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Effect of carbon nanofiber surface morphology on convective heat transfer from cylindrical surface: Synthesis, characterization and heat transfer measurement

T.J. Taha [a,*], B.L. Mojet [b], L. Lefferts [b], T.H. van der Meer [a]

[a] Thermal Engineering, Faculty of Engineering and Technology, University of Twente, 7500 AE, Enschede, Netherlands
[b] Catalytic Processes and Materials, Faculty of Science and Technology, University of Twente, 7500 AE, Enschede, Netherlands

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A B S T R A C T

In this work, heat transfer surface modification is made by layers of carbon nanofiber (CNF) on a 50 μm nickel wire using Thermal chemical vapor deposition process (TCVD). Three different CNF layer morphologies are made, at 500 °C, 600 °C and 700 °C, to investigate the influence of morphology on heat transfer performance characteristics. Experimental results show that a CNF layer made at 500 °C behaves like an additional heat resistance, which is attributed to the dense structure of the layer of fibers. This results in 25% lower heat transfer compared to the heat transfer performance of the bare wire. However, samples made at 600 °C, exhibit a relatively porous layer of CNFs with relatively lower thermal conductivity compared to samples made 500 °C, resulting in an enhancement of 24%. This is because the relative porous structure leads to relatively better flow permeability which reduces the thermal resistance of the layer. Samples made at 700 °C are partly covered with a dense CNFs layer and partly with an amorphous layer of carbon. Heat transfer enhancement of 34% is achieved which is attributed to the combined effect of the highly conductive layer, high effective heat transfer surface area and rough surface morphology.

1. Introduction

Advancements of current heat transfer technologies are triggered by energy, material and economic considerations, which contribute to more sustainable, efficient and cost effective systems. Both passive [1–6] and active [7–10] methods of enhancing heat transfer have been the focus of many studies in the heat transfer research community. The classical approach of enhancing heat transfer equipment is by modifying the heat transfer surface, which leads to maximizing the surface area and better hydrodynamic boundary layers.

Heat transfer surface modification – on micro-scale – plays a significant role on the current technological advancements where space, mass and power density are important. The remarkable discovery of the CNTs [11] – with extremely high thermal conductivity and mechanical properties - paved the way to harness the novel properties in many industrial applications. This novel material is a potential candidate for application areas such as electronic chips, catalyst support materials, micro-electro-mechanical systems (MEMS), evaporator walls (cryogenic refrigeration), regenerators (stirling engines, thermo-acoustic heat pumps, thermo-chemical heat pumps), where heat removal is a critical design parameter. Due to their extremely high thermal conductivity, attributed to the strength of the carbon–carbon bond within graphene layers, carbon nanotubes are considered as a novel material in heat transfer research [12–15]. This new material however has a highly anisotropic thermal conductivity. The thermal conductivity at room temperature along the a-axis (in-plane) of the graphene layer is greater than 3000 W/m K [16] while the conductivity along the c-axis (out of plane) can be as poor as 1.52 W/m K [17]. As a result, the structural arrangement of graphene layers has a tremendous influence on the thermal properties. Carbon nanostructures exist in three different graphene layer arrangements: perfect cylindrical arrangement of graphene sheets (Tubes), conical arrangement of the graphene sheet (fish-bone) and flat graphene arrangement (stacked). Fig. 1 shows the structural arrangement of the graphene layer on the CNFs produced. The black lines signify the graphene layer (one-atom thick layer)

* Corresponding author.
E-mail addresses: t.j.taha@utwente.nl, t_1915@yahoo.com (T.J. Taha).

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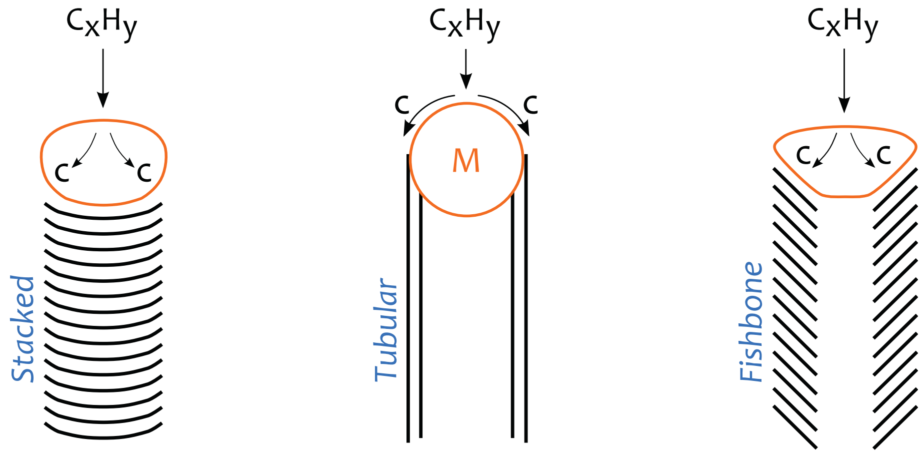

Fig. 1. Schematic illustration of the different forms of Carbon nanofibers with different graphene layer arrangement, where the black lines represent the graphene layer arrangement.

arrangement. These different structures are believed to have different effective thermal conductivities. Moreover, the thermal conductivity of carbon nanostructures is strongly dependent on the degree of crystallinity, crystallite shape, crystallite size, and presence of impurities. However, quantitative measurement of thermal transport properties of individual fibers remains challenging, due to technological difficulties associated with nano-scale experimental measurements [18].

Preliminary experimental research has shown that carbon-nano-fibers deposition may lead to both increase and decrease in heat transfer performance. Tuzovskaya et al. [19] performed experimental investigations on stainless steel and on carbon foam. CNF's on stainless steel resulted in enhancement of heat transfer ranging from 30% to 75%, while CNF's on carbon foam decrease heat transfer by 40%. It was explained that the cumulative effect of an increase of heat exchange surface area, the structural arrangement of the graphene layer and the higher crystallinity results in the overall performance of the stainless steel foam.

Kordas et al. [20] have reported an efficient chip cooling by integrating both laser patterned CNT and copper micro fin structures on a silicon chip. It was reported that micro-fin chip dissipates more power (up to ~1 W from1mm2 surface) compared to a bare chip. Similar enhancement results were reported for both CNTs and copper structures for both natural and forced convection with an enhancement of 11% and 19% respectively. However, an un-patterned CNTs layer shows poor heat transfer performance due to the dense nature of the CNTs layer hampering the flow of N_2 in the film, limiting the heat transfer only to the upper facet of the films, resulting in limited cooling capabilities. It is also suggested that by changing fin geometry, dimension and fin densities more efficient cooling can be achieved.

Zhimin Mo et al. [21] reported effective cooling for microelectronic applications using integrated CNT fins made by lithographic technique and CVD on a micro-channel surface. It was mentioned that the flow rates were decreased by 12% whereas the heating power input is increased by 23% keeping the transistor temperature 6 °C below the reference cooler. It was also suggested that self-aligned CNTs would increase the heat transfer even more than what was achieved.

The aim of the present work is to explore the influence of the morphology of carbon-nanostructured surfaces on heat transfer performance characteristic. The heat transfer performance test was made on a 50 μm diameter nickel wire by modifying the surface with a layer of carbon nanofibers-(CNFs) with varying surface morphology.

2. Materials

Polycrystalline Ni wire (99.9%, Ni270, Alloy Wire International Ltd.), made by a wire drawing mechanism, with a uniform diameter of 50 μm was used in this study to represent a differential strand of common regenerator element such as metallic foam, see Fig. 2. The surface of the wire was modified by depositing carbon nanostructural layer. High purity gases were used during the synthesis process: hydrogen (99.999%, INDUGAS), nitrogen (99.999% INDUGAS) and ethylene (99.95% PRAXAIR).

3. Experiment

3.1. CNFs layer synthesis

Three different sample synthesis procedures were used to obtain different CNFs topological structures. Prior to CNF-synthesis, the Nickel micro wire samples were pretreated under a reducing atmosphere in a 50 mm diameter vertical quartz reactor which was heated from outside by an electrical furnace. The samples were heated to 600 °C with a heating rate of 6 °C/min under a nitrogen (inert medium) stream with a total flow rate of 100 ml/min. After reaching 600 °C, 30 vol.% hydrogen was introduced in the nitrogen stream to reduce the samples for 1 h, while maintaining the total flow rate at 100 ml/min. It should be noted that all samples undergo the same pretreatment in order to have a relatively equal number of nucleation sites, which helps to determine the influence of the synthesis temperature on the morphology of the synthesized nanofibers. After the reduction pretreatment, the samples were brought to the synthesis temperature (500 °C, 600 °C and 700 °C) at a rate of 6 °C/min under a nitrogen stream with a total flow rate of 100 ml/min. The samples were further exposed to a reactive gas mixture of 20 vol.% C_2H_4, 5 vol.% H_2 and 75 vol.% N_2 at 500 °C, 600 °C and 700 °C with total flow rate of 100 ml/min. Subsequently, the samples were cooled down in N_2 to room temperature. Finally, samples were further exposed to a jet of air in order to remove any loosely attached carbon nanofibers. The samples synthesized at 500 °C, 600 °C and 700 °C with respect to the synthesis duration will be referred throughout the paper as “CNF5-[*n*]”, “CNF6-[*n*]” and “CNF7-[*n*]” respectively, where *n* stands for the synthesis duration.

3.2. Characterization of CNFs layer

The morphology of the samples was studied with high resolution Scanning Electron microscopy (HR-SEM-LEO-1550)