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Review

Recent developments on fractal-based approaches to nanofluids and nanoparticle aggregation

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ABSTRACT

The properties of nanoparticles and its aggregation as well as convective heat transfer of nanofluids have received great attentions over the last few decades. It is well certified that nanoparticles and its aggregation can be successfully described by fractal theory and technology. In this review, the fractal properties of nanoparticle and its aggregation are firstly introduced, and then the recent investigations on the fractal models and fractal-based approaches that applied for effective thermal conductivity, convective heat transfer, critical heat flux and subcooled pool boiling of nanofluids, fractal clusters and yield stress property of nanoparticle aggregation are summarized.

Contents

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Nomenclature

A	total area of nanoparticles
c	empirical constant in Eq. (18)
c_p	specific heat at constant pressure
D	fractal dimension of nanoparticle
D_a	fractal dimension of active cavity
D_c	fractal dimension of aggregate
$d_{c,\max}$	maximum diameters of active cavity
$d_{c,\min}$	minimum diameters of active cavity
d_E	Euclidean dimension
d_f	diameter of base liquid molecule
g	gravity acceleration
h	heat transfer coefficient
I	scattered light intensity
Ja^*	Jakob number
k	thermal conductivity
k_B	Boltzmann constant
M	mass of a fractal object
m	constant in Eq. (41)
m_a	total mass of particles aggregate
m_p	dispersed particle mass
N	number of particle
Nu	Nusselt number
Pr	Prandtl number
q	heat transfer
Q	scattering vector
R	cumulative probability
R_a	gyration aggregate radius
Ra	Rayleigh number
Re	Reynolds number
r_p	single particle radius
T	temperatures
t_p	aggregation time constant
T_s	saturation temperature of liquids
W	stability ratio
X	backbone fractal dimension

Subscripts

a	aggregate
av	average
c	convection
eff	effective
f	fluid
h	heating
min	minimum
max	maximum
p	particle
s	stationary
t	total
w	wall

Greek letters

α	thermal diffusivity
γ_1	volumetric thermal expansion coefficient
δ_T	thermal boundary layer thickness
ε	measured scale
θ	contact angle
λ	particle size
μ	yield stress
ξ	dimensionless coefficient
ρ_p	nanoparticle density
ρ_g	vapor density
σ	surface tension of liquid
υ	kinematic viscosity
ϕ	volume fraction
ϕ_{in}	volume fraction of particles in aggregates

1. Introduction of nanoparticle and fractal geometry

Nanoparticles are ultrafine particles, in which the particle is thought as a small object that behaves as a whole unit of its transport and properties. Since the unique properties of the nanoscale, nanoparticles have been extensively used in a variety of applications, such as medicine, optics, electronics, manufacturing, materials, solar cells and catalysts [1–6]. Fluids with suspended nanoparticles are termed as nanofluids by Choi and Eastman [7]. There is a growing interest in experimental, theoretical and numerical investigations on yield stress property of nanoparticle aggregate and the thermal conductivity of nanofluids from theoretical perspectives to engineering applied science [8–11].

There are different views about the effect of nanoparticles on the fluid composites. On one hand, a large amount of works reported that the effective thermal conductivity of liquids with suspension of nanoparticles are anomalously larger than that of conventionally nanoparticle free heat transfer fluids [12–18]. Recently, Keblinski et al. [19] collected experiment data from a wide range of published articles and summarized how the relative increase in the thermal conductivity as a function of the volume fraction of nanoparticles. Also see Table 1, in which some lage enhancement, 6.55–40%, could be found after adding a volume fraction of 0.1–5% nanoparticles. For the case of a lower particle loading, adding 0.00026% of volume fraction nanoparticle result in 21% thermal conductivity enhancement [20]. On the other hand, some studies do not exhibit anomalous enhancements of the thermal conductivity. For instance, Putnam et al. [21] experimentally observed that the largest increase in thermal conductivity is 1.3% for Au particles of diameter 4 nm suspended in ethanol at the volume fraction of 0.018%. Utomo et al. [22] found that TiO_2 and Al_2O_3 nanofluids do not show unusual enhancement in thermal conductivity. Buongiorno et al. [23] performed a study of nanofluids using a variety of experimental approaches, and their results suggested that nanoparticles could not enhance the thermal conductivity substantially. Hence it can be seen that the intrinsic mechanism for enhancement in the thermal conductivity of nanofluids should be further analysed from theoretical aspect.

However, the macroscopic theory of heat transport in composite materials is failed to nanofluids [21,37–40], such as effective medium theory. And thus a generally accepted theory or modelling for explaining the mechanisms of enhancing thermal conductivity using nanoparticles is necessary [41–47]. Keblinski et al. [48] suggested that the particle size, liquid-particle interface and the clustering of nanoparticles are major enhancement factors compared to Brownian motion of nanoparticles. They also pointed out that it is important to characterize the distribution of nanoparticles in liquid by scattering technique. A complete particle distribution function is essential for evaluating the enhancement of thermal conductivity that produced by the coherent heat transport between particles separated by thin liquid layers [49–52].

As claimed by some researchers, the uniform distribution assumption is not capability to characterize most behaviours of nanoparticle aggregation [53,54]. In reality, particles in nanofluids