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Heat transfer and pressure drop correlations of nanofluids: A state of art review

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ABSTRACT

Nanofluids, a new class of thermo-fluids engineered by the stable suspension of nano-sized metallic and non-metallic entities (particles, fibers, tubes, droplets) in base fluids with optimized thermal conductivity, demonstrate the advantages of efficient thermal management with miniaturization. However, thermal conductivity intensification is not the only mechanism responsible for the enhanced thermal efficiency of the nanofluids, other factors including gravity, inter-phase frictional force, sedimentation, dispersion, ballistic phonon advection, non-uniform shear rate, nanoparticle migration induced by viscosity gradient and layering at the solid-liquid interface also play a significant role. The hydrothermal characteristics of nanofluids are determined by the net influence of the relative modifications in the thermophysical properties of the nanofluids which are sensitive towards multiple parameters including particle morphology (size and shape), material and concentration, base fluid properties and pH value, fluid temperature and additives. Consequently, conventional correlations remain unsuccessful in explaining idiosyncrasies of nanofluids and a few studies contributed to the formulation of heat transfer and friction factor correlations for multifarious combinations of nanofluids and operating conditions. Although a group of researchers validated the applicability of the classical friction factor models for nanofluids, nevertheless, a few contradictory studies emphasized that penalty in pressure drop effectuated by nanoparticles is sufficiently large to be neglected. The primary objective of the present manuscript is to review the research progress in the development of heat transfer and pressure drop correlations for nanofluids under miscellaneous geometrical, operating and boundary conditions. Furthermore, a comprehensive comparison of the few heat transfer correlations proposed under identical construction and flow conditions has been also presented.

1. Introduction

Thermal management is one of the prime technical challenges encountered by high-tech industries today. The paradigm shift in mechanical designs to satisfy the appetite of speed, power, and miniaturization, requires adequate thermal management techniques for efficient operations. However, the existing design solutions such as engineered surface texturing, fins and microchannels [1–6], have already attained their ultimate limits. Moreover, the growth of carbon emitting processes i.e. heating, ventilation, and air-conditioning, has adversely intensified global warming way more than ever before [7]. In such a predicament situation, nanofluids offer compact, green approach to answer high thermal loads as well as climate chaos.

Nanofluids, nanotechnology-based a new class of thermal fluids with augmented thermal conductivity superior to both of the hosting fluid and suspended particles, was first introduced by Choi (1995) after his successful attempt to synthesize a colloidal mixture of conventional fluids and nanoparticles [8]. Though, the basic concept behind this heat transfer optimization technique with metallic additives was originally coined by Maxwell in 1873 [9], but the undesirable features instigated by micron-sized particles i.e. rapid sedimentation, clogging, erosion and immense pressure drop, renounced the practicality of technology until advancements in colloid and interface science allowed its revision with nanoparticles. In contrast to micron-sized particles, nanoparticles exhibit 1000 times higher particle surface to volume ratio and hence offer better suspension stability, improved microchannel heat transfer capacity with least particle clogging, flexible properties and enlarged particle effective surface area for maximum inter-phase heat exchange. Moreover, high thermal conductivity, negligible pressure drop and mechanical deterioration make nanofluids extremely feasible for numerous industrial applications i.e. microelectronics, transportation, space technology, biomedical, nuclear, solar and refrigeration systems [10–17].

A substantial amount of research has been carried out in past years to explore nanofluids' preparation techniques, characterization, modeling, convection, boiling heat transfer and applications [10–43].

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Nomenclature

A	Wave amplitude [m]
AR	Aspect ratio [Dimensionless]
a	Elliptic cylinder major axis [Dimensionless]
B_r	Brinkman number [Dimensionless]
C_r	Curvature ratio [Dimensionless]
C_p	Specific heat [J/kg. K]
CFD	Computational fluid dynamics [Dimensionless]
CHF	Constant heat flux [W/m^2]
CWT	Constant wall temperature [K]
D	Channel/tube diameter [m]
DPM	Discrete phase model [Dimensionless]
d_p	Nanoparticle diameter [nm]
d	Nozzle diameter [m]
e	Wire diameter [m]
f	Darcy friction factor [Dimensionless]
$\underline{\vee}$	Function [Dimensionless]
G_r	Grashof number [Dimensionless]
GNP	Graphene nano-platelets [Dimensionless]
H	Channel/cylinder height [m]
Ha	Hartmann number [Dimensionless]
H/d	Jet to target ratio [Dimensionless]
h_{fg}	Latent heat [J/kgK]
h	Convective heat transfer coefficient [W/m^{2}K]
K_b	Boltzmann constant [J/K]
k	Thermal conductivity [W/mK]
L	Channel/tube length [m]
l	Wavelength [m]
$MWCNT$	Multi-walled carbon nanotubes [Dimensionless]
N_b	Brownian diffusion parameter [Dimensionless]
N_t	Thermophoresis parameter [Dimensionless]
Nu	Nusselt number [Dimensionless]
Pr	Prandtl number [Dimensionless]
P	Pitch [m]
Pe	Peclet number [Dimensionless]
Q	Heat flux [W/m^2]
Ra	Rayleigh number [Dimensionless]
Re	Reynolds Number [Dimensionless]
S_{te}	Stefan Number [Dimensionless]
Sb_{in}	Modified inlet subcooling parameter [Dimensionless]
SANSS	Submerged arc nanoparticles synthesis system [Dimensionless]
TT	Typical twisted tape [Dimensionless]
TA	Modified twisted tape [Dimensionless]
T	Temperature [K]
T_0	Reference temperature (273 K)
V	Volumetric flow rate [m^3/s]
VOF	Volume of fluid model
x	Characteristic length [m]
y	Twist ratio of insert [Dimensionless]

Greek Symbols

α	Area modified factor [$^\circ$]
β	Coefficient of thermal expansion [1/K]
ε	Eccentricity [Dimensionless]
ρ	Density of fluid [kg /m^3]
φ	Particle volume fraction [Dimensionless]
ψ	Particle mass fraction [Dimensionless]
τ	Shear stress [Pascal]
μ	Viscosity [kg/ms]

Subscripts

AR	Aspect ratio
avg	Average
bf	Base fluid
$Bulk$	Bulk
con	Convection
f	Fluid
g	Gas phase
h	Hydraulic
hw	Hot wall
hl	Helical
i	Inside
m	Mean
l	Liquid phase
nf	Nanofluid
p	Particle
pcm	Phase change material
0	Reference
s	Channel/tube surface
v	Laminar sublayer
w	Horizontal velocity
$wall$	Wall
wr	Wire coil
x	Characteristic length

Despite ongoing extensive research for more than two decades, the underlying physical mechanism behind the anomaly high thermal efficiency of these innovative fluids is still ambiguous [34,42,44,45]. However, nanofluids' thermal conductivity has been enormously expressed as the key parameter characterizing nanofluids' intensified hydrothermal attributes. Multiple theories have been postulated in literature to develop a physical understanding of the thermal conductivity amplification of nanofluids. Liu et al., Goodarzi et al., and Nieh et al. [46–49] explained this thermal conductivity augmentation of nanofluids as a consequence of nanoparticles' Brownian motion along with thermophoresis and diffusiophoresis for the case of laminar flows, whereas eddy-induced particle motion contributes primarily in turbulent flows. Keblinski et al. [50] proposed that in addition to particles' Brownian motion, liquid layering encapsulating liquid-particle interface, nature of heat transfer inside the particles and nanoparticles' clustering play a significant role in optimizing the thermal conductivity of nanofluids. Nieh et al. [47] reported that particles' Brownian motion incite inter-phase heat transmission which results in layered structures surrounded by particles. Wang et al. [51] attributed particles' Brownian motion actuated by macroscopic Vander Waals, electrostatic and stochastic forces, for the heat transfer improvement. Additionally, they highlighted contributions of particle chain structures for thermal conductivity escalation. Ghadimi et al. [52] proposed dynamic and static models to explain heat transfer by nanofluids. In static model, similar to Maxwell and Hamilton-Crosser model, conduction is the only mode of heat transmission as particles possess zero relative velocity, whereas, in the dynamic model, particle-particle and particle-liquid interactions stimulate heat transfer. Furthermore, particle driven natural convection along with convection induced by electrophoresis and thermophoresis are also possible explanations for nanofluids' higher thermal conductivity [42]. In addition to thermal conductivity, the past surveys also demonstrate that factors including gravity, the frictional force between particle-liquid phases, sedimentation, dispersion, ballistic phonon advection, non-uniform shear rate, particle migration induced by viscosity gradient, also play a significant role in determining heat transfer potential of nanofluids [53–59]. A number of investigations on the hydrothermal characteristics of nanofluids demonstrated that the idiosyncratic features of the nanofluids renounced the applicability of