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Sizes dependence of electrothermal temperature of carbon nanotube films and evaluation method of electrical conductivity by thermal parameter

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Abstract

Carbon nanotube films have a great potential for the application of flexible electrothermal film, most attention has been only devoted into aspects of three different electrical heating sections, including the temperature growth section, the steady-state maximum temperature section and the temperature decay section, of electric heating carbon nanotube films in terms of electrothermal characteristics, a systematical study concerning the sizes dependence of electrothermal characteristics is inadequate. Herein, quantitative expressions concerning electric heating temperature and geometrical dimension of carbon nanotube film were proposed, and according to the relationships, the steady-state temperature could be determined by the length, width, thickness or area of carbon nanotube film, as well as other electrical and thermal parameters. The results demonstrated that smaller area, length-to-width ratio and thickness are conducive to reach a higher electric heating temperature of films at same applied electrical power while hysteresis of response time and cooling time would not be introduced, comparing to other types of carbon nanotube films. These characteristics and the obtained quantitative relations could contribute to design of carbon nanotube films as electric heater efficiently. On the other hand, a method to estimate electrical conductivity of conductive film materials was proposed on the basis of the aforementioned relationships, which put forward a way of thinking from the thermal point of view.

Keywords: carbon nanotube films; electric heating; quantitative expressions; electrical conductivity

1. Introduction

The planar electric heater has been extensively used to diverse electrical heating filed like transparent defoggers, de-icing systems, heat chairs in vehicles, for winter clothes in the military, and as a heating element in mobile heaters [1-5]. Traditionally, metal or metal alloy wires have been used as heating materials [6]. However, the plenty of limitations of these types of heaters come from their electrical heating characteristics, lifetime and other physical features. The main difficulties in the use of conventional electric heater like indium tin oxide, nickel alloy or ferroalloy lie in their brittleness, heavy weight, rigidity and intolerance to chemicals such as acids or bases. On the other hand, their stiff price and environment-unfriendly development, which is due to the limitation of the supply of metal precursors and high cost of complex multi-step ore production, restrict its further application [7, 8]. Therefore, other materials and different structures for heaters are desirable in order to overcome these issues. Carbon nanotube (CNT) has been stimulating great interests since the report by Sumio Iijima in 1991[9]. Carbon nanotube film is one of the macroscopic forms of carbon nanotubes, conductive films made of CNTs offer ultra-light weight, flexibility without fracture and other superior mechanical properties of Young's modulus of 0.27-1.25 TPa, faster and more efficient heating, uniform temperature distribution, room-temperature thermal conductivity of 3500 $W \cdot m^{-1} \cdot K^{-1}$ along the nanotube axis, superb thermal stability up to ~700°C in air and impressive electrical conductivity of 10^4-10^5 $S \cdot cm^{-1}$[10-14]. In the meanwhile, carbon nanotube films were found to be very successful in conversion of electric energy to thermal energy in a so-called electrothermal effect [15, 16]. Importantly, from the economic and renewable raw materials point of view, carbon nanotube films can readily be prepared from a plethora of carbon precursors present all around us in virtually unlimited amounts, which significantly fits well into the modern strategy of sustainable development [17]. Because of its unique physical properties and a range of advantages over currently employed materials such as indium tin oxide, nickel alloy or ferroalloy, out of the many innovative applications of CNT such as in transistors, electrodes in photovoltaics or sensors, there has been a growing interest in employing them as two-dimensional heating elements on the macroscopic scale, and carbon nanotube film materials have the great potential to replace the conventional electrical heating materials in the foreseeable future [18, 19]. In recent applications and researches, electric heaters made from carbon tube films have been envisioned as a kind of ideal candidate for application in vehicle window defrosters, defoggers for periscopes, heatable glove with carbon nanotube films which did not add significant mass and could be operated with a low voltage and, finally, aircraft wing deicing systems on account of all these mentioned assets [20-22]. The research and development of these inventions has rendered carbon nanotube film as the most competitive flexible heater exponential growth.

In spite of the application with explosive growth of carbon nanotube films as electric heater, research on what is the influence of carbon nanotube film’s own characteristics, such as the geometrical dimension of it especially, on the electrothermal properties of carbon nanotube film is inadequate, most of them focus on qualitative relationship of the films' features with electric heating temperature, as well as three temperature stages, i.e. heating stages, steady stages and cooling stages, during electric heating. For instance, the electro-heating behaviors of CNTF with various dimensions and deformations were investigated by applying various voltages, indicating that average steady-state temperature would decrease with the growth of the film length, and the uniform temperature distribution would be obtained, resulting from the uniform and order CNTs in CNTF according to the consequence reported by Mohamed *et al* [23]. Seyram *et al* [22]. reported a carbon nanotube film drawn from CNT arrays and used it to make the heaters, which demonstrated that average steady-state temperature is dependent on the number of layers accumulated during their formation and the same electrical energy could be converted into more thermal energy by carbon nanotube film with lower layers. Dawid *et al* [20]. presented a fitting of heat exchange mechanisms governing heat exchange from the surface of a perpendicularly-aligned CNT film, and proposed a possible relationship of electrical energy with temperature via fitting figure. Hoon-Sik *et al* [24]. prepared MWCNT sheets by continuously pulling on well-aligned MWCNTs and claimed a steep rise in sheet temperature was induced at low length-to-width ratios while the applied voltage regulated from 5 to 40 V, which was inadequate to the demands of theoretical explanation. What's more, to analyze the electric heating behavior of the films or their composites in detail when the electrical power was applied, the time-dependent temperature curves can be divided into three different sections: the temperature growth section, the steady-state maximum temperature section and the temperature decay section under previous reports, and this electric heating behavior of the carbon nanotube films was found to be strongly dependent on the carbon nanotube films thickness as well as the applied voltage [5, 25-27]. Besides the above-mentioned researches, some of researches on carbon nanotube films' relevant electrothermal characterizations have been reported as well [28, 29]. Nevertheless, to our best knowledge, an explicit quantitative relationship between the steady-state maximum temperature and film sizes, such as length, width and thickness, is still unclear, except for the qualitative relations mentioned above, which can not explicitly determine the accurate size of film at the need of certain electrical heating temperature and reveal the reasons of sizes dependence of temperature.

In consideration of the aforementioned aspects, the goal of this work is to study how the carbon nanotube films heater's dimension (length-to-width ratio, area and thickness, i.e., number of collected layers in the CNT sheets by floating catalyst chemical vapor deposition (FCCVD)), electrical and thermal parameters influence its electrothermal performance quantitatively. For this purpose, the quantitative relationships concerning electric heating temperature and geometrical dimension of film were deduced. And we fabricated carbon nanotube films via FCCVD process reported previously [30]. In particular, carbon nanotube films with three kinds of collected layers, 3 layers, 20 layers and 50 layers, were prepared by FCCVD process, and the carbon nanotube films with various geometrical dimensions, including length-to-width ratio and area, were obtained subsequently. The parameter of α_w in relationship was determined by the investigation of electrothermal characterizations of carbon nanotube films, and the size dependence of steady-state electrothermal temperature was quantitatively confirmed based on them. What’s more, a method, considering aspects of thermal, electrical and size parameters of conductive films, to estimate electrical conductivity of conductive film materials was proposed on the basis of the aforementioned relationships.

2. Results and discussion

2.1 Model of size dependence of steady-state temperature

In order to determine the model of relationships of steady-state temperature with geometrical dimension of CNTF during electric heating, a more detailed deduction showed as follow: When electric power is applied to a plane conductor, the temperature of the plane conductor rises from the initial temperature and reaches a steady-state temperature after a period of time. The heating process of the conductor can be described in terms of heat balance. The heat dissipated by the conductor without contact with substrates to the surrounding medium is the sum of the convective heat transfer Q_I and the radiant heat transfer Q_f (generally, the amount of heat conduction to air medium is small and can be ignored), which is a kind of compound heat transfer, and the total heat transfers are often expressed as

$$Q_I+Q_f=\alpha_w (T_s-T_0)A \qquad (1)$$

Where α_w, T_s, T_0, A are total heat transfer coefficient, increased temperature while electrical power applied, initial temperature and the area of plane conductor, respectively. During the electric heating process of the conductor, the heat (Q_R) generated by the conductor owing to applied electrical power, Joule heat, contain the heat (Q_c) absorbed by itself resulting in temperature rise, and the other part of it dissipate into the surrounding (Q_I+Q_f). Therefore, the heat balance equation could be represented by the equation shown below

$$Q_R= Q_c+ Q_I+Q_f \tag{2}$$

during electrical heating the Joule heat, the heat absorbed by conductor and convective and the radiant heat can be defined as I^2Rdt, cmdT and α_w $(T_s-T_0)Adt$, respectively. Therefore, the heat balance equation can be obtained by inserting the relations into equation (2)

$$I^2Rdt=cmdT+\alpha_w(T_s-T_0)Adt \tag{3}$$

where I, R and dt are current applied to the conductor, the resistance of it and electrical heating time, respectively. After deduction, the equation could be given by

$$dt=-\frac{mc}{\alpha_w A}\times\frac{1}{I^2R-\alpha_w A(T_s-T_0)}d[I^2R-\alpha_w A(T_s-T_0)]$$

and $\int_0^t dt=\int_{T_0}^{T_1}\frac{-cm}{\alpha_w A[I^2R-\alpha_w A(T_w-T_0)]}d[I^2R-\alpha_w A(T_s-T_0)]$,

$$1-\alpha_w A(T_1-T_0)/I^2R=\exp(-\alpha_w A/cm\ t)$$

while the electric heating time is sufficient, the temperature of plane conductor reaches a steady-state temperature T, the relationship governing steady-state temperature, electrical and thermal parameters, as well as area could be converted into formulas described by the following relations:

$$T=T_0+I^2R/(\alpha_w A) = T_0+P/ (\alpha_w A) \tag{4}$$

or

$$T=T_0+ V^2/ (R\alpha_w A) = T_0+ P/(\alpha_w A) \tag{5}$$

In addition, the resistance of the conductor can be evaluated by using equations of $R=LR_s/W=L/(Wt\sigma)$, where L, W, t are the length, width and thickness of a plane conductor, and R_s, σ are sheet resistance and electrical conductivity of a plane conductor, respectively. On the basis of the above relationships, quantitative relationships concerning steady-state electric heating temperature and geometrical dimension of film were described by the following equation

$$T=T_0+(t/L^2)\cdot(V^2\sigma)\cdot(1/\alpha_w) \tag{6}$$

which obviously revealed the sizes dependence of steady-state electrical heating temperature T quantitatively. However, it is worth noting that the parameter of α_w is still unclear for carbon nanotube films. The determination of it and influence on electrothermal characteristics of films would be carried out by a series of electrothermal investigations subsequently.

2.2 Sizes dependence of steady-state temperature of CNTFs

To assure parameter of deduced relationship and sizes dependence of steady-state temperature of carbon nanotube films with various geometrical dimension, we carried out investigations of electric heating of carbon nanotube films, which owned size of same length-to-width ratios and collected layers and different areas, same areas and collected layers and different length-to-width ratio, as well as same length-to-width ratios and areas and different collected layers, respectively.

2.2.1 Effect of area on steady-state temperature of CNTFs

In order to estimate α_w in the deduced relationship and what is the impact of the area on steady-state temperature of carbon nanotube films, which possessed the characteristics of same collected layers and length-to-width ratio and different area, carbon nanotube films with 3 collected layers and length-to-width ratio of 1:1 were prepared, which owned the area of $3\times3cm^2$, $5\times5cm^2$ and $10\times10cm^2$, respectively. The surface temperature of the carbon nanotube films was measured by the infrared thermal camera, while different levers of electrical power were supplied. The effect of the areas on the power needed to reach a particular temperature is illustrated in Figure 1(a). It can be seen that, as the areas of the carbon nanotube films increased, the power needed to generate a particular temperature also increased. On the other hand, a linear relationship of steady-state temperature with electrical power was present in Figure1(a). The increase of electrical power needed is explainable by a bigger area of carbon nanotube films leading to a marked enhancement in the resistance of them. In addition, these occurrences could be revealed by the above deduced relationship (4) noticeably. As we can see from the equation, the temperature increment is inversely proportional to area of films, that is, the steady-state temperature of a certain carbon nanotube film with a bigger area would be lower as compared with the one of smaller area at same electrical power applied. Meanwhile, linear relation between steady-state temperature T and applied electrical power could be received obviously based on the equation (1). The above tests were also conducted by various areas' carbon nanotube films with 3 collected layers and other length-to-width ratios of 3:1 and 5:2, which showed in Figure 1(b)-(c) and indicated identical consequences. Besides, carbon nanotube films with other collected layers, such as 20 and 50 layers, were fabricated to comprehensively carry out the investigation portrayed in Figure 2-3 and demonstrated the outcomes gotten. Overall, caron nanotube films with smaller area was more beneficial to generate a higher steady-state temperature while an electrical power applied, and the reached temperature was in proportion to power, which was correspond to the deduced relationships of above section.

According to the analysis mentioned above, the equations related to steady-state temperature of various areas' carbon nanotube films with same length-to-width ratios and 3 collected layers and electrical power, as well as parameter of α_W were summarized in Table 1. For the same carbon nanotube films of 3 collected layers, an average of α_W of 2.65×10^{-3} W/(cm^2·℃) was obtained, which is not significantly relevant to the length-to-width ratio for a kind of certain carbon nanotube film due to the results with fewer variation for each length-to-width ratios. Furthermore, carbon nanotube films with other collected layers of 20 and 50 layers show an increase trend of α_W with the increased thicknesses, which possessed average of α_W of 4.55×10^{-3}, 4.96×10^{-3}W/(cm^2·℃) respectively and illustrated in Table 2 and 3. On the other hand, all of the intercepts of approximately 30 in the equations from the results shown in Tables were present, these occurrences are attributable to the initial temperature at electrical heating test, which was in agreement with the meaning of equations.

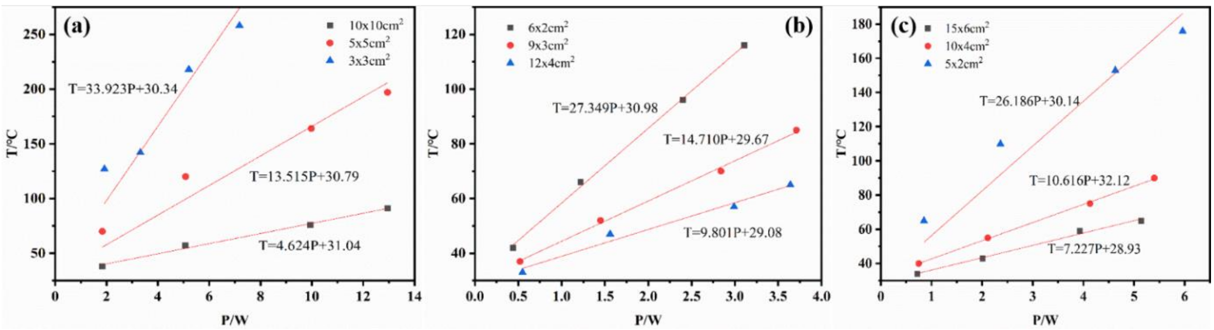

Figure 1: The relationships of input power with steady-state temperature of various areas' CNTFs with 3 collected layers and length-to-width ratios of (a)1:1, (b)3:1 and

(c)5:2.

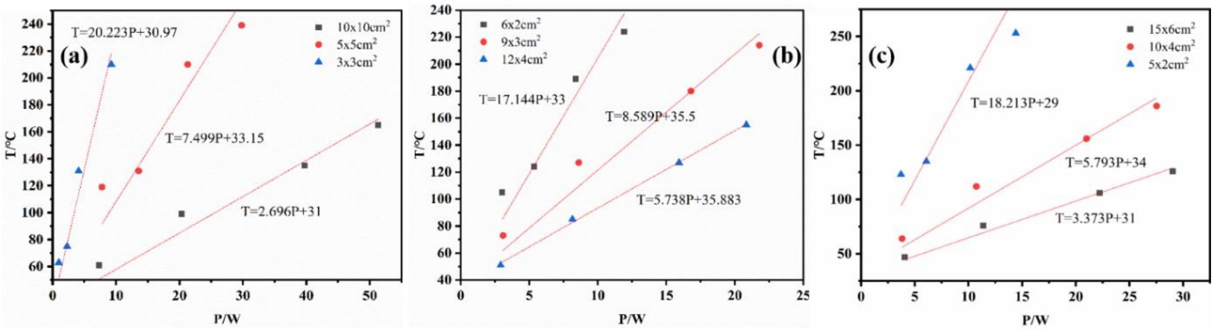

Figure 2: The relationships of input power with steady-state temperature of various areas' CNTFs with 20 collected layers and length-to-width ratios of (a)1:1, (b)3:1 and (c)5:2.

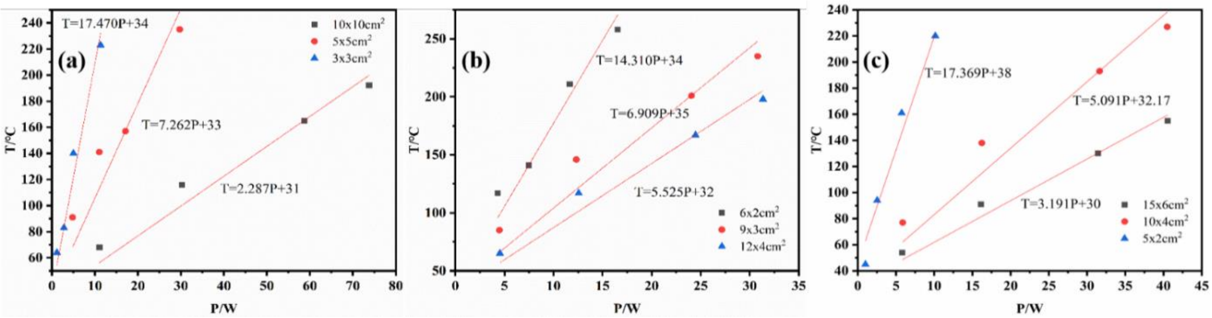

Figure 3: The relationships of input power with steady-state temperature of various areas' CNTFs with 50 collected layers and length-to-width ratios of (a)1:1, (b)3:1 and (c)5:2.

Table 1: Results of parameters of CNTFs with 3 collected layers

length-to-width ratio	A/cm^2	equations	α_w/ $W/(cm^2\cdot℃)$
1:1	10×10	T=4.624P+31.04	2.16×10^{-3}
	5×5	T=13.515P+30.79	2.96×10^{-3}
	3×3	T=33.923P+30.34	3.27×10^{-3}
3:1	6×2	T=27.349P+30.98	3.05×10^{-3}
	9×3	T=14.710P+29.67	2.52×10^{-3}
	12×4	T=9.801P+29.08	2.13×10^{-3}
5:2	15×6	T=7.227P+28.93	1.54×10^{-3}
	10×4	T=10.616P+32.12	2.35×10^{-3}
	5×2	T=26.186P+30.14	3.82×10^{-3}
1:1, $\bar{\alpha}_w=2.80\times10^{-3}$; 3:1, $\bar{\alpha}_w=2.57\times10^{-3}$; 5:2, $\bar{\alpha}_w=2.57\times10^{-3}$;			$\bar{\alpha}_w=2.65\times10^{-3}$

Table 2: Results of parameters of CNTFs with 20 collected layers

length-to-width ratio	A/cm^2	equations	α_w/ $W/(cm^2\cdot℃)$
1:1	10×10	T=2.696P+31	3.71×10^{-3}
	5×5	T=7.499P+33.15	5.33×10^{-3}
	3×3	T=20.223P+30.97	5.49×10^{-3}
3:1	6×2	T=17.144P+33	4.86×10^{-3}
	9×3	T=8.589P+35.5	4.31×10^{-3}
	12×4	T=5.738P+35.883	3.63×10^{-3}
5:2	15×6	T=3.373P+31	3.29×10^{-3}
	10×4	T=5.793P+34	4.31×10^{-3}
	5×2	T=18.213P+29	5.49×10^{-3}
1:1, $\overline{\alpha}_w=4.84\times10^{-3}$; 3:1, $\overline{\alpha}_w=4.27\times10^{-3}$; 5:2, $\overline{\alpha}_w=4.36\times10^{-3}$;			$\overline{\alpha}_w=4.49\times10^{-3}$

Table 3: Results of parameters of CNTFs with 50 collected layers

length-to-width ratio	A/cm^2	equations	α_w/ $W/(cm^2 \cdot ℃)$
1:1	10×10	T=2.287P+31	4.37×10^{-3}
	5×5	T=7.262P+33	5.51×10^{-3}
	3×3	T=17.470P+34	6.36×10^{-3}
3:1	6×2	T=14.310P+34	5.82×10^{-3}
	9×3	T=6.909P+35	5.36×10^{-3}
	12×4	T=5.525P+32	3.77×10^{-3}
5:2	15×6	T=3.191P+30	3.48×10^{-3}
	10×4	T=5.091P+32.17	4.91×10^{-3}
	5×2	T=17.369P+38	5.76×10^{-3}
1:1, $\bar{\alpha}_w=5.41 \times 10^{-3}$; 3:1, $\bar{\alpha}_w=4.98 \times 10^{-3}$; 5:2, $\bar{\alpha}_w=4.72 \times 10^{-3}$;			$\bar{\alpha}_w=5.04 \times 10^{-3}$

2.2.2 Effect of length-to-width ratio on steady-state temperature of CNTFs

The evaluation of influence of the carbon nanotube films' length-to-width ratio on the reached steady-state temperature while electrical power was applied was carried out subsequently. Carbon nanotube films possess the characteristics of same collected layers, areas and diverse length-to-width ratios. Herein, carbon nanotube films owned three kind of collected layers of 3, 20 and 50 were utilized to estimate the factor simultaneously, and various areas of carbon nanotube films would be taken into account to eliminate the impact of it as well. Figure 4 displays the surface steady-state temperatures plotted against the applied electrical power for different length-to-width ratios of carbon nanotube films with 3 collected layers. As we can see from it, a linear relate of steady-state temperature and applied electrical power was present for different length-to-width ratio, too. Meanwhile, an approximately parallel curves were exhibited, for example shown in Figure 4(a), which mean the parameter of α_w without bigger variation could be received for a certain carbon nanotube film to some extent on the basis of the deduced relationships above. This phenomenon was consistent with the resultant consequence summarized in Table 4.

According to the observation of steady-state temperature change with electrical parameters and length-to-width ratios displayed in Figure 4, while the applied voltage regulated from 3 to 8 V, that is, with the increase of electrical power, the trend of steady-state temperature was gradually rising, and we found that at lower length-to-width ratios, a steep rise in carbon nanotube films temperature was induced at a certain applied voltage as indicated by the arrows in Figure 4. The main cause for the noticeably increase was that the lower length-to-width ratio played a role in reducing the electrical resistance of the carbon nanotube film, and theoretically the conversion of electrical energy to thermal energy follows the Joule's Law: $P = V^2/R$ (where P is the electric power, V is the input voltage, and R is the resistance) [31]. Therefore, with the reduction of the length-to-width ratio, the resistance of CNTF is decreased and thus the transformed electric power as well as the steady-state temperature is increased. From another point of view, this increase could be also explainable by relationships deduced.

The deduced equation (6) could be converted into a form like this:

$$T = T_0 + (W/L)\ (t/A) \cdot (V^2\sigma) \cdot (1/\alpha_w) \qquad (7)$$

it is apparent that a lower length-to-width ratio of carbon nanotube films can contribute to a higher steady-state surface temperature for a certain kind of carbon nanotube film at applied voltage. And the intercepts of them basically were equal to 30, which corresponded to meaning of the equation (7). The carbon nanotube films with 20 and 50 collected layers were further compared these performances to determine the impact of the length-to-width ratio present in Figure 5-6, these explicated same results demonstrated that a certain carbon nanotube film could reach a higher steady-state temperature while a bigger applied voltage and lower length-to-width ratio were available. Furthermore, the parameter of α_w without bigger variation could be received for a certain carbon nanotube film to a certain degree elaborated in Table 4-6.

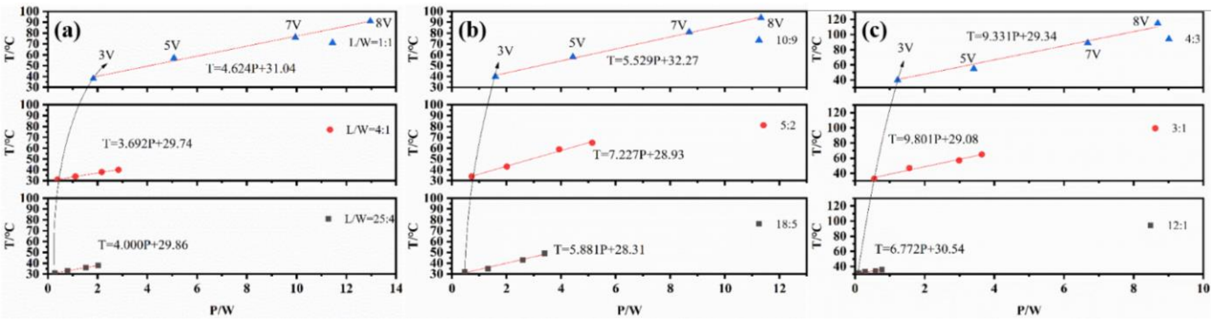

Figure 4: The relationships of input power with steady-state temperature of various length-to-width ratios' CNTFs with 3 collected layers and areas of (a)100, (b)90 and (c)48cm^2.

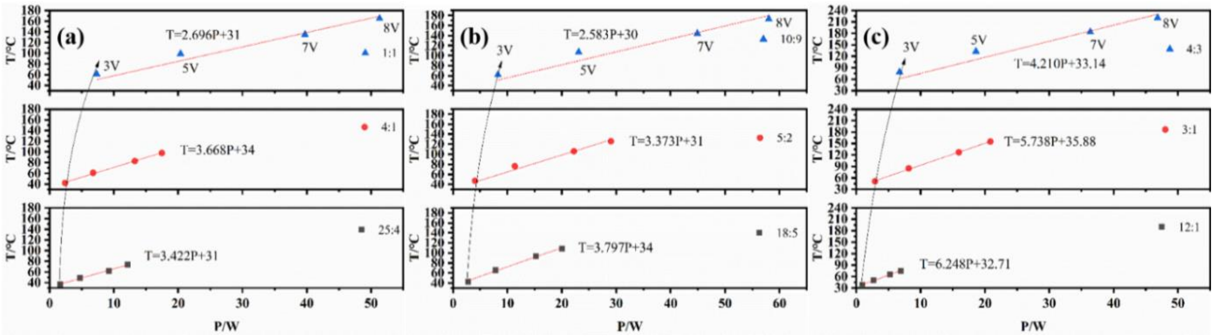

Figure 5: The relationships of input power with steady-state temperature of various length-to-width ratios' CNTFs with 20 collected layers and areas of (a)100, (b)90 and (c)48cm^2.

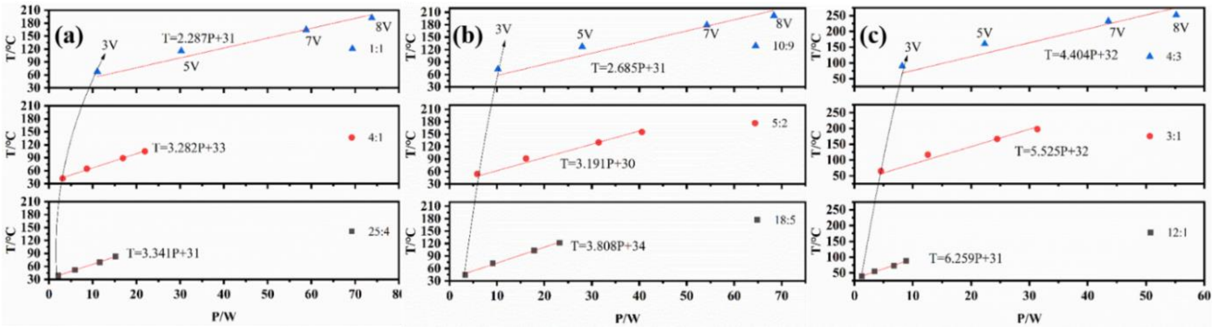

Figure 6: The relationships of input power with steady-state temperature of various length-to-width ratios' CNTFs with 50 collected layers and areas of (a)100, (b)90 and (c)48cm^2.

Table 4: Results of parameters of CNTFs with 3 collected layers

A/cm^2	length-to-width ratio	equations	α_w/ $W/(cm^2\cdot ℃)$
100	25:4	T=4.000P+31.04	2.5×10^{-3}
	4:1	T=3.692P+29.74	2.71×10^{-3}
	1:1	T=4.624P+31.04	2.16×10^{-3}
48	4:3	T=9.331P+29.34	2.23×10^{-3}
	12:1	T=6.772P+30.54	3.08×10^{-3}
	3:1	T=9.801P+29.08	2.13×10^{-3}
90	18:5	T=5.881P+28.31	1.89×10^{-3}
	10:9	T=5.529P+32.27	2.01×10^{-3}
	5:2	T=7.227P+28.93	1.54×10^{-3}
$100cm^2$, $\bar{\alpha}_w=2.46\times10^{-3}$; $48cm^2$, $\bar{\alpha}_w=2.48\times10^{-3}$; $90cm^2$, $\bar{\alpha}_w=1.81\times10^{-3}$; $\bar{\alpha}_w=2.25\times10^{-3}$			

Table 5: Results of parameters of CNTFs with 20 collected layers

A/cm^2	length-to-width ratio	equations	α_w/ $W/(cm^2{\cdot}℃)$
100	25:4	T=3.422P+31	2.92×10^{-3}
	4:1	T=3.668P+34	2.73×10^{-3}
	1:1	T=2.696P+31	3.71×10^{-3}
48	4:3	T=4.210P+33.14	4.95×10^{-3}
	12:1	T=6.248P+32.71	3.33×10^{-3}
	3:1	T=5.738P+35.88	3.63×10^{-3}
90	18:5	T=3.797P+34	2.93×10^{-3}
	10:9	T=2.583P+30	4.30×10^{-3}
	5:2	T=3.373P+31	3.29×10^{-3}
$100cm^2$, $\bar{\alpha}_w=3.12\times10^{-3}$; $48cm^2$, $\bar{\alpha}_w=3.97\times10^{-3}$; $90cm^2$, $\bar{\alpha}_w=3.51\times10^{-3}$; $\bar{\alpha}_w=3.53\times10^{-3}$			

Table 6: Results of parameters of CNTFs with 50 collected layers

A/cm^2	length-to-width ratio	equations	α_w/ W/(cm^2·℃)
100	25:4	T=3.341P+31	2.99×10^{-3}
	4:1	T=3.282P+33	3.05×10^{-3}
	1:1	T=2.287P+31	4.37×10^{-3}
48	4:3	T=4.404P+32	4.73×10^{-3}
	12:1	T=6.259P+31	3.33×10^{-3}
	3:1	T=5.525P+32	3.77×10^{-3}
90	18:5	T=3.808P+34	2.92×10^{-3}
	10:9	T=2.685P+31	4.14×10^{-3}
	5:2	T=3.191P+30	3.48×10^{-3}
$100cm^2$, $\bar{\alpha}_w=3.47\times10^{-3}$; $48cm^2$, $\bar{\alpha}_w=3.94\times10^{-3}$; $90cm^2$, $\bar{\alpha}_w=3.51\times10^{-3}$; $\bar{\alpha}_w=3.64\times10^{-3}$			

2.2.3 Effect of thickness on steady-state temperature of CNTFs

The efforts, performing electrothermal characteristics researches of carbon nanotube films with various thickness, have been undertaken to ensure the dependence of steady-state temperature on thickness. The temperature profiles of the CNT film heater are plotted with respect to the applied electrical power depicted in Figure 7. According to the results of them, the reached steady-state temperature of the films would be higher as the decrease of the thickness, i.e. collected layers, at a given electrical power. The specific surface area change of films is the main reason for the improvement, along with the density. The dominant heat transfer losses in the CNT film may be affected by the porous morphology of the network. At the stage of steady-state maximum temperature of film, heat was mainly dissipated by convection to the air and radiation, resulting in altering temperature, while CNTF had no contact with any substrate according to the heat loss mechanism. Heat convection occurs near the hot surface of CNT to the surrounding air medium. As the increase of density and thickness of CNT network, the specific surface area of CNT films drastically increases. Thermal loading or heat accumulation may occur in CNT film with high density. Radiation loss may also be explained by the increase in the CNT density and the specific surface area. The radiated heat from the hot surface of CNT may be scattered or absorbed by another CNT in films due to the characteristic of high optical absorption [18, 21]. On the account of the decrease of heat dissipated into the surrounding by heat convection and radiation, these aspects cause a decrease of surface temperature detected by apparatus. Additionally, this kind of trend of the temperature change could be explainable by the aforementioned proposed relationships and analysis, which demonstrated the enhancement of α_w with increase of the collected layers, thickness of films, leading to a marked reduction in the reached steady-state temperature of carbon nanotube films applied a certain amount of electrical power as the Figures showed below. The same consequences could be received by the films with other length-to-width ratios and areas based on the Figure 1-3, which did not present here.

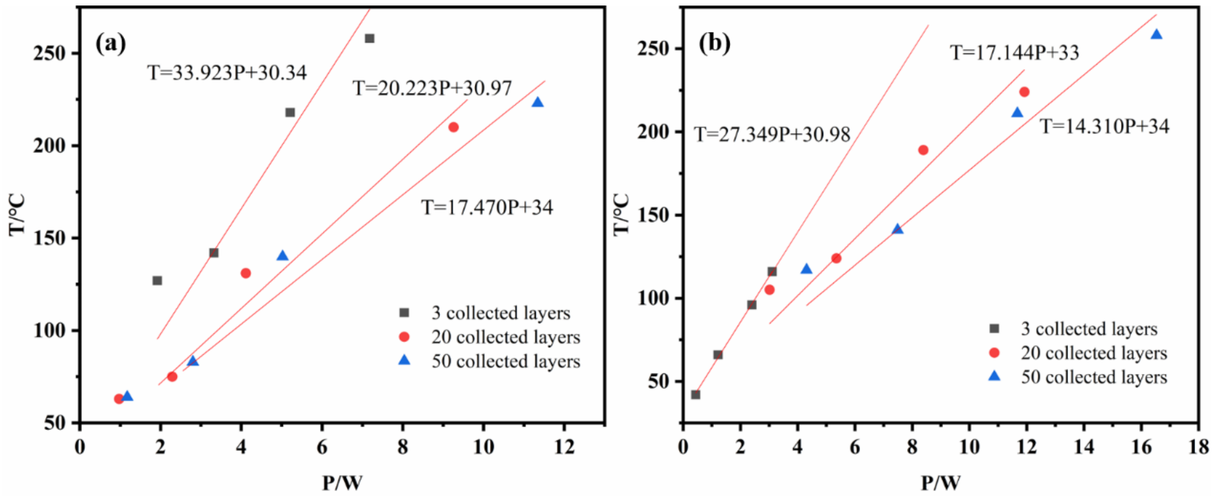

Figure 7: The relationships of input power with steady-state temperature of various collected layers' CNTFs with length-to-width ratio and areas of (a)1:1, 9cm^2, (b)3:1, 12cm^2, respectively.

According to the above obtained results concerning relation of steady-state electrothermal temperature with the sizes of carbon nanotube films, we can conclude that a lower length-to-width ratio, smaller area and lower thickness would benefit to more efficient electric heating while a same electric power was applied and other two sizes of carbon nanotube film was same, comparing to carbon nanotube film with larger length-to-width ratio, same area and thickness, or larger area, same length-to-width ratio and thickness, or higher thickness, same length-to-width ratio and area. In the meanwhile, the electrothermal response time t_r, from room temperature to steady-state temperature, and cooling time t_c, of such carbon nanotube films would not exhibit hysteresis in contrast with other types of carbon nanotube films, which portrayed in Figure 8. The t_r and t_c of carbon nanotube films with 3, 20 and 50 collected layers could be maintained at similar level of 3~5 second while the length-to-width ratio and area were larger or smaller. Therefore, sizes dependence of temperature of electric heating films was determined quantitatively, which would facilitate design of carbon nanotube film as an efficient heater including the more accurate determination of sizes and steady-state temperature or other parameters.

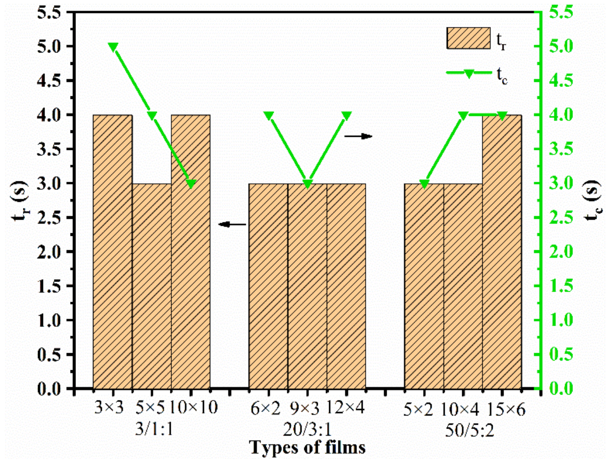

Figure 8: Trend of t_r and t_c of different types of films

2.3 Evaluation of conductive films' electrical conductivity

Generally, the electrical conductivity of film materials could be detected via a four-point probe method, which is a widely accepted test method. Herein, a new method to estimate the electrical conductivity of film was proposed, which aimed at providing a kind of novel thinking to get the electrical parameter rather than replacing the universal four-probe method. On the basis of the above deduced equation (6), a formula could be derived from it and expressed as following:

$$\sigma=\Delta T\cdot(\alpha_w/V^2)\cdot(L^2/t)$$

where ΔT is the difference between steady-state temperature and initial temperature of film. The relationship, containing thermal and electrical parameter, as well as sizes of film, could be utilized to compute the electrical conductivity roughly. For instance, electrothermal tests and four-point-probe tests were performed by carbon nanotube film with 3 collected layers and thickness of 0.0036mm and length of 25cm to determine the electrical conductivity of it. The electrical conductivity was received with respect to the applied voltages and corresponding temperature difference between steady-state temperature and initial temperature as depicted in Table 7. As compared to the electrical conductivity value of 5.12×10^4S/m obtained by four-point-probe method, an average of 5.19×10^4S/m with smaller variation was acquired based on the proposed method mentioned above, which revealed a feasible solution to estimate the electrical conductivity in combination with the thermal and electrical parameters as well as sizes of film materials.

Table 7: Electrical conductivity of 3 collected layers detected by four-point-probe and the proposed method

Voltages/V	3	5	7	8
ΔT/℃	1	3	6	8
σ（S/m）	4.82×10^4	5.21×10^4	5.31×10^4	5.43×10^4

$\bar{t}$=0.0036mm, S=100cm^2, L=25cm, $\bar{\sigma}_{\text{four-point probe method}}=5.12\times10^4$S/m, $\bar{\sigma}=5.19\times10^4$S/m.

3. Conclusion

In this paper, the investigations, concerning carbon nanotube films' size dependence of steady-state temperature while electrical power was applied, were performed under circumstance of previous unclear research. Herein, firstly we deduced the relation, $T=T_0+(t/L^2)\cdot(V^2\sigma)\cdot(1/\alpha_w)$, and confirmed the effect of length-to-width ratio, area and thickness on the steady-state temperature and the trend of factor of α_w, the main causes for that changes were described according to the structural characteristics of carbon nanotube films and the deduced relationships aforementioned. Owing to the fact that a lower length-to-width ratio, smaller area and lower thickness would contribute to a higher steady-state temperature at the same applied electrical power, carbon nanotube films with this kind of geometry characteristic could possess more outstanding electrothermal capability without hysteresis of response time and cooling time, which are supposed to be taken into consideration to adjust temperature conveniently while an efficient film heater need to be designed. And based on the results, steady-state temperature could be determined at certain applied electrical power for certain sizes film according to the equation, and the suitable sizes of carbon nanotube films can be given with regard to the actual requirements of certain steady-state temperature. All of these achievements would significantly facilitate the applications of carbon nanotube films as heater. In the meanwhile, a new method to estimate the electrical conductivity of conductive film was proposed by combining with the thermal and electrical parameters as well as size of film on the basis of transformation form of the proposed equation, which was different from four-point-probe method owing to the perspective involving thermal parameter.

4. Experimental

The carbon nanotube films were manufactured via FCCVD process, and the thickness of carbon nanotube films was determined by the amount of collection layers during FCCVD process, then densification of the as-prepared carbon nanotube sheets was performed by spraying mixed solvent of ethanol/water. Afterward, the carbon nanotube films with different geometrical dimension were prepared by cutting from the above fabricated CNTFs with various layers.

In order to ensure the electrothermal parameter α_W of the deduced relationships and determine sizes dependence of electrical heating steady state temperature of carbon nanotube films while electrical power was applied, electrothermal investigations were carried out. The films with three kinds of thicknesses were cut into various areas and length-to-width ratios by a laser cutter, and adhered on two copper foil electrodes with silver paste to eliminate the possible effect of contact resistance between nanocarbon and the Cu terminals through when electric power was applied. For the electrical heating test, measurements were taken at room temperature and pressure, we applied an electrical potential across the two electrodes using a DC power supply (6575A, Agilent) and monitored the surface temperature of carbon nanotube films by using a thermal imaging camera (A320, Flir) after the film heaters were allowed to reach an equilibrium temperature. To estimate the electrical conductivity of carbon nanotube films with different layers, the sheet resistance of the CNTFs was measured using a four-probe meter (H7756, Beijing Heng'aode Technology Co., China) firstly, and then the electrical conductivity was calculated by the formula: $\sigma = 1/(R_s \cdot t)$, where R_s is the sheet resistance and t is the thickness of CNTF.

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