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Materials Today: Proceedings XX (2016) XXX–XXX

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PMME 2016

Theoretical Investigation into the Thermal Conductivity of Particle Filled Polypropylene Composites☆

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Abstract

Theoretical models have, over the years, tried to explain the thermal conductivity of two-phased composites. This present work focuses on investigating theoretically the thermal conductivity of particle filled polypropylene composites with emphasis on micro scale irregular shaped particles. Mathematical model developed by Bruggeman, De Loor, Nan et al including the rule of mixture also known as the parallel model and the series model were used to predict the thermal conductivity of particle filled polypropylene composites. The theoretical results were validated using experimental data. It was discovered that the model proposed by Bruggeman and De Loor gave reasonable predictions of the thermal conductivity of the composites for all the particle sizes and volume content considered with the least variation of 0.10 % and 0.15 % recorded for 75 µm particle size inclusions, respectively. The Maxwell, Nan et al, parallel and series model showed poor predictability with increasing volume content.

Selection and Peer-review under responsibility of International Conference on Processing of Materials, Minerals and Energy (July 29th – 30th) 2016, Ongole, Andhra Pradesh, India.

Keywords: Composites; Iron ore tailings; Particle; Polypropylene; Model; Thermal conductivity

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1. Introduction

Composites are combination of two or more physically distinct materials, which are combined in a controlled way so that a significant proportion of the properties of both constituent phases are exhibited such that a better combination of properties is realized. Among the challenges which particle reinforced plastics composites (PRPC) present is the complexity of their mechanical, chemical and thermal behavior. This makes it difficult to predict performance analytically and hence leads to conservative designs and extensive test programs [1]. Theoretical models have, over the years, tried to explain the thermal conductivity of two-phased composites. This present work focuses on investigating theoretically the thermal conductivity of particle filled polypropylene composites with emphasis on micro scale irregular shaped particles. The mathematical models developed by Bruggeman [2], De Loor [3], Nan et al [4], parallel [5,6], series [5,6] and Maxwell [5-7] for predicting the thermal conductivity of two-phased composites were considered and the results validated experimentally.

Nomenclature

K_c	thermal conductivity of composite
K_f	thermal conductivity of filler
K_m	thermal conductivity of matrix
ϕ_f	volume fraction of filler

2. Theory

Efforts have been made by various mathematical models to predict the thermal conductivity of two-phase composites. Some of the mathematical models developed include Bruggeman's model [2] shown in Eq. 1 below;

$$K_c = \frac{K_m}{\left(1-\phi_f\right)}. \tag{1}$$

where K_c is thermal conductivity of composite, K_m is thermal conductivity of matrix and ϕ_f is volume fraction of filler.

De Loor [3] also developed a mathematical model Eq. 2;

$$K_c = \frac{K_m\left(1+\phi_f\right)}{1-2\phi_f}. \tag{2}$$

where K_c is thermal conductivity of composite, K_m is thermal conductivity of matrix and ϕ_f is volume fraction of filler.

In an effort to improve on the earlier models, Nan et al [4] proposed Eq. 3;

$$K_c = \frac{K_m\left(3+\phi_f\left(\frac{K_f}{K_m}\right)\right)}{3-2\phi_f}. \tag{3}$$

where K_c is thermal conductivity of composite, K_m is thermal conductivity of matrix and ϕ_f is volume fraction

of filler;

The two basic models representing the upper and lower bound for thermal conductivity of composites are the rule of mixture also known as the parallel model (Eq. 4) and the series model (Eq. 5) [5,6], respectively. The former assumes perfect contact between particles and that each phase is assumed to contribute independently to the overall conductivity while the latter assumes no contact between particles and thus the contribution of particles is confined to the region of matrix embedding the particle. For the parallel model:

$$K_c = \phi_f K_f + (1-\phi_f) K_m . \quad (4)$$

while for the series model:

$$\frac{1}{K_c} = \frac{\phi_f}{K_f} + \frac{1-\phi_f}{K_f} . \quad (5)$$

where ϕ_f is the volume fraction of filler and K_m, K_f and K_c are thermal conductivities of matrix, filler and composite, respectively.

Maxwell [5-7] obtained a simple relationship for the conductivity of randomly distributed and non-interacting homogeneous spheres in a homogeneous medium using potential theory in Eq. 6:

$$K_c = K_m \frac{K_f + 2K_m + 2\phi_f (K_f - K_m)}{K_f + 2K_m - \phi_f (K_f - K_m)} . \quad (6)$$

where, ϕ_f is the volume fraction of filler and K_m, K_f and K_c are thermal conductivities of matrix, filler and composite, respectively.

3. Results and discussion

Fig. 1, 2 and 3 shows the theoretical and experimental thermal conductivity versus volume of 53, 75 and 100 µm iron ore tailings in polypropylene curves, respectively. It can be seen in Fig. 1 that the experimental values is greater than the theoretical thermal conductivity values obtained from the mathematical models with the Bruggeman and De Loor model having the best prediction. This trend is observed for the other particle sizes considered. The lowest variation occurred at 5 % vol. (0.01390 W/m-K) and 30 % vol. (0.0062 W/m-K).

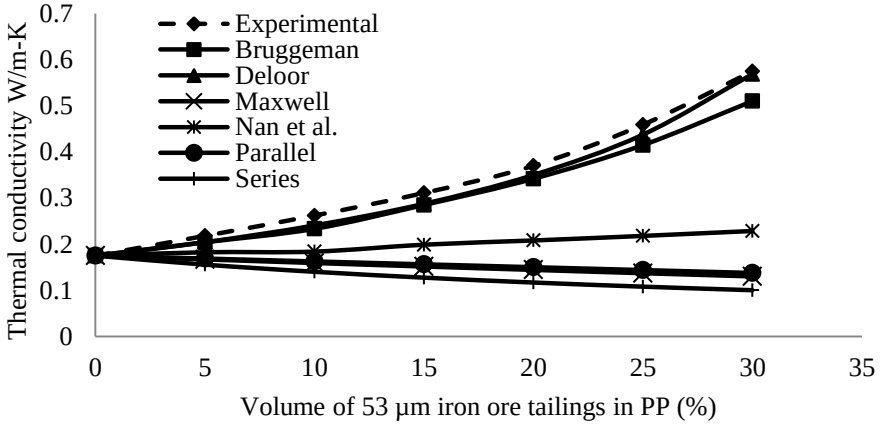

Fig. 1: Thermal conductivity versus volume of 53 µm iron ore tailings in PP

In the case of Fig. 2, an improved predictability was observed for the Bruggeman and De Loor models while the other showed poor prediction with increasing volume content of filler. The Bruggeman and De Loor model showed lowest variation in predictability at 15 % vol. of filler; 0.0010 W/m-K and 0.0015 W/m-K, respectively. The De Loor model gave a perfect prediction at 27 % vol. inclusion.

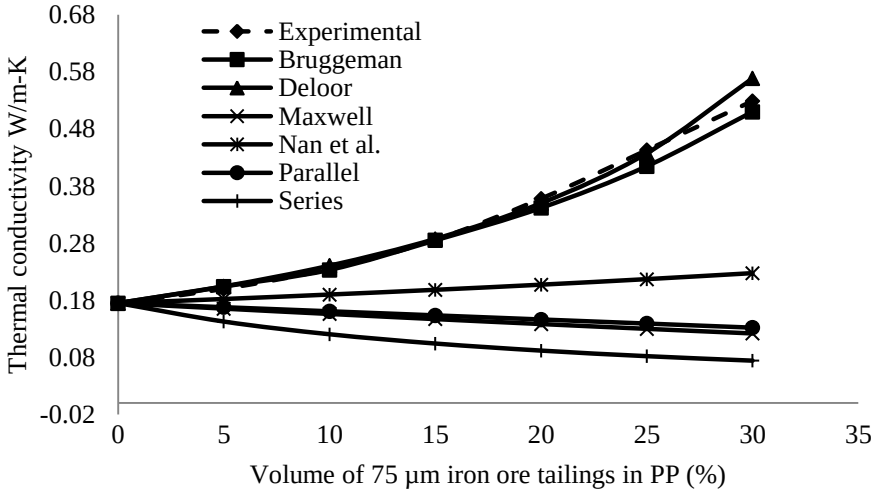

Fig. 2: Thermal conductivity versus volume of 75 µm iron ore tailings in PP

Fig. 3 shows that the Bruggeman and De Loor models' predictability reduces with increased volume content of particles with the lowest variation of 0.0081 W/m-K and 0.0082 W/m-K, respectively, recorded at 5 % vol. content.

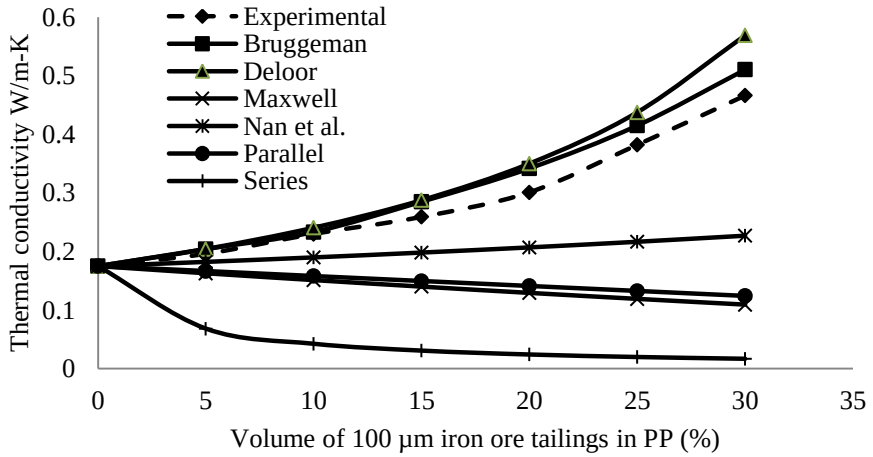

Fig. 3: Thermal conductivity versus volume of 100 µm iron ore tailings in PP

4. Conclusion

It was discovered that the model proposed by Bruggeman and De Loor gave the best reasonable predictions of the thermal conductivity of the composites for all the particle sizes considered. The best prediction for the two

models occurred at 75 μm particle size and it improves with reducing percentage volume of filler. It is interesting to note that the predictability of the Maxwell, Nan et al., parallel and series models exhibited poor predictability with increasing volume inclusion and for all the particle sizes, with the latter exhibiting increased poor prediction with increasing particle size.

5. References

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