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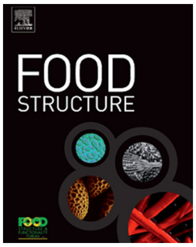

Review

Multi-scale properties of protein-stabilized foams

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ABSTRACT

Protein-stabilized foams can be analyzed into 4 levels. Level 1 corresponds to the nanometer range of molecules. Level 2 is represented by the gas/liquid interfaces and thin liquid films. Level 3 is defined by the size of the gas cells that form the foam and spans from micrometers to a millimeters. Level 4 is when the foam is considered a continuum. The objectives of this article are: to revise the techniques used to analyze foams and the gathering of quantitative information, and to review current efforts into improving our knowledge of the role of proteins in foams and their structures.

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Abbreviations: CLSM, confocal laser scanning microscopy; DB, diminishing bubble; G-function, nearest-neighbor distribution function; GLCM, gray level co-occurrence matrix; ITA, image texture analysis; K-function, second-moment distribution function; LM, light microscopy; MRI, magnetic resonance imaging; SEM, scanning electron microscopy.

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Nomenclature

Notation

$a(t)$	scaling factor in Eq. (18)
a	Frumkin-type intermolecular interaction parameter
A	interfacial area, m^2
B	fitting parameter in Eq. (20)
$b(t)$	scaling factor in Eq. (18)
b	radius of curvature of the drop/bubble apex in Eq. (3), m^{-1}
c	capillary constant in Eq. (3), m^{-2}
c	protein bulk concentration in Eq. (2), mol/L
c_0	initial bulk protein concentration, mol/L
d	distance, pixels
D	protein diffusion coefficient in the bulk, m^2/s
D_{32}	Sauter mean bubble diameter, m
G^*	complex shear modulus, Pa
G'	storage modulus, Pa
G''	loss modulus, Pa
G_0	elastic modulus, Pa
G_{surf}	surface free energy, J
h	distance
h_i	distance of a point i to its nearest neighbor
I	indicator function, dimensionless
i	intensity level of a pixel within an image
j	intensity level of a pixel within an image
K	film permeability coefficient, cm/s
m_c	weight of the continuous phase, kg
m_f	weight of the foamed dispersion, kg
n	empirical parameter in Eq. (22)
P_{atm}	atmospheric pressure, atm
p	fitting parameter in Eq. (20)
q	fitting parameter in Eq. (20)
R	bubble radius, m
r	film radius, m
R	ideal gas law constant in Eq. (7)
R_0	bubble radius at $t = 0$, m
R_{32}	Sauter mean bubble radius, m
R_t	bubble radius at $t = t$, m
$\bar{R}$	mean bubble radius, m
T	temperature, °C
t	time, s
t'	dummy integration variable

Greek letters

ε_0	limiting Gibbs' elasticity, N/m
φ	phase angle, rad
$\dot{\varepsilon}$	shear strain rate, 1/s
ε	surface dilatational modulus, N/m
ε'	elastic modulus, N/m
ε''	viscous modulus, N/m
μ_{eff}	effective viscosity, Pa s
ϕ	gas hold-up or volume fraction of the dispersed phase, dimensionless
ϕ_c	critical volume fraction of the dispersed phase, dimensionless
α	dimensionless prefactor in Eq. (15)
γ	interfacial (surface) tension, N/m
ΔP	pressure difference, Pa
θ	angle of the tangent to the drop/bubble profile in Eq. (3), rad
θ	direction defining the GLCM
ξ	empirical parameter in Eq. (22)
ω	frequency, 1/s
ω	mean molar area defined as the weighted average over all protein states in the interfacial layer in Eq. (7), m^2/mol
ω_0	partial molar area of the solvent molecules, m^2/mol
Γ	protein adsorption, mg/m^2
β	factor in Eq. (19), dimensionless
σ	shear stress, Pa
σ_y	yield stress, Pa

1. Introduction

Food products include a wide variety of ingredients used in their manufacture. This encompasses basic raw materials such as sugar, flour and oils, as well as more elaborate ones, for example, emulsifiers and preservatives. Some food products that contain different but significant levels of a gas include soufflés, whipped cream, mousses, ice cream, popcorn, bread, cakes, some biscuits, waffles, pancakes, aerated chocolate bars, meringues, marshmallow, carbonated soft drinks, cornflakes, milkshakes, etc. The key point is that most of them would not exist if it were not for the bubbles present in their structures.

An increasing academic and industrial interest to study food foams and aerated food products comes from the attributes provided by bubbles. Campbell and Mougeot (1999) had listed some properties imparted by bubbles: density reductions, rheology and texture changes, appearance and mouthfeel modifications, surface area increments, improved digestibility and shelf-life due to increased porosity, and flavor