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Scale effects on evaporative heat transfer in carbon nanotube wick in heat pipes

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ABSTRACT

The heat transfer capability of conventional materials like copper or devices like heat pipes are challenged by the growing trend of miniaturization of integrated circuit and exponentially increasing density of heat generation. Vertically aligned carbon nanotube (CNT) array has been recognized as a promising wicking structure of new generation heat pipes for higher heat transfer capability and more compact size. In contrast to conventional grooved or powder-sintered wicks, the CNT wick behaves differently due to the scale effects, which has been investigated through physical models extracted from its working conditions. The influence by the velocity slip of the liquid at the CNT wall is evaluated, which shows that the slip leads to considerable enhancement of the flow near the CNT wall. Calculation of the overall flow resistance indicates higher permeability due to the slip. The gaps between CNTs create exceptionally high capillary pressure due to the nanoscale pores. It proves to be apparently superior to conventional structures in micrometer scale. The effective thermal conductance of the CNT wick benefits from the extremely high thermal conductivity of CNTs thanks to the non-Fourier conduction. The effects emerged in the non-evaporating and thin-film regions are analyzed, which clearly shows that the evaporation at the liquid-vapor interface is dramatically affected by these nanoscale effects. The present study on scale effects identifies the advantages of the CNT wick in capillary ability, effective conductivity, and evaporative flux, etc. Meanwhile, it also reveals the disadvantage of relatively lower dry-out limit of the CNT wick.

1. Introduction

The boosting development of electronic technologies has enabled smart devices that are smaller but more powerful. A growing challenge under such a trend is to develop matching cooling technologies with higher heat transfer capability but in more compact size. In order to address this challenge, some attempts have been made to enhance the traditional materials and cooling devices such as heat pipes and vapor chambers by introducing carbon nanotubes (CNTs) [1,2], microscale or nanoscale pillar array [3,4], and other nanoscale enhancing structures [5], etc. A common feature of these approaches is the adoption of micro- or nanoscale structures, for the purpose of taking advantage of their superior interfacial and thermal properties over traditional materials. At the same time, introducing the nanostructures also leads to some unusual effects due to the length scales. A better understanding of the heat and mass transfer mechanism in the micro- and nanoscale structures considering the scale effects is essential for their further developments aimed at advanced commercial applications.

It is well recognized that the fluid flow and heat transfer in nanoscale devices exhibit some fundamentally different behaviors compared with those in macroscopic scale. Such behaviors, termed as scale effects, could be the sources of the exceptional properties to achieve desired performance gains. A significant enhancement of water flow through carbon nanotube membrane has been observed due to the velocity slip at nanotube walls [6,7]. The velocity of liquid was measured to be over five orders of magnitude larger than that predicted by regular no-slip flow modeling [7]. The weak frictional interactions were thought to be induced by the ordered molecular arrangements and the nanoscale confinements. Such a slip effect is apparently a non-negligible factor in the liquid flow inside a carbon nanotube array. The extremely high intrinsic thermal conductivity of carbon nanotube [8] is essentially also a result of the scale effect. The heat conduction through the carbon nanotube is largely transferred by the ballistic propagation of phonons instead of the diffusive propagation process. In addition to the extremely high thermal conductivity along the axial direction, this mechanism also leads to strong anisotropic thermal transportation,

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Nomenclature

A	area
A_{unit}	projected area of a CNT unit
D_{CNT}	diameter of CNT
h_{fg}	latent heat
K	permeability
K'	dimensionless permeability
Kn	Knudsen number
$\vec{k}$	unit vector along the CNT axis
L_{CNT}	length of CNT
L_w	wicking length
p_{cap}	capillary pressure
p_{sat}	saturation pressure
p_V	vapor pressure
$\dot{q}''$	heat flux
R	thermal resistance
Re	Reynolds number
L_{slip}	slip length
U	characteristic velocity
u_{slip}	slip velocity
u_{tan}	tangential velocity along the wall
Δp	pressure difference
δx	pitch between CNTs
μ	dynamic viscosity
v	kinetic viscosity
ϕ	diameter of CNT or micro-pillar
ρ	density
σ	surface tension

both of which cannot be precisely described by the conventional Fourier conduction law. Furthermore, the evaporation at nanoscale is affected by the intermolecular forces such as the disjoining pressure. As the thickness of liquid film reaches nanometer scale, a part of the liquid is "adsorbed" on the solid surface which makes it unable to evaporate; another small part of it is showing vast evaporation rate instead, in which the heat flux may approach the upper limit allowed by kinetic theories according to molecular dynamics simulations [9]. Such effects are not as significant as for macroscopic problems, since they only occupy a very small portion of the total area. However, it may become the dominant factor for the nanoscale flow. And in wicks consisting of CNT array, the nanoscale effects may accumulate and finally lead to profound influence on the thermal performance.

There have been extensive researches in the last decade regarding fundamental aspects of the scale effects via theoretical modeling under idealized conditions. The interactions between the CNT wall and various kinds of liquid have been investigated by molecular dynamics (MD) or continuum method [10–13], through which the slip flow of water have been confirmed. The Fourier conduction in a single carbon nanotube [14] and the conjugate heat transfer between CNT and other liquid have been studied [15], in which the MD method and Boltzmann phonon transport equations were widely adopted. The evaporation at nanometer scale and the influences of the disjoining pressure and non-equilibrium/non-local effects have been incorporated [16,17] to account for the deviations from the classical kinetic theory.

On the other hand, in the engineering applications that utilizes carbon nanotube or micro-/nanoscale pillar array wicks, the practical implications of the scale effects have not been put much attention with respect to the scale effects in the objects such as the CNT wicking structure. As stated above, those effects could be quite critical in nanoscale, which in turn also leads to substantial influence on the heat and mass transfer performance in macroscopic scale. The liquid flow through a CNT array has been normally modeled as regular liquid flow problem [4,18,19]. At the interfaces between the CNT wall and the liquid, the no-slip boundary condition commonly used in macroscale was applied. Although some local wetting effects in the liquid evaporation in the wick have been taken into account, for instance the extended evaporation area due to the meniscus [20], the evaporation rate was still calculated from the equations for the bulk liquid [21]. The thermal conduction of the CNT has been modeled using conductivity for bulk CNT materials [22], without considerations on the ballistic phonon transportation as observed in nanotubes [23].

Due to the significance of the scale effects as summarized above, it is of interest to examine their actual influence on the nanoscale wicking structures. Therefore, this work presents an investigation on the wick consisting of aligned carbon nanotube array, with special considerations focusing on the effects of interfacial velocity slip, nanoscale wetting and capillarity, and evaporation corrections. The considerable contribution by the scale effects have been confirmed through comparisons with the corresponding calculations by the regular method employing the macroscopic laws only. Herein the advantages and potential applications of carbon nanotube wick in heat pipes will be discussed.

2. Model and methodology

The working principle of a heat pipe [24] is schematically shown at the left part of Fig. 1. The heat absorbed from the evaporator section mainly turns to the latent heat of the working substance and then transfers to and releases at the condenser section. Since heat transfer through the transportation of mass is the dominant mechanism, the wick becomes the essential component, which offers the capillary pressure to drive the circulation of the working substance. Conventional wicks use grooves, meshes or sintered particles to create channels or pores in the size of micrometers, while the CNT wick consists of aligned CNT array grown directly on the inner wall substrate, as shown at the right part of Fig. 1. The wicking effect is provided by the capillary action from the nanoscale gaps between the tubes. Typical CNT array consists of CNTs with mean diameter of 10–500 nm, mean length of 50 nm–1 mm, and mean spacing between tubes of 3–8 times of the diameter. The corresponding effective porosity is about 90–99%. These characteristics of CNT wicks give it the potential to achieve more favorable performance in some aspects, by offering much higher capillary pressure, superior thermal conductance, and realizing more compact sizes.

The working performance of CNT wick is primarily characterized by its wicking capability, which can be evaluated in two folds, the ability to drive the fluid flow and the ability to transfer heat. Both the fluid flow and heat transfer are closely coupled with the scale effects introduced by the CNTs. In order to quantify the influence of the scale effects such as the interfacial velocity slip and evaporation from nanoscale pores, simplified physical model is extracted and investigated through numerical calculations.

The liquid flow across the wick of CNT forest is illustrated in Fig. 2(a) via the 2-D projection view on the substrate plane. Due to the vast number of CNTs, the flow can be treated as a periodic flow through a series of "CNT units", as presented by Fig. 2(b). In