



Boiling dynamics on well-ordered porous layers: A lattice Boltzmann simulation study

Hengyu Hu¹, Haibo Huang^{1,*}

Department of Modern Mechanics, University of Science and Technology of China, Hefei, 230026, Anhui Province, China

ARTICLE INFO

Keywords:

Lattice Boltzmann method
Pool boiling
Porous media
Critical heat flux
Direct numerical simulation

ABSTRACT

This study investigates pool boiling enhanced by the well-ordered porous layers using direct numerical simulations based on a coupled lattice Boltzmann method (LBM) and finite difference method (FDM). The simulations capture the dynamic behavior of the vapor–liquid interface during boiling. A physical model is developed to establish a scaling law relating the thickness of porous layers H to critical boiling times. Specifically, the inception time t_i , phase change time t_p , and gross boiling time t_g all exhibit a quadratic dependence on H . Furthermore, the study shows that under certain conditions, boiling bypasses the nucleate and transition regimes and proceeds directly to film boiling, resulting in the absence of a critical heat flux (CHF). This phenomenon is explained using Rayleigh–Taylor instability theory, from which a criterion is derived to predict the existence of CHF based on the relationship between the critical instability wavelength and the spacing between nucleation sites. The findings offer new insight into boiling mechanisms on porous layers and provide theoretical guidance for designing thermally efficient porous structures.

1. Introduction

Efficient thermal management is critical for numerous industrial applications that involve continuous heat generation and transport, such as power generation, chemical processing, refrigeration, and electronics cooling systems [1]. In particular, high-power energy systems demand advanced heat dissipation techniques to overcome thermal bottlenecks [2,3]. Among various cooling mechanisms, boiling heat transfer stands out due to its high heat transfer capacity, driven by the latent heat of phase change between liquid and vapor [4,5]. This makes boiling a widely adopted mode in thermal management systems [6].

Boiling performance is typically characterized by two key parameters: the heat transfer coefficient (HTC) and the critical heat flux (CHF) [7]. CHF represents the upper limit of heat flux before transition to film boiling occurs, where heat transfer efficiency drops sharply and may cause thermal failure [8–10]. Besides, a rapid expansion of the vapor front can lead to a direct transition from natural convection to film boiling, resulting in a rapid drop in heat flux, known as the third boiling crisis [11,12]. These transient boiling processes can be separated into multiple stages, as described by Pavlenko et al. [12]. Enhancing CHF and HTC is thus vital to improving boiling performance and reliability. Researchers have developed both active and passive enhancement methods. Active techniques, such as applying electric fields [13], magnetic fields [14], and mechanical vibration [15], require external energy input. In contrast, passive methods, including the

use of porous, structured, and rough surfaces, have gained popularity due to their effectiveness without additional energy consumption [5,6,16,17].

Among passive strategies, porous layers, comprising interconnected micro- or nano-sized pores, have demonstrated notable enhancement in boiling performance [18]. The improved performance arises primarily from: (1) an increased density of active nucleation sites, (2) capillary wicking that facilitates liquid replenishment, and (3) vapor–liquid flow separation that reduces flow interference [19,20]. Experimental studies have confirmed these benefits. For instance, Li et al. [20] demonstrated efficient film boiling on porous layers due to optimized wicking and bubble dynamics. Lee et al. [19] demonstrated that copper-based micro-porous layers can enhance HTC and CHF by 500% and 270%, respectively, compared to smooth surfaces.

Despite these promising results, a fundamental understanding of boiling mechanisms in porous structures remains limited, primarily due to experimental challenges. The microscale and opaque nature of porous media make direct observation of internal thermal and fluid dynamics extremely difficult. To address this, numerical simulations have become indispensable tools for analysis. While Molecular Dynamics (MD) simulations have been used to study boiling in nanoporous environments [5,21,22], they are computationally expensive and constrained to small spatial and temporal scales [23].

* Corresponding author.

E-mail address: huanghb@ustc.edu.cn (H. Huang).

Nomenclature

Symbols

ΔT	Superheat
Δt	Time step
$\Delta x, \Delta y, \Delta z$	Lattice spacing
κ	Surface tension parameter
λ	Thermal conductivity
λ_c	Critical wavelength
$\mathbf{e}_\alpha$	Discrete velocity vectors
ν	Kinematic viscosity
ω_f	Acentric factor
$\overline{Q}$	Temporally averaged heat flux
ϕ_p	Porosity
ψ	Effective number density
ρ	Density of fluid
σ	Surface tension
τ	Relaxation time
θ_i	Contact angle parameter
φ	Order parameter
ξ	Interfacial thickness
a, b, R	Parameters in the P–R equation of state
c_{vol}	Specific heat at constant volume
c_s	Lattice sound speed
D_d	Size of the calculation domain
d_p	Center-to-center spacing of particles
f_α	Density distribution function
f_α^{eq}	Equilibrium distribution function
H	Thicknesses of the porous layer
H_s	Thicknesses of the substrate
h_{fg}	Specific latent heat
L_x, L_y, L_z	Size of the calculation domain
p	Pressure
s	Entropy
S_v	Vapor saturation
T	Temperature
t	Time
T_{sat}	Saturated temperature
w_α	Weighting coefficients
$\mathbf{F}$	Body force
$\mathbf{g}$	Gravitational acceleration
$\mathbf{v}$	Actual whole fluid velocity
Ja	Jakob number
Q	Spatial-averaged heat flux

Subscripts or Superscripts

α	Lattice direction
$\bar{\cdot}$	Temporal average
l	Liquid
s	Solid
v	Vapor
ave	Spacial average
sat	Saturated

Mesoscopic methods such as the lattice Boltzmann method (LBM) have been widely adopted to bridge this scale gap. LBM provides a simple kinetic-based framework that handles complex boundary conditions and multiphase interfaces with high numerical stability and parallel

efficiency, making it particularly suitable for simulating phase-change and boiling phenomena in complex porous geometries. Recent advances in GPU-based implementations have significantly enhanced LBM's computational performance, enabling large-scale, high-resolution simulations for engineering applications [24–26]. This method, particularly when integrated with the Shan–Chen pseudo-potential model [27], has proven effective in simulating multiphase flows in complex geometries [28–35]. When combined with the finite difference method (FDM), LBM enables detailed, direct numerical simulation (DNS) of boiling phenomena on structured surfaces [6,17]. For instance, a recent numerical study of porous-wick structures under non-gravity conditions [36] demonstrated the decoupling of the liquid and solid phases in boiling processes. In those simulations, when gravity was reduced, the capillary return flow could no longer sustain liquid replenishment, leading to near-complete evaporation within porous layers and the formation of a stable vapor film, which results in the bypass of the nucleate and transition regimes. Although other methods (e.g., the thermal LBM) have also been successfully applied to many problems, several studies have noted that it can suffer from numerical instabilities and spurious temperature oscillations when applied to high-density-ratio or large-viscosity-contrast flows-conditions that frequently occur in boiling simulations [37]. Moreover, solving the energy equation using FDM is computationally more efficient and requires significantly less memory, which is a key advantage in large-scale three-dimensional simulations.

However, boiling simulations on porous layers are still relatively underexplored. While studies such as Guan et al. [5] have provided early theoretical insights, their models rely on assumptions, such as uniform temperature within solid layers, that may not hold during dynamic phase-change processes. These simplifications result in notable discrepancies between theoretical predictions and simulation outcomes. Furthermore, the definition and characterization of boiling timescales, including inception time and phase change duration, have not been rigorously explored in relation to porous layer geometry.

This study addresses these gaps by investigating the boiling process on porous layers using a coupled LBM-FDM framework. The method allows detailed tracking of vapor–liquid interface evolution and thermal field development. In contrast to previous research [6,17], our study targets well-ordered porous layers with interconnected pores—a far more complex configuration relevant to high-performance thermal management. Using the coupled framework, we directly simulated boiling inside porous layers, capturing internal vapor generation, migration, and phase-change dynamics. A key focus is placed on understanding how the thickness of a porous layer affects critical boiling timescales, leading to the development of a scaling law. In addition, this study reveals a phenomenon where, under certain conditions defined by Rayleigh–Taylor instability, the boiling process can bypass the nucleate and transition regimes entirely, proceeding directly to film boiling, effectively eliminating CHF. A criterion based on Rayleigh–Taylor instability analysis is proposed to predict the occurrence of this behavior.

The remainder of this paper is organized as follows: Section 2 presents the simulation methods. Section 3 discusses the results and analysis. Conclusions are drawn in Section 4. Simulation validation and theoretical derivations are provided in Appendix A and Appendix B, respectively.

2. Simulation methods

We assume that boiling on porous layers is a single-component two-phase process, without any chemical reactions, and neglect viscous heat dissipation. The skeleton of porous media is rigid, and its physical properties (density, heat capacity, and thermal conductivity) remain constant during simulation. These assumptions are reasonable and consistent with many prior studies [5,6,17,19,22,38,39]. Therefore, we construct a direct numerical simulation model by combining LBM and FDM. The former simulates fluid flow and phase change, and the latter is applied to calculate heat transfer.

$$\mathbf{e}_\alpha = \begin{bmatrix} 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 1 & -1 & -1 & 1 & 0 & 0 & 0 & 0 & 1 & -1 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 1 & -1 & -1 & 1 & 1 & -1 & -1 & 1 \end{bmatrix}. \quad (1)$$

Box 1.

2.1. LBM with Shan–Chen pseudo-potential model

In this study, the characteristic size is several orders of magnitude larger than the molecular mean free path, ensuring a small Knudsen number ($Kn \ll 1$). Therefore, the continuum assumption underlying the Navier–Stokes and heat conduction equations remains valid. Under these conditions, the governing equations are scale-invariant. Hence, we adapt the lattice Boltzmann method (LBM). The D3Q19 velocity model is adopted. By setting the lattice sound speed $c_s = 1/\sqrt{3}$ (lu · ts), lattice spacing $\Delta x = \Delta y = 1$ (lu), and time step $\Delta t = 1$ (ts), the discrete velocity vectors $\mathbf{e}_\alpha$ are given by the equation in Box 1:

In the single relaxation time lattice Boltzmann equation, we applied the Bhatnagar–Gross–Krook (BGK) collision term to describe the evolution of the density distribution function $f_\alpha(\mathbf{x}, t)$, $\alpha = 0, 1, 2, \dots, 18$. Thus, it can be expressed as follows:

$$f_\alpha(\mathbf{x} + \mathbf{e}_\alpha \Delta t, t + \Delta t) = f_\alpha(\mathbf{x}, t) - \frac{\Delta t}{\tau} [f_\alpha(\mathbf{x}, t) - f_\alpha^{eq}(\mathbf{x}, t)] + \Delta f_\alpha(\mathbf{x}, t), \quad (2)$$

In Eq. (2), τ is the relaxation time, which is related to the kinematic viscosity as $\nu = c_s^2(\tau - 0.5\Delta t)$. The relaxation times of liquid and vapor are τ_l and τ_v , respectively. The equilibrium distribution function $f_\alpha^{eq}(\mathbf{x}, t)$ can be calculated as

$$f_\alpha^{eq}(\mathbf{x}, t) = w_\alpha \rho \left[1 + \frac{\mathbf{e}_\alpha \cdot \mathbf{u}}{c_s^2} + \frac{(\mathbf{e}_\alpha \cdot \mathbf{u})^2}{2c_s^4} - \frac{\mathbf{u}^2}{2c_s^2} \right], \quad (3)$$

where w_α are the weighting coefficients. In D3Q19 model, $w_\alpha = 1/3$ for $\alpha = 0$, $w_\alpha = 1/18$ for $\alpha = 1-6$, $w_\alpha = 1/36$ for $\alpha = 7-18$. In Eq. (3), ρ is the density of fluid and $\mathbf{u}$ is the velocity. They are obtained by:

$$\rho = \sum_\alpha f_\alpha, \quad \rho \mathbf{u} = \sum_\alpha \mathbf{e}_\alpha f_\alpha. \quad (4)$$

The actual whole fluid velocity $\mathbf{v}$ is defined as [40,41]:

$$\mathbf{v} = \mathbf{u} + \frac{\mathbf{F}}{2\rho}, \quad (5)$$

The body force acting on the fluid nodes $\mathbf{F}$ is given by:

$$\mathbf{F}(\mathbf{x}) = \mathbf{F}_{\text{int}}(\mathbf{x}) + \mathbf{F}_g(\mathbf{x}), \quad (6)$$

which is conducted based on the exact difference method [42] is used to implement the body force term. $\mathbf{F}(\mathbf{x})$

By considering the inter-fluid and fluid–solid interaction comprehensively, $\mathbf{F}_{\text{int}}(\mathbf{x})$ extends the capability of LBM, making it able to simulate complex multiphase phenomena and fluid–solid interaction. $\mathbf{F}_{\text{int}}(\mathbf{x})$ is only calculated in fluid nodes:

$$\mathbf{F}_{\text{int}}(\mathbf{x}) = -\beta \psi(\mathbf{x}) \sum_{\mathbf{x}'} G(\mathbf{x}, \mathbf{x}') \psi(\mathbf{x}') (\mathbf{x}' - \mathbf{x}) - \frac{1-\beta}{2} \sum_{\mathbf{x}'} G(\mathbf{x}, \mathbf{x}') \psi^2(\mathbf{x}') (\mathbf{x}' - \mathbf{x}), \quad (7)$$

where $\mathbf{x}'$ is the location of a nearby fluid or solid node, which can be written to $\mathbf{x}' = \mathbf{x} + \mathbf{e}_\alpha \Delta t$. The $\psi(\mathbf{x})$ is the effective number density [27], and β is the weighting coefficient related to the equation of state [32]. For the P–R equation of state, the weighting coefficient β is chosen as 1.16. Function $G(\mathbf{x}, \mathbf{x}')$ reflecting interaction strength in D3Q19 scheme is defined as [43]:

$$G(\mathbf{x}, \mathbf{x}') = \begin{cases} G, & |\mathbf{x}' - \mathbf{x}| = 1 \\ G/2, & |\mathbf{x}' - \mathbf{x}| = \sqrt{2} \\ 0, & |\mathbf{x}' - \mathbf{x}| = 0 \end{cases}, \quad (8)$$

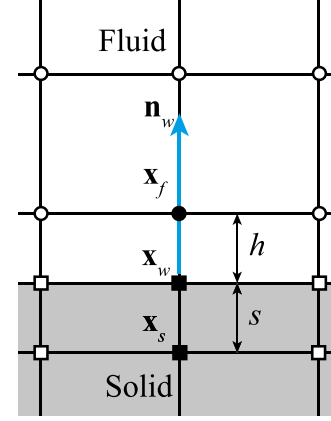


Fig. 1. Schematic diagram for the implementation of wetting condition.

where G is a parameter that controls the strength. The calculation of $\psi(\mathbf{x})$ depends on the node type.

For **fluid nodes**, it can be given by a modified form [44]:

$$\psi(\mathbf{x}) = \sqrt{\frac{2(\kappa p - c_s^2 \rho)}{c_s^2 G}}, \quad (9)$$

κ is a parameter controlling the surface tension [6]. The pressure p can be calculated by introducing the state equation. In this research, the Peng–Robinson (P–R) equation of state is implied:

$$p = \frac{\rho RT}{1 - b\rho} - \frac{a\rho^2 \alpha(T)}{1 + 2b\rho - b^2 \rho^2}, \quad (10)$$

$$\alpha(T) = \left[1 + \left(0.37464 + 1.54226\omega_f - 0.26992\omega_f^2 \right) \left(1 - \sqrt{T/T_c} \right) \right]^2.$$

In Eq. (10), the ω_f is acentric factor. Parameter R is the quotient of the ideal gas constant $R_c = 8.314$ (J mol^{−1} K^{−1}) divided by molar density ρ_m . The critical properties for the P–R equation of state, such as p_c , ρ_c , and T_c , can be obtained by setting the first and second pressure derivatives concerning density to zero. Thus, the parameters a and b can be calculated by:

$$a = 0.45724 (RT_c)^2 / p_c, \quad b = 0.0778 RT_c / p_c. \quad (11)$$

For **solid nodes**, the calculation of $\psi(\mathbf{x})$ needs some additional process. To accurately simulate the conditions, we implemented the surface energy method developed by Fakhari et al. [45] and further refined by Chang et al. [46]. This method is easy to implement and can accurately simulate the contact angle.

Fig. 1 illustrates the wetting condition setup. As an initial step, the order parameter of the nearby fluid node $\varphi(\mathbf{x})$ is calculated based on the density:

$$\varphi(\mathbf{x}_f) = \frac{\rho(\mathbf{x}_f) - \rho^{\min}}{\rho^{\max} - \rho^{\min}}. \quad (12)$$

Using the finite difference method to discretize the derivative, the wetting condition is expressed as:

$$\mathbf{n}_w \cdot \nabla \varphi|_{x_w} = \frac{\varphi(\mathbf{x}_f) - \varphi(\mathbf{x}_s)}{s + h} = -\frac{4}{\lambda} \Theta \varphi(\mathbf{x}_w) [1 - \varphi(\mathbf{x}_w)]. \quad (13)$$

The order parameter at wall point $\mathbf{x}_w$ can be obtained through:

$$\varphi(\mathbf{x}_w) = \frac{h\varphi(\mathbf{x}_s) + s\varphi(\mathbf{x}_f)}{s+h}. \quad (14)$$

Substituting Eq. (14) into (13), we have:

$$\varphi(\mathbf{x}_s) = \begin{cases} \frac{s+h}{2hm} [1+m - \sqrt{(1+m)^2 - 4m\varphi(\mathbf{x}_f)}] - \frac{s}{h}\varphi(\mathbf{x}_f), & \theta \neq 90^\circ, \\ \varphi(\mathbf{x}_f), & \theta = 90^\circ, \end{cases} \quad (15)$$

where $m = -(4h/\xi)\theta$ and $\theta = \cos(\theta)$. ξ is the interfacial thickness [46]. We set $h = s = 0.5lu$ to ensure compatibility with the halfway bounce-back scheme. Virtual density of solid nodes $\rho_v(\mathbf{x})$ can be calculated by the reconstruction of Eq. (12):

$$\rho_v(\mathbf{x}) = \rho^{\min} + \varphi(\mathbf{x}_s)[\rho^{\max} - \rho^{\min}] \quad (16)$$

Substitute $\rho_v(\mathbf{x})$ for ρ in Eq. (9)–(10), and calculate the effective number density of nearby solid nodes in Eq. (7).

The gravity $\mathbf{F}_g(\mathbf{x})$ is calculated according to the average density ρ_{ave} and gravitational acceleration $\mathbf{g}$ of the calculation domain [47]:

$$\mathbf{F}_g(\mathbf{x}) = [\rho(\mathbf{x}) - \rho_{ave}] \cdot \mathbf{g}. \quad (17)$$

2.2. FDM for solving energy equation

In the simulations, fluid properties are not kept fully constant. The density evolves dynamically according to the Peng–Robinson (P–R) equation of state (Eq. (10)). According to Ref. [48], the balance equation of entropy s can be written as:

$$\rho T \frac{Ds}{Dt} = \nabla \cdot (\lambda \nabla T), \quad (18)$$

where λ is the thermal conductivity. Using the thermodynamic relation [49] given by:

$$T ds = c_{vol} dT + T \left(\frac{\partial p}{\partial T} \right)_{vol} dv = c_{vol} dT - T \frac{1}{\rho^2} \left(\frac{\partial p}{\partial T} \right)_{\rho} d\rho, \quad (19)$$

where c_{vol} is the specific heat at constant volume. Substituting the mass conservation equation $\partial \rho / \partial t + \nabla \cdot (\rho \mathbf{v}) = 0$ into Eq. (19), and using the relation $dT/dt = \partial T / \partial t + \mathbf{v} \cdot \nabla T$ to obtain:

$$\frac{\partial T}{\partial t} = -\mathbf{v} \cdot \nabla T + \frac{1}{\rho c_{vol}} \nabla \cdot (\lambda \nabla T) - \frac{T}{\rho c_{vol}} \left(\frac{\partial p_{EoS}}{\partial T} \right)_{\rho} \nabla \cdot \mathbf{v}, \quad (20)$$

where the convection term $-\mathbf{v} \cdot \nabla T$ naturally appears in this formulation, confirming that the convective heat transfer has been fully considered in our model. The heat transfer, especially that due to phase change, has been included in the energy equation (the last term in Eq. (20)).

Although the LBM itself is second-order accurate in space and time, the energy equation solved by the FDM involves strong temporal gradients near the liquid–vapor interface during phase change. In such cases, a higher-order time-integration scheme provides improved numerical stability and accuracy when resolving rapid temperature variations, especially under large local heat-flux fluctuations [50]. The 4th-order Runge–Kutta scheme [51] is therefore adopted to minimize temporal truncation errors and ensure stable coupling between the LBM flow field and the temperature field solved by FDM. The additional computational cost is minor compared to the overall LBM–FDM framework, but it yields noticeably smoother and more accurate transient temperature evolutions. The 4th-order Runge–Kutta scheme is directly applied to solve Eq. (20):

$$\begin{cases} T(\mathbf{x}, t + \Delta t) = T(\mathbf{x}, t) + (h_1 + 2h_2 + 2h_3 + h_4) \cdot \Delta t / 6, \\ h_1 = M[T(\mathbf{x}, t)] \\ h_2 = M[T(\mathbf{x}, t) + \Delta t \cdot h_1 / 2] \\ h_3 = M[T(\mathbf{x}, t) + \Delta t \cdot h_2 / 2] \\ h_4 = M[T(\mathbf{x}, t) + \Delta t \cdot h_3] \end{cases} \quad (21)$$

The $M(T)$ is the right-hand side of the above Eq. (20). The temperature field is updated using the standard 4th-order Runge–Kutta

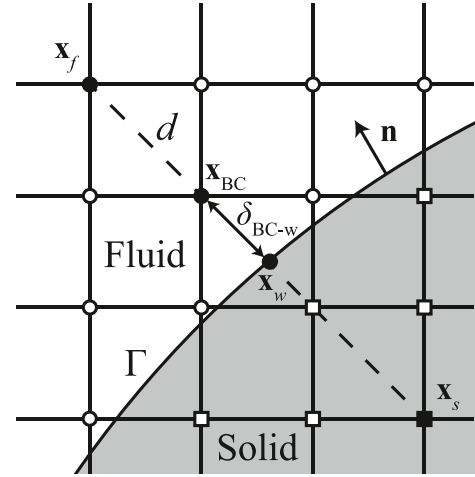


Fig. 2. Schematic diagram for the fluid–solid conjugate heat transfer interface.

method, where all intermediate values h_1 , h_2 , h_3 , and h_4 are computed sequentially within each time step based on the local temperature field and source terms obtained from the LBM flow field at the same time level. No information from future timesteps is required. The same computational strategy has been widely adopted in various LBM–FDM models [52–56].

For the first derivative and second derivative, Ref. [57] presents the second-order central discretization in LBM:

$$\frac{\partial \phi}{\partial x_i} = \frac{1}{2c_s^2 \Delta t} \sum_{\alpha} w_{\alpha} \mathbf{e}_{\alpha} \cdot \mathbf{i} [\phi(\mathbf{x} + \mathbf{e}_{\alpha} \Delta t) - \phi(\mathbf{x} - \mathbf{e}_{\alpha} \Delta t)] \quad (22)$$

$$\frac{\partial^2 \phi}{\partial x_i \partial x_i} = \frac{1}{c_s^2 (\Delta t)^2} \sum_{\alpha} w_{\alpha} [\phi(\mathbf{x} + \mathbf{e}_{\alpha} \Delta t) - 2\phi(\mathbf{x}) + \phi(\mathbf{x} - \mathbf{e}_{\alpha} \Delta t)] \quad (23)$$

The $\mathbf{i}$ is the unit vector pointing along the i -coordinate axis, and ϕ represents a physical variable.

2.3. Fluid–solid conjugate heat transfer interface treatment

We adopt a fluid–solid conjugate heat transfer interface approach, successfully applied by Chang et al. [6], to accurately model heat transfer across the fluid–solid boundary. This method ensures local energy conservation at the interface where the fluid and solid have different physical properties, such as density, thermal conductivity, and specific heat capacity.

A schematic illustration of the interface treatment is shown in Fig. 2, where $\mathbf{x}_f$ and $\mathbf{x}_s$ represent fluid and solid nodes, respectively. The point $\mathbf{x}_{BC}$ denotes a boundary node, and $\mathbf{x}_w$ is the actual interface point located between the fluid and solid nodes (not necessarily aligned with the computational mesh). The distance between $\mathbf{x}_{BC}$ and $\mathbf{x}_w$ is denoted by δ_{BC-w} , while d represents the spacing between adjacent nodes (e.g., $\mathbf{x}_{BC}$ and $\mathbf{x}_f$). The vector $\mathbf{n}$ is the normal to the fluid–solid interface Γ .

To satisfy the continuity of temperature and heat flux at the interface, the following interface condition is applied:

$$T(\mathbf{x}_w)|_{\text{Fluid}} = T(\mathbf{x}_w)|_{\text{Solid}} \quad (24)$$

$$-\lambda_f \frac{\partial T}{\partial \mathbf{n}}|_{\mathbf{x}_w, \text{Fluid}} = -\lambda_s \frac{\partial T}{\partial \mathbf{n}}|_{\mathbf{x}_w, \text{Solid}}, \quad (25)$$

where λ_s and λ_f are thermal conductivity of solid and fluid, respectively. Temperature T in $\mathbf{x}_s$ and $\mathbf{x}_f$ are solved by the method mentioned on Section 2.2. Using a semi-second-order approximation [58] to discretized Eq. (25):

$$-\lambda_f \frac{T(\mathbf{x}_f) - T(\mathbf{x}_w)}{d} = -\lambda_s \frac{T(\mathbf{x}_w) - T(\mathbf{x}_s)}{d}. \quad (26)$$

Therefore, bilinear interpolation is used to calculate the temperatures in $\mathbf{x}_w$:

$$T(\mathbf{x}_w) = \frac{\lambda_s T(\mathbf{x}_s) + \lambda_f T(\mathbf{x}_f)}{\lambda_s + \lambda_f}. \quad (27)$$

For the temperature on boundary node $\mathbf{x}_{BC}$, it can be calculated by:

$$T(\mathbf{x}_{BC}) = T(\mathbf{x}_w) + \frac{\delta_{BC-w}}{d} [T(\mathbf{x}_f) - T(\mathbf{x}_w)] \quad (28)$$

The same conjugate heat transfer scheme is applied to boundary nodes within the solid domain.

In summary, the simulation procedure at each time step consists of the following steps:

- (i) The LBM is used to compute the fluid density and velocity distributions. This step also evaluates the virtual density at solid nodes near the fluid–solid interface. (Section 2.1)
- (ii) Using the LBM results, the FDM is employed to solve the temperature distribution in both fluid and solid regions. (Section 2.2)
- (iii) The temperature at boundary nodes is updated using the fluid–solid conjugate heat transfer scheme. (Section 2.3)

Model validation is provided in Appendix A.

3. Results and discussion

This section investigates boiling heat transfer on a representative porous layer. The face-centered cubic arrangement of spherical particles generates the porous structure to form a packed skeleton with a solid density of ρ_s . To realistically represent a sintered porous medium, particle fusion at contact points is considered. As shown in Fig. 3(a), particles are fused, and the particle distance d_p is defined as the center-to-center spacing between two neighboring, non-overlapping particles of diameter D_d . By periodically replicating this fused particle arrangement in three dimensions, the porous structure depicted in Fig. 3(b) is constructed, having a uniform width in both the x - and y -directions, denoted by L_x and L_y , respectively. Its bottom layer of particles is fused with a solid substrate to incorporate porous layers into the computational domain, as illustrated in Fig. 3(c). The thicknesses of porous layers, substrate, and the overall computational domain are represented by H , H_s , and L_z , respectively. Periodic boundary conditions are applied along the horizontal directions (x and y). The top boundary (highlighted in blue in Fig. 3c) is modeled as an open boundary maintained at the saturated temperature T_{sat} and the bottom boundary (highlighted in red) is a Dirichlet boundary fixed at a higher constant temperature $T_b = T_{\text{sat}} + \Delta T$, where ΔT is the imposed superheat. At all fluid–solid interfaces, the no-slip condition, wetting condition, and fluid–solid conjugate heat transfer condition are enforced. The gravitational acceleration vector $\mathbf{g}$ is assumed to be constant in both magnitude and direction throughout the domain $\mathbf{g} = [0, 0, -g]$.

Initially, the entire domain, including the solid substrate and the porous skeleton, is filled with saturated liquid at density $\rho_{l,\text{sat}}$. At the same temperature, the corresponding vapor phase has a density of $\rho_{v,\text{sat}}$. The initial temperature of the domain is set to T_{sat} . The thermal conductivities of the liquid, vapor, and solid phases are denoted by λ_l , λ_v , and λ_s , respectively. At the same time, their volumetric specific heats are given by $c_{l,\text{vol}}$, $c_{v,\text{vol}}$, and $c_{s,\text{vol}}$. The specific latent heat of vaporization, h_{fg} , is calculated following the method in Ref. [59]. All relevant parameters and variables are summarized in Tables 1 and 2.

The lattice Boltzmann method (LBM) employs linear conversions between lattice and physical units, and these conversions are determined through dimensionless parameters such as Reynolds, Prandtl, Weber, and Jakob numbers [60]. As long as these nondimensional numbers are kept consistent, the simulated system remains dynamically similar to the real physical system. Therefore, the conclusions derived in lattice

units remain valid after conversion to physical units. In our simulations, the characteristic length, velocity, and time are chosen as [61,62]:

$$l_0 = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}, \quad u_0 = \sqrt{gl_0}, \quad t_0 = l_0/u_0. \quad (29)$$

The dimensionless parameters involved in this research are dimensionless time t^* , and Jakob numbers Ja , which are defined as [17]:

$$t^* = \frac{t}{t_0}, \quad Ja = \frac{c_{l,\text{vol}} \Delta T}{h_{fg}}. \quad (30)$$

The spatial-averaged heat flux $Q(t)$ is define as:

$$Q(t) = -\frac{\lambda_s}{L_x \cdot L_y} \int_{\Gamma} \frac{\partial T}{\partial \mathbf{n}} \cdot d\mathbf{A}, \quad (31)$$

which can be calculated by Eq. (25)–(28) on the fluid–solid interface Γ noted in Fig. 2.

Supposing that, the temporally averaged heat flux can be calculated when $t \in [t_1, t_2]$, $Q(t)$ is nearly steady:

$$\bar{Q} = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} Q(t) dt. \quad (32)$$

The calculation stops after the $Q(t)$ is steady.

Referring to the definition of saturation in research about porous media and the nucleation analysis by Guan et al. [22,63], we use the vapor saturation S_v to represent the boiling state directly:

$$S_v = \frac{V_{\text{vapor}}}{V_{\text{pore}}}, \quad (33)$$

where V_{vapor} is the volume of vapor in porous layers, and V_{pore} is the pore volume (space unoccupied by solid, i.e., blank in Fig. 3 a). We use density to determine the state of fluid: if $\rho < \rho_c$, it is vapor; if $\rho > \rho_c$, it is liquid. The vapor–liquid interface is the iso-surface that satisfies $\rho(\mathbf{x}) = \rho_c$. Thermal parameters and viscosity are computed in real time as functions of the local liquid volume fraction ϕ [17]:

$$\begin{aligned} \lambda(\mathbf{x}_f) &= \phi(\mathbf{x}_f) \cdot (\lambda_l - \lambda_v) + \lambda_v \\ c_{\text{vol}}(\mathbf{x}_f) &= \phi(\mathbf{x}_f) \cdot (c_{l,\text{vol}} - c_{v,\text{vol}}) + c_{v,\text{vol}} \\ v(\mathbf{x}_f) &= \phi(\mathbf{x}_f) \cdot (v_l - v_v) + v_v. \end{aligned} \quad (34)$$

3.1. Boiling phenomena in porous layer

We conducted a series of simulations under varying Jakob numbers (Ja) to investigate the influence of thermal driving force on the boiling process. In our model, nucleation sites are not explicitly prescribed as fixed cavities. Instead, they emerge naturally due to local thermal non-uniformities within porous layers. By visualization of results, we can determine the distribution of nucleation sites. Representative snapshots of the boiling dynamics are shown in Fig. 4. To clearly visualize the location and evolution of the vapor–liquid interface, the vapor–liquid interface is highlighted in cyan, along with the solid interface covered by liquid.

Initially, bubble nucleation occurs at the bottom of porous layers (Fig. 4a). As boiling progresses, individual bubbles grow and coalesce, forming a continuous vapor film that gradually rises through porous layers (Fig. 4b–c). When the vapor front approaches the upper portion of porous layers, it begins to penetrate through pore channels between the particles (indicated by blue arrows in Fig. 4d), creating horizontal vapor columns (Fig. 4e). This phenomenon has also been reported in Ref. [17]. The significant expansion of the area of the vapor–liquid interface enhances the heat flux, as shown in Fig. 6(a). These vapor columns continue to expand and merge, eventually forming a nearly planar vapor–liquid interface at the top of porous layers. By $t^* = 155.33$, the liquid within porous layers is fully evaporated, and the entire region is occupied by vapor (Fig. 4f).

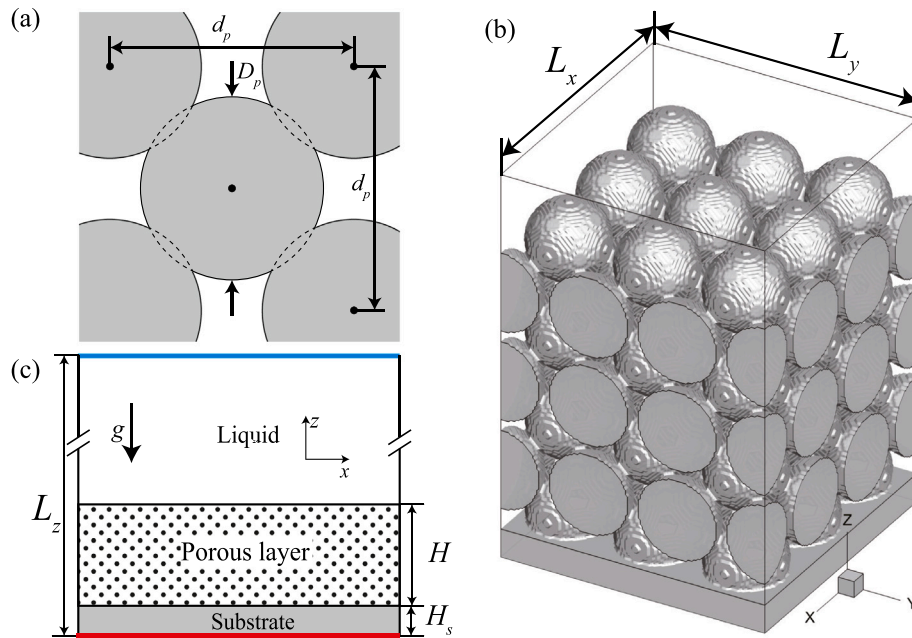


Fig. 3. (a) Schematic diagram illustrating fused particles after sintering. (b) Geometry of the complete porous layer constructed from periodic particle packing. (c) Schematic of the computational domain incorporating porous layers and substrate. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1

Parameters with lattice unit (l.u.) or without dimension in simulation.

Parameters	Values	Lattice units
κ	5.00	—
λ_l	1.40	$\text{mu} \cdot \text{lu} \cdot \text{ts}^{-3} \cdot \text{tu}^{-1}$
λ_v	0.140	$\text{mu} \cdot \text{lu} \cdot \text{ts}^{-3} \cdot \text{tu}^{-1}$
λ_s	140	$\text{mu} \cdot \text{lu} \cdot \text{ts}^{-3} \cdot \text{tu}^{-1}$
ω_f	0.344	—
v_l	0.100	$\text{lu}^2 \cdot \text{ts}^{-1}$
v_v	0.167	$\text{lu}^2 \cdot \text{ts}^{-1}$
$\rho_{l,\text{sat}}$	6.62	$\text{mu} \cdot \text{lu}^{-3}$
$\rho_{v,\text{sat}}$	0.343	$\text{mu} \cdot \text{lu}^{-3}$
ρ_s	80.0	$\text{mu} \cdot \text{lu}^{-3}$
σ	0.051	$\text{mu} \cdot \text{ts}^{-2}$
τ_l	0.80	$\text{lu}^2 \cdot \text{ts}^{-1}$
τ_v	1.00	$\text{lu}^2 \cdot \text{ts}^{-1}$
θ	90.0	°
ξ	2.40	lu
a	2/98	$\text{mu}^{-1} \cdot \text{lu}^5 \cdot \text{ts}^{-2}$
b	2/21	$\text{mu}^{-1} \cdot \text{lu}^3$
$c_{l,\text{vol}}$	8.00	$\text{lu}^2 \cdot \text{ts}^{-2} \cdot \text{tu}^{-1}$
$c_{v,\text{vol}}$	6.00	$\text{lu}^2 \cdot \text{ts}^{-2} \cdot \text{tu}^{-1}$
$c_{s,\text{vol}}$	4.00	$\text{lu}^2 \cdot \text{ts}^{-2} \cdot \text{tu}^{-1}$
h_{fg}	0.1725	$\text{lu}^2 \cdot \text{ts}^{-2}$
H_s	15	lu
l_0	13.93	lu
L_x	135	lu
L_y	135	lu
L_z	480	lu
R	1	$\text{lu}^2 \cdot \text{ts}^{-2} \cdot \text{tu}^{-1}$
T_c	0.0365	tu
T_{sat}	$0.850T_c$	tu

As the Jakob number increases, both bubble nucleation and vapor film formation occur more rapidly, leading to a shorter boiling period (Fig. 5a–c). With higher superheat Ja, new nucleation sites become active even before vapor escapes from the pore network, as indicated by the red arrows in Fig. 5(d). But the small bubbles at these nucleation sites merge into a film quickly. Despite this early activation, the subsequent evolution of the vapor–liquid interface follows a similar

Table 2

Variates with lattice unit (l.u.) or without dimension in simulation.

Variates	Lattice units
ρ	$\text{mu} \cdot \text{lu}^{-3}$
ΔT	tu
d_p	lu
$D_p (= 0.435d_p)$	lu
g	$\text{lu} \cdot \text{ts}^{-2}$
H	lu
Ja	—
Q	$\text{mu} \cdot \text{ts}^{-3}$
t	ts
T	tu
x	lu
y	lu
z	lu

pattern to that observed at lower Ja: vapor columns form, merge into a horizontal interface, and ultimately result in the complete evaporation of the liquid within porous layers.

The time evolution of the transient heat flux, $Q(t)$, for various superheats is shown in Fig. 6(b), highlighting the influence of the vapor–liquid interface on heat transfer behavior. Similar to the observation in Ref. [11,36,63,64], the variation of $Q(t)$ can be divided into four distinct stages, as illustrated in Fig. 6(a):

- (1) **Inception.** At the beginning of the simulation, the large temperature difference between the heated solid and the initially saturated liquid causes a rapid surge in heat flux to a peak value. This is followed by a decline as the temperature field begins to equilibrate. During this stage, vapor bubbles start to nucleate and coalesce at the bottom of porous layers (see Fig. 4a and Fig. 5a), but the fluid in the porous structure remains predominantly in the liquid state.
- (2) **Fluctuation.** As vapor formation intensifies, a vapor film emerges and begins to push upward through the porous medium. This increases the vapor–solid contact area, resulting in a gradual decline in the average heat flux. At the same time, the dynamic

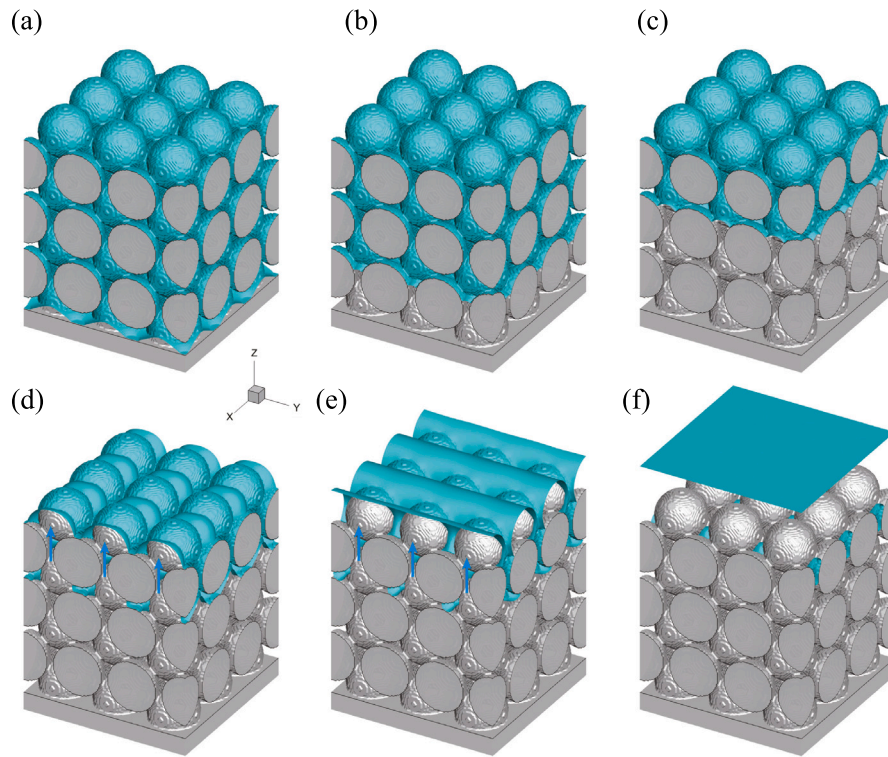


Fig. 4. Snapshots of boiling at $Ja = 0.254$ when (a) $t^* = 18.95$, (b) $t^* = 66.31$, (c) $t^* = 116.52$, (d) $t^* = 134.51$, (e) $t^* = 140.20$, and (f) $t^* = 155.33$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

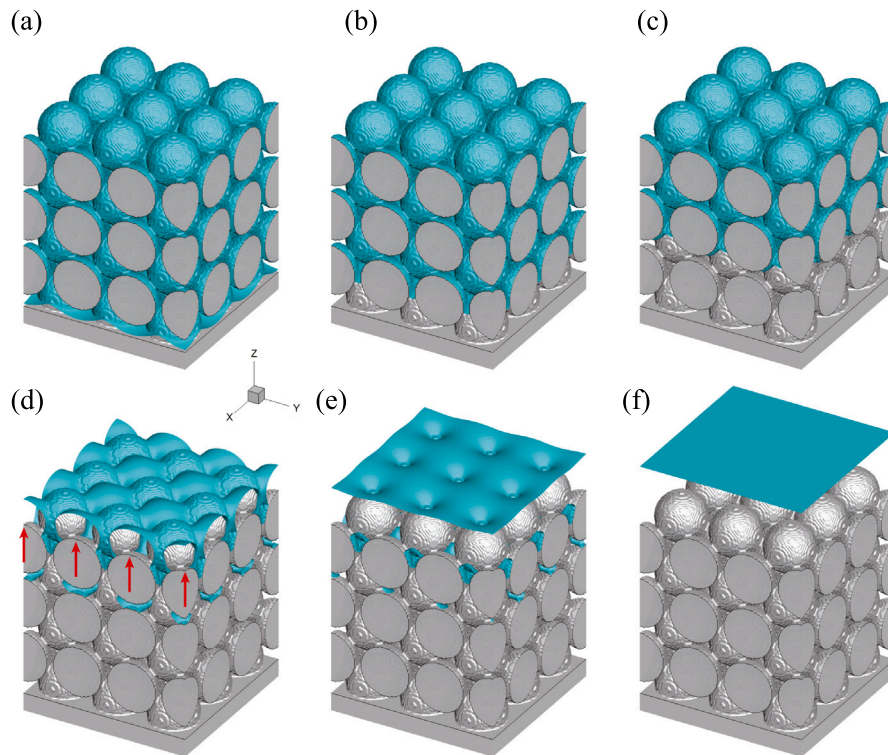


Fig. 5. Snapshots of boiling at $Ja = 0.338$ when (a) $t^* = 14.21$, (b) $t^* = 31.26$, (c) $t^* = 65.36$, (d) $t^* = 98.51$, (e) $t^* = 104.20$, and (f) $t^* = 113.67$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

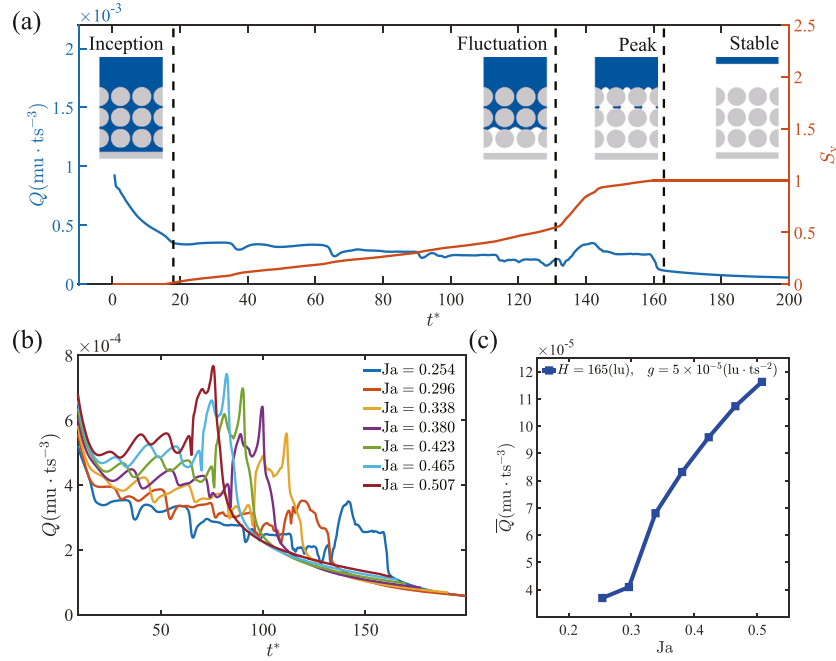


Fig. 6. (a) Transient heat flux of porous layers $Q(t)$ and vapor saturation S_v as functions of time at $Ja = 0.254$. Four stages: Inception, Fluctuation, Peak, and Stable, are labeled. (b) the transient heat flux of porous layers with different Ja , (c) The time-averaged heat flux $\bar{Q}$ as a function of Ja , in all cases $H = 165$ (lu), $g = 5 \times 10^{-5}$ (lu $\cdot$ ts $^{-2}$).

deformation of the vapor–liquid interface within the porous structure introduces substantial fluctuations in heat flux. The vapor saturation continues to rise during this period.

- (3) **Peak.** When the vapor front reaches the top of the porous structure, the exposed vapor–liquid interface area increases significantly, resulting in enhanced evaporation and a sharp rise in heat flux. At higher Ja , new nucleation sites at the top layer of porous layers are activated, generating additional vapor bubbles and a secondary vapor film (e.g., Fig. 5d). These events result in two distinct peaks in the heat flux curve. Simultaneously, the vapor saturation S_v rapidly rises, fully occupying porous layers.
- (4) **Stable.** Once the vapor film entirely covers porous layers, the overall heat transfer efficiency deteriorates due to the low thermal conductivity of vapor. As a result, the heat flux stabilizes at a significantly lower level, which is aligned with the non-gravity simulation results in Ref. [36]. During this stage, the temporally averaged heat flux $\bar{Q}$ can be computed, and the vapor phase becomes fully saturated.

Throughout all simulations, neither nucleate boiling nor transition boiling regimes are observed. Instead, the boiling process transitions directly to film boiling, bypassing the classical boiling process. The boiling curve for porous layers, depicted in Fig. 6(c), shows a stark contrast to the classical pool boiling curve. Notably, the temporally averaged heat flux increases monotonically with the Jakob number, indicating the absence of a critical heat flux (CHF). This deviation stems from the lack of nucleate and transition boiling regimes, as also illustrated in Figs. 4 and 5. Similar to some experimental research [11,12] and simulation [36], the boiling in our simulation directly transitions from natural convection to film boiling, which is discussed in Section 3.3.

A key observation in our simulations, absent in previous studies, is the pronounced fluctuation in heat flux. This behavior is illustrated for $Ja = 0.254$ in Fig. 7(a), where a local zoom of the heat flux curve is presented. To investigate the physical mechanism underlying these fluctuations, a sequence of snapshots ($P_1 - P_6$) is shown in Fig. 7(b). Each snapshot includes both a visual representation of the vapor–liquid interface and a corresponding temperature contour. In the contours,

black lines mark the interface between vapor and liquid as well as the fluid–solid boundary.

Between P_1 and P_2 , the vapor–liquid interface-carrying high-temperature vapor moves upward and approaches the upper layer of cooler particles. Despite the solid’s relatively high thermal conductivity, its temperature remains close to that of the adjacent fluid at the same vertical position, due to the limited thermal contact area between neighboring particles (as shown in Fig. 3a). At P_3 , the vapor directly contacts the solid particles, resulting in reverse heat conduction (from vapor to solid), which is opposite to the direction defined for $Q(t)$ in Eq. (31). Consequently, the heat flux decreases as the contact area expands ($P_3 - P_4$). As the particle temperature increases due to this reverse heat flow, the net heat transfer direction stabilizes, and the heat flux begins to recover ($P_4 - P_6$). This oscillatory behavior repeats as the vapor–liquid interface successively interacts with upper layers of particles, continuing until the vapor exits the porous structure.

This interaction between the vapor–liquid interface and the solid matrix controls the thermal distribution across the domain, resulting in a predominantly vertical (z -direction) temperature gradient throughout the boiling process.

3.2. Boiling time analysis

As illustrated in Fig. 6(a), the boiling process can be separated into multiple stages, in which the vapor saturation can be characterized. To further investigate, we perform a series of simulations for different porous layer thicknesses H . The results are shown in Fig. 8. All curves follow a similar trend: initially, no vapor exists within porous layers until boiling begins—this pre-boiling period is defined as the ‘inception time’, t_i . Once boiling initiates, S_v increases steadily due to the generation and growth of the vapor film and rises rapidly as the film expands. Eventually, S_v reaches 1, indicating complete evaporation of the remaining liquid. The total duration of the boiling process is defined as the ‘gross boiling time’, t_g , and the ‘phase change time’ is given by t_p . These critical times are related to:

$$t_g = t_i + t_p. \quad (35)$$

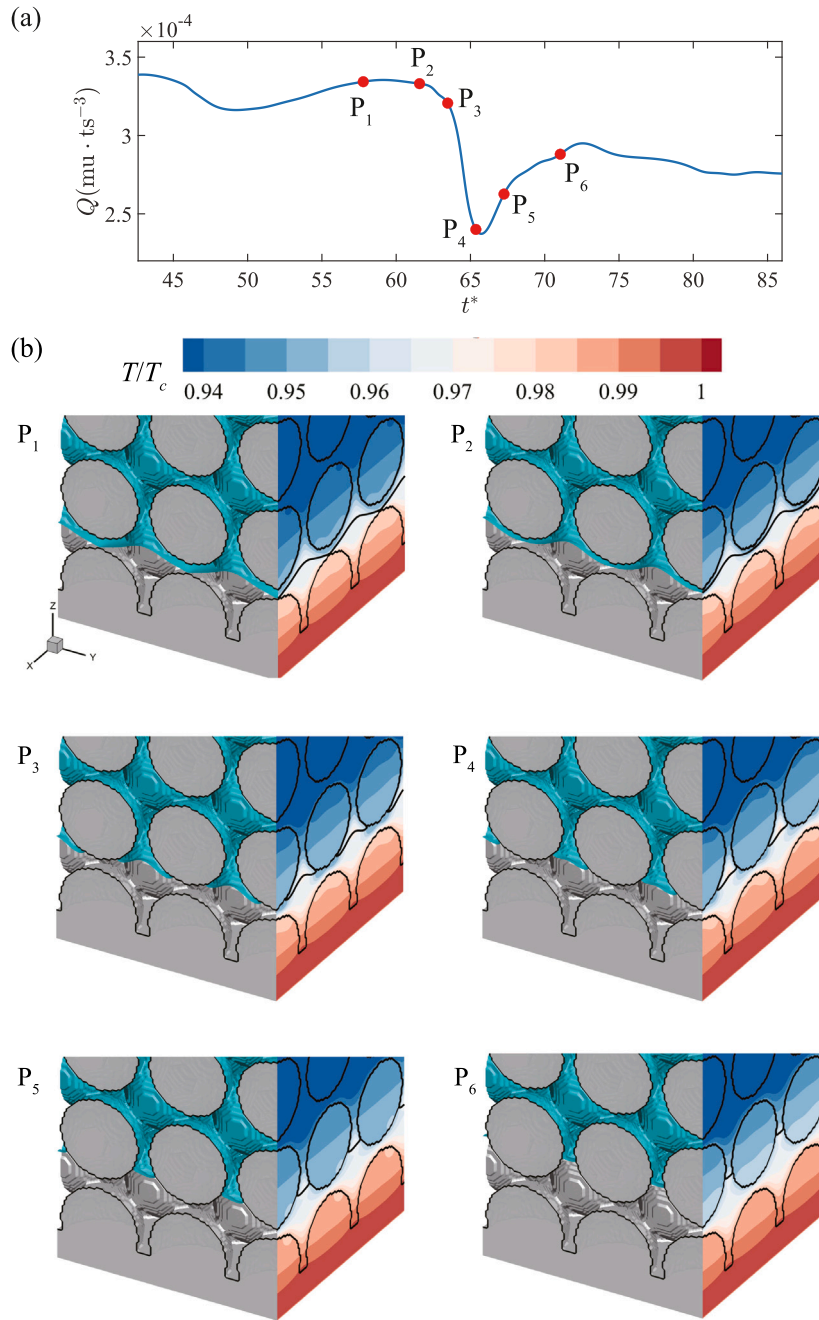


Fig. 7. (a) Local zoom-in of the transient heat flux curve for $\text{Ja} = 0.254$, highlighting fluctuations. (b) Snapshots of the boiling process at selected time points P_1 – P_6 , corresponding to key events in the heat flux evolution. Each snapshot shows both the vapor–liquid interface (interface) dynamics and temperature contours.

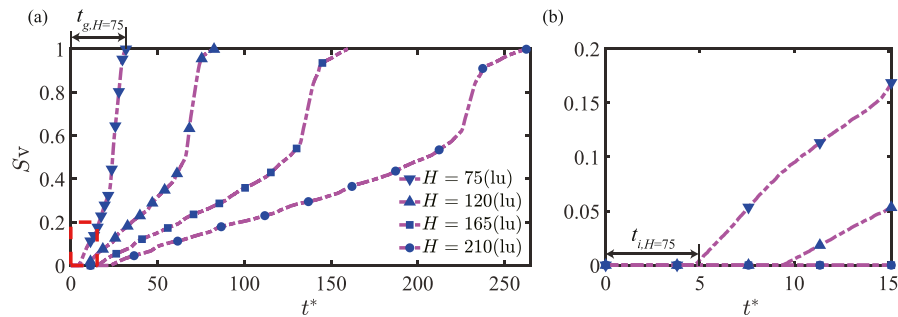


Fig. 8. (a) Transient vapor saturation profiles for different porous layer thicknesses H at $\text{Ja} = 0.254$. (b) Magnified view of the lower-left corner of (a), highlighting the early-stage behavior.

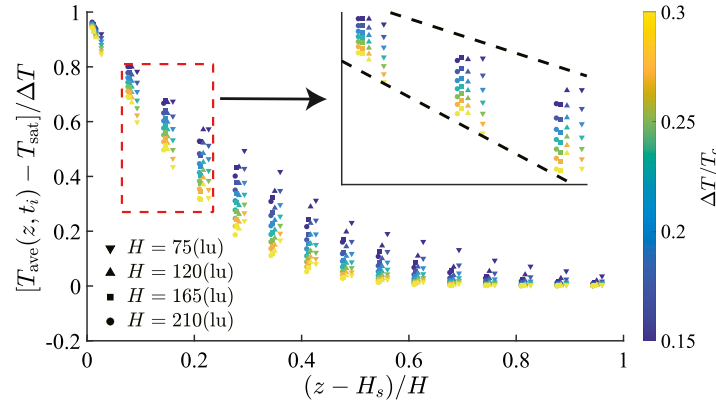


Fig. 9. Temperature distribution along the z -direction at the inception time. Each group of data points corresponds to a specific simulation case, where identical marker shapes and colors denote the same porous thickness H and normalized Superheat $\Delta T/T_c$. For instance, all yellow triangles represent the case with $H = 120(\text{lu})$ and $\Delta T/T_c \approx 0.3$. The figure displays the spatially averaged temperature profiles along the z -direction, providing insight into the thermal distribution before the onset of boiling. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

As an example, the values of t_g and t_i for $H = 75$ are marked in Fig. 8. Increasing porous layers thickness noticeably and nonlinearly extends all critical boiling times. To investigate the underlying mechanism, we analyze the temperature distribution within the porous structure. As shown in Fig. 7, temperature variations are predominantly along the z -direction. To generalize this analysis across all simulations, we define the spatially averaged temperature along z as:

$$T_{\text{ave}}(z, t) = \frac{1}{L_x \cdot L_y} \int_0^{L_x} \int_0^{L_y} T(x, y, z, t) dx dy. \quad (36)$$

The normalized curves at inception time $T_{\text{ave}}(z, t_i)$ are presented in Fig. 9, where the horizontal and vertical axes are normalized z location and spatial average temperature, respectively. Results are colored by the superheat of the substrate ΔT . The enlarged image of the domain near the substrate (marked by a red dashed box) is shown. Fig. 9 shows that the temperature distributions with the same ΔT tend to be consistent. That is, points of the same color tend to cluster together regardless of H . Besides, the comparison with the linear reference line proves the linearity of the temperature distribution near the substrate. Because of the high thermal conductivity of the solid and the absence of a limited contact area, the substrate's upper boundary temperature maintains $T_{\text{sat}} + \Delta T$.

The normalized temperature profiles at the inception time $T_{\text{ave}}(z, t_i)$ are shown in Fig. 9, where both the vertical and horizontal axes are normalized by the domain height and temperature, respectively. Colors indicate different substrate Superheating values ΔT . A zoomed-in view of the region near the substrate (highlighted by a red dashed box) is also included.

Fig. 9 reveals that temperature distributions with the same color (identical ΔT) tend to collapse onto similar curves, indicating a consistent thermal behavior regardless of H . Furthermore, the linearity of the temperature profiles near the substrate is confirmed by comparison with a reference dashed straight line. This behavior is attributed to the high thermal conductivity of the solid substrate and its continuous structure, which ensures that the upper boundary of the substrate maintains a temperature close to $T_{\text{sat}} + \Delta T$.

Based on the results mentioned above, we construct a theoretical analysis from a macroscopic perspective to describe boiling on porous layers.

(1) The $t_i - H$ scale law.

No phase change happens on porous layers during boiling inception. Neglecting fluid flow. The lower boundary of porous layers is set as a temperature Dirichlet boundary, as determined by the above analysis. According to the simulation setting in Ref. [19], the temperature

Dirichlet boundary is also applied to the upper boundary of porous layers. Thus, the one-dimensional heat conduction equation is built as:

$$\begin{cases} \frac{\partial T_{\text{ave}}}{\partial t} - D^2 \frac{\partial^2 T_{\text{ave}}}{\partial z_p^2} = 0 & 0 \leq z_p \leq H \\ T_{\text{ave}}(z_p = 0, t) = T_{\text{sat}} + \Delta T \\ T_{\text{ave}}(z_p = H, t) = T_{\text{sat}}, t > 0 \\ T_{\text{ave}}(z_p, 0) = T_{\text{sat}} \\ z_p = z - H_s \end{cases} \quad (37)$$

In this physical model, the porous matrix is rigid, with uniform porosity and constant thermophysical properties (density, thermal conductivity, and specific heat), and it contains a single-component working fluid whose properties are temperature-independent [65]. These assumptions allow the effective thermal conductivity to be expressed through a constant macroscopic diffusivity D . The detailed solution process is presented in Appendix B. Ultimately, the solution is:

$$\frac{1}{\Delta T} [T_{\text{ave}}(m, t) - T_{\text{sat}}] = \frac{1}{\Delta T} \sum_{n=1}^{\infty} C_n e^{(\frac{n\pi D}{H})^2 t} \sin(mn\pi) - m + 1 \quad (38)$$

where $m = z_p/H, 0 \leq m \leq 1$ is the normalized z location, and $C_n = -2\Delta T/n\pi$.

Fig. 9 has shown that at the boiling inception time t_i , if the superheat ΔT and normalized z location m is fixed, the normalized temperature will not change with H . That is, if ΔT is constant, the equation is always valid:

$$\frac{1}{\Delta T} [T_{\text{ave}}(m, t_i) - T_{\text{sat}}] = \frac{1}{\Delta T} \sum_{n=1}^{\infty} C_n e^{(\frac{n\pi D}{H})^2 t_i} \sin(mn\pi) - m + 1 = \text{const.} \quad (39)$$

Keep ΔT unchanged, make H become p times of its original value, then the boiling inception time t_i will become p^2 times of its original value. Thus, the scale law between t_i and H is:

$$t_i \propto H^2. \quad (40)$$

(2) The $t_p - H$ scale law.

In the phase change stage, we assume that the fluid's temperature is constant $T_{\text{ave}}(z_p, t_i)$ and that all heat transferred from the solid contributes to the evaporation from liquid to vapor until all the liquid in porous layers disappears.

Fig. 9 shows the linear distribution of normalized temperature, which can be written as:

$$\frac{d[T_{\text{ave}}(m, t_i) - T_{\text{sat}}]}{dm} = \text{const.} \quad (41)$$

The heat transfer equation is:

$$-\lambda_p \cdot L_x \cdot L_y \int_0^{t_p} \frac{dT_{\text{ave}}(z, t_i)}{dz} dt = H \cdot L_x \cdot L_y \cdot \phi_p \cdot h_{fg}, \quad (42)$$

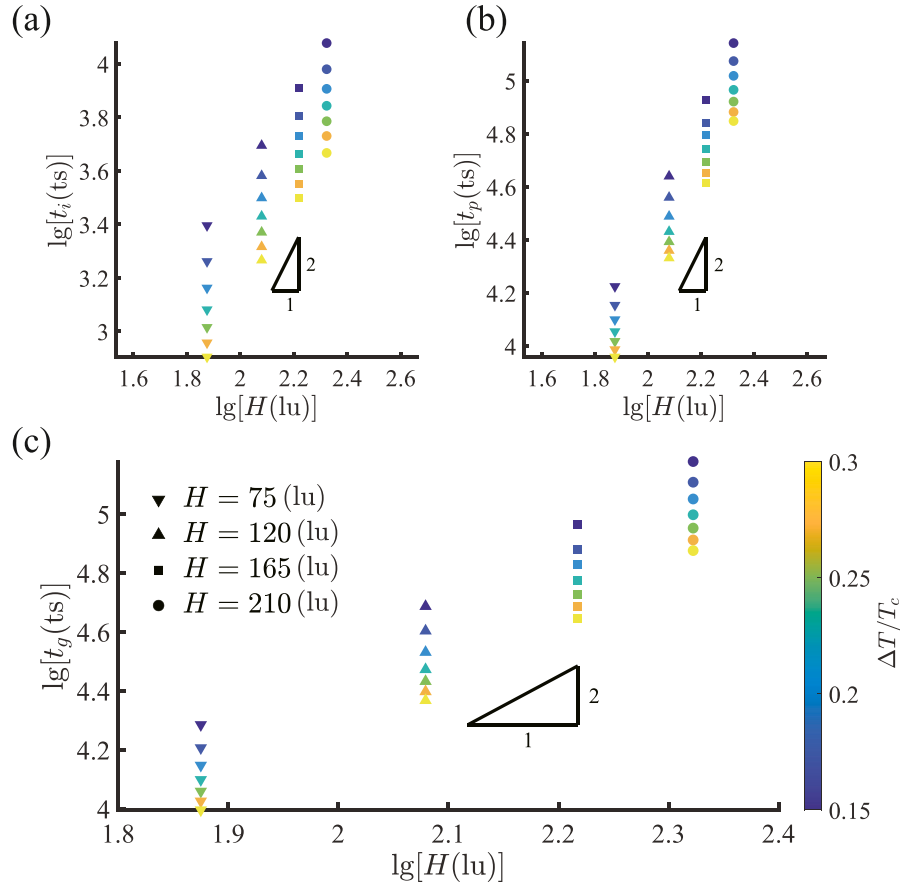


Fig. 10. The simulation results of (a) t_i , (b) t_p , and (c) t_g .

where λ_p and ϕ_p are the porous layers' macroscopic thermal conductivity and porosity, both of which are constant. Substitute Eq. (41) into Eq. (42), the scale law between phase change time t_p and thickness H is:

$$t_p \propto H^2. \quad (43)$$

(3) The $t_g - H$ scale law.

According to the definition of gross boiling time Eq. (35), the scale law can be easily derived from the linear superposition of Eq. (40) and (40):

$$t_g \propto H^2. \quad (44)$$

As illustrated in Fig. 10, all scale laws between critical boiling time and porous layer thickness are square and unchanged with superheat. The results are in agreement with the theoretical analysis presented. Notably, the quadratic dependence of the characteristic boiling time on porous-layer thickness arises from solving the heat conduction equation under diffusion-limited (thermally controlled) conditions, rather than mass transfer limitations. As thickness increases, the temperature gradient across the layer decreases for a given superheat, reducing the effective heat flux. In addition, the total heat capacity of porous layers increases proportionally with H , so the time required for heating and phase change scales with H^2 .

The derivation of the $t_i, t_p, t_g \propto H^2$ scaling law is based on a one-dimensional heat-transfer model. In this analysis, porous layers are treated as a continuum with constant thermophysical properties (such as density and conductivity) and Dirichlet boundary conditions. Because the model does not depend on the specific internal arrangement of pores, the derived scaling remains valid for both ordered and moderately disordered porous layers. Only in cases with strong non-uniformity (e.g., spatially varying properties or structural collapse) would the present formulation lose applicability.

3.3. Analysis of the existence of critical heat flux

Section 3.1 demonstrated that, under specific conditions, pool boiling on porous layers proceeds directly to film boiling, with no critical heat flux (CHF) plateau observed (see Fig. 6). In this section, we explain this behavior and propose a criterion that predicts when CHF will be present.

Zuber's classical analysis [66,67] attributes CHF to the onset of Rayleigh–Taylor (R-T) instability at the liquid-vapor interface. Immediately before CHF, unstable wavelengths grow into vapor ‘jets’ that vent through the liquid column; if the interface remains stable, a continuous vapor film blankets the surface, and heat transfer collapses.

In contrast to the two-dimensional R-T instability on smooth flat plates [68,69], porous layers contain regularly distributed protrusions that restrict the horizontal expansion and coalescence of bubbles to predefined locations. Consequently, this research adapts the one-dimensional R-T instability analysis to predict the transition to film boiling. Comprehensively considering the viscosity and surface tension, the equation of the growth rate n and wave number k is [70]:

$$\begin{aligned} & [-\alpha + (\rho_l + \rho_v) n^2] [(\mu_l k + \mu_v m_v) + (\mu_v k + \mu_l m_l)] \\ & + 4nk(\mu_l k + \mu_v m_v)(\mu_v k + \mu_l m_l) = 0 \end{aligned} \quad (45)$$

where $\alpha = -g(\rho_v - \rho_l)k - \sigma k^3$, and $\mu m = \sqrt{\mu^2 k^2 + \mu \rho n}$. The stable condition is $\alpha < 0$, so the critical wavelength λ_c is:

$$\lambda_c = 2\pi \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}}. \quad (46)$$

At the microscopic level, each solid sphere within the porous network may contain multiple potential nucleation centers due to surface roughness, temperature non-uniformity, and local superheat variations. However, the narrow gaps between adjacent spheres restrict bubble

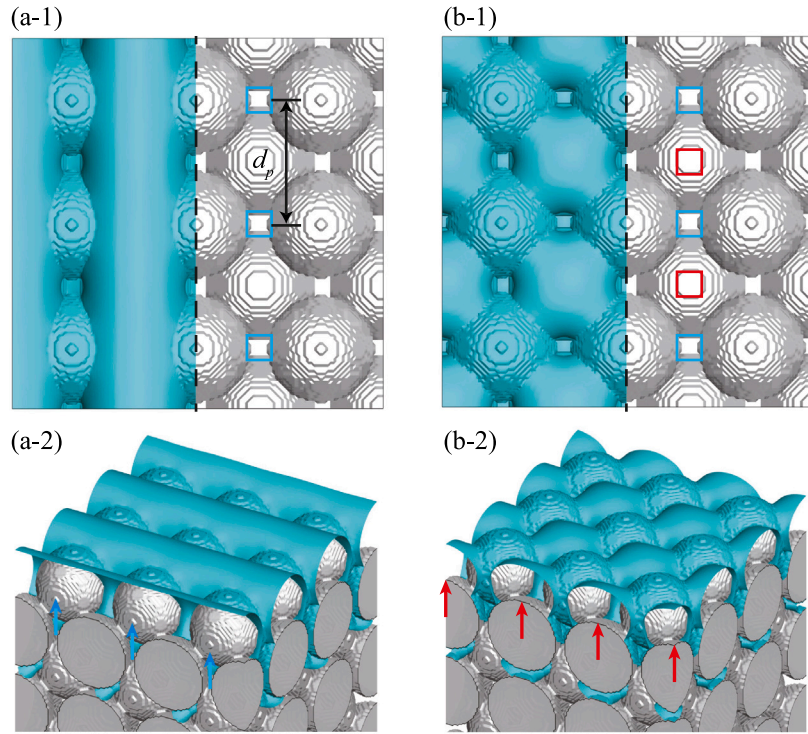


Fig. 11. The top and upper oblique view of simulation results at (a) $Ja = 0.254$, $g = 5 \times 10^{-5}$ ($lu \cdot ts^{-2}$), $t^* = 140.0$ and (b) $Ja = 0.338$, $g = 5 \times 10^{-5}$ ($lu \cdot ts^{-2}$), $t^* = 98.33$. Blue boxes and arrows mark the continuous vapor-escape channels, and red ones mark the new nucleation sites active in high superheat. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

growth, causing the small bubbles generated at different locations to merge quickly into larger vapor structures. This process can be observed in Fig. 5(a–b) (boiling snapshots at $Ja = 0.338$), where small bubbles initially appear near the bottom of porous layers, merge laterally, and eventually develop into an interconnected vapor film that fills nearby pores. Hence, we define the nucleation sites from the macroscopic perspective. As shown in Fig. 11(a1–a2), the continuous vapor-escape channels within porous layers act as effective nucleation sites, whose interval is d_p . The increase of superheat can activate new nucleation sites located on the upper surface of porous layers, which are illustrated in Fig. 11 (b1–b2). However, even if these new nucleation sites are inactive, boiling still bypasses the nucleation and transition regimes (as shown in Figs. 4, 5, and 6), which demonstrates a significant difference from flat-plate boiling. To explain this phenomenon, we mainly analyze it by comparing the interval d_p between the critical wavelength λ_c , referring to Zuber's model [10]:

$$\begin{cases} d_p \leq \lambda_c & \text{Stable, CHF unexist.} \\ d_p > \lambda_c & \text{Unstable, CHF exist.} \end{cases} \quad (47)$$

We simulate the boiling with $g = 2 \times 10^{-4}$ ($lu \cdot ts^{-2}$), which is unstable according to Eq. (46)–(47). The snapshots are presented in Figs. 12 and 13, which are at $Ja = 0.338$ and $Ja = 0.456$, respectively. When the superheat is low (Fig. 12), nucleate boiling is observed on the top of porous layers. Bubbles are generated from the active nucleation sites and detach after they grow large enough. They leave the vapor columns attached to the surface, repeating the grow-detach cycle constantly. When the superheat is high enough, boiling will be in the film boiling regime. The vapor film completely covers porous layers, bubbles can only detach from the film, and the heat transfer performance becomes poorer.

To further discuss the criterion, we conduct a series of simulations by varying the gravitational acceleration, g , and the particle distance, d_p . The R-T instability analysis results are illustrated in Fig. 14(a), where each point represents a series of simulations with different

superheat Ja (a heat transfer curve in Fig. 14b). By this means, the existence of CHF is determined according to the LBM's results. Aligning with the criterion we present, the existence of CHF can be characterized using Eq. (46) with an error of less than 10%. We also investigate the influence of gravity by selecting four cases (A–D) with the same d_p . In case A, the instability of the surface causes nucleate boiling, which is shown in the snapshot (1) in Fig. 14. With the growth of superheat, the vapor isolates the liquid and solid, and the boiling process reaches a film stage, resulting in a plunge in heat flux. The CHF can be observed during this process. The boiling in case B is similar to that in case A; however, due to the variation in gravity, case B reaches the CHF at a lower superheat. The snapshot (2) illustrates the gas-liquid interface under transition boiling. Compared with case A at the same superheat (snapshot (1)), the area of porous layers' upper surface covered by vapor is noticeably larger, leading to the deterioration of the heat transfer. Case C–D illustrates the situation where gravity is sufficiently small (i.e., $\lambda_c > d_p$): the sustainable vapor film separates the solid and fluid phases, and boiling skips the nucleate regime and directly transitions into film boiling (Fig. 14 Snapshot (3–4)). As a result, the heat transfer performance of porous layers remains at a relatively low level throughout the process.

Besides, the criterion can be expanded using dimensionless analyses. The CHF existence is determined by comparing two characteristic length scales—the critical Rayleigh–Taylor wavelength λ_c and the nucleation-site spacing d_p . This relationship can be expressed in a dimensionless form using the characteristic length l_0 , which can be calculated by Eq. (29). Hence, the dimensionless spacing becomes $d_p^* = d_p/l_0$. The existence of CHF can then be evaluated by comparing d_p^* with 2π . This dimensionless approach naturally incorporates solid and fluid parameters such as surface tension, density difference, and gravity, allowing the analysis to be extended to other surface structures or fluids.

The well-ordered packing mainly affects the spatial distribution of nucleation sites. In our model, these sites are uniformly spaced,

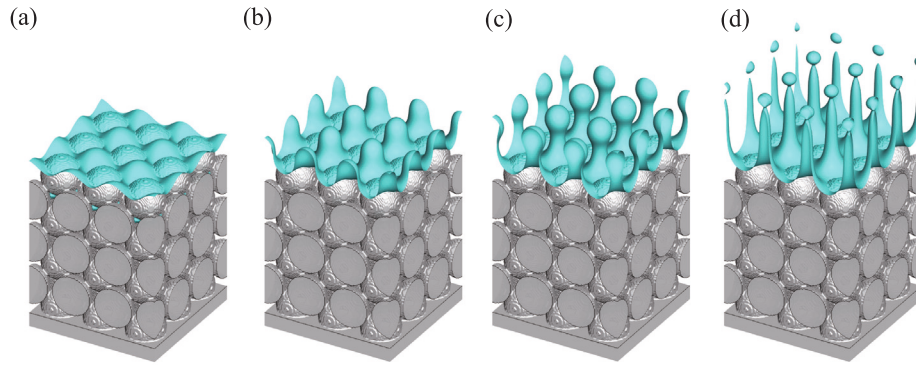


Fig. 12. Snapshots of nucleate boiling at $Ja = 0.338$, $g = 2 \times 10^{-4} (\text{lu} \cdot \text{ts}^{-2})$ when (a) $t = 60\,000$ (ts), (b) $t = 62\,500$ (ts), (c) $t = 64\,000$ (ts), and (d) $t = 66\,500$ (ts).

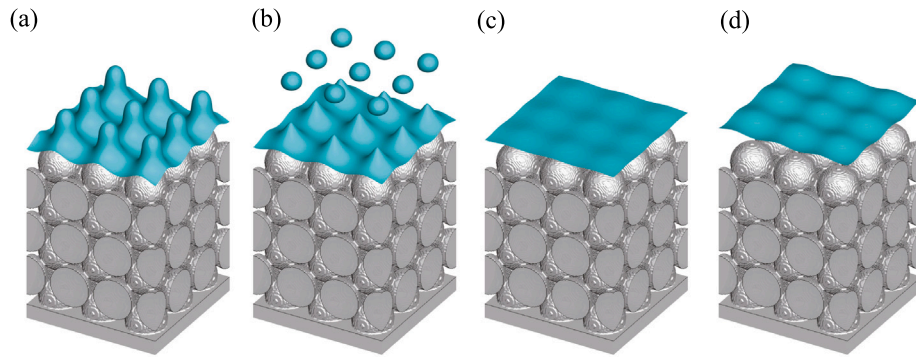


Fig. 13. Snapshots of film boiling at $Ja = 0.465$, $g = 2 \times 10^{-4} (\text{lu} \cdot \text{ts}^{-2})$ when (a) $t = 75\,000$ (ts), (b) $t = 77\,500$ (ts), (c) $t = 80\,000$ (ts), and (d) $t = 90\,000$ (ts).

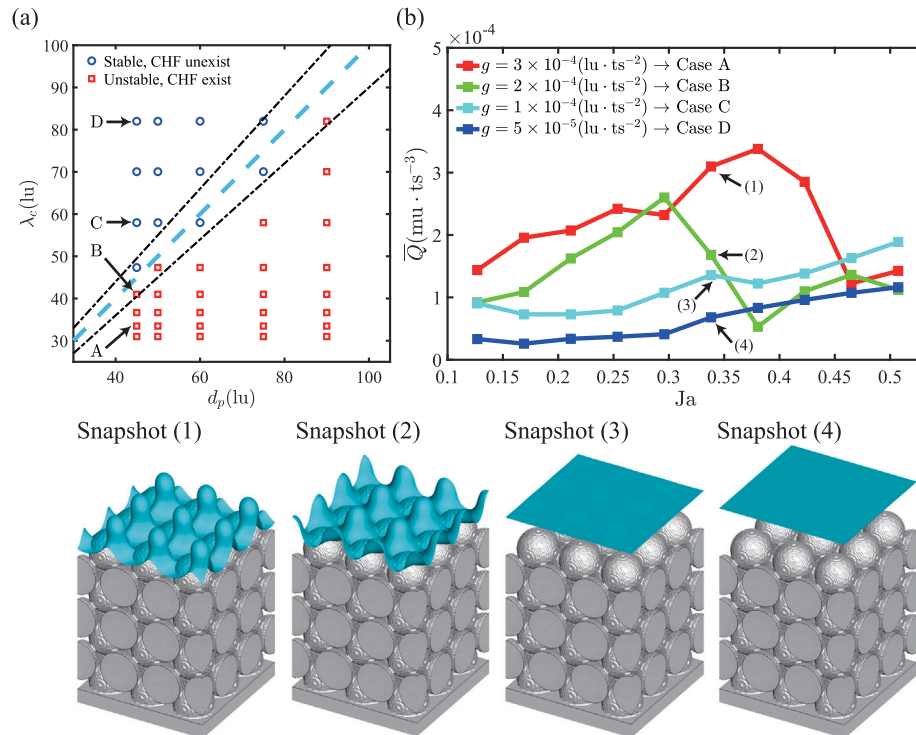


Fig. 14. (a) Rayleigh–Taylor instability analysis, where each point represents a LBM simulation case, and the dashed line represents the criterion $\lambda_c = d_p$, and dash-dotted lines represent the $\pm 10\%$ bounds. (b) The boiling curves for the case A–D, which are marked by arrows in (a). Snapshot (1–4): The snapshots of different cases with $Ja = 0.338$, when the heat transfer is stable.

whereas in real porous media, they are random and heterogeneous. As a result, our simulations may overpredict the likelihood of film boiling compared with experiments, since irregular surfaces can include regions where the nucleation-site spacing exceeds the critical Rayleigh–Taylor wavelength λ_c , thereby sustaining nucleate boiling. Nevertheless, our study still provides valuable insight. Ordered porous materials — such as inverse-opal (IO) structures [71] — closely resemble our geometry, and the established CHF criterion offers a limiting case that helps interpret boiling behavior on engineered surfaces with regular or quasi-regular arrangements (e.g., pillar arrays [36,72], wettability-modified [73,74], and composite geometries [17,75]).

4. Conclusion

In this study, we performed direct numerical simulations of boiling on well-ordered porous layers using a lattice Boltzmann two-phase model. The investigation focused on heat transfer performance, vapor–liquid interface dynamics, and the physical mechanisms underlying critical boiling behavior. The primary advancement of our study lies in establishing a unified physical framework for boiling in porous layers, which includes the time-thickness scaling law for the boiling process, and a Rayleigh–Taylor-based criterion for determining the existence or disappearance of the critical heat flux (CHF). The main conclusions are as follows:

1. During the initial stages of boiling, the interaction between the vapor film and the solid matrix significantly influences heat transfer. As high-temperature vapor rises and approaches the cooler upper solid particles, heat can flow in the opposite direction, from the solid to the vapor. This thermal inversion causes pronounced and repeated fluctuations in heat flux, which persist until the vapor film exits the porous region.
2. Based on the evolution of vapor saturation, we identify three critical time scales: the inception time t_i , the phase change time t_p , and the gross boiling time t_g , related by $t_g = t_i + t_p$. Analytical models are developed to describe heat transfer during each stage. These models reveal a consistent quadratic dependence of all critical times on the thickness of porous layers H , a result confirmed by simulation data.
3. Simulations show that the critical heat flux (CHF) may be absent under certain conditions, with boiling transitioning directly to the film regime. Using Rayleigh–Taylor instability theory, we derive a criterion for CHF occurrence based on the comparison between the critical instability wavelength λ_c and the spacing between nucleation sites d_p . Simulations across different configurations validate this criterion, distinguishing regimes with and without observable CHF.

This study offers a detailed physical understanding of boiling dynamics on porous layers and establishes predictive models that link structure, heat transfer, and phase change behavior. When $\lambda_c > d_p$, vapor generated within neighboring pores rapidly coalesces into a continuous film, which is thermally safe but less efficient. Conversely, when d_p is comparable to or greater than λ_c , isolated vapor columns can persist, leading to nucleate boiling with much higher heat fluxes before the onset of CHF. These configurations are more efficient but also more prone to the boiling crisis if operated near the limit. Generally, the disappearance of CHF is neither purely advantageous nor detrimental—its impact depends on the design goal. Our study provides a quantitative criterion (λ_c/d_p) to guide the optimization of porous structures for either stable or high-efficiency boiling regimes.

Obviously, due to the assumptions adopted in this study, the conclusions are subject to certain limitations. In cases with strong non-uniformity (e.g., spatially varying properties or structural collapse), the present model will lose applicability. Furthermore, the present model does not apply to more complex cases (e.g., multicomponent boiling or porous medium melting). We encourage researchers to refine this model further to achieve a broader scope of applicability.

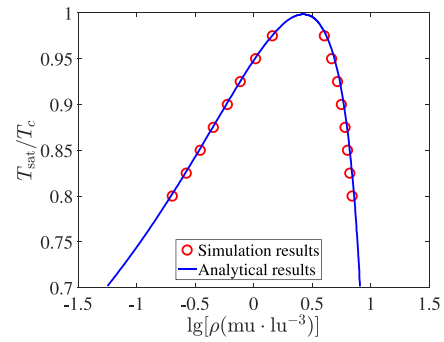


Fig. A.15. Validations of thermodynamic consistency.

CRediT authorship contribution statement

Hengyu Hu: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Haibo Huang:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the Natural Science Foundation of China (NSFC) grant nos 12372253. Calculations are performed at the Supercomputing Center of the University of Science and Technology of China.

Appendix A. Validation

A.1. Validation of thermodynamic consistency

Fig. A.15 shows our simulation's validations of thermodynamic consistency. These validations are conducted in a $L_x \times L_y \times L_z = 100 \text{ (lu)} \times 100 \text{ (lu)} \times 100 \text{ (lu)}$ domain, which is enclosed by periodic boundaries. The analytical results derived from Maxwell's equations are depicted. Notably, the numerical data align closely with the analytical solutions, indicating that the current numerical model effectively ensures thermodynamic consistency.

A.2. Validation of surface wettability

Due to the involvement of heat transfer in the simulation, a wide range of temperatures exists on the fluid–solid surface. Thus, it is necessary to validate the consistency of surface wettability under different temperatures. We construct a computational domain without gravitational acceleration. A solid layer with a thickness of 15 lattices is set at the top and bottom of the domain, and the side boundaries are set to be periodic. A hemispherical droplet with radius $R_0 = 25 \text{ (lu)}$ is placed on the solid, and the remainder is filled with saturated vapor. The density of fluid and vapor is set according to Maxwell's equation at the temperature T_{sat} . When the droplet is finally stable (Fig. A.16 a–d), we measure the spreading length l and droplet height h , as illustrated in Fig. A.16(e). By the law of mass conservation, the analytical values of l and h are derived as [46]:

$$l = 2R_0 \sin \theta_i \sqrt{\frac{\pi}{2(\theta_i - \sin \theta_i \cos \theta_i)}}, \quad (\text{A.1})$$

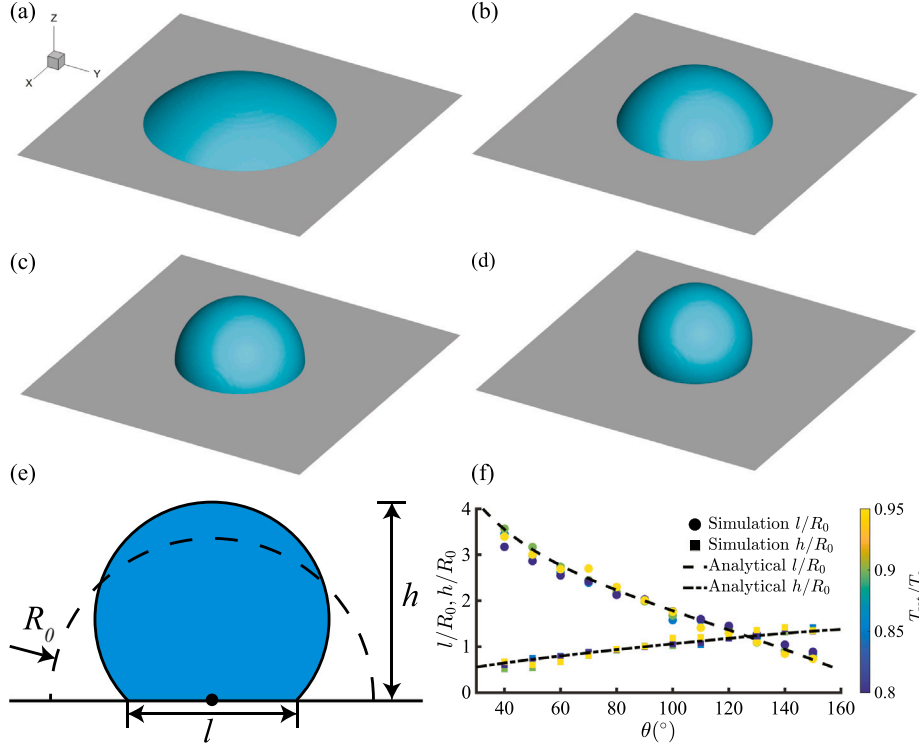


Fig. A.16. Droplet on a flat (a) $\theta = 50^\circ$, (b) $\theta = 70^\circ$, (c) $\theta = 90^\circ$ and $\theta = 110^\circ$. (e) Schematic diagram for measuring the spreading length and height of the droplet. (f) Analytical and numerical results with different contact angles θ under different temperatures T_{sat} .

$$h = R_0 (1 - \cos \theta_i) \sqrt{\frac{\pi}{2 (\theta_i - \sin \theta_i \cos \theta_i)}}. \quad (\text{A.2})$$

By varying a series of contact angles θ and temperature T_{sat} , the deformation of the droplet is illustrated in Fig. A.16, which shows that our numerical results agree well with the analytical solutions.

A.3. Bubble departure validation

According to research from Fritz [76], the relationship between bubble departure diameter (D_d) and the gravitational acceleration (g) satisfies $D_d \propto g^{-0.5}$. The bubble release period (t_d) varies proportionally with g raised to a power of -0.75 based on the research from Zuber [77]. Thus, we use the bubble departure to validate our simulation. A computational domain with $L_x \times L_y \times L_z = 120(\text{lu}) \times 120(\text{lu}) \times 200(\text{lu})$ lattices is constructed. The bottom is a solid wall with a no-slip condition. A circular heater with a constant temperature $T_b = T_{\text{sat}} + \Delta T$ is set, and the remaining portion is adiabatic. All sides are periodic boundaries; the top is a non-slip wall with constant T_{sat} . Both walls have a contact angle of 90° . $2/3$ of the lower part of the computational domain is liquid, and the remaining portion is saturated vapor. The results are shown in Fig. A.17(b). The fitted curve of the simulation result closely aligns with the correlation proposed.

Appendix B. Solution of one-dimensional heat conduction equation

$$\begin{cases} \frac{\partial T_{\text{ave}}}{\partial t} - D^2 \frac{\partial^2 T_{\text{ave}}}{\partial z_p^2} = 0 & 0 \leq z_p \leq H \\ T_{\text{ave}}(z_p = 0, t) = T_{\text{sat}} + \Delta T \\ T_{\text{ave}}(z_p = H, t) = T_{\text{sat}}, t > 0 \\ T_{\text{ave}}(z_p, 0) = T_{\text{sat}} \\ z_p = z - H_s \end{cases} \quad (\text{B.1})$$

Setting that:

$$T_{\text{ave}}(z_p, t) = v(z_p, t) + w(z_p, t), \quad (\text{B.2})$$

where $w(z_p, t)$ is:

$$w(z_p, t) = \frac{-\Delta T}{H} f(z_p) + T_{\text{sat}} + \Delta T. \quad (\text{B.3})$$

The auxiliary function $f(z_p)$ satisfies:

$$\begin{cases} f''(z_p) = 0 & 0 \leq z_p \leq H \\ f(0) = 0 \\ f(H) = H \end{cases} \quad (\text{B.4})$$

The solution is $f(z_p) = z_p$. Then another auxiliary function $v(z_p, t)$ is solved based on the equation:

$$\begin{cases} \frac{\partial v}{\partial t} - D^2 \frac{\partial^2 v}{\partial z_p^2} = 0 & 0 \leq z_p \leq H \\ v(z_p = 0, t) = 0 \\ v(z_p = H, t) = 0, t > 0 \\ v(z_p, 0) = \frac{\Delta T}{H} z_p - \Delta T \end{cases} \quad (\text{B.5})$$

which is a partial differential equation with homogeneous boundaries. The separation of variables can solve it:

$$v(z_p, t) = \sum_{n=1}^{\infty} C_n e^{(\frac{n\pi}{H} D)^2 t} \sin(\frac{n\pi z_p}{H}), \quad (\text{B.6})$$

where constant coefficient C_n is:

$$C_n = \frac{-2\Delta T}{n\pi}. \quad (\text{B.7})$$

Define the normalized z location $m = z_p/H$. Thus, the solution of Eq. (B.1) is:

$$T(m, t) = \sum_{n=1}^{\infty} C_n e^{(\frac{n\pi D}{H})^2 t} \sin(mn\pi) - \Delta T \cdot m + T_{\text{sat}} + \Delta T, \quad (\text{B.8})$$

which can be rewritten to Eq. (38).

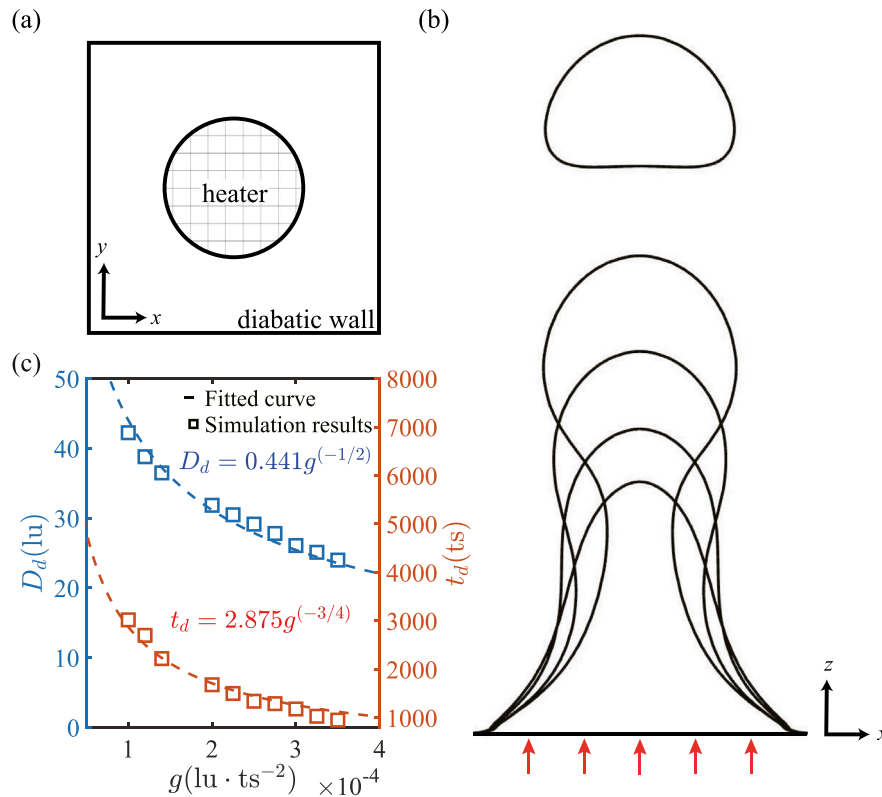


Fig. A.17. (a) Schematic diagram for the bottom boundary. (b) The growth and detachment of bubbles with $g = 3 \times 10^{-4} (\text{lu} \cdot \text{ts}^{-2})$. (c) Validation of bubble departure diameter D_d and release period t_d .

Data availability

Data will be made available on request.

References

- [1] M. Mahmoud, T. Karayiannis, Bubble growth models in saturated pool boiling of water on a smooth metallic surface: Assessment and a new recommendation, *Int. J. Heat Mass Transfer* 208 (2023) 124065, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2023.124065>.
- [2] S.V. Garimella, A.S. Fleischer, J.Y. Murthy, A. Keshavarzi, R. Prasher, C. Patel, S.H. Bhavnani, R. Venkatasubramanian, R. Mahajan, Y. Joshi, et al., Thermal challenges in next-generation electronic systems, *IEEE Trans. Compon. Packag. Technol.* 31 (4) (2008) 801–815, <http://dx.doi.org/10.1109/TCAPT.2008.2001197>.
- [3] R. Van Erp, R. Soleimanzadeh, L. Nela, G. Kampitsis, E. Matioli, Co-designing electronics with microfluidics for more sustainable cooling, *Nature* 585 (7824) (2020) 211–216, <http://dx.doi.org/10.1038/s41586-020-2666-1>.
- [4] R. Wen, X. Ma, Y.-C. Lee, R. Yang, Liquid-vapor phase-change heat transfer on functionalized nanowired surfaces and beyond, *Joule* 2 (11) (2018) 2307–2347, <http://dx.doi.org/10.1016/j.joule.2018.08.014>.
- [5] S. Guan, Z. Zhang, R. Wu, X. Gu, C. Zhao, Pool boiling inside micro-nano composite pores: Thermofluids behaviors and heat transfer enhancement, *Appl. Phys. Lett.* 124 (9) (2024) <http://dx.doi.org/10.1063/5.0185421>.
- [6] X. Chang, H. Huang, Y.-P. Cheng, X.-Y. Lu, Lattice Boltzmann study of pool boiling heat transfer enhancement on structured surfaces, *Int. J. Heat Mass Transfer* 139 (2019) 588–599, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2019.05.041>.
- [7] A.R. Betz, J. Xu, H. Qiu, D. Attinger, Do surfaces with mixed hydrophilic and hydrophobic areas enhance pool boiling? *Appl. Phys. Lett.* 97 (14) (2010) <http://dx.doi.org/10.1063/1.3485057>.
- [8] J. Li, D. Kang, K. Fazle Rabbi, W. Fu, X. Yan, X. Fang, L. Fan, N. Miljkovic, Liquid film-induced critical heat flux enhancement on structured surfaces, *Sci. Adv.* 7 (26) (2021) eabg4537, <http://dx.doi.org/10.1126/sciadv.abg4537>.
- [9] L. Zhang, J.H. Seong, M. Bucci, Percolative scale-free behavior in the boiling crisis, *Phys. Rev. Lett.* 122 (13) (2019) 134501, <http://dx.doi.org/10.1103/PhysRevLett.122.134501>.
- [10] G. Liang, I. Mudawar, Pool boiling critical heat flux (CHF)—Part 1: Review of mechanisms, models, and correlations, *Int. J. Heat Mass Transfer* 117 (2018) 1352–1367, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.09.134>.
- [11] B.P. Avksentyuk, V.V. Ovchinnikov, Third heat-transfer crisis with stepwise heat supply, *J. Appl. Mech. Tech. Phys.* 42 (5) (2001) 857–863, <http://dx.doi.org/10.1023/A:1017908929848>.
- [12] A. Pavlenko, E. Tairov, V. Zhukov, A. Levin, A. Tsoi, Investigation of transient processes at liquid boiling under nonstationary heat generation conditions, *J. Eng. Thermophys.* 20 (4) (2011) 380–406, <http://dx.doi.org/10.1134/S1810232811040060>.
- [13] M. Rouzbahani, S. Mortazavi, Numerical simulation of film boiling heat transfer in the presence of a uniform electric field using front tracking, *Int. J. Multiph. Flow* 161 (2023) 104386, <http://dx.doi.org/10.1016/j.ijmultiphaseflow.2023.104386>.
- [14] F. Chang, Y. Shang, H. Hu, X. Li, K. Guo, H. Li, Numerical study on magnetic nanofluid (MNF) film boiling in non-uniform magnetic fields generated by current carrying wires, *Int. J. Therm. Sci.* 175 (2022) 107461, <http://dx.doi.org/10.1016/j.ijthermalsci.2022.107461>.
- [15] N. Unno, K. Yuki, J. Taniguchi, S.-i. Satake, Boiling heat transfer enhancement by self-excited vibration, *Int. J. Heat Mass Transfer* 153 (2020) 119588, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2020.119588>.
- [16] J.P. McHale, S.V. Garimella, Nucleate boiling from smooth and rough surfaces—Part 1: Fabrication and characterization of an optically transparent heater-sensor substrate with controlled surface roughness, *Exp. Therm. Fluid Sci.* 44 (2013) 456–467, <http://dx.doi.org/10.1016/j.expthermflusci.2012.08.006>.
- [17] C. Luo, T. Tagawa, Enhanced boiling heat transfer on structured surfaces with linear and staggered arrangements of hydrophilic and hydrophobic micro-pillars, *Int. J. Heat Mass Transfer* 225 (2024) 125394, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2024.125394>.
- [18] X. Dai, F. Yang, R. Yang, Y.-C. Lee, C. Li, Micromembrane-enhanced capillary evaporation, *Int. J. Heat Mass Transfer* 64 (2013) 1101–1108, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.05.030>.
- [19] D.J. Lee, Y.J. Yang, D.E. Kim, Boiling performance enhancement and self-recovery of nucleate boiling regime on micro- and nanostructured porous surfaces, *Int. J. Heat Mass Transfer* 238 (2025) 126516, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2024.126516>.
- [20] P. Li, X. Liu, R. Wen, R. Yang, Hierarchical ordered perforated surface for highly efficient liquid film boiling, *Cell Rep. Phys. Sci.* 6 (5) (2025) <http://dx.doi.org/10.1016/j.xcrp.2025.102601>.

- [21] Q. Cao, Z. Cui, W. Shao, Optimization method for grooved surface structures regarding the evaporation heat transfer of ultrathin liquid films at the nanoscale, *Langmuir* 36 (11) (2020) 2802–2815, <http://dx.doi.org/10.1021/acs.langmuir.9b03989>.
- [22] S. Guan, Z. Zhang, S. Gong, R. Wu, X. Gu, C. Zhao, Molecular insights into the mechanism of nucleation in nanopores: Heat transfer characteristics and two-phase behaviors, *Int. J. Heat Mass Transfer* 241 (2025) 126775, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2025.126775>.
- [23] X. Zhang, H. Yang, T. Huang, J. Li, P. Li, Q. Wu, Y. Wang, P. Zhang, Research progress of molecular dynamics simulation on the formation-decomposition mechanism and stability of CO₂ hydrate in porous media: A review, *Renew. Sustain. Energy Rev.* 167 (2022) 112820, <http://dx.doi.org/10.1016/j.rser.2022.112820>.
- [24] A. Xu, L. Shi, T. Zhao, Accelerated lattice Boltzmann simulation using GPU and OpenACC with data management, *Int. J. Heat Mass Transfer* 109 (2017) 577–588, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.02.032>.
- [25] A. Xu, B.-T. Li, Multi-GPU thermal lattice Boltzmann simulations using OpenACC and MPI, *Int. J. Heat Mass Transfer* 201 (2023) 123649, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2022.123649>.
- [26] A. Xu, B.-T. Li, Particle-resolved thermal lattice Boltzmann simulation using OpenACC on multi-GPUs, *Int. J. Heat Mass Transfer* 218 (2024) 124758, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2023.124758>.
- [27] X. Shan, H. Chen, Lattice Boltzmann model for simulating flows with multiple phases and components, *Phys. Rev. E* 47 (3) (1993) 1815, <http://dx.doi.org/10.1103/PhysRevE.47.1815>.
- [28] T. Vijayababu, K. Anirudh, S. Dhinakaran, LBM simulation of unsteady flow and heat transfer from a diamond-shaped porous cylinder, *Int. J. Heat Mass Transfer* 120 (2018) 267–283, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.11.010>.
- [29] A. Scagliarini, L. Biferale, M. Sbragaglia, K. Sugiyama, F. Toschi, Lattice Boltzmann methods for thermal flows: Continuum limit and applications to compressible Rayleigh–Taylor systems, *Phys. Fluids* 22 (5) (2010) <http://dx.doi.org/10.1063/1.3392774>.
- [30] A. Márkus, G. Ház, Simulation of evaporation by an extension of the pseudopotential lattice Boltzmann method: A quantitative analysis, *Phys. Rev. E-Statistical Nonlinear Soft Matter Phys.* 83 (4) (2011) 046705, <http://dx.doi.org/10.1103/PhysRevE.83.046705>.
- [31] L. Biferale, P. Perlekar, M. Sbragaglia, F. Toschi, Convection in multiphase fluid flows using lattice Boltzmann methods, *Phys. Rev. Lett.* 108 (10) (2012) 104502, <http://dx.doi.org/10.1103/PhysRevLett.108.104502>.
- [32] S. Gong, P. Cheng, A lattice Boltzmann method for simulation of liquid-vapor phase-change heat transfer, *Int. J. Heat Mass Transfer* 55 (17–18) (2012) 4923–4927, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.04.037>.
- [33] Q. Li, Q. Kang, M.M. Francois, Y. He, K. Luo, Lattice Boltzmann modeling of boiling heat transfer: The boiling curve and the effects of wettability, *Int. J. Heat Mass Transfer* 85 (2015) 787–796, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.01.136>.
- [34] W.-Z. Fang, L. Chen, Q.-J. Kang, W.-Q. Tao, Lattice Boltzmann modeling of pool boiling with large liquid-gas density ratio, *Int. J. Therm. Sci.* 114 (2017) 172–183, <http://dx.doi.org/10.1016/j.ijthermalsci.2016.12.017>.
- [35] X. Chang, H. Huang, X.-Y. Lu, Thermal lattice Boltzmann study of three-dimensional bubble growth in quiescent liquid, *Comput. & Fluids* 159 (2017) 232–242, <http://dx.doi.org/10.1016/j.compfluid.2017.10.005>.
- [36] H. Zhang, B. Xu, Y. Fei, X.-n. Chen, G. Pei, Improving flat heat pipe performance with lattice Boltzmann method: Evaluating flow and heat transfer in typical porous wick structures, *Energy* 315 (2025) 134445, <http://dx.doi.org/10.1016/j.energy.2025.134445>.
- [37] Q. Li, P. Zhou, H. Yan, Improved thermal lattice Boltzmann model for simulation of liquid-vapor phase change, *Phys. Rev. E* 96 (6) (2017) 063303, <http://dx.doi.org/10.1103/PhysRevE.96.063303>.
- [38] C.-Y. Zhao, L.-Y. Yang, X.-S. Zhao, L.-W. Liang, F.-F. Zhang, D. Qi, B.-Y. Song, K.-N. Xiong, J.-M. Jiang, Numerical study on flow-boiling heat transfer in square channels partially centrally filled with gradient porous media, *Int. J. Heat Mass Transfer* 235 (2024) 126170, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2024.126170>.
- [39] S.G. Liter, M. Kaviany, Pool-boiling CHF enhancement by modulated porous-layer coating: theory and experiment, *Int. J. Heat Mass Transfer* 44 (22) (2001) 4287–4311, [http://dx.doi.org/10.1016/S0017-9310\(01\)00084-9](http://dx.doi.org/10.1016/S0017-9310(01)00084-9).
- [40] X. Shan, G. Doolen, Multicomponent lattice-Boltzmann model with interparticle interaction, *J. Stat. Phys.* 81 (1995) 379–393, <http://dx.doi.org/10.1007/BF02179985>.
- [41] E. Ezzatneshan, Study of surface wettability effect on cavitation inception by implementation of the lattice Boltzmann method, *Phys. Fluids* 29 (11) (2017) <http://dx.doi.org/10.1063/1.4990876>.
- [42] A. Kupershtokh, D. Medvedev, Lattice Boltzmann equation method in electrohydrodynamic problems, *J. Electrostat.* 64 (7–9) (2006) 581–585, <http://dx.doi.org/10.1016/j.elstat.2005.10.012>.
- [43] S. Gong, P. Cheng, Numerical investigation of droplet motion and coalescence by an improved lattice Boltzmann model for phase transitions and multiphase flows, *Comput. & Fluids* 53 (2012) 93–104, <http://dx.doi.org/10.1016/j.compfluid.2011.09.013>.
- [44] A. Wagner, C. Pooley, Interface width and bulk stability: Requirements for the simulation of deeply quenched liquid-gas systems, *Phys. Rev. E-Statistical Nonlinear Soft Matter Phys.* 76 (4) (2007) 045702, <http://dx.doi.org/10.1103/PhysRevE.76.045702>.
- [45] A. Fakhari, D. Bolster, Diffuse interface modeling of three-phase contact line dynamics on curved boundaries: A lattice Boltzmann model for large density and viscosity ratios, *J. Comput. Phys.* 334 (2017) 620–638, <http://dx.doi.org/10.1016/j.jcp.2017.01.025>.
- [46] X. Chang, H. Huang, X.-Y. Lu, J. Hou, Width effect on contact angle hysteresis in a patterned heterogeneous microchannel, *J. Fluid Mech.* 949 (2022) A15, <http://dx.doi.org/10.1017/jfm.2022.763>.
- [47] B. Bunner, G. Tryggvason, Dynamics of homogeneous bubbly flows Part 1. Rise velocity and microstructure of the bubbles, *J. Fluid Mech.* 466 (2002) 17–52, <http://dx.doi.org/10.1017/S0022112002001179>.
- [48] D.M. Anderson, G.B. McFadden, A.A. Wheeler, Diffuse-interface methods in fluid mechanics, *Annu. Rev. Fluid Mech.* 30 (1) (1998) 139–165, <http://dx.doi.org/10.1146/annurev.fluid.30.1.139>.
- [49] P.K. Kundu, I.M. Cohen, D.R. Dowling, J. Capecelatro, *Fluid Mechanics*, Elsevier, 2024, <https://www.sciencedirect.com/book/9780124059351/fluid-mechanics>.
- [50] J.C. Butcher, *Numerical Methods for Ordinary Differential Equations*, John Wiley & Sons, 2016, <http://dx.doi.org/10.1002/9781119121534>.
- [51] T. Sauer, *Numerical Analysis*, Addison-Wesley Publishing Company, 2011, <https://dl.acm.org/doi/abs/10.5555/2161609>.
- [52] H. Liu, A.J. Valocchi, Y. Zhang, Q. Kang, Phase-field-based lattice Boltzmann finite-difference model for simulating thermocapillary flows, *Phys. Rev. E—Statistical Nonlinear Soft Matter Phys.* 87 (1) (2013) 013010, <http://dx.doi.org/10.1103/PhysRevE.87.013010>.
- [53] P. Lallemand, L.-S. Luo, Theory of the lattice Boltzmann method: Acoustic and thermal properties in two and three dimensions, *Phys. Rev. E* 68 (3) (2003) 036706, <http://dx.doi.org/10.1103/PhysRevE.68.036706>.
- [54] H. Huang, T. Lee, C. Shu, Hybrid lattice Boltzmann finite-difference simulation of axisymmetric swirling and rotating flows, *Internat. J. Numer. Methods Fluids* 53 (11) (2007) 1707–1726, <http://dx.doi.org/10.1002/fld.1380>.
- [55] F. Verhaeghe, B. Blanpain, P. Wollants, Lattice Boltzmann method for double-diffusive natural convection, *Phys. Rev. E—Statistical Nonlinear Soft Matter Phys.* 75 (4) (2007) 046705, <http://dx.doi.org/10.1103/PhysRevE.75.046705>.
- [56] A. Tiribocchi, N. Stella, G. Gonnella, A. Lamura, Hybrid lattice Boltzmann model for binary fluid mixtures, *Phys. Rev. E—Statistical Nonlinear Soft Matter Phys.* 80 (2) (2009) 026701, <http://dx.doi.org/10.1103/PhysRevE.80.026701>.
- [57] H. Huang, M. Sukop, X. Lu, *Multiphase Lattice Boltzmann Methods: Theory and Application*, John Wiley & Sons, 2015, <http://dx.doi.org/10.1002/9781118971451>.
- [58] G. Pareschi, N. Frapolli, S.S. Chikatamarla, I.V. Karlin, Conjugate heat transfer with the entropic lattice Boltzmann method, *Phys. Rev. E* 94 (1) (2016) 013305, <http://dx.doi.org/10.1103/PhysRevE.94.013305>.
- [59] S. Gong, P. Cheng, Numerical simulation of pool boiling heat transfer on smooth surfaces with mixed wettability by lattice Boltzmann method, *Int. J. Heat Mass Transfer* 80 (2015) 206–216, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.08.092>.
- [60] S.-C. Wang, Z.-X. Tong, Y.-L. He, X. Liu, Unit conversion in pseudopotential lattice Boltzmann method for liquid-vapor phase change simulations, *Phys. Fluids* 34 (10) (2022) <http://dx.doi.org/10.1063/5.0106079>.
- [61] G. Son, V.K. Dhir, N. Ramanujapu, Dynamics and heat transfer associated with a single bubble during nucleate boiling on a horizontal surface, *J. Heat Transf.* 121 (3) (1999) 623–631, <http://dx.doi.org/10.1115/1.2826025>.
- [62] S. Gong, P. Cheng, Two-dimensional mesoscale simulations of saturated pool boiling from rough surfaces. Part II: Bubble interactions above multi-cavities, *Int. J. Heat Mass Transfer* 100 (2016) 938–948, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.04.082>.
- [63] S. Guan, Z. Zhang, R. Wu, X. Gu, C. Zhao, Boiling on nano-porous structures: Theoretical analysis and molecular dynamics simulations, *Int. J. Heat Mass Transfer* 191 (2022) 122848, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2022.122848>.
- [64] A.S. Gordanlou, M. Zarringhalam, N. Shirani, A.a. Alizadeh, D. Toghrade, S. Rostami, Investigation the effects of an external driving force and cone shape of roughness on the phase change behavior of Argon fluid within a microchannel by molecular dynamic simulation, *J. Mol. Liq.* 313 (2020) 113503, <http://dx.doi.org/10.1016/j.molliq.2020.113503>.
- [65] Y. Lu, D. Liu, Electrowetting modulated enhancement of critical heat flux in pool boiling, *Int. J. Heat Mass Transfer* 208 (2023) 124055, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2023.124055>.
- [66] N. Zuber, On the stability of boiling heat transfer, *Trans. Am. Soc. Mech. Eng.* 80 (3) (1958) 711–714, <http://dx.doi.org/10.1115/1.4012484>.
- [67] N. Zuber, The hydrodynamic crisis in pool boiling of saturated and subcooled liquids, *Int. Dev. Heat Transf.* 27 (1961) 230–236, <https://ci.nii.ac.jp/naid/10010165734/>.
- [68] V. Sernas, The Taylor wave configuration during boiling from a flat plate, *Int. J. Heat Mass Transfer* 16 (9) (1973) 1820–1821, [http://dx.doi.org/10.1016/0017-9310\(73\)90175-0](http://dx.doi.org/10.1016/0017-9310(73)90175-0).

- [69] V.I. Zhukov, A.N. Pavlenko, Symmetry of structures under two-dimensional instability in a finite-height horizontal layer of boiling liquid, *Symmetry* 15 (9) (2023) 1792, <http://dx.doi.org/10.3390/sym15091792>.
- [70] R. Bellman, R.H. Pennington, Effects of surface tension and viscosity on Taylor instability, *Quart. Appl. Math.* 12 (2) (1954) 151–162, <http://dx.doi.org/10.1090/qam/63198>.
- [71] Q.N. Pham, S. Zhang, S. Hao, K. Montazeri, C.-H. Lin, J. Lee, A. Mohraz, Y. Won, Boiling heat transfer with a well-ordered microporous architecture, *ACS Appl. Mater. Interfaces* 12 (16) (2020) 19174–19183, <https://pubs.acs.org/doi/10.1021/acsami.0c01113>.
- [72] M. Hamidnia, Y. Luo, Z. Li, X. Wang, Capillary and thermal performance enhancement of rectangular grooved micro heat pipe with micro pillars, *Int. J. Heat Mass Transfer* 153 (2020) 119581, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2020.119581>.
- [73] Y.-J. Chen, J.-H. Gong, J. Ding, B. Yu, L. Chen, Y.-G. Li, W.-Q. Tao, Lattice Boltzmann method study of pool boiling on an electrowetting substrate, *Int. Commun. Heat Mass Transfer* 149 (2023) 107160, <http://dx.doi.org/10.1016/j.icheatmasstransfer.2023.107160>.
- [74] C.-C. Hsu, M.-R. Lee, C.-H. Wu, P.-H. Chen, Effect of interlaced wettability on horizontal copper cylinders in nucleate pool boiling, *Appl. Therm. Eng.* 112 (2017) 1187–1194, <http://dx.doi.org/10.1016/j.applthermaleng.2016.10.176>.
- [75] H. Chang, B. Liu, Q. Li, X. Yang, P. Zhou, Effects of electric field on pool boiling heat transfer over composite microstructured surfaces with microcavities on micro-pin-fins, *Int. J. Heat Mass Transfer* 205 (2023) 123893, <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2023.123893>.
- [76] W. Fritz, Maximum volume of vapor bubbles, *Physic. Zeitsch.* 36 (1935) 379–384, <https://cir.nii.ac.jp/crid/1571135650749426560>.
- [77] N. Zuber, Nucleate boiling. The region of isolated bubbles and the similarity with natural convection, *Int. J. Heat Mass Transfer* 6 (1) (1963) 53–78, [http://dx.doi.org/10.1016/0017-9310\(63\)90029-2](http://dx.doi.org/10.1016/0017-9310(63)90029-2).