

格子玻尔兹曼方法：基于聚结效应的脊状超疏水表面液滴跳跃研究

摘要

聚结诱导液滴跳跃 (CIDJ) 是超疏水表面上的一类高效的被动液滴去除机制，在冷凝传热、自清洁及防冰等领域具有重要应用前景。然而，针对介观尺度液滴在脊状结构及脊状晶格系统中的聚结行为，尤其是多液滴排列方式与能量转换机制的协同调控，仍缺乏系统分析。本研究采用三维多弛豫时间 (MRT) 伪势格子玻尔兹曼方法 (D3Q19)，系统模拟了脊状及脊状晶格超疏水表面上液滴的聚结跳跃过程，分析了结构参数、液滴排列方式及尺寸比对动力学行为与能量演化路径的影响。结果表明，脊高是主导跳跃性能的关键几何参数，高脊结构可有效约束液桥扩展，提升垂直动量转化效率；脊状晶格系统在无量纲脊高 $h^* = 0.83$ 时可使跳跃速度提升 10.1%。液滴排列对称性显著影响能量转换效率，非对称排列易引发水平振荡，而晶格结构可补偿其动能损失，对 V 型排列液滴提升幅度达 98.68%。本研究对 CIDJ 现象的解释从单脊、双液滴系统拓展至脊状晶格、多液滴场景，明确了结构参数、液滴排列及尺寸比对跳跃行为的调控机制，为超疏水表面结构设计及介观液滴操控提供了理论依据与技术支撑。

关键词

格子玻尔兹曼方法；聚结诱导液滴跳跃；超疏水表面；脊状晶格系统；液滴排列对称性

Abstract

Coalescence-induced droplet jumping (CIDJ) is a highly efficient passive droplet removal mechanism on superhydrophobic surfaces, which has important application prospects in fields such as condensation heat transfer, self-cleaning, and anti-icing. However, there is still a lack of systematic analysis of the coalescence behavior of mesoscale droplets in ridge structures and ridge lattice systems, especially the collaborative regulation of the multi-droplet arrangement and the energy conversion mechanism. In this study, the three-dimensional multi-relaxation time (MRT) pseudo-potential lattice Boltzmann method (D3Q19) was used to systematically simulate the coalescence and jumping process of droplets on ridge and ridge lattice superhydrophobic surfaces, and the influence of structural parameters, droplet arrangement, and size ratio on the dynamic behavior and energy evolution path was analyzed. The results show that the ridge height the geometric key is parameter governing the jumping performance. The high-ridge structure can effectively constrain the expansion of the liquid bridge and improve the vertical momentum conversion efficiency. The ridge lattice system can increase the jumping velocity by 10.1% when the dimensionless ridge height $h^* = 0.83$. The symmetry of droplet arrangement significantly affects the energy conversion efficiency. Asymmetric arrangement is prone to cause horizontal oscillations, while the lattice structure can compensate for its kinetic energy loss, with an improvement amplitude of 98.68% for V-shaped arranged droplets. This study extends the explanation of the CIDJ phenomenon from single-ridge and two-droplet systems to ridge lattice and multi-droplet scenarios, clarifies the regulatory mechanism of structural parameters, droplet arrangement, and size ratio on the jumping behavior, and provides a theoretical basis and technical support for the structural design of superhydrophobic surfaces and the manipulation of mesoscale droplets.

Keywords

Lattice Boltzmann method, Coalescence-induced droplet jumping, Superhydrophobic surface, Ridge lattice system, Droplet arrangement symmetry

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