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A theoretical analysis on self-organized formation of microbial biofilms

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Abstract

Biofilms with a conspicuous hierarchical and fractal structure have been paid much attention in recent years. Available analyses of biofilm formation typically employed macroscopic differential equations, simulation approaches such as cellular automaton (CA), diffusion limited aggregation (DLA), Monte Carlo simulation, and hybrid model, etc. This paper proposed a new non-equilibrium statistical mechanics framework to analyze the interactions among cells and their environment, and the self-organizing formation process of biofilm was elaborated. The paper tried to make a renewed attempt to illustrate the emergence of complexity of the biofilm community and reveal the mechanism of producing a macroscopic microbial biofilm pattern from the microscopic microbial cells' interaction. These studies may not only provide a more reasonable physical description on microbial biofilms, but also finds important engineering instructions.

Keywords: Biofilm; Microbial colony; Nonlinear interaction; Structure; Fractal

1. Introduction

Microbial biofilms are encountered in a wide variety of applications, including traditional industrial processes, such as various biochemical operations, wastewater treatment, pipes for water supply and sewers, and various aqueous environments, etc. The importance of biofilms in a wide variety of applications has provided motivation for numerous investigations on its mechanisms during the past several decades. A substantial number of efforts have been devoted to understanding and modeling the microbial colonies and biofilms. Many empirical correlations are now available in the literature [1]. Existing researches show that microbial biofilms are remarkably heterogeneous virtually in all parameters that can be measured accurately and reproducibly [2–4]. The emergence of these heterogeneities: structural, physiological, ecological, electrical, metabolic, etc. have not been well understood yet. Due to the multiplicity and complexity of variables

Abbreviations: 2D, two dimension; CA, cellular automaton; DLA, diffused-limited aggregation; IbM, individual-based model; Eq., equation

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Nomenclature

$b_1 \sim b_4$	constants
f_i	functions introduced in Eq. (17)
F_u, F_s	fluctuation forces introduced in Eqs. (15) and (16)
h	mass transfer coefficient, mg/m^2 h
$J, \bar{J}$	flux, mg/m^3 h
l	characteristic length, m
p	exponential coefficient
S	function defined in Eq. (15)
t	time, s
T	function introduced in Eq. (16)
u	velocity, m/s
$\boldsymbol{W}_s$, $\boldsymbol{W}_u$	potential functions of stable modes and unstable modes
x	driving force
$\mathbf{x}$	driving force vector
δ_t	boundary layer thickness

Greek Symbols

ρ	probability density
$\boldsymbol{\sigma}, \bar{\boldsymbol{\sigma}}$	constants
η	constants
λ	damping coefficient
α	controlling parameter
β	the fraction
$\boldsymbol{\Phi}, \bar{\boldsymbol{\Phi}}$	potential functions
ζ	constant
ξ	normalized concentration difference variable
μ	constant
ψ	constant
Ω	area unit

Subscripts

0	reference state
S	bulk
s, s', s'', s'''	stable modes
u, u', u'', u'''	unstable modes

influencing the biofilm systems and strong nonlinear features [3,4], a complete theory on the formation of biofilms is still far from being created.

In classical theories, the predictions of biofilm formation and structure remained principally an empirical art, and traditional modeling efforts typically used a linearized or discrete approach or differential equations [5]. For example, the physical phenomena were analyzed based on one-dimensional (1D) assumption, and the mass transfer rate was obtained for a given biofilm thickness by assuming the uniform density [6], i.e., the cells had no effect on the formation of adjacent cells. Consequently, possibly important interactions between cells were ignored. However, for practical biofilm process, interactions did occur between adjacent cells [7,8]. Also, the traditional 1D model assumptions often conflicted with observations of heterogeneous biofilm with channels, holes or cavities [3,4]. More severely, many available theories could not effectively