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Effective thermal conductivities of a novel fuzzy carbon fiber heat exchanger containing wavy carbon nanotubes

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ABSTRACT

A novel fuzzy carbon fiber heat exchanger (FFHE) is proposed in this study. The novel constructional feature of the FFHE is that the sinusoidally wavy carbon nanotubes (CNTs) are radially grown on the outer circumferential surface of the hollow cylindrical carbon fiber (HCF) heat exchanger. The effective thermal conductivities of the FFHE have been estimated by employing the method of cells (MOC) approach and the effective medium (EM) approach. The present study reveals that if the amplitudes of the radially grown sinusoidally wavy CNTs are parallel to the axis of the HCF then the effective axial thermal conductivity of the FFHE is significantly improved over that of the bare HCF heat exchanger (i.e., without CNTs). On the other hand, if the amplitudes of the radially grown wavy CNTs are transverse to the axis of the HCF, the effective transverse thermal conductivity of the FFHE is significantly improved over that of the bare HCF heat exchanger. It is also found that the CNT/polymer matrix interfacial thermal resistance does not affect the effective thermal conductivities of the FFHE. The present investigation suggests that exploiting the waviness of radially grown CNTs on the HCF a truly multifunctional and promising heat exchanger can be developed for advanced technological applications.

1. Introduction

The discovery of carbon nanotubes (CNTs) [1] has stimulated a tremendous research on the prediction of their remarkable mechanical and thermal properties. Many research studies reported that the axial Young's modulus of single-walled CNTs is in the TeraPascal range [2–7]. As nanoscale graphite structures, CNTs are of great interest not only for their mechanical properties but also for their thermal properties. CNTs exhibit thermal properties that are remarkably different from other known materials and are expected to be a promising candidate in many advanced applications. Hone et al. [8] estimated the thermal conductivity of a single-walled CNT at room temperature based on the measured thermal conductivity of high-purity mats of tangled CNT bundles and found that its value lies in the range of 1750–5800 W/mK. However, due to the high thermal contact resistance between CNTs, the experimental results obtained for single-walled CNT mats are usually two orders of magnitude lower than for single CNTs [8]. The thermal conductivity of a single-walled CNT was evaluated by Yu et al. [9] using a suspended microdevice on which a single CNT was grown by chemical vapor deposition technique. Despite some uncertainty on the actual CNT diameter, the thermal conductivity was evaluated to be higher than 2000 W/mK, and it decreases with decrease in the temperature. Li et al. [10] introduced a non-contact Raman spectra shift method to measure the thermal conductivity of single-walled and multi-walled CNTs. In their study, the measured values of the thermal conductivities of the single-walled and multi-walled CNTs are 2400 W/mK and 1400 W/mK, respectively. Samani et al. [11] estimated the thermal conductivity of individual multi-walled CNTs using a pulsed reflectance technique. Their study reported that the intrinsic thermal conductivity of an individual multi-walled CNT with diameter 150 nm and length 2 μm at room temperature is 2586 W/mK.

In addition to experimental studies, theoretical thermal conductivities measurements of CNTs have also been reported. Che et al. [12] employed molecular dynamics simulation to estimate the thermal conductivity of a single-walled CNT and suggested that it is dependent on the concentration of vacancies and defects in CNTs. Their predicted value is nearly 2980 W/mK along the CNT axis which is even higher than that of good conventional thermal conductors such as diamond. Berber et al. [13] determined the thermal conductivity of single-walled CNTs and its dependence on the temperature by combining equilibrium and non-equilibrium molecular dynamics simulations. Their results indicated an unusually high value of the thermal conductivity as 6600 W/mK for an isolated armchair (10, 10) CNT at room temperature. Kim et al. [14] reported that the thermal conductivity of an individual multi-walled CNT with the diameter of 14 nm is more than 3000 W/mK at room temperature. Shelly et al. [15] performed

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Nomenclature

Abbreviations

CNT	carbon nanotube
EM	effective medium
FFHE	fuzzy carbon fiber heat exchanger
HCF	hollow cylindrical carbon fiber
MOC	method of cells
PMNC	polymer matrix nanocomposite

Notations

A	amplitude of the CNT wave [m]
a_k	Kaptiza radius [m]
b	width of the cell [m]
b_γ	width of the subcell [m]
d, a	outer diameter and radius of the HCF in the FFHE [m]
d_o, r_o	outer diameter and radius of the FFHE or the bare HCF heat exchanger, respectively [m]
d_i, r_i	inner diameter and radius of the FFHE or the bare HCF heat exchanger, respectively [m]
d_n	diameter of the CNT [m]
h	height of the representative unit cell [m]
h_β	height of the subcell [m]
K_i	effective thermal conductivities of the FFHE [W/mK]
K^f	thermal conductivity of the HCF [W/mK]
K^n	thermal conductivity of the CNT [W/mK]
K_i^{nc}	effective thermal conductivities of the unwound PMNC lamina containing straight CNTs [W/mK]
$\overline{K}_i^{NC}$	effective thermal conductivities of the unwound PMNC lamina containing wavy CNTs [W/mK]
K^p	thermal conductivity of the polymer [W/mK]
K_i^{PMNC}	effective thermal conductivities of the PMNC [W/mK]
L	length of the FFHE [m]
l	length of the subcell [m]
L_N	length of the straight CNT [m]
L_n	straight distance between the two ends of the CNT wave [m]
L_{nr}	running length of the CNT wave [m]
N	number of sinusoidally CNT waves [–]
$(N_{CNT})_{max}$	maximum number of radially grown aligned CNTs on the outer circumferential surface of the HCF [–]
q_i	heat flux in the unwound PMNC [W/m^2]
$\overline{q}_i^{(\beta\gamma)}$	average heat flux in the $\beta\gamma$-th subcell [W/m^2]
R_k	interfacial thermal resistance between the CNT and the polymer [m^{2}K/W]
T	temperature [K]
[T],[T$_1$],[T$_2$]	transformation matrices [–]
V	volume of the FFHE [m^3]
V^i	volume of the i-th phase [m^3]
$(V_{CNT})_{max}$	maximum volume fraction of the CNT in the FFHE [–]
v_f	volume fraction of the HCF in the FFHE [–]
v_n	volume fraction of the CNT in the PMNC [–]
v_p	volume fraction of the polymer in the PMNC [–]
$V_{\beta\gamma}$	volume of the $\beta\gamma$-th subcell [m^3]
θ	angle between the radial axis (3'-axis) along which the wavy CNT is grown and the 3-axis in the 2–3 plane
λ_n	wavelength of the CNT wave [m]
ϕ	angle between the CNT axis at any point and the 3 or 3'-axis which is varying over the linear distance between the CNT ends
ω	wave frequency of the CNT wave [m^{-1}]

Superscripts

f	carbon fiber
p	polymer
nc	unwound polymer matrix nanocomposite containing straight CNTs
NC	unwound polymer matrix nanocomposite containing wavy CNTs
PMNC	polymer Matrix Nanocomposite

Subscripts

n	CNT
p	Polymer

non-equilibrium molecular dynamics simulation to determine the thermal conductivity of single-walled CNTs. Their study indicates that the thermal conductivity of CNTs increases with the increase in the lengths of CNTs and then stabilized for the longer ones. Wei et al. [16] determined the thermal conductivity of single-walled CNTs with Stone–Wales defects using non-equilibrium molecular dynamics method. They reported that with the same radius, the thermal conductivity of an armchair CNT is higher than that of the zig-zag CNT and the shorter CNT is more sensitive to the defects than the longer CNT.

Both experimental measurements and theoretical calculations agree that a CNT has higher thermal conductivity or even higher than that of diamond. The quest for utilizing such exceptional thermal properties of CNTs created enormous interest among the researchers for developing highly conductive two-phase CNT-reinforced nanocomposites. For example, Choi et al. [17] produced nanotube-in-oil suspensions and measured their thermal conductivity. They compared their test results with other nanostructured materials dispersed in fluids and reported that CNTs provide the highest thermal conductivity enhancement, opening the door to a wide range of CNTs applications. Biercuk et al. [18] demonstrated that CNT-reinforced polymer composites have enhanced thermal conductivity, and CNTs are much more effective as reinforcements than carbon fiber reinforcements. Bryning et al. [19] reported the thermal conductivity measurements of the purified CNT-reinforced composites prepared by using suspensions of single-walled CNTs in N-N-Dimethylformamide and surfactant stabilized aqueous single-walled CNT suspensions. Thermal conductivity enhancement is observed as 80% and 8% for N-N-Dimethylformamide processed composites and surfactant processed samples, respectively, at 1 wt% single-walled CNTs loading. The difference in the enhancement of the thermal conductivity is attributed to a ten-fold larger CNT/matrix interfacial thermal resistance in surfactant processed composites compared to N-N-Dimethylformamide processed composites. Haggenmueller et al. [20] investigated the thermal conductivities of single-walled CNT/polyethylene nanocomposite in terms of single-walled CNTs loading, polyethylene crystallinity and polyethylene alignment. They reported that the thermal conductivity of single-walled CNT/high density polyethylene is higher than that of single-walled CNT/low density polyethylene. They attributed this effect primarily due to the aligned polyethylene matrix which eventually reduces the interfacial thermal resistance between CNTs and high density polyethylene. Yang et al. [21] investigated the dispersion behavior and the thermal conductivity of the CNT-reinforced composite. Their results showed that the thermal conductivity of the CNT-reinforced composite enhanced up to 120% with 5 wt% CNTs loading. Edtmaier et al. [22] presented an evaluation of the thermal conductivity and the coefficient of thermal expansion as a function of multi-walled CNTs concentration and the presence of active elements cobalt, molybdenum or nickel in the silver