THERMAL CONDUCTIVITY OF UNIDIRECTIONAL COMPOSITES WITH SMALL CROSS-SECTIONS

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ABSTRACT

In this paper, optimal transient and steady state experiments are described for efficient estimation of thermal properties of unidirectional composites with small cross-section. The method is fast and simple comparing to the ASTM C177 standard, where large specimen and long time duration for the experiment are needed. The heating source is simple and no special regulation or boundary conditions are necessary. A theoretical study showed that an optimal location for the temperature sensors, exist, leading to a rapid evaluation of the material thermal conductivity. Data are presented for unidirectional glass fiber reinforced polyester and glass fiber reinforced epoxy. These results are compared with values predicted by models found in literature.

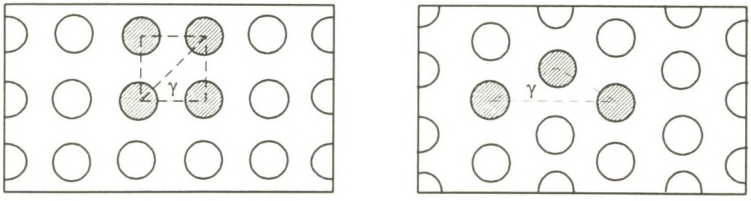
INTRODUCTION

In several applications, it is important for the use and manufacture of composite structures to have reliable and accurate values of their thermal properties. Pultrusion process optimization [1,2] and laser cut [3] are some examples that could be cited. There are three principal thermal conductivities (TC) for unidirectional composites. The conductivity along the fibres that could be simply obtained by the linear combination of the two constituent's properties, usually called rule of mixture, and the conductivity in the two directions perpendicular to the fibres, also called transverse conductivities. These conductivities are more difficult to determine with a good accuracy. In literature, a large number of theories are available to predict the TC of continuous fibre composites. The basic model assumes an ordered arrangement of fibres in the matrix. Literature abounds with both analytical [4-5] and numerical [6-7] results for the effective TC of ordered arrays. However, in the composites found in practice, the fibres hardly assume an ordered arrangement. This is especially true for the products of continuous manufacturing systems such as pultrusion [8]. Without going into the details of these models, generally speaking, the ratio between the effective transverse conductivity (k_e) and the matrix conductivity (k_m) takes the form:

$$\frac{k_e}{k_m} = f\,(\beta, v_f\ ,\ \text{relative fiber arrangement}\ ) \qquad (1)$$

Where β is the fibre to matrix conductivity ratio and v_f the fibre volume fraction. The relative fibre arrangement for ordered arrays is quantified using a pitch-to-diameter ratio and a fibre packing angle γ (Figure 1). These methods, however, suffer from many drawbacks [9]. The pitch-to-diameter ratio and the fibre packing angle are in practice non-unique quantities even in the case of some ordered arrangements. Also, these methods could not take into account the presence of voids that might be created during the material manufacture [10]. In general, the results are more accurate for small fibre volume fractions and small ratio of the fibre conductivity to the matrix conductivity.

We can say that model based on a representation of the material by a unit cell is subjected to uncertainties that could lead to innacurate results. However, they can still offer a good approximation of the conductivity in some applications.



(a) Rectangular Array (b) Staggered Array

Figure 1. Ordered fibre arrangements

When theoritical predictions do not work, experimental measurement should be used. Two techniques are available, the steady state method and the transient method. The first method uses the " Hot Guarded Plate " apparatus described in the ASTM C177 standard [11]. The principle of the method is to impose two isotherms T_1 and T_2 on the specimen opposite parallel faces, and to measure the heat flux Φ through its thickness e. The thermal conductivity k is then obtained by the formula:

$$k = \frac{\Phi}{\left(\frac{T_1 - T_2}{e}\right)} \qquad (2)$$

This method needs a long experimentation time to reach the steady state and large specimens with an important regulation system. These inconveniences could constitute a serious handicap for small size specimens, or when a rapid and wrought thermal conductivity determination is needed in non-specialized laboratories.

Another method, the " Flash " method [12] is the most well known and used technique. It consists of imposing a heat flux of a very small duration (Dirac) on one of the specimen face, and to measure the temperature rise on the opposite side.
The thermal diffusivity "a" is obtained from the following equation,

(3)

Where $t_{1/2}$ represents the time required to reach one-half of the maximum back surface temperature and "e" the sample thickness. A laser source is often used to ensure an homogeneous and brief heating. The method is very attractive and many studies have been conducted to refine it and to take into consideration heat losses [13,14] and finite heat flux duration [15]. The application of this method leads to an apparent thermal diffusivity of the material that is correct, only if the specimen homogeneity is good. When measurement are made, the values obtained with some composite materials are found to be dependant on the specimen thickness, time and boundary conditions [16,17] . In reality, This is due to the fact that the tested specimen were not homogeneous.

In the present study, we propose a much faster method using a very simple apparatus that doesn't need sophisticated equipment. This method is developed for small specimen but can also be used for larger ones. Specimen of different thicknesses from unidirectional composites were tested in order to verify the effect of inhomogeneity.

Theory

The proposed method utilizes the Fourier's law principle during the transient evolution of the temperature and flux in a heated specimen. A theoretical analysis shows that the ratio between the heat flux and the temperature gradient in the direction of the heat flux in a specimen insulated on it's lateral faces parallel to the heat flux, becomes constant after a certain period of continuous heating. This period to reach a constant ratio depends on the heat flow through the specimen faces perpendicular to the direction of the heat flux. The dimensionless value of this period of time called α is given by the relation:

$$\alpha = \frac{at}{e^2} \qquad \textbf{(4)}$$

where a, e and t are respectively the thermal diffusivity, the thickness of the specimen, and the time. The value of α is 0.9 and 1.8 for respective values of Biot numbers of 1.0 and 5.0. For a 10 mm thick PVC specimen with heat transfert coefficient on the specimen face of 15 $W/m^2/K$ and 75 $W/m^2/K$, this translates into necessary heating times of 30 and 15 minutes respectively. It shows that the a good thermal contact must be provided on the sample faces perpendicular to the heat flux to reduce the time necessary for the experiments. The ratio α also depends on the thermal conductivity of the sample and the distance Δx between the points used to measure the temperature gradient. It was noticed that when the distance Δx is large the ratio α becomes constant more rapidly when the thermocouples are located near the two non insulated faces of the specimen. With this method, the thermal conductivity is determined by replacing the thickness e by Δx in the Eqn (2).

Apparatus and procedure

The experimental apparatus is shown in Figure 2. It comprises an electrical heater embedded in a copper block to supply a constant heat source and an other copper block located on the other side of the specimen to increase the heat exchange coefficient and to assure a uniform heat flux. The electrical resistance is placed in a copper block to increase and to homogenise the heat flux on one side of the specimen. A silicon heat conductive compound is applied between the copper blocks and the specimen to reduce the contact resistance in the flux direction. As shown in Figure 2, the

specimen is surrounded with insulation material made of Kaowool fibres. The assembly is clamped together and placed in a PVC tube to prevent radial heat losses and to maintain unidirectional heat flow in the sample.

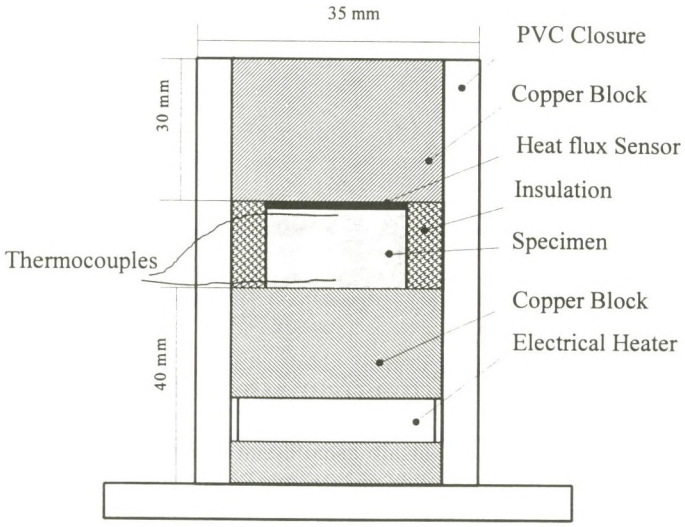


Figure 2. Experimental apparatus

On each sample, a set of two iron-constantin (Type J) thermocouples are cemented into holes located 1 mm underneath the surface. An epoxy based structural adhesive is used to cement the thermocouples. It was choosen so that its thermal properties are close to those of the specimen to maximize the thermal contact between the thermocouples and the specimen. The heat flux is measured with a heat flow sensor of $3.154\ 10^{-5}\ \mu W/cm^2$ sensitivity.

To validate the method, a PVC specimen of known conductivity was used. Glass fibre reinforced epoxy (GFRE) and glass fibre reinforced polyester (GFRP) with 65% and 55% fibre volume fraction respectively were tested in this study. These unidirectional composites were pultruded into rods of small cross-sections. The materials properties of the composites constituents and the PVC are given in Table 1. The conductivities along the fibres and in the direction perpendicular to the fibres were determined using specimen cut and placed in the apparatus in such a way that the heat flux occurred in the desired direction for the thermal conductivity measurement. The dimensions of the specimens used are given in Table 2.

Table 1. Materials properties

Material	Glass fibre	Epoxy	Polyester	PVC
density (Kg/m^3)	2490	1130	1200	1450
specific heat (J/Kg/K)	710	1050	1950	690
thermal Conductivity (W/m/K)	1.04	0.2	0.2	0.16

Table 2. Specimen dimensions

Material	GFRE*		GFRP**		PVC
	Long.	Trans.	Long.	Trans.	
cross-section (mm.mm)	6 x 4	8 x 4	8 x 8	8 x 8	10 x 10
thickness (mm)	4, 8 et 15	4 and 5	5 and 10	5 and 8	5 and 10

* **Glass fibre reinforced epoxy**
** **Glass fibre reinforced polyester**

Each test begins with the sample in thermal equilibrium at room temperature. Power is then applied to the resistance heater and the temperatures from both thermocouples and the heat flux are monitored. The ratio between the heat flux and the temperature gradient is computed until a constant value is reached. The thermal conductivity of the sample in the tested direction is obtained from Equation (2) which can be rewritten as follows:

$$k = \frac{\phi}{\Delta T} . \Delta x \qquad (5)$$

Where Δx is the distance between the thermocouples and ΔT the correspondent temperature difference.

In addition to the proposed method, and for comparison purposes, a modified "Flash" technique was also used to determine the thermal conductivities by measuring the specimen thermal diffusivities and multiplying them by the specific heat. The specific heat can be measured or determined from the rule of mixture if the constituents properties are known.
Each specimen, previously studied, was put in contact with the heated copper block during 10 to 30 seconds depending on the specimen thickness. The specimen was then removed and it's temperature rise measured, using the thermocouple located near the opposite heated face. A modified formula derived from Eqn (3) to take into account heat losses from the specimen and the finite heat duration,was used to determine the thermal diffusivity of the composites.

Results and discussion

Table 3 shows the measured values for various thicknesses for the three materials tested. We can see that the effect of the specimen thickness on the composites TC is less than 3%. This is an indication that the specimen are quite homogeneous. Also, the measured values for the PVC are very close to

the published thermal conductivity for this material given in table 1, this is a good indication that the proposed method is reliable.

Table 4 shows comparison between the results obtained with the transient and the steady-state methods. It is interesting to notice that the values of the thermal conductivities obtained with the transient technique are quite close despite the simplicity of the the transient method.

Finally, table 5 shows the experimental results for the transverse conductivity compared with values predicted by some well-known models. Unexpectedly, it can be seen that the electrical analogy gives the best results. The values obtained from the other models are considerably different from the experimental ones. However, the TC predicted using Springer's model can be considered to be in reasonable agreement with the experimental one. These findings for the applicability of the models cannot be extended to other materials. It should be noticed that all the experiments were performed at an average specimen temperature of about 40°C. Since the temperature range used was narrow, the thermal conductivity of the material has been assumed constant during the experiments. The estimated error on the thermal conductivity is about 3%. This error is mainly due to the exactness of the distance between the thermocouples which is difficult to know precisely because they can move slightly in their hole while being glued.

Table 3. TC for various thicknesses. The average value for each direction is shown in brackets.

Material	Thickness (mm)	Longitudinal TC (W/m/K)	Thickness (mm)	Transversal TC (W/m/K)
PVC	9 5	0.166 0.164 [0.165]		
GFRE	4 8 15	0.797 0.773 0.807 [0.792]	4 5	0.471 0.459 [0.465]
GFRP	8 12	0.627 0.644 [0.636]	5 8	0.349 0.357 [0353]

Table 4. Steady state and Transient methods results comparison

Material	$K_{steady\ state}$	$K_{transient}$	% difference
PVC	0.165	0.161	2.4
GFRE			
Longitudinal	0.792	0.817	3.2
Transversal	0.465	0.443	4.7
GFRP			
Longitudinal	0.634	0.605	4.6
Transversal	0.353	0.334	5.4

Table 5. Comparison between the measured TC and predicted by various models.

Material	Measured (Average)	Electrical analogy	Springer and al.[4]	Hashin [7]	Thornburg [5]
GFRE	0.465	0.421 (9.5)	0.534 (15)	0.561(20.6)	0.469 (32.8)
GFRP	0.353	0.360 (2)	0.499 (16.1)	0.438 (24.1)	0.499 (41.4)

( ) % difference

Conclusion

For composites, experimental determination of the thermal conductivity is usually necessary since the various models have difficulties to consider the real fibre arrangement, the thermal contact resistance between the fibre and the matrix, the voids effects etc.. In this paper, a low cost and rapid technique to measure the thermal conductivity is proposed.
The main advantage of this method is the fact that none of the material properties are needed to measure the thermal conductivity as opposed to the flash technique for which the specific heat of the material is needed. An other advantage is the fact that even small specimen can be used. Finally, this method is much faster than the ASTM 177 method which takes a long time, mostly because specific surface temperatures are needed to calculate the thermal conductivity. It was also shown that great care must be taken with models published in literature because their applicability to a specific material is not obvious.

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