AN ANALYSIS OF THERMAL INSULATION CHARACTERISTICS OF POLYMER COMPOSITES REINFORCED BY UNIDIRECTIONAL NATURAL FIBER

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1. Background

In recent years, natural fiber reinforced green composite materials have attracted the attention of scientists and technologists in the fields of aerospace, automotive, construction and sporting industries due to their unique advantages of low density, high specific properties, non-corrosive and degradable properties, low-cost and readily available comparable to those of conventional fiber composite materials[1, 2]. Especially, the thermal insulation property of natural fiber composite have been considered as an potential function. Because of the hollow structure of natural fiber, the design of composites with a good thermal insulation property by using natural fiber and polymer will be of great value. In the last few years, many works have been started on thermal conductivity of natural fiber composites[3-7]. Furthermore, due to transverse thermal conductivity is lower than longitudinal thermal conductivity[7], Study on the transverse thermal conductivity of unidirectional composites has been one of focuses of many investigators, including numerical solutions and theoretical approaches as well as experiments[8-12]. However, only few paper about transverse thermal conductivity of natural fiber composites is reported[5, 7], they haven’t considered the effect of the hollow structure on the thermal conductivity of the composite. Natural fibers have lumen which is filled with air, and some fibers have very large lumen like Manila hemp fiber, cotton fiber and kapok fiber, such large size lumen can lead to a very low transverse thermal conductivity when these fibers were used to fabricate composites, So it is essential to evaluate the function of lumen size of the fiber to the transverse thermal conductivity. Thermal–electrical analogy technique is a very useful method. The thermal–electrical analogy technique have been successfully employed for the thermal system of heat flow governed by the Fourier law. To our best knowledge, there are so many works demonstrating the successful applications of this analogy method[9, 12-14], which not only support the practicability of this analogy method but also supply elicitation for solving the similar problem about natural fiber composites. So far, no work was reported to analyze the transverse thermal conductivity of the unidirectional natural fiber composites by using this method.

2. Methods

The thermal-electrical analogy is established based on the similarity between the partial differential equations governing the thermal potential temperature and the electrical potential $E$ distributions, which leads to the analogy between the thermal resistance $R$, heat flow $Q$ in a thermal system and the electrical resistance $r$, current flow $I$ in a electrical system, respectively.
By using this method, cylinder filament with hollow in square array (CHS), are presented to analyze the relationship between transverse thermal conductivity and the lumen size in unidirectional natural fiber composites.

Effective assumptions are listed as follows:
1. The heat flow line is perpendicular to the fiber direction and each phase in the ways as thermal resistor obeys Fourier’s Law.
2. The thermal resistance between matrix and fiber, fiber and lumen is neglected.
3. The matrix is homogenous and no transverse heat transfer through the way of convection and radiation due to the fibers’ small size less than 1cm[15].
4. Air is filled in the lumen, and it’s density is same to atmosphere.
5. Unidirectional fibers are arrayed in square (Figure 1 (a)).

Figure 1 (a) Schematic diagram of unidirectional fiber composite cross section, (b) three dimensional and (c) two dimensional unit cell model, (d) thermal resistance networks of (c).

The three dimensional unit cell Figure 1 (b) can be simplified into the two dimensional unit cell (CHS) shown in Figure 1 (c), and the effective transverse thermal conductivity can be obtained by analyzing the thermal resistance networks shown in Figure 1 (d):

\[
R = \left( \frac{1}{R_t} + \frac{1}{R_m} + \frac{1}{R_{mm}} \right)^{-1}
\]

\[
K_t = \frac{a}{Ra} = R^{-1} = \frac{1}{R_t} + \frac{1}{R_m} + \frac{1}{R_{mm}}
\]

\[
= K_m \left( 1 - \left( \frac{4}{\pi} V_f \right)^{1/2} \right) + \frac{\beta K_m \cos \theta d \theta}{\cos \theta + \beta \left( \frac{4}{\pi} V_f \right)^{1/2} - \cos \theta}
\]

\[
+ \int_{\theta_1}^{\theta_2} \beta K_m K_r \cos \theta d \theta \alpha \beta K_m \left[ \cos \left( \sin^{-1} \left( \frac{\sin \theta}{\alpha} \right) \right) \right]
\]

\[
+ K_i \left( \cos \theta - \alpha \cos \left( \sin^{-1} \left( \frac{\sin \theta}{\alpha} \right) \right) \right) + \beta K_i \left( \frac{4}{\pi} V_f \right)^{1/2} - \cos \theta \right]^{-1}
\]

where
\[ \theta = \arcsin \alpha, \alpha = \frac{r_l}{r_f}, \beta = \frac{K_f}{K_m}, V_f = \pi \left( \frac{r_f}{2a} \right)^2 = \frac{\pi v}{4} \]

\(\alpha\) is the geometrical ratio of lumen radius \((r_l)\) to fiber radius \((r_f)\) and \(0 < \alpha < 1\), \(V_f\) is the volume fraction of fiber, \(V_f = (r_f/a)^2\) and it is constrained no larger than \(\pi/4\).

3. Results and Discussion

Figure 2 Results of present model, Pitchumani & Yao’s fractal model and Zou’s C-S unit cell model with two phases: (a) fiber and matrix, (b) air and matrix, and three phases: (c) \(\beta = 2\), (d) \(\beta = 5\), (e) \(\beta = 10\) and (f) \(\beta = 100\).

To check the rationality of the present models, we compare the present CHS model when \(\alpha\) is infinitely near to 0 and 1, with Pitchumani & Yao’s fractal model and Zou’s C-S unit cell model[12], which give the same result by using the different method, local fractal techniques for and thermal-electrical analogy technique, respectively. The result is shown in Fig. 2. It is obvious that the present model is in great agree with the results of Pitchumani & Yao’s fractal model and Zou’s C-S unit cell model when the composite is composed of two phases.

Figure 2(c) presents the \(K_r V_f\) curves of the natural fiber composite with three phases, which is from the present theoretical analysis Eq.(2) when \(\alpha\) is 0.1, 0.3, 0.5, 0.7 and 0.9 (\(K_m = 0.01\) and
We can see that $K_t$ increases with increasing $V_f$ when $\alpha=0.1$ and 0.3, and decreases when $\alpha=0.7$ and 0.9; but when $\alpha=0.5$, $K_t$ seems to be a constant with small variety (about %). It means that larger $\alpha$ leads to the lower transverse thermal conductivity of unidirectional fiber composite materials, we can also see that $\alpha_c$ depends on $\beta$. when $\beta=5$, $\alpha_c=0.6$ (Figure 2(d)), when $\beta=10$, $\alpha_c=0.65$ (Figure 2(e)), and when $\beta=100$, $\alpha_c=0.68$ (Figure 2(f)). It illustrates that larger $\beta$ leads to larger $\alpha_c$. So it can be predicted that a unidirectional fiber composite materials with large lumen fiber ($\alpha>0.5$) will have a great thermal insulation property, on the contrary, the composite with great thermal conducting property comes from the small lumen fiber.

4. Conclusions

In this paper, a cylinder filament with hollow in square array model is presented to analyze the transverse thermal conductivities of unidirectional natural fiber reinforced composites. Some interesting and effective results have been obtained:

(1) SHC model describes that the transverse thermal conductivity $K_t$ of natural fiber is affected by the geometrical ratio $\alpha=r_l/r_f$, fiber volume fraction $V_f$ and ratio $\beta=K_f/K_m$.

(2) $K_t$ increases with $V_f$ when $\alpha$ smaller than critical value $\alpha_c$ and $K_t$ decreases with $V_f$ when $\alpha>\alpha_c$; $\alpha_c$ of the fiber with higher thermal conductivity (larger $\beta$) is larger than the one of fiber with lower thermal conductivity (smaller $\beta$).

(3) Those results illustrate that fiber composite applied for thermal insulation can be designed by using natural fiber and choosing the larger $\alpha$, smaller $\beta$ and higher volume percent of fiber.

5. References