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Optimization of the production of carbon nanotube yarns in a continuous chemical vapour deposition and application in incandescent bulb

Igbokwe, Ezinne

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ABSTRACT

Incandescent light bulb technology in its current state is an embodiment of inefficient use of energy resources. Visible light is emitted from the tungsten wire used as filament in the incandescent bulb when it is heated to high temperatures by electrical energy. Less than 10% of the energy applied reaches the visible light wavelength. Most of the energy is radiated away in the infrared (IR) wavelength. To retain the incandescent light bulb technology, a new material with a high melting point, low vapour pressure, and the ability to radiate more in the visible light wavelength is required. Prospects of using carbon nanotubes (CNTs) as a replacement for tungsten filament in incandescent bulbs have inspired lots of research on the field emission properties of carbon nanotubes. However, a widespread application of CNTs in the macroscale has been limited because of the challenge involved in transferring its properties in the nanosize to the macroscale. The exciting prospect for the production of macroscopic CNT yarn in a continuous chemical vapour deposition (CVD) process for application in advanced technology is the focus of this study.

In this study, low-cost synthesis of spinnable CNT aerosol from methane carbon source and ferrocene catalyst in a floating catalyst chemical vapour deposition (FC-CVD) is presented. The direct spinning of as-synthesized CNT aerosol in the reactor system is used to produce macroscopic CNT yarn for application as a filament in incandescent light bulbs. The quality and quantity of CNT aerosol produced are influenced by many factors. A basic understanding of how these factors affect the quality and quantity of CNT yarns produced is an essential tool for the optimization of CNT yarn production. Statistical Design of Experiments was used to design and carry out experiments varying seven factors in two steps. From the experimental data, quadratic regression models were developed to explain the effect of synthesis conditions on the amount of

CNTs produced (quantity) and oxidation temperature (quality). Consequently, optimal synthesis parameters for the production of CNT yarns with a direct spinning system were determined. CNT yarns synthesized under the optimal conditions resulted in 3.23 g mass of CNTs produced with oxidation temperature of 438.26 °C.

Hydrogen co-feeding in CNTs synthesis from methane carbon source rarely considers the effect of the partial pressure of hydrogen, discounting it as insignificant in kinetic modelling. Therefore, to date, there is no derived kinetic model for the synthesis of CNT using methane as the carbon source with hydrogen co-feeding in an ideal plug flow reactor. In this study, the initial rate of decomposition of methane was derived as follows: $-\mathrm{r}_{CH_{4.0}} = \frac{6.475*10^{-2}e^{\left(-\frac{7330.99}{T}\right)}P_{CH_4}}{1+\sqrt{(1.28P_{H_2})}}$, where the catalytic decomposition of methane is the rate-limiting step. This indicates that an increase in the feed rate of hydrogen reduces the rate of reaction while an increase in the feed rate of methane increases the rate of formation of CNTs. The effect of temperature on the rate of reaction was obtained using Arrhenius and Eyring equations.

This study also investigated the light-emitting capacity and the mechanical properties of as-synthesized CNT yarns. It was established in this study that multi-walled CNTs were predominantly synthesized in the FCCVD system at the optimum conditions with an I_D/I_G ratio of about 0.3. A comparative study of the light emission capacities of the CNT yarn against commercial 60-Watt tungsten filament in an argon environment showed CNT yarns onset voltage to be twice lower, and the power consumption was about 5 times lower in CNT yarn. Consequently, as-synthesized CNT yarn from methane with Hydrogen co-feeding using ferrocene catalyst in a floating catalyst chemical vapour deposition reactor with direct spinning could be

considered a viable blackbody material for replacement of tungsten filament in incandescent bulbs with high energy efficiency.