \quad (10)$$

where τ_α is the longitudinal dispersivity, calculated using the Millington model 22; D_{α}^q is the effective molecular diffusion coefficient of the LNAPL phase (m^2/s), which can be water or gas; σ_{ij} is the Kronecker delta; α_L and α_T are the longitudinal and transverse dispersion coefficients (m^2/s); U_α is the flux in the gas phase (m/s); and $U_{\alpha i}$ and $U_{\alpha j}$ represent the pore velocities of phase α in the x and y directions, respectively. This model consists of two continuity equations (Equations (5) and (6)), representing the flow of fluid phases (gas, water, and LNAPL) within the pore space. The two mass conservation equations corresponding to the water and gas phases (Equations (8) and (9)) can simulate the migration of LNAPL under variations in the water table direction, as well as the migration of dissolved and volatile LNAPL phases.

2.3. Constitutive Model

The model established in this study is based on a structured mesh in ANSYS FLUENT. Flow and chemical components are coupled to solve the model's saturation, concentration, and temperature variations. In ANSYS FLUENT, a physics-field-controlled mesh division is used, which adapts the mesh density and cell type to the current physics field settings. The model mesh is set to 400×410 finite cells. Nonlinear iteration is employed, allowing a relative tolerance of 1×10^{-6} to ensure convergence and obtain results.

To solve the continuity equation of the liquid phase, this paper applies the K-S-P model proposed by Parker and Lenhard to link relative permeability, saturation, and pressure 23. In this model, the two-phase relative permeability–saturation relationship proposed by Van Genuchten is extended to a three-phase water–oil–gas system as follows:

$$\begin{cases} k_{rW}(S_W) = (S_{rw})^l \left[1 - \left(1 - S_{rw}^{\frac{1}{m}} \right)^m \right]^2 \\ k_{rG}(S_G) = (S_{rg})^l \left[1 - \left(1 - S_{rg}^{\frac{1}{m}} \right)^m \right]^2 \\ k_{rN}(S_W, S_G) = (S_{rn})^l \left\{ \left[1 - \left(S_{rw}^{\frac{1}{m}} \right)^m \right] - \left[1 - \left(S_{rTw}^{\frac{1}{m}} \right)^m \right] \right\}^2 \end{cases} \quad (11)$$

where S_{rw} , S_{rg} , and S_{rn} are the residual saturations of the water, gas, and LNAPL phases, respectively; and S_{rTw} is the effective saturation of the liquid phase. The saturation of each phase can be linked to the corresponding pressure using the model provided by Parker et al. [21]:

$$S_{rTw}(P_{CGN}) = \frac{S_W + S_N - S_{Wr} - S_{Nr}}{1 - S_{Wt}} = \begin{cases} \left(1 + \left(\gamma_{GN} \alpha \frac{P_{CGN}}{\rho_w g} \right)^n \right)^{-m} & P_{CGN} > 0 \\ 1 & P_{CGN} \leq 0 \end{cases} \quad (12)$$

$$S_{rw}(P_{CNW}) = \frac{S_W - S_{Wr}}{1 - S_{Wt}} = \begin{cases} \left(1 + \left(\gamma_{NW} \alpha \frac{P_{CNW}}{\rho_w g} \right)^n \right)^{-m} & P_{CNW} > 0 \\ 1 & P_{CNW} \leq 0 \end{cases} \quad (13)$$

$$\gamma_{GN} = \frac{\delta_{GN} + \delta_{NW}}{\delta_{GN}} \quad (14)$$

$$\gamma_{NW} = \frac{\delta_{GN} + \delta_{NW}}{\delta_{NW}} \quad (15)$$

where γ_{NW} and γ_{GN} are scaling factors for converting a two-phase system to a three-phase system; δ_{GN} and δ_{NW} are the interfacial tensions between the gas and LNAPL phases and between the LNAPL and water phases (N/m); P_{CGN} ($P_G - P_N$) and P_{CNW} ($P_N - P_W$) are the capillary pressures between the gas and LNAPL phases and between the LNAPL and water phases (Pa); and α , n , and m are parameters of the VG model.

Variations in the direction of the water table are controlled by acceleration due to gravity. In this study, the x -axis is the longitudinal direction, with the acceleration due to

gravity being -9.81 m/s^2 ; the y-axis is the horizontal direction, i.e., the horizontal migration direction of LNAPL, with accelerations of -0.25 m/s^2 and -0.30 m/s^2 , corresponding to water table tilt angles of -14.04° and -16.70° .

The settings for variations in the water table direction in the model are shown in Figure 2. Figure 2a shows an acceleration due to gravity of -0.25 m/s^2 and a water table tilt angle of -14.04° , while Figure 2b shows an acceleration due to gravity of -0.30 m/s^2 and a water table tilt angle of -16.70° (the straight line in the figure represents the horizontal reference plane).

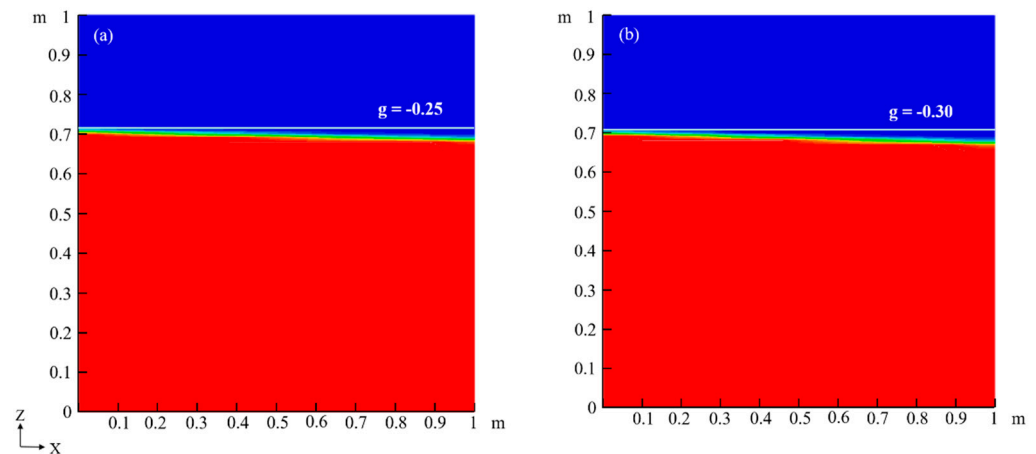


Figure 2. Setting of water table direction variations for (a) gravity of -0.25 m/s^2 and (b) gravity of -0.25 m/s^2 in the model.

2.4. Temperature Variation Equation

Since temperature affects ice saturation, which in turn affects water and NAPL phase saturation, this study incorporates a temperature field to consider the migration of LNAPL under freeze–thaw conditions with the change in the water table direction. The temperature field can be expressed by the energy conservation equation [20,22–26]:

$$(\rho_P C_P)_{eff} \frac{\partial T}{\partial t} + \rho^w v^w C_w \nabla T + \rho^N v^N C_n \nabla T - K_{eff} (\nabla T) = L_f \rho_i \frac{\partial (\varepsilon_1 S_i)}{\partial t} \quad (16)$$

where PC is the effective heat capacity of the soil ($\text{J}/(\text{m}^3 \cdot \text{K})$); $(\rho C)_w$ and $(\rho C)_n$ are the volumetric heat capacities of the water and NAPL phases ($\text{J}/(\text{m}^3 \cdot \text{K})$); L is the latent heat of water condensation or ice melting (J/m^3); and λ is the effective thermal conductivity of the soil ($\text{W}/(\text{m} \cdot \text{K})$). The effective heat capacity and thermal conductivity can be expressed as the volume-weighted average of various material components. The effective heat capacity and thermal conductivity of the soil matrix can be expressed as follows [21,26–28]:

$$(\rho_P C_P)_{eff} = \rho^S C_s (1 - \varepsilon_1) + \rho^W C_w \theta_w + \rho^i C_i \theta_i + \rho^N C_n \theta_n \quad (17)$$

$$K_{eff} = K_s (1 - \varepsilon_1) + K_w \theta_w + K_i \theta_i + K_n \theta_n \quad (18)$$

where C_s , C_w , and C_i are the volumetric heat capacities of the soil matrix, water, ice, and NAPL phases ($\text{J}/(\text{m}^3 \cdot \text{K})$); K_s , K_w , K_i , and K_n are the thermal conductivities of the soil matrix, water, ice, and NAPL phases ($\text{W}/(\text{m} \cdot \text{K})$); θ_w , θ_n , and θ_i are the contents of the water, NAPL, and ice phases.

To obtain the coupled solution of the energy and flow continuity equations, including the impact of the change in the water table direction on temperature (T), ice saturation (S_i),

water saturation (S_w), and temperature as a function of initial water saturation and soil freezing point, the following empirical equations are given [18]:

$$B(T) = \begin{cases} S_i = \frac{B(T) \times S_w}{1 + B(T) \times S_w} \\ 1.1 \times \left(\frac{T}{T_f}\right)^B - 1 & T < T_f \\ 0 & T \geq T_f \end{cases} \quad (19)$$

where T_s is the soil temperature ($^{\circ}\text{C}$), S is the solid–liquid ratio [29]; C is an empirical parameter of the soil; and T_f is the freezing temperature of the soil ($^{\circ}\text{C}$), which depends on the water phase saturation. It should be noted that S_w will never reach zero, as liquid water always exists regardless of how low the soil temperature is.

3. Case Study and Model Construction

Overview of Case Study and Initial and Boundary Conditions

This paper establishes a numerical simulation conceptual model based on Figure 3 to simulate the migration of LNAPL under variations in the water table orientation. The literature has confirmed that the rainfall process can affect variations in the water table orientation [24]. This paper first establishes an LNAPL migration model without variations in the water table orientation and then constructs an LNAPL migration model with variations in the water table orientation based on this model.

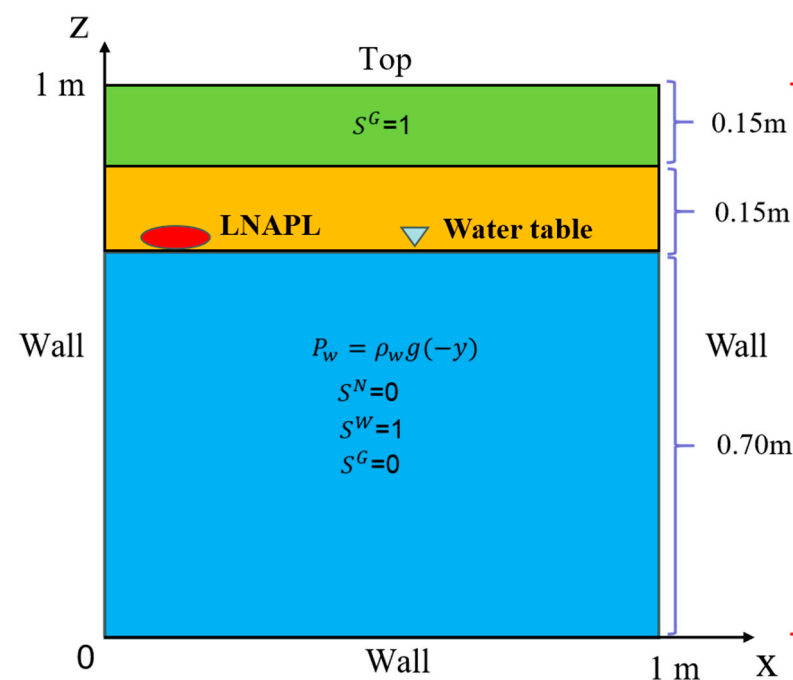


Figure 3. Numerical modeling of variations in submerged surface orientation.

The numerical case of LNAPL migration under variations in water table orientation is shown in Figure 3. The case involves establishing a multiphase model to first simulate the migration of LNAPL in porous media under saturated and unsaturated conditions and then simulate the migration of LNAPL under the same conditions with variations in the water table orientation. The model established in this study is a three-dimensional model with dimensions of 1 m in length, 1 m in width, and 1 m in height. The water table is taken as the reference plane, with the lower 0.7 m being a saturated zone composed of silty soil; the middle layer of 0.15 m being an unsaturated zone composed of sandy soil; and the upper 0.15 m being an unsaturated zone composed of silty sandy soil. The

center of the LNAPL source is located at (0.20, 0.70, 0.50) m, with an initial thickness of 1 cm of accumulated LNAPL on the water table, a radius of 7.5 cm, and a volume of 176.6 cm³. The mesh division is carried out using the ICEM CFD mesh generation tool for structured mesh division. Compared with unstructured mesh division, structured mesh division can improve the accuracy and efficiency of flow simulation and provide more accurate numerical solutions, reducing interpolation errors and false numerical diffusion at boundaries.

The initial conditions for the unsaturated and saturated zones in the model are set as follows:

$$\begin{aligned}\text{Gasphase : } S_G &= 1 - \left((1 + (\alpha y)^n)^{-m} (1 - S_{Wr}) + S_{Wr} \right) \\ \text{Saturationzone : } S_G &= 0 \\ \text{LNAPLPhase : } S_N &= 0 \\ \text{WaterPhase : } P_w &= \rho_w g(-y) \\ \text{LNAPLPhase : } P_n &= \rho_n g(-y) \\ \text{Temperature : } T &= 2[^\circ\text{C}]\end{aligned}$$

The boundary conditions of the model are set as follows:

(1) Flow field

$$\begin{cases} \text{Upperboundary : } \nabla S_G = 0, \nabla S_N = 0, \nabla P_W = 0 \\ \text{Rightborder : } \nabla S_G = 0, S_N = 0, P_W = \rho_W g(-y) \\ \text{Leftborder : } \nabla S_G = 0, S_N = 0, P_W = \rho_W g(-y) \\ \text{Leakpoint : } \text{viscous resistance and inertial resistance} \end{cases}$$

(2) Chemical field

$$\begin{aligned}\text{Upperboundary : } V^W c_1 - D^W \nabla c_1 &= 0, D^G \nabla c_2 = 0 \\ \text{Leftandrightborders : } D^W \nabla c_1 &= 0, V^G c_2 - D^G \nabla c_2 = 0 \\ \text{Lowerboundary : } V^W c_1 - D^W \nabla c_1 &= 0, V^G c_2 - D^G \nabla c_2 = 0\end{aligned}$$

Model parameters are shown in Table 1.

Table 1. Model parameters.

Material	Quality	Parameter	Value
Soil	α -VG Model parameters	α	6.1
	n -VG Model parameters	n	6
	m -VG Model parameters	m	0.83
	l -VG Model parameters	l	0.5
	porosity	ε_1	0.445
	Specific heat capacity of the soil	C_s	722 J/(kg K)
	Organic carbon content	f_{oc}	0.03
LNAPL Phase	LNAPL density	ρ^N	700 kg/m ³
	LNAPL Phase viscosity	μ^N	0.0017 kg/(m s)
	LNAPL Specific heat capacity	C_N	1006.43 J/(kg K)
	LNAPL Thermal conductivity	K_N	0.0242
	LNAPL Henry's constant	H	0.27
Water Phase	Water density	ρ^W	998.2 kg/m ³
	Gravitational acceleration	g_y	−9.80999 m/s ²
		g_{x1}	−0.25 m/s ²
		g_{x2}	−0.3 m/s ²
	Aqueous viscosity	μ^W	0.001003 kg/(m s)
	Water thermal conductivity	K_W	0.55
	Water compared to heat capacity	C_W	4182 J/(kg K)

4. Results

4.1. Migration Process of LNAPL Without Variations in Water Table Orientation

4.1.1. Flow Field

The migration process of LNAPL without variations in the water table orientation is shown in Figures 4 and 5. When the acceleration due to gravity is -0.25 m/s^2 and the water table tilt angle is 14.04° , the LNAPL phase mainly migrates along the direction of the water table. The maximum saturation decreases from 1 to 0.53. LNAPL migrates horizontally in the direction of the x-axis, with the distance traveled in the x-axis direction being greater than that in the y-axis and z-axis directions. Advection dominates. At $t = 30 \text{ T}$ ($T = 360 \text{ s}$), when LNAPL is at position (0.5 m, 0.7 m, 0.14 m), it migrates 0.38 m forward due to advection. At $t = 60 \text{ T}$, the maximum saturation of LNAPL decreases from 0.53 to 0.39. LNAPL continues to migrate along the water table (x-axis direction), moving from position (0.5 m, 0.7 m, 0.14 m) to (0.5 m, 0.7 m, 0.54 m), a distance of 0.40 m. At this moment, the area of the pollution plume is 0.04 m^2 . Under the condition of no variations in the water table orientation, LNAPL migrates under the influence of gravity, with relatively stable saturation variations, as the water table maintains the same acceleration due to gravity. At $t = 90 \text{ T}$, LNAPL continues to migrate along the water table direction (x-axis direction), with the maximum saturation decreasing from 0.39 to 0.16. LNAPL moves from point (0.5 m, 0.7 m, 0 m) to (0.5 m, 0.7 m, 1 m), a distance of 1 m. Under the influence of gravity, the migration speed of LNAPL along the water table direction gradually increases, and LNAPL continues to move along the water table direction. When $t = 120 \text{ T}$, the distribution of the LNAPL pollution plume is more uniform, with a larger vertical distribution range. Compared to $t = 90 \text{ T}$, the vertical thickness of the pollution plume increases by 0.01 m at this moment. LNAPL continues to migrate forward along the water table direction with (0.5 m, 0.7 m, 0.14 m) as the reference point, a distance of 0.65 m. The gradual increase in lateral migration distance is due to the dominant advection effect in the absence of water table orientation effects. The migration speed of LNAPL under the influence of gravity gradually increases, and the longitudinal migration distance increases due to the upward movement of water and the pressure variations caused by LNAPL migration. Subsequently, the saturation of LNAPL varies gradually with the variations in water saturation. Among them, the maximum saturation of LNAPL at position (0.5 m, 0.7 m, 0.14 m) shows a discontinuous state. The reason is that the LNAPL and water phases are immiscible. When LNAPL migrates along the water table direction, the intermolecular forces between the two phases are very small. LNAPL tends to interact at the contact area between the two phases, forming a hydrophobic oil layer, while water forms a hydrophilic water layer, causing discontinuity in LNAPL. From $t = 90 \text{ T}$ (0.5 m, 0.7 m, 0.14 m) to $t = 120 \text{ T}$ (0.5 m, 0.7 m, 0.14 m), the migration distance is 0.25 m. The thickness of the pollution plume decreases progressively from left to right, and the isopleths are more densely distributed near the wall. From the above results, it can be concluded that LNAPL mainly migrates along the hydraulic gradient when there are no variations in the water table orientation.

4.1.2. Temperature Field

Figure 6 demonstrates temperature evolution in soil under stable water table conditions, revealing distinct thermal characteristics across different depth zones. During the initial phase ($t = 30 \text{ T}$), significant temperature fluctuations ($6.85\text{--}20.52^\circ\text{C}$) occur in the upper 0.3 m (y-axis: 0.7–1 m), characterized by steep thermal gradients and densely distributed isotherms near the surface. This dynamic regime stems from natural convective heat exchange between air and ambient-temperature water. As the simulation progresses, thermal stratification intensifies: at $t = 60 \text{ T}$, the upper zone reduces to $6.85\text{--}18.57^\circ\text{C}$, while by $t = 120 \text{ T}$, it stabilizes at $6.85\text{--}8.80^\circ\text{C}$. Conversely, the lower aquifer (0–0.7 m)

maintains smaller temperature variations (16.62–26.38 °C) due to water’s high thermal inertia. The analysis reveals two dominant heat transfer mechanisms: vertical conduction predominates perpendicular to flow, while along the water table direction, LNAPL leakage significantly alters thermal dynamics through its dual role as convective modifier and insulating layer. The low thermal conductivity of LNAPL concentrates thermal resistance and temperature differentials along the water table interface, with small Darcy numbers (<1) further suppressing convective heat transfer through reduced permeability effects. This coupled behavior highlights the critical influence of multiphase interactions on subsurface thermal regimes.

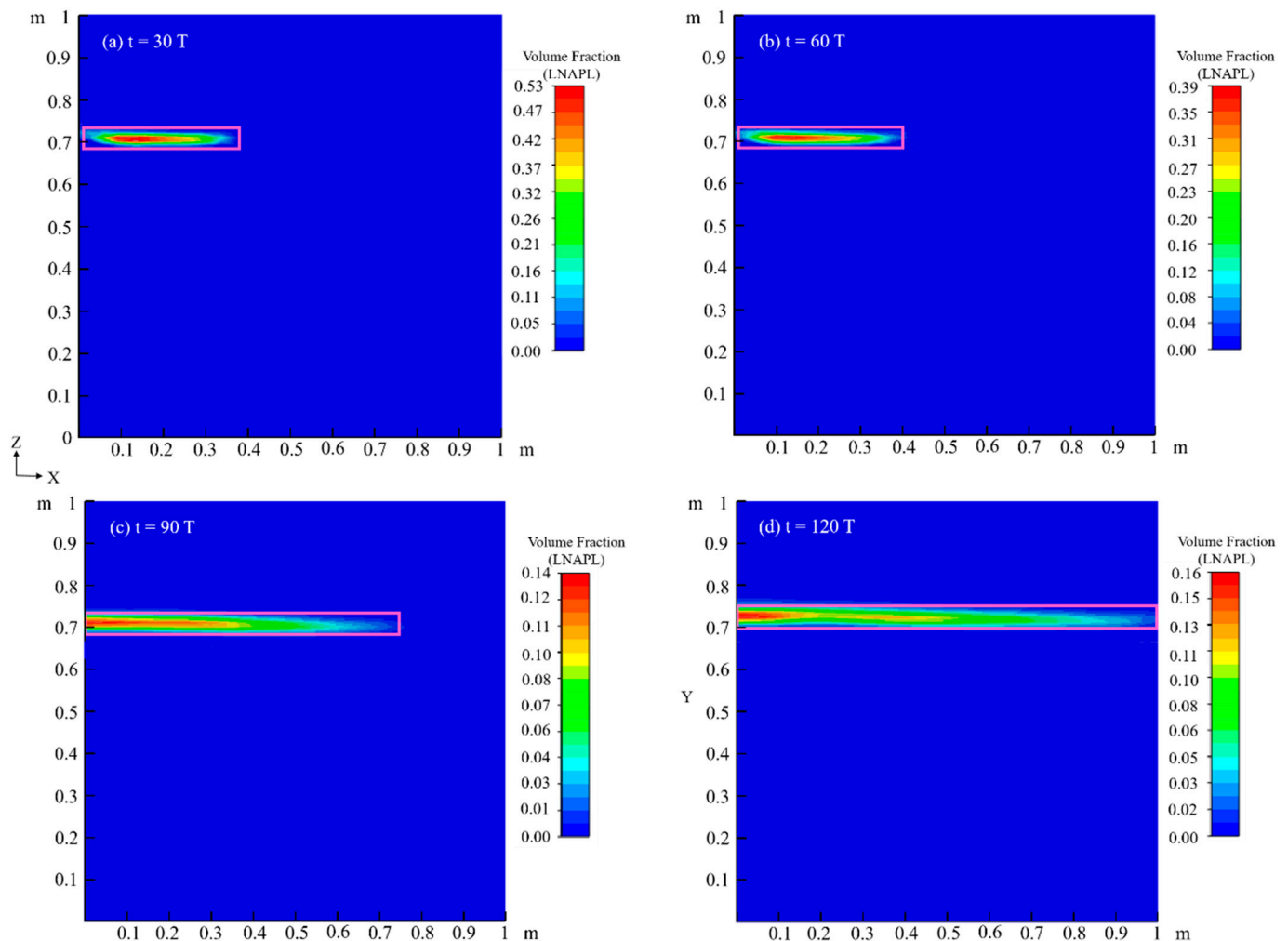


Figure 4. Migration process of LNAPL under no variations in water table orientation (x-z surface) at four time steps: (a) $t = 30$ T, (b) $t = 60$ T, (c) $t = 90$ T, and (d) $t = 120$ T.

4.2. Migration Process of LNAPL with Variations in Water Table Orientation

4.2.1. Flow Field

The migration process of LNAPL with variations in the water table orientation is shown in Figure 7. The direction of the water table varies due to the variation in acceleration due to gravity. From $t = 0$ T to $t = 120$ T, the settings for acceleration due to gravity and tilt angle in the model are the same as those without variations in the water table orientation ($g = -0.25$ m/s², tilt angle 14.04°). From $t = 90$ T to $t = 120$ T, the acceleration due to gravity and tilt angle in the model vary ($g = -0.3$ m/s², tilt angle 16.70°) to simulate the migration process of LNAPL with variations in the water table orientation. According to the x-y plane figures (Figures 5 and 8), when there are no variations in the water table

orientation ($g = -0.25 \text{ m/s}^2$, Figure 5), the shape of the LNAPL plume varies from an initial circular ring shape at $T = 30$ (Figure 5a) to an elliptical shape at $T = 60$ and to a conical shape at $T = 90$. This is because, without the effect of variations in the water table orientation, LNAPL migrates along the hydraulic gradient (acceleration due to gravity) direction. At $T = 120$, the shape of the LNAPL pollution plume is basically consistent with that at $T = 90$, forming a conical circle. Under conditions without variations in the water table orientation, LNAPL mainly migrates along the direction of the hydraulic gradient, with some migration behavior in other directions. In the case of variations in the water table orientation ($g = -0.30 \text{ m/s}^2$, Figure 8), the shape of the LNAPL plume remains consistent from $T = 30$ to $T = 90$. At $T = 120$, due to the variations in the water table orientation (the acceleration due to gravity varies from $g = -0.25 \text{ m/s}^2$ to $g = -0.30 \text{ m/s}^2$), the shape of the LNAPL plume varies from a conical shape to an arc shape. The migration trajectory of LNAPL shifts horizontally along the x-axis and then continues to move horizontally along the x-axis. Compared to the condition without variations in the water table orientation, the migration trajectory of LNAPL varies under the condition of variations in the water table orientation (Figure 8d). According to the x-z plane figures (Figures 4 and 7), when $t = 120 \text{ T}$, the migration distance of LNAPL with variations in the water table orientation is farther (0.05 m). Variations in acceleration due to gravity can cause variations in the migration speed of LNAPL. When the water table becomes steeper, the migration speed increases; when the water table becomes flatter, the migration speed decreases. The two are positively correlated. The vertical distribution of LNAPL is more uneven compared to the scenario without variations in the water table orientation, especially at positions (0.5 m, 0.7 m, 0.14 m) and (0.36 m, 0.7 m, 0.56 m) (Figure 5d). The reason is that variations in the tilt angle can alter the pressures experienced by the water and LNAPL phases, accelerating or decelerating the migration speed of LNAPL. For example, at $t = 120 \text{ T}$, when the water table tilt angle increases from 14.04° to 16.70° , the horizontal migration speed of LNAPL is accelerated (Figure 5d). At the same time, the migration trajectory of LNAPL changes, with LNAPL moving diagonally downward and then continuing to move horizontally along the x-axis (Figure 5d). Variations in the water table orientation can cause disturbances in the water body, affecting the vertical distribution of LNAPL and resulting in a thicker distribution on both sides and a thinner distribution in the middle.

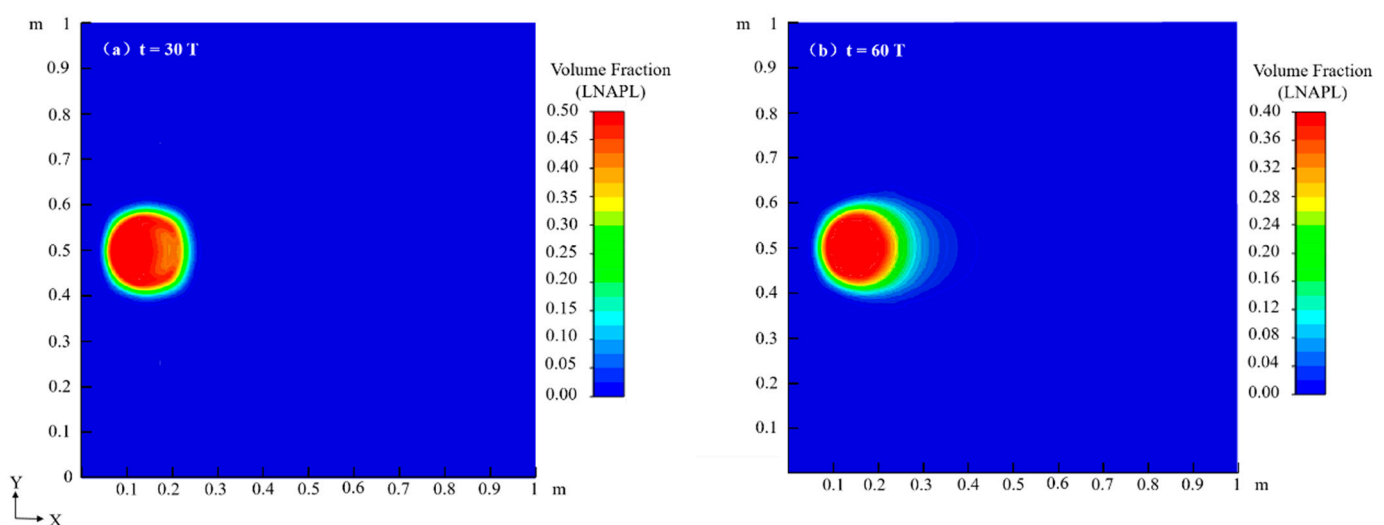


Figure 5. Cont.

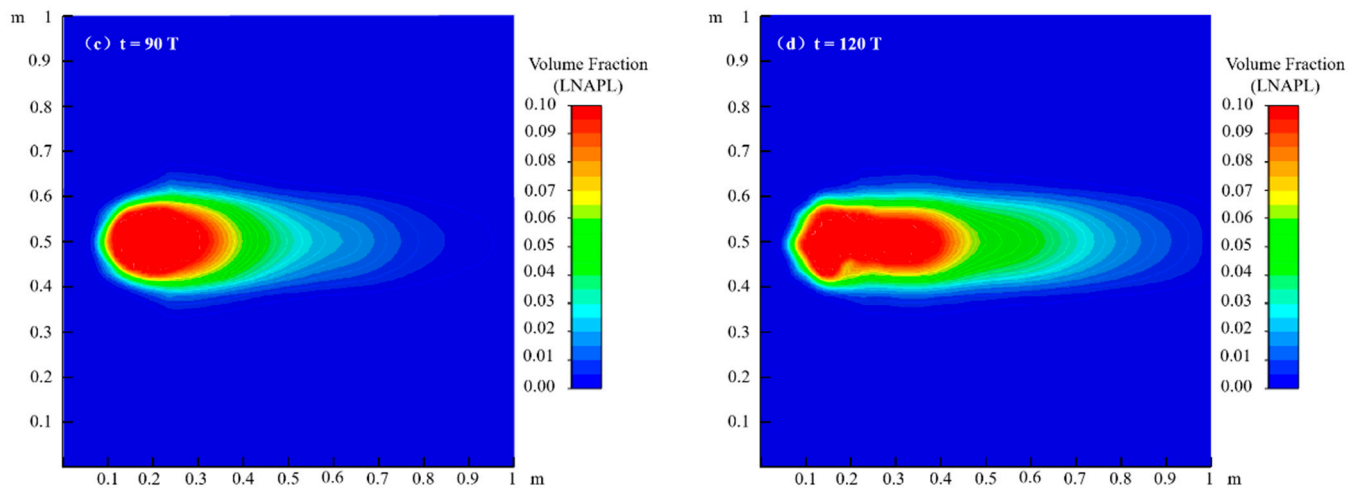


Figure 5. Migration process of LNAPL under no variations in water table orientation (x-y surface) at four time steps: (a) $t = 30 T$, (b) $t = 60 T$, (c) $t = 90 T$, and (d) $t = 120 T$.

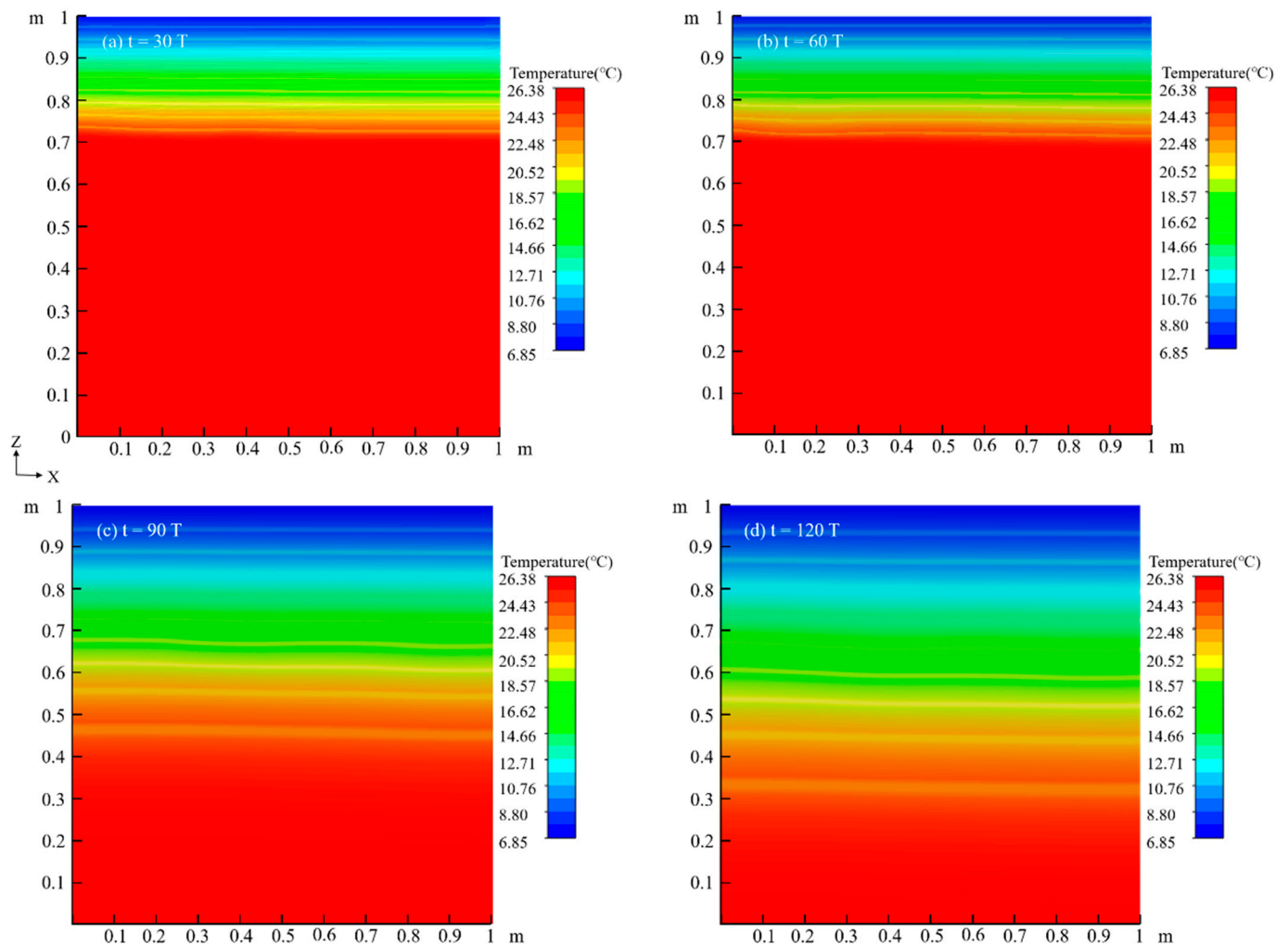


Figure 6. Temperature field variation (x-z plane) with no variations in submerged surface orientation at four time steps: (a) $t = 30 T$, (b) $t = 60 T$, (c) $t = 90 T$, and (d) $t = 120 T$.

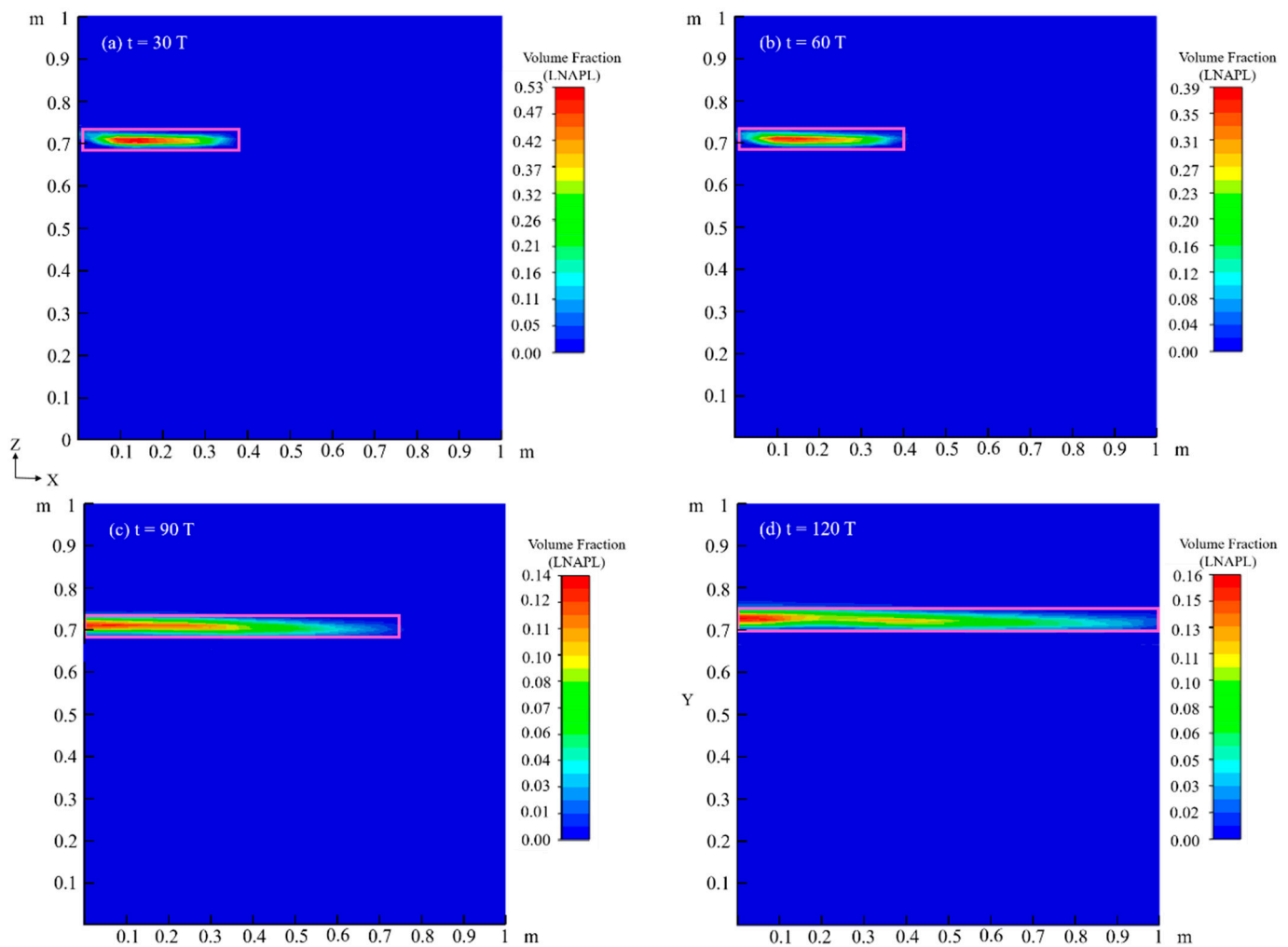


Figure 7. Migration process of LNAPL under variations in water table orientation (x-z surface) at four time steps: (a) $t = 30 T$, (b) $t = 60 T$, (c) $t = 90 T$, and (d) $t = 120 T$.

4.2.2. Temperature Field

The temperature variations with variations in the water table orientation are shown in Figure 9. At $t = 30 T$, $t = 60 T$, and $t = 90 T$, the conditions are consistent with those without variations in the water table orientation. At $t = 120 T$, when the water table orientation changes from 14.04° ($g = -0.25 \text{ m/s}^2$) to 16.70° ($g = -0.30 \text{ m/s}^2$), the temperature gradient fluctuates dramatically in the 0.7–1 m range (y-axis direction), with a variation range of 6.85 to 12.71. Near 0.7 m, the temperature variations are mainly concentrated around 18.57°C . This is because variations in the water table orientation can cause variations in the water level. The lower water layer has a higher temperature, while the upper part of the water layer has a lower temperature. The interaction between the two causes the temperature near the water table to vary dramatically, which tends to become uniform near the water table.

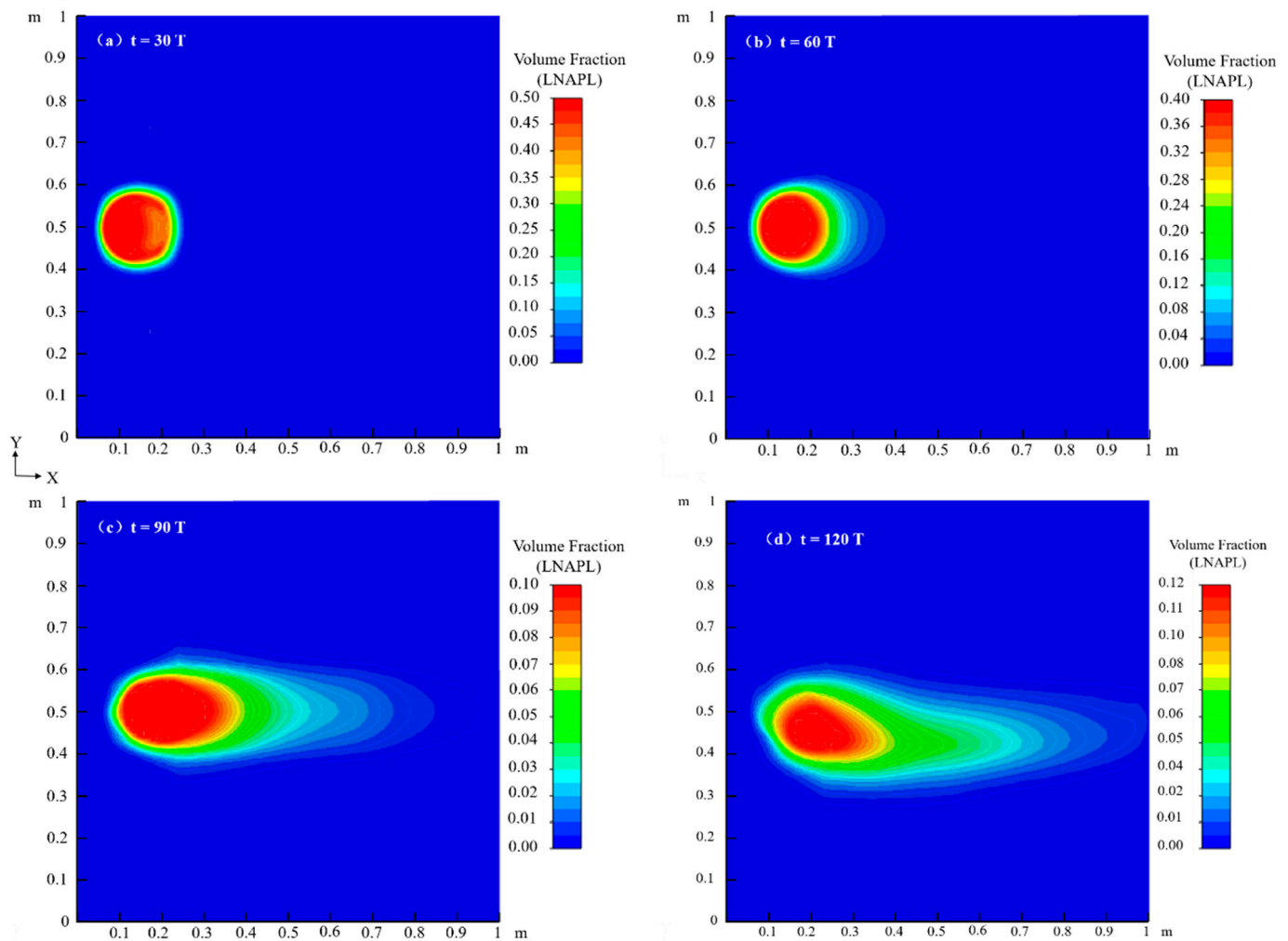


Figure 8. Migration process of LNAPL under variations in water table orientation (x-y surface) at four time steps: (a) $t = 30 T$, (b) $t = 60 T$, (c) $t = 90 T$, and (d) $t = 120 T$.

4.2.3. Chemical Field

The migration characteristics of the dissolved and volatile phases of LNAPL with variations in the water table orientation are shown in Figure 10. As LNAPL moves in the direction of the water table, the solubility of LNAPL in water gradually decreases, with the maximum solubility decreasing from 7.42 mg/L to 1.82 mg/L. At $t = 30 T$, the dissolved phase is distributed in a long strip shape, with diffusion speed in the horizontal direction greater than that in the vertical direction. The concentration in the saturated zone can reach 7.42 mg/L. At $t = 60 T$, the dissolved phase moves with the water table orientation, with the maximum solubility decreasing from 7.42 mg/L to 5.46 mg/L. At $t = 90 T$, after the water table stabilizes, the maximum solubility decreases from 5.46 mg/L to 1.96 mg/L. This is because, without variations in the water table orientation, the dissolved and volatile phases of LNAPL mainly move through soil pores via molecular diffusion. The molecular action is relatively stable without variations in the water table orientation, and advection has a significant effect on molecular diffusion. At $t = 120 T$, with variations in the water table orientation, the maximum solubility of LNAPL decreases from 1.96 mg/L to 1.82 mg/L. Compared to the scenario without variations in the water table orientation, the maximum solubility variation in LNAPL with variations in the water table orientation is smaller, at 0.14 mg/L. Under conditions of variations in the water table orientation, the dissolution and volatilization of LNAPL are both smaller. This is because, under the influence of the water table, LNAPL mainly moves through diffusion. Variations in the water table orientation

have a smaller impact on diffusion. The distribution of the volatile phase of LNAPL with variations in the water table orientation is shown in Figure 11, with the volatile phase of LNAPL moving along the water table direction and reaching a concentration of 0.42 mg/L above the water table.

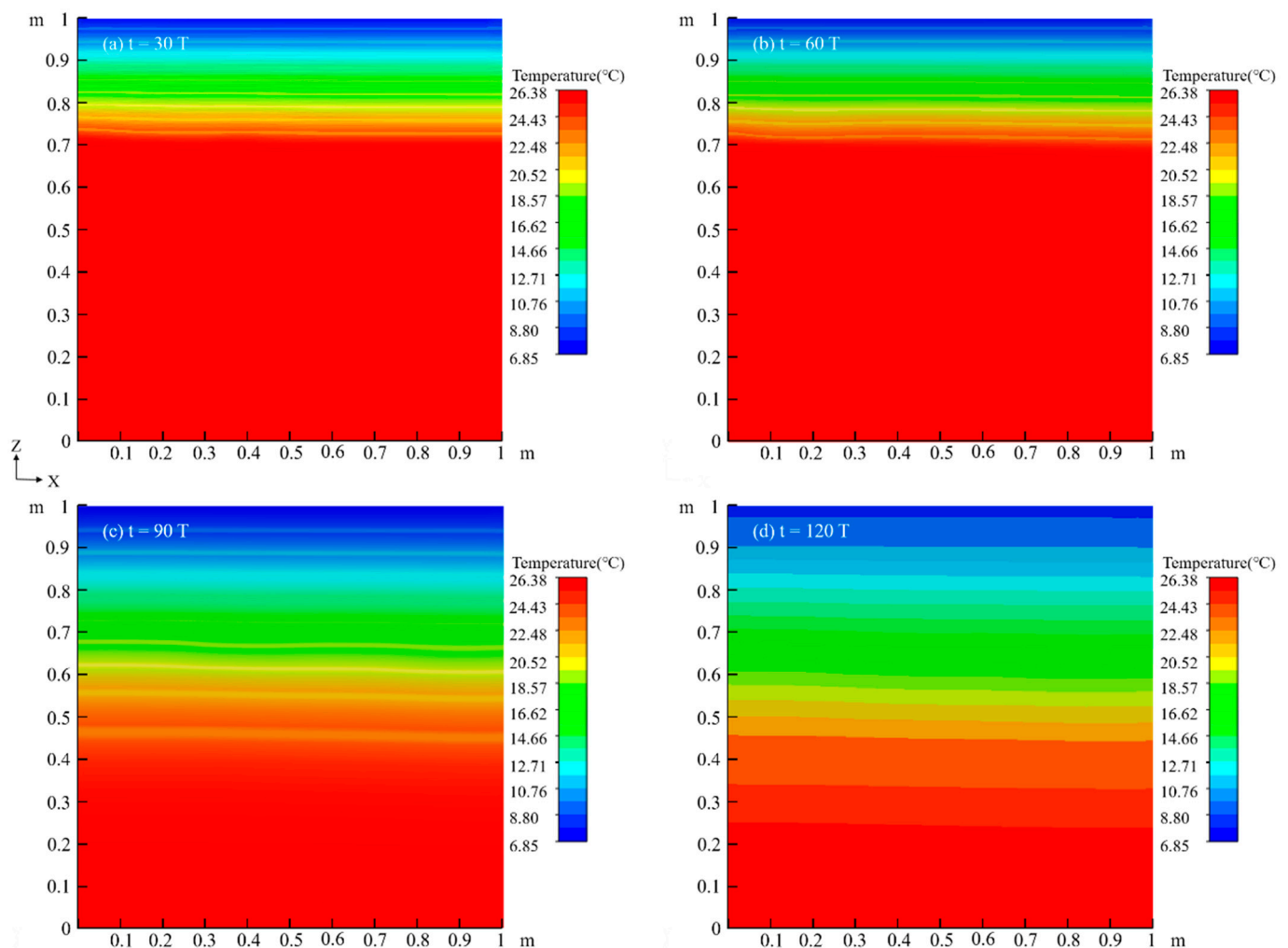


Figure 9. Temperature field variations (x-z plane) for variations in submerged surface orientation at four time steps: (a) $t = 30$ T, (b) $t = 60$ T, (c) $t = 90$ T, and (d) $t = 120$ T.

4.3. Effects of Capillary Action on LNAPL Migration Distribution with Variations in Water Table Orientation

Figures 12 and 13 show the effects of capillary action on the migration distribution of LNAPL with and without variations in water table orientation, respectively. Given a water table tilt angle of 14.04° , at the initial moment, it can be seen from Figures 12a and 13a that LNAPL migrates along the water table direction. Variations in the water table orientation result in relatively larger saturation variations, with the saturation decreasing from 1 at the center of the pollution plume (0.5 m, 0.7 m, 0.14 m) to 0.38. From Figures 12a and 13a, it can be seen that without capillary action, the saturation at the center of the pollution plume is relatively high, at 0.58. Under capillary action, the vertical migration distance of LNAPL is farther, at 0.41 m, compared to 0.38 m without capillary action. As time progresses ($t = 60$ T), due to capillary action, part of the LNAPL migrates vertically, while another part migrates radially along the water table. The maximum saturation at the center of the pollution plume (0.5 m, 0.7 m, 0.14 m) decreases from 0.38 to 0.36 (Figures 12b and 13b), with relatively small saturation variations. Capillary fringe development initiates at the

LNAPL–air interface at the ends of the LNAPL. When $t = 90$ T, LNAPL migrates forward 0.68 m (Figure 12); whereas in Figure 4c, LNAPL migrates forward 1 m. In Figure 7c, the saturation of LNAPL decreases from 0.36 to 0.21. In Figure 13, the saturation of LNAPL decreases from 0.53 to 0.17. In Figure 7c, LNAPL migrates forward 1 m. In Figure 13b LNAPL migrates forward to 0.65 m. Therefore, under capillary action, the migration distance of LNAPL is smaller. The capillary pressure increases, and the saturation of the water and LNAPL phases increases in the capillary tube. Part of the LNAPL enters the capillary tube, while another part of the LNAPL, due to the pressure difference in the vicinity of the capillary tube, slows down its migration speed. The migration distribution of LNAPL under capillary action when the water table tilt angle increases from 14.04° to 16.70° is shown in Figure 12a,b and Figure 13a,b. Without variations in the water table orientation (tilt angle 14.04° , Figures 12a and 13a), part of the LNAPL migrates along the water table direction, while another part migrates upward due to capillary action. The maximum saturation at the center of the pollution plume decreases from 0.21 to 0.11, and LNAPL migrates forward 0.3 m. With variations in the water table orientation (tilt angle 16.70°), the migration distance of LNAPL under capillary action is relatively smaller (Figures 12b and 13b). Variations in the water table orientation alter the capillary pressure experienced by the water and LNAPL phases. When the water table fluctuates, the capillary pressure increases, and the migration speed of LNAPL slows down. When the water table becomes steeper, the migration speed of LNAPL increases.

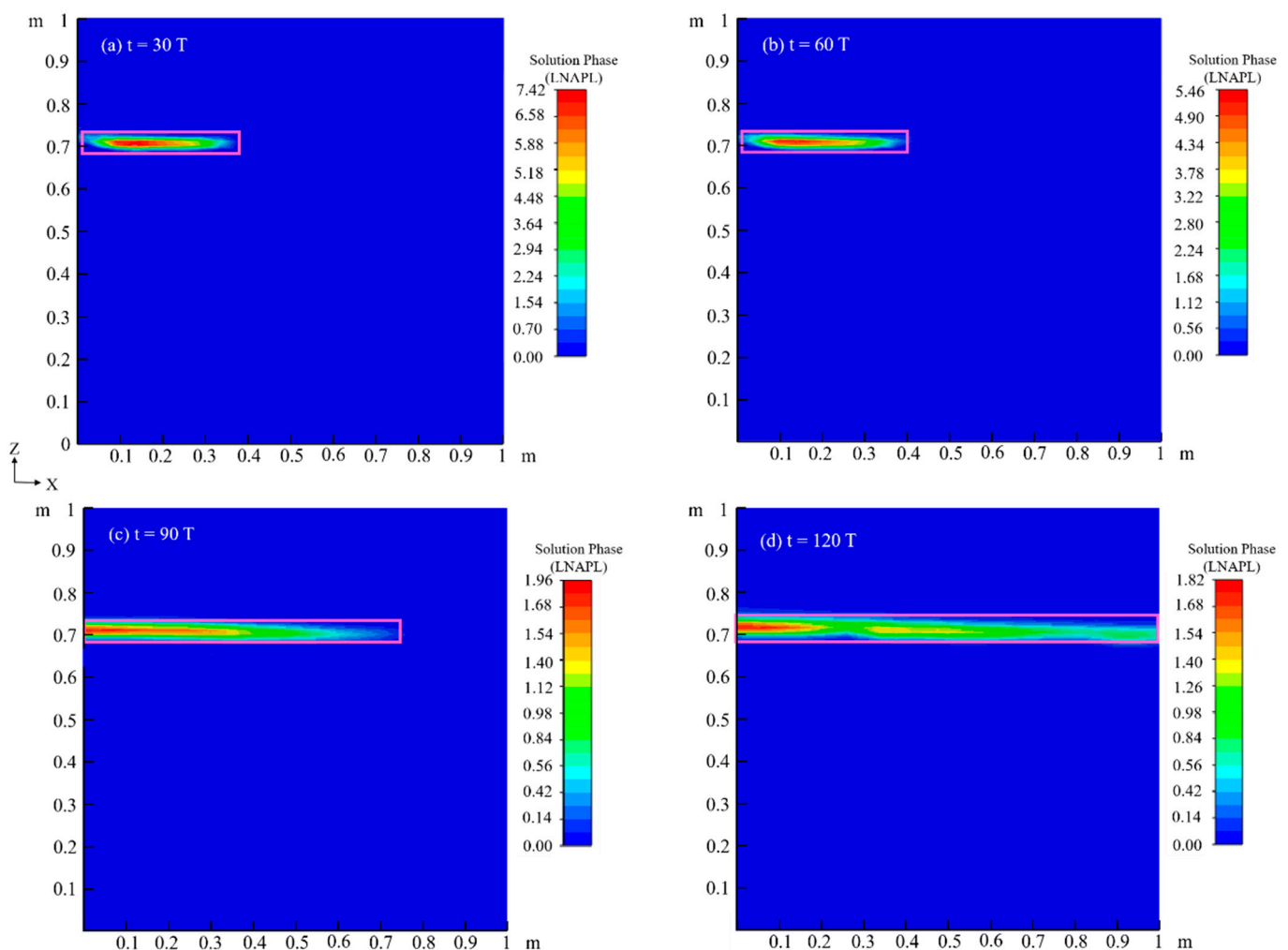


Figure 10. Concentration distribution of LNAPL dissolved phase under variations in water table orientation at four time steps: (a) $t = 30$ T, (b) $t = 60$ T, (c) $t = 90$ T, and (d) $t = 120$ T.

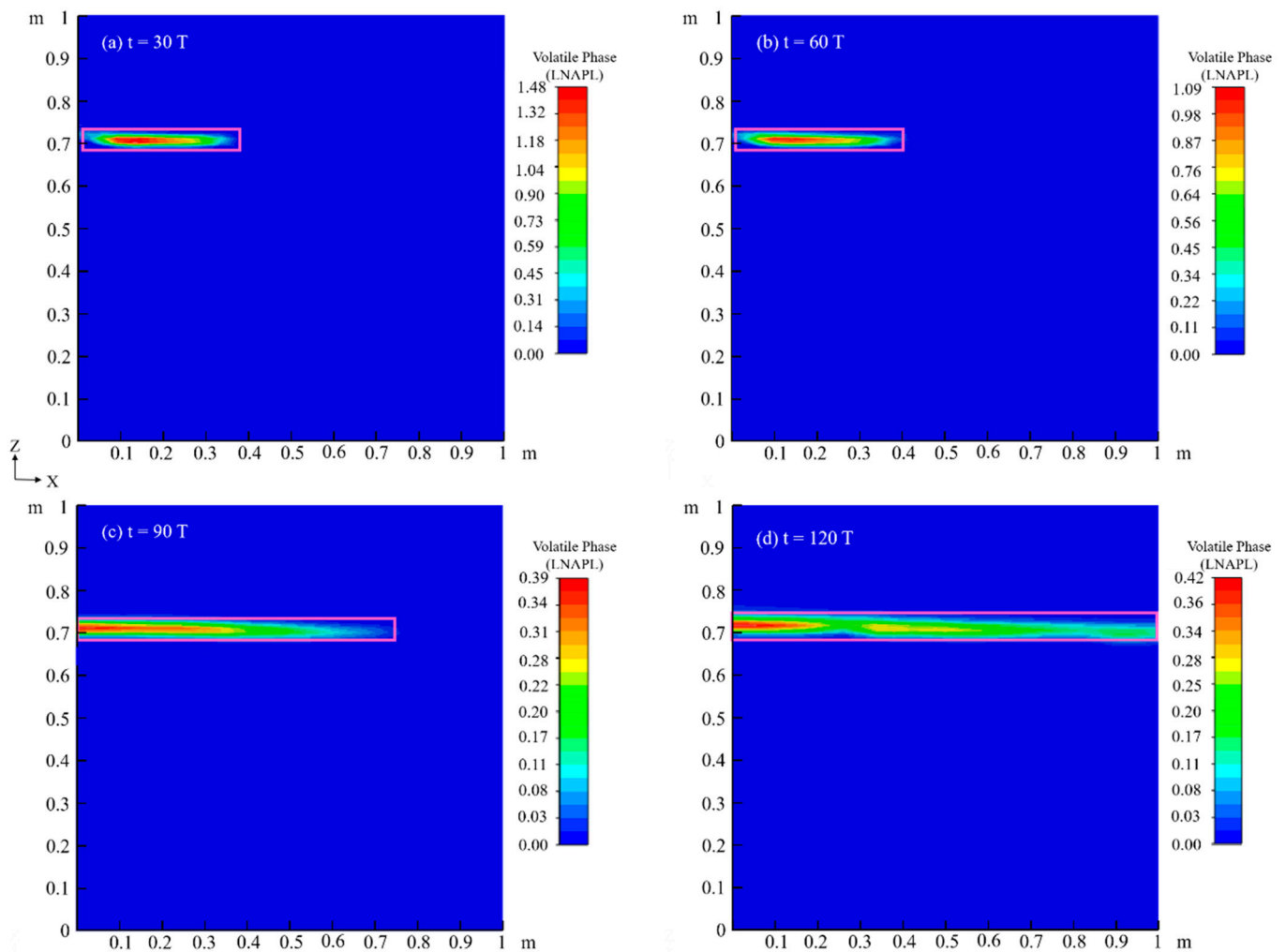


Figure 11. Concentration distribution of LNAPL volatile phases under submerged surface orientation variations at four time steps: (a) $t = 30 T$, (b) $t = 60 T$, (c) $t = 90 T$, and (d) $t = 120 T$.

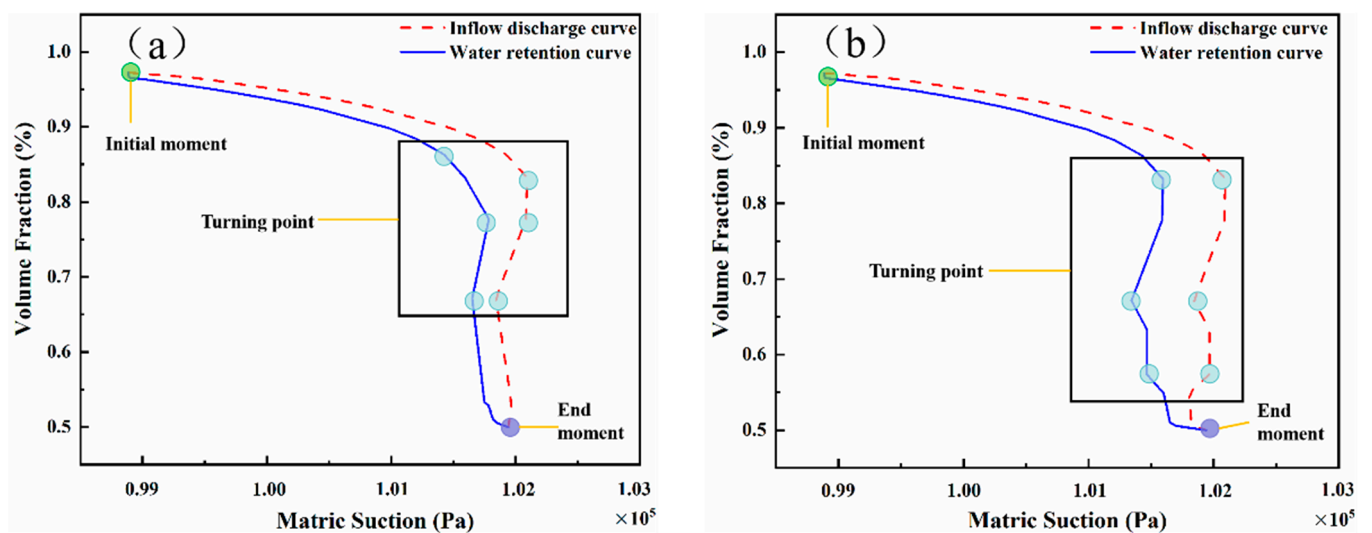


Figure 12. $P_C - S_w$ relationship under variations in submerged surface direction; (a) curved plot of $P_C - S_w$ relationship without variations in submerged surface; (b) curved plot of $P_C - S_w$ relationship under variations in submerged surface.

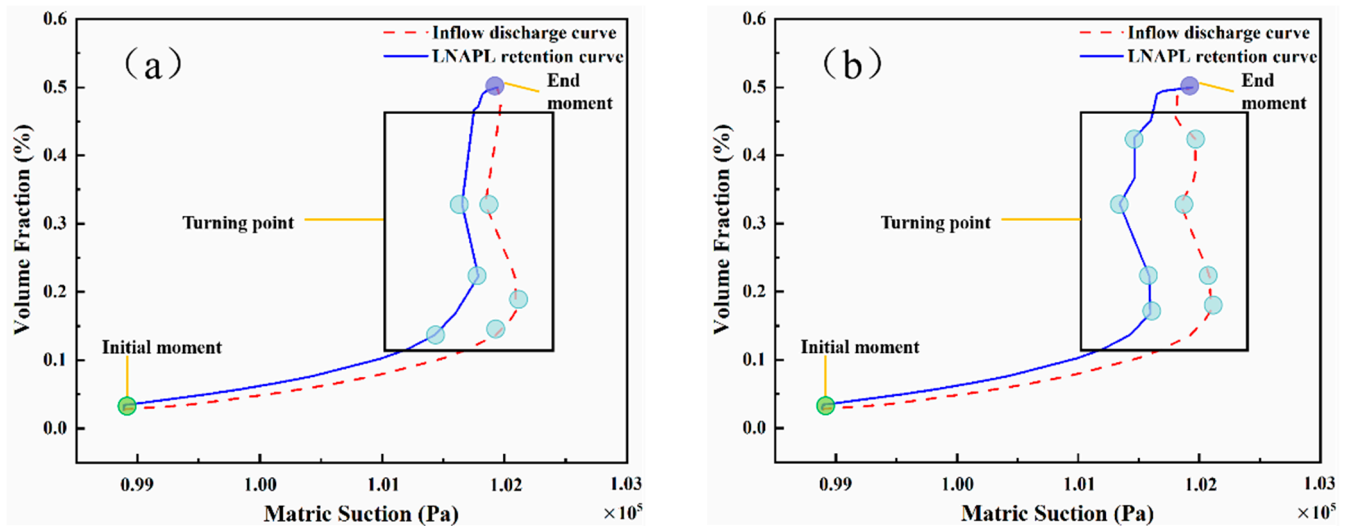


Figure 13. $P_C - S_N$ relationship under variations in submerged surface direction; (a) curved plot of $P_C - S_N$ relationship without variations in submerged surface; (b) curved plot of $P_C - S_N$ relationship under variations in submerged surface.

The relationship curves of capillary pressure, P_c , with water saturation, S_w , and LNAPL saturation, S_n , under variations in water table orientation are shown in Figure 12. The capillary pressure and water saturation, as well as LNAPL saturation, are selected at the point of interest (0.5 m, 0.7 m, 0.14 m). When the water table orientation is 14.04° , the saturation varies exponentially between 0.95 and 0.8. Between saturation levels of 0.8 and 0.5, the intake curve (LNAPL) and the drainage curve (LNAPL) show inflection points. This is because when the water table (LNAPL) is higher than the surface of the porous medium, capillary action promotes the upward movement of water (LNAPL), increasing the water absorption capacity of the porous medium. When the water table (LNAPL) is lower than the surface of the porous medium, capillary action causes disturbances, weakening the water absorption (LNAPL) capacity of the porous medium. When the water table orientation varies, the drainage (LNAPL) conditions in the surrounding porous medium also vary accordingly. When the water table (LNAPL) is higher than the porous medium surface, water (LNAPL) infiltrates the porous medium, increasing the water content and saturation (LNAPL) of the porous medium. When the water table (LNAPL) is lower than the porous medium surface, the water content and saturation (LNAPL) in the porous medium decrease due to gravity. In summary, variations in the water table orientation have a significant impact on the water (LNAPL) content in the porous medium. If the water table (LNAPL) is higher than the porous medium, the water content in the porous medium increases, and capillary action weakens. If the water table (LNAPL) is lower than the porous medium, the water content (LNAPL) in the porous medium decreases, and capillary action strengthens.

5. Discussion

Compared with traditional models that only consider single-phase flow or simple hydraulic gradients, this study establishes a multiphase flow coupling model, which integrates hydraulic, gaseous, LNAPL, and chemical fields, and more comprehensively simulates multiple physical phenomena and interactions during LNAPL migration, such as the water–air–LNAPL interaction and the complex effects of water level direction changes. Some of the existing studies may have simplified or fixed values for some key parameters when simulating LNAPL migrations. In this study, the change in water level direction was quantified through continuous multi-point water level data, and the influence of various parameters such as soil porosity, permeability, and organic carbon content on LNAPL

migration was considered in detail in the model, so that the simulation results could better reflect the migration law under the comprehensive action of different parameters, and the accuracy and reliability of the model were improved. However, there are some limitations, and despite the construction of models that consider multiphysics coupling, in the actual subsurface environment, the geological conditions are more complex and diverse, such as the presence of various fractures, karsts, and other special geological formations, which may affect the migration of LNAPL, and the current model may not fully cover these complex geological features. Some of the parameters involved in the model, such as the hydraulic properties of the soil, the physicochemical properties of the LNAPL, etc., are assumed under specific conditions, and these parameters may vary in different regions and under different geological conditions, affecting the applicability and prediction accuracy of the model. However, the research time span may not be sufficient for long-term environmental changes, the migration evolution process of LNAPL, and the possible long-term environmental risks, and longer simulations and observations are needed to verify the long-term applicability of the model. However, the influence mechanism of change in the water level direction on the LNAPL migration process is deeply revealed, and the key role of on the LNAPL migration direction, rate, saturation dynamics, and dissolution volatilization rate is clarified, which enriches the theoretical understanding of LNAPL migration law in multiphase media and provides a theoretical basis for establishing a more accurate LNAPL pollution prediction model.

6. Conclusions

In this study, the influence of change in the water level direction on the migration process of light non-aqueous phase liquid (LNAPL) was deeply analyzed by establishing a VOF numerical model. The results show that the change in water level direction significantly affects the migration path of LNAPL, and the migration speed of LNAPL accelerates when the water level direction becomes steeper. Conversely, when the direction of the water level slows down, the migration rate slows down. In addition, changes in the direction of the water level also affect the saturation of the LNAPL, the temperature field distribution, and the distribution of the dissolved and volatile phases. In the absence of water level direction change, LNAPL mainly migrates radially along the water level direction. In the case of a change in the direction of water level, LNAPL migrates in the direction of change in water level direction. The temperature gradient changes mainly along the direction of the water level, and the isotherms become much denser when the direction of the water level changes. At the same time, the dissolved and volatile phases of LNAPL change with the direction of water level, and their concentrations gradually decrease. The change in water level direction has a significant impact on the migration path of LNAPL, and when the water level direction becomes steeper, the migration rate of LNAPL increases, and the path deflection angle reaches $15\text{--}35^\circ$. When the water level gradient increases by 30–50% (steepening), the LNAPL migration rate accelerates by 40–70%, while when the water level gradient decreases by 20–40% (slowing), the migration rate decreases by 25–60%. In terms of multiphysics effects, LNAPL saturation varies by 0.15–0.25 and the dissolved and volatile phases are reduced by 18–30%. In terms of migration mode comparison, under a constant gradient, LNAPL spreads radially along the water level (diffusion angle $\approx 180^\circ$). When the gradient changes, the migration direction is deflected with the gradient vector [15,30–32].

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and Q.G.; project administration, Y.G. and H.Y.; funding acquisition, Y.G. and H.Y. All authors have read and agreed to the published version of the manuscript.

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References

1. Maire, J.; Joubert, A.; Kaifas, D.; Invernizzi, T.; Marduel, J.; Colombano, S.; Cazaux, D.; Marion, C.; Klein, P.-Y.; Dumestre, A.; et al. Assessment of flushing methods for the removal of heavy chlorinated compounds DNAPL in an alluvial aquifer. *Sci. Total Environ.* **2018**, *612*, 1149–1158. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Alazaiza, M.Y.; Coptly, N.K.; Abunada, Z. Experimental investigation of cosolvent flushing of DNAPL in double-porosity soil using light transmission visualization. *J. Hydrol.* **2020**, *584*, 124659. [\[CrossRef\]](#)
3. Qiang, S.; Shi, X.; Revil, A.; Kang, X.; Liu, Y.; Wu, J. Residual NAPL morphology effects on electrical resistivity: Insights from micromodel displacement experiments and pore network simulations. *Water Resour. Res.* **2022**, *58*, e2022WR033233. [\[CrossRef\]](#)
4. Xu, J.-C.; Yang, L.-H.; Yuan, J.-X.; Li, S.-Q.; Peng, K.-M.; Lu, L.-J.; Huang, X.-F.; Liu, J. Coupling surfactants with ISCO for remediation of NAPLs: Recent progress and application challenges. *Chemosphere* **2022**, *303*, 135004. [\[CrossRef\]](#)
5. Mateas, D.; Tick, G.; Carroll, K. In situ stabilization of NAPL contaminant source-zones as a remediation technique to reduce mass discharge and flux to groundwater. *J. Contam. Hydrol.* **2017**, *204*, 40–56. [\[CrossRef\]](#)
6. Shi, Y.; Sun, Y.; Gao, B.; Xu, H.; Shi, X.; Wu, J. Retention and Transport of Bisphenol A and Bisphenol S in Saturated Limestone Porous Media. *Water Air Soil. Pollut.* **2018**, *229*, 260. [\[CrossRef\]](#)
7. Kechavarzi, C.; Soga, K.; Illangasekare, T.; Nikolopoulos, P. Laboratory Study of Immiscible Contaminant Flow in Unsaturated Layered Sandy soils. *Vadose Zone J.* **2008**, *7*, 1–9. [\[CrossRef\]](#)
8. Simantiraki, F.; Aivalioti, M.; Gidakos, E. Implementation of an image analysis technique to determine LNAPL infiltration and distribution in unsaturated porous media. *Desalination* **2009**, *248*, 705–715. [\[CrossRef\]](#)
9. Pan, Y.; Yang, J.; Jia, Y.; Xu, Z. Experimental study on non-aqueous phase liquid multiphase flow characteristics and controlling factors in heterogeneous porous media. *Environ. Earth Sci.* **2016**, *75*, 75. [\[CrossRef\]](#)
10. Teng, Y. Analysis of the LNAPL Migration Process in the Vadose Zone under Two Different Media Conditions. *Int. J. Environ. Res. Public Health* **2021**, *18*, 11073. [\[CrossRef\]](#)
11. Man, J.; Zhou, Q.; Wang, G.; Yao, Y. Modeling and evaluation of NAPL-impacted soil vapor intrusion facilitated by vadose zone breathing. *J. Hydrol.* **2022**, *615*, 128683. [\[CrossRef\]](#)
12. Suk, H.; Zheng, K.; Liao, Z.; Liang, C.; Wang, S.; Chen, J. A new analytical model for transport of multiple contaminants considering remediation of both NAPL source and downgradient contaminant plume in groundwater. *Adv. Water Resour.* **2022**, *167*, 104290. [\[CrossRef\]](#)
13. Cavelan, A.; Golfier, F.; Colombano, S.; Davarzani, H.; Deparis, J.; Faure, P. A critical review of the influence of groundwater level fluctuations and temperature on LNAPL contaminations in the context of climate variations. *Sci. Total. Environ.* **2022**, *806*, 150412. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Gatsios, E.; Jonás, G.; Rayner, J.L.; McLaughlan, R.G.; Davis, G.B. LNAPL transmissivity as a remediation metric in complex sites under water table fluctuations. *J. Environ. Manag.* **2018**, *215*, 40–48. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Onaa, C.; Olaobaju, E.A.; Amro, M.M. Experimental and numerical assessment of light non-aqueous phase liquid (LNAPL) subsurface migration behavior in the vicinity of groundwater table. *Environ. Technol. Innov.* **2021**, *23*, 101573. [\[CrossRef\]](#)
16. Libera, A.; Barros, F.P.J.; Guadagnini, A. Influence of pumping operational schedule on solute concentrations at a well in randomly heterogeneous aquifers. *J. Hydrol.* **2017**, *546*, 490–502. [\[CrossRef\]](#)
17. Atlabachew, A.; Shu, L.; Wu, P.; Zhang, Y.; Xu, Y. Numerical modeling of solute transport in a sandy soil tank physical model under varying hydraulic gradient and hydrological stresses. *Hydrogeol. J.* **2018**, *26*, 2089–2113. [\[CrossRef\]](#)

18. Bai, Q.; Li, X.; Tian, Y.; Fang, J. Equations and numerical simulation for coupled water and heat transfer in frozen soil. *Chin. J. Geotech. Eng.* **2015**, *37*, 131–136. [[CrossRef](#)]
19. Gao, Y. Particle tracking using dynamic water-level data. *Water* **2020**, *12*, 2063. [[CrossRef](#)]
20. Kacem, M.; Benadda, B. Mathematical Model for Multiphase Extraction Simulation. *J. Environ. Eng.* **2018**, *144*, 04018040. [[CrossRef](#)]
21. Parker, J.C.; Lenhard, R.J.; Kuppusamy, T. A parametric model for constitutive properties governing multiphase flow in porous media. *Water Resour. Res.* **1987**, *23*, 618–624. [[CrossRef](#)]
22. Dou, Z.; Chen, Y.C.; Zhuang, C.; Zhou, Z.F.; Wang, J.G. Emergence of non-aqueous phase liquids redistribution driven by freeze-thaw cycles in porous media based on low-field NMR. *J. Hydrol.* **2022**, *612*, 128106. [[CrossRef](#)]
23. Kacem, M.; Esrael, D.; Boeije, C.S.; Benadda, B. Multiphase Flow Model for NAPL Infiltration in Both the Unsaturated and Saturated Zones. *J. Environ. Eng.* **2019**, *145*, 04019072. [[CrossRef](#)]
24. Millington, R.J. Gas Diffusion in Porous Media. *Science* **1959**, *130*, 100–102. [[CrossRef](#)]
25. Zhang, M.L.; Wen, Z.; Xue, K.; Chen, L.Z.; Li, D.S. A coupled model for liquid water, water vapor and heat transport of saturated-unsaturated soil in cold regions: Model formulation and calibration. *Environ. Earth Sci.* **2016**, *75*, 701. [[CrossRef](#)]
26. Luo, C.-L.; Yu, Y.-Y.; Zhang, J.; Tao, J.-Y.; Ou, Q.-J.; Cui, W.-H. Thermal-water-salt coupling process of unsaturated saline soil under unidirectional freezing. *J. Mt. Sci.* **2023**, *20*, 557–569. [[CrossRef](#)]
27. Parker, J.C.; Lenhard, R.J. Determining three-phase permeability—Saturation—Pressure relations from two-phase system measurements. *J. Pet. Sci. Eng.* **1990**, *4*, 57–65. [[CrossRef](#)]
28. Wang, C.; Su, X.; Lyu, H.; Yuan, Z. Remobilization of LNAPL in unsaturated porous media subject to freeze-thaw cycles using modified light transmission visualization technique. *J. Hydrol.* **2021**, *603*, 127090. [[CrossRef](#)]
29. Zhang, J.; Lai, Y.; Li, J.; Zhao, Y. Study on the influence of hydro-thermal-salt-mechanical interaction in saturated frozen sulfate saline soil based on crystallization kinetics. *Int. J. Heat. Mass. Transf.* **2020**, *146*, 118868. [[CrossRef](#)]
30. Koohbor, B.; Colombano, S.; Harrouet, T.; Deparis, J.; Lion, F.; Davarzani, D.; Ataie-Ashtiani, B. The effects of water table fluctuation on LNAPL deposit in highly permeable porous media: A coupled numerical and experimental study. *J. Contam. Hydrol.* **2023**, *256*, 104183. [[CrossRef](#)]
31. Ismail, R.; Al-Raoush, R.; Alazaiza, M. The impact of water table fluctuation and salinity on LNAPL distribution and geochemical properties in the smear zone under completely anaerobic conditions. *Environ. Earth Sci.* **2023**, *82*, 368. [[CrossRef](#)]
32. Huntley, D.; Beckett, G. Persistence of LNAPL sources: Relationship between risk reduction and LNAPL recovery. *J. Contam. Hydrol.* **2002**, *59*, 3–26. [[CrossRef](#)] [[PubMed](#)]

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