THERMAL CONDUCTIVITY OF CARBON FIBER FABRICS

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Abstract
Thermal conductivity of dry carbon fiber fabrics is required for modelling heat transfer during infusion processes. This paper reports in-plane and through-thickness thermal conductivities, measured for a non-crimp carbon fabric and a twill carbon fabric as a function of fiber volume fraction (Vf). Well-defined trends were observed for both directions and values suggest that the thermal conductivity of dry fabrics is independent of fabric architecture. The in-plane thermal conductivity of dry fabrics and composites made from the same fabrics were similar. This demonstrates that the in-plane thermal conductivity depends primarily on the axial fiber thermal conductivity. Current models, such as Clayton, predict the through-thickness thermal conductivity of composites accurately, but do not account for fiber contacts and hence cannot predict that of dry fabrics. Simulations were developed to predict the through-thickness thermal conductivity of dry fabrics by accounting for the fiber contacts and results match experimental values. This shows that the through-thickness thermal conductivity of dry fabrics depends on the evolution of heat paths in the through-thickness direction as a result of the improvement in the fiber contact network during compaction. Through-thickness thermal conductivity measured for the composites are 2 to 3 times higher than those for the dry fabrics. This shows that the through-thickness thermal conductivity depends heavily on the thermal conductivity of the second phase, whether it is air for the dry fabrics or epoxy for the composites.

1 Introduction
Carbon fiber fabrics come in a variety of architectures and are used extensively in the composites and aerospace industries. Knowledge of their thermal conductivity is paramount in modelling heat transfer during processes such as resin film and autoclave infusion, where the thermal properties of dry fabrics must be known prior to impregnation. This would also benefit the understanding of heat diffusion in similar materials [1], and also other applications such as firefighter clothing design [2].

Thermal conductivity values for the constituent carbon fibers are found readily in the literature [3-5] and are often reported by manufacturers [6]. Thermal conductivity of composites made using such fabrics has also been studied extensively [7-8]. The rule of mixture (1) is widely used and acknowledged for predicting the in-plane thermal conductivity of unidirectional fiber-reinforced composites:

\[ k_x = k_{fa}Vf + k_m(1-Vf) \] (1)

where \( k_x \) is the 0° in-plane thermal conductivity of the composite, \( k_{fa} \) is the thermal conductivity of the fiber in the axial direction and \( k_m \) is the thermal conductivity of the matrix. The in-plane thermal conductivity is a linear function of fiber volume fraction (Vf) [9-10]. The Clayton analytical model (2) is widely used for predicting the transverse thermal conductivity of unidirectional fiber-reinforced composites [9] and yields a slightly exponential trend as a function of Vf [7]. The Clayton model can also be used to predict the through-thickness thermal conductivity of laminates manufactured from unidirectional plies, as the through-thickness thermal conductivity of such laminates is equal to the transverse conductivity of a single ply [11].

However, little is known about the thermal conductivity of dry carbon fiber fabrics. The clothing industry has studied thermal insulation for textiles such as woven cotton in a broad sense [12], but there are no studies on the effect of Vf and few regarding fabric architecture [13-14]. There are even
fewer results from the composites community, where one study measured the through-thickness thermal conductivity of a carbon T300 plain weave fabric to be 0.074 W/mK with no stated Vf, and developed an analytical model using an electric circuit analogy [15]. No computational models for the thermal conductivity of dry fabrics were found in the literature.

This paper reports in-plane and through-thickness thermal conductivities for two carbon fiber fabrics and systematically investigates the effect of Vf and architecture. Experimental values are compared to analytical predictions and simulations, and also to thermal conductivity values measured for composites made from the same fabrics.

2 Methodology
2.1 Experimental Details
In-plane and through-thickness thermal conductivities of Saertex bidirectional ±45° non-crimp 534 g/m² and JB Martin 2x2 twill 215 g/m² carbon fiber fabrics were measured using Hukseflux THASYS and THISYS devices as shown in Fig.1. Both fabrics are made of Toho Tenax HTS40 fiber; the non-crimp and twill feature 12K and 3K yarns, respectively. The devices require flat plate samples 70x110 mm within a thickness range of 0.1 to 6 mm. Having very clean sample edges is not critical, as shown by the indifference in results from prior testing of composite samples cut roughly on the edges compared with the same samples cut smoothly. THASYS requires two identical samples to measure the through-thickness thermal conductivity, while THISYS requires one sample to measure the in-plane thermal conductivity.

In THASYS, the two samples are placed between two heat sinks with a thin heater in between them. Fig.2. THASYS calculates the through-thickness thermal conductivity based on direct measurements of the temperature difference and the heat flux generated across the samples, known from the heater power using Fourier’s Law. [16] In THISYS, the sample is placed in between two thin heaters, which are in turn between two heat sinks featuring air-filled insulation cavities close to the samples, Fig.3. The cavities are covered by thin heaters to reduce lateral heat losses. THISYS calculates the bulk in-plane thermal conductivity based on direct measurements of the temperature difference and the heat flux generated across the plane of the samples, known from the heater power. The samples are inserted and manually tightened to position in both devices to apply contact pressure on the heaters, heat sinks and samples via a spring. The heater, heat sinks and samples are immersed in glycerol to minimize thermal contact resistance in both devices. [17]
Samples were prepared by stacking six non-crimp or 16 twill layers so as to reach comparable thickness, and sealed with 25 µm thick Dahlar 125 release film from Airtech on three sides, Fig.4. This procedure was used so as to avoid penetration of glycerol into the dry textile samples. Samples that were not vacuumed were exposed to air as they were not sealed along the upper edge, so as to enable their progressive compaction and increase in Vf within the devices. Polymeric spacers were milled to five thicknesses within the range 3.39 to 4.76 mm to impart corresponding Vfs to the samples within the range of 38.5 to 56.4%.
Variability was quantified by repeating the tests for a number of data points. Within-sample variability is based on measurements performed on the same fabric sample at a common Vf, taken one after another without remounting the sample. This represents the variability of the THASYS and THISYS devices. Between-samples variability is based on measurements taken on different fabric samples at a common Vf, and it represents sample data variability.

Two carbon fiber-epoxy composite plates were manufactured using the same fabrics described above; one for each fabric using resin film infusion (RFI) under vacuum. The resin film used is 120 µm thick epoxy film from Axson. The fabric and resin film were intercalated, vacuum bagged and cured in a PF120 Carbolite oven, Fig.7. The temperature profile was programmed to ramp at 2°C/min up to 130°C, dwell for two hours, then ramp at 2°C/min up to 200°C and dwell for two hours. Two samples were cut from each cured plate for thermal conductivity measurements in THASYS and THISYS. The Vfs of the plates were obtained by image analysis on a Nikon XJP-3A optical microscope.

2.2 Modeling

2.2.1 Analytical Model

Eqn. (2) shows the Clayton model [9] for predicting the through-thickness thermal conductivity of composites as a function of Vf given the thermal conductivity of the two constituents:

\[
k_{tt} = \frac{k_m}{4} \left[ \sqrt{\left(1 - Vf\right)^2 \left(\frac{k_{ft}}{k_m} - 1\right)^2 + \frac{4k_{ft}}{k_m}} \right]
\]  

\[- \left(1 - Vf\right)\left(\frac{k_{ft}}{k_m} - 1\right) \right]^2 \right) \right]
\]

(2)
where \( k_{tt} \) is the through-thickness thermal conductivity of the composite, \( k_m \) is the thermal conductivity of the matrix or second phase and \( k_f \) is the thermal conductivity of the fiber in the through-thickness direction.

This model is used in attempting to predict the through-thickness thermal conductivity of the non-crimp fabric but not that of the twill fabric, as the non-crimp fabric is bidirectional but the twill fabric is woven and has crimps and air rich zones which Clayton does not account for. The thermal conductivity of air was used for \( k_m \) and \( k_f \) was back-calculated from the Clayton model after measuring the thermal conductivity of epoxy only plates and the through-thickness thermal conductivity of the carbon fiber-epoxy composite plates made from the same non-crimp fabric in THASYS and THISYS and knowing the Vf from image analysis, Table1. Corresponding predictions were calculated at the Vf of each data point. An additional prediction was added at 33.4% Vf to compare Clayton predictions with results for case 1 of the simulation series accounting for fiber contacts.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Thermal conductivity (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>carbon fiber</td>
<td>( k_f = 1.36 )</td>
</tr>
<tr>
<td>matrix (air)</td>
<td>( k_m = 0.03 )</td>
</tr>
</tbody>
</table>

### 2.2.2 Simulations

Two-dimensional steady state simulations performed in Ansys Fluent 13.0 were also used in attempting to predict the through-thickness conductivity of the dry fabric samples and replicate the trend seen in thermal conductivity as a function of Vf. The top and bottom walls of the virtual domain were set to constant temperatures while others were set as adiabatic. The thermal conductivity was calculated using Fourier's Law based on the resulting heat flux.

Two types of simulations were done. First, simulations were developed in attempting to replicate experimental results without modelling fiber contacts. Fiber sections were represented by circles and models consist of eight square unit cells as shown in Fig.8. Height and width are varied proportionally with Vf. Five cases were run for Vfs within the range of 38.0 to 53.0%. These cases have incremental changes in Vf resulting from reduced distances between adjacent fibers.

Then, simulations were developed in attempting to model thermal conductivity accounting for fiber contacts. Fiber sections were represented by 24-sided polygons to yield small contact lines between adjacent fibers. Five cases were run as shown in Fig.9 for Vfs within the range of 33.4 to 65.8%. Whilst they represent a few simple configurations taken for illustration among a wide array of possible fiber arrangements, these cases have representative incremental changes in fiber contact and configuration along with corresponding increases in Vf. Height is decreased during compaction while width remains constant. All simulations were developed not accounting for the fabric architecture, based on the indifference in measured values for the two fabrics.
3 Results

3.1 Experimental

Experimental results appear in Figs.10-15. For dry fabrics in the in-plane direction, Figs.10-11 show that thermal conductivity values for both fabrics vary linearly with Vf, ranging from 1.303 to 2.249 W/mK and from 1.367 to 2.092 W/mK for the non-crimp and twill fabrics, respectively. The vacuumed non-crimp sample returned a value of 2.188 W/mK at 52.6% Vf; 2.4% lower than that of its non-vacuumed counterpart. Still for dry fabrics but in the through-thickness direction, Figs.12-13 show that thermal conductivity values for both fabrics have an exponential recovery trend with Vf, ranging from 0.112 to 0.209 W/mK and from 0.145 to 0.219 W/mK for the non-crimp and twill fabrics, respectively. The vacuumed non-crimp sample returned a value of 0.182 W/mK at 52.6% Vf; 7.4% lower than that of the non-vacuumed counterpart.

Variability data appear in Tables 2-5. Within-sample variability values are below 1% except for that of the vacuumed sample with a maximum of 2.8%, Tables 2-3. Values generally confirm the 1% and 2% variability figures reported by Hukseflux for THASYS and THISYS respectively, indicating that the devices operate satisfactorily with the non-homogeneous materials tested here. Between-samples variability showed values within 6.7 to 11.2% range, Tables 4-5.
### Table 2. In-plane variability, within sample

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Vf</th>
<th>Thermal conductivity (W/mK)</th>
<th>Variability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>twill</td>
<td>0.401</td>
<td>1.371</td>
<td>0.7</td>
</tr>
<tr>
<td>twill</td>
<td>0.564</td>
<td>2.089</td>
<td>0.6</td>
</tr>
</tbody>
</table>

### Table 3. Through-thickness variability, within sample

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Vf</th>
<th>Thermal conductivity (W/mK)</th>
<th>Variability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-crimp</td>
<td>0.398</td>
<td>0.187</td>
<td>0.5</td>
</tr>
<tr>
<td>non-crimp</td>
<td>0.398</td>
<td>0.195</td>
<td>0.5</td>
</tr>
<tr>
<td>non-crimp</td>
<td>0.526</td>
<td>0.184</td>
<td>2.8</td>
</tr>
<tr>
<td>twill</td>
<td>0.491</td>
<td>0.208</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### Table 4. In-plane variability, between samples

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Vf</th>
<th>Thermal conductivity (W/mK)</th>
<th>Variability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>twill 1</td>
<td>0.456</td>
<td>1.562</td>
<td>6.7</td>
</tr>
<tr>
<td>twill 2</td>
<td>1.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td>twill 3</td>
<td>1.597</td>
<td></td>
<td></td>
</tr>
<tr>
<td>twill 4</td>
<td>1.666</td>
<td></td>
<td></td>
</tr>
<tr>
<td>non-crimp 1</td>
<td>0.425</td>
<td>1.597</td>
<td>9.2</td>
</tr>
<tr>
<td>non-crimp 2</td>
<td>1.668</td>
<td></td>
<td></td>
</tr>
<tr>
<td>non-crimp 3</td>
<td>1.744</td>
<td></td>
<td></td>
</tr>
<tr>
<td>non-crimp 4</td>
<td>1.663</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 5. Through-thickness variability, between samples

<table>
<thead>
<tr>
<th>Fabric</th>
<th>Vf</th>
<th>Thermal conductivity (W/mK)</th>
<th>Variability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>twill 1</td>
<td>0.491</td>
<td>0.208</td>
<td>11.2</td>
</tr>
<tr>
<td>twill 2</td>
<td>0.193</td>
<td></td>
<td></td>
</tr>
<tr>
<td>twill 3</td>
<td>0.188</td>
<td></td>
<td></td>
</tr>
<tr>
<td>twill 4</td>
<td>0.187</td>
<td></td>
<td></td>
</tr>
<tr>
<td>non-crimp 1</td>
<td>0.457</td>
<td>0.189</td>
<td>7.7</td>
</tr>
<tr>
<td>non-crimp 2</td>
<td>0.190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>non-crimp 3</td>
<td>0.196</td>
<td></td>
<td></td>
</tr>
<tr>
<td>non-crimp 4</td>
<td>0.182</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Conductivity data for composites made using the same carbon fabrics as reinforcements appear in Figs. 14-15. The plates made from the non-crimp and the twill fabrics have Vfs of 58% and 54%, respectively from image analysis. The in-plane thermal conductivity values of composite and dry fabric are 2.5 and 2.3 W/mK respectively for the non-crimp fabric, and 2.5 and 2.1 W/mK respectively for the twill fabric, Fig. 14. The same comparisons for through-thickness thermal conductivity show much more significant differences, with values of 0.5 and 0.2 W/mK for the non-crimp composite and fabric respectively, and 0.55 and 0.22 W/mK for the twill composite and fabric respectively, Fig. 15. The in-plane to through-thickness conductivity ratio is approximately five for carbon fiber-epoxy composites, compared to ten for dry fabrics.

![Fig. 14. Thermal conductivity of carbon fiber-epoxy composites vs. dry fabrics, in-plane](image-url)
3.2 Analytical Model and Simulations

Through-thickness thermal conductivity predictions attempted for the dry fabric using the Clayton model and both types of simulations are compared with experimental values for the non-crimp fabric, Fig.16. The same information for the twill fabric appears in Fig.17, without the Clayton predictions. The first point at 33.4% Vf has matching values of 0.064 and 0.063 W/mK obtained from the Clayton model and simulation. For the non-crimp fabric, experimental values range from 0.112 to 0.209 W/mK and show an exponential recovery trend while corresponding Clayton predictions range from 0.072 to 0.117 W/mK and show a linear trend with Vf. Simulations without fiber contacts show values and trend close to those from Clayton predictions while simulations accounting for fiber contacts show values and trend close to the experimental results. The same observations are found for the twill fabric where the experimental values range from 0.145 to 0.219 W/mK. Again, simulations accounting for fiber contacts offer better results than those without fiber contacts.

4 Discussion

In the in-plane direction, thermal conductivity values measured for carbon fiber-epoxy composites are not remarkably different from those obtained for the dry fabrics, Figs.14-15. This, along with values showing only a 2.4% difference between vacuumed and non-vacuumed dry fabrics samples, confirms that in-plane heat transfer occurs primarily along the fibers and is driven by the axial fiber thermal conductivity. Therefore, since both fabrics consist of the same fiber, the non-crimp and the twill fabrics show similar conductivities, Figs.10-11. Similar to fiber-reinforced composites, thermal conductivity values
for dry fabrics vary linearly with Vf. The effect of cycling the dry fabric samples can also be seen, Figs.10-11, as the fiber network improves slightly upon each compaction, as shown by higher values upon successive compaction cycles beyond the first.

In the through-thickness direction, thermal conductivity values measured for carbon fiber-epoxy composites are two to three times larger than those measured for the dry fabrics, Figs.14-15. This, along with a 7.4% decrease in the conductivity of vacuumed samples compared to that of their non-vacuumed counterparts, confirms that the thermal conductivity in this direction is affected significantly by that of the second phase, whether it is air for dry fabrics or resin for composites.

Values predicted by the Clayton model and simulations without contacts are much lower than experimental results and trends do not agree, Fig.16, because Clayton predicts thermal conductivity in a manner equivalent to this series of simulations by increasing Vf through reduced distances between adjacent fibers; the model and this series of simulations do not account for contact between fibers. Therefore, Clayton predicts through-thickness thermal conductivity values for fiber-reinforced composites accurately as there is little contact between fibers due to the presence of resin, but it cannot predict the conductivity of dry fabrics which is influenced by the evolution of heat paths in the through-thickness direction as a result of the improvement in the fiber contacts with Vf in this direction and its eventual stagnation.

The second series of simulations represent the physical phenomenon better by representing and accounting for the evolution of the fiber contact network along with increases in Vf, Fig.9. Model 1 represents an initial state at the onset of compaction where there is limited contact between adjacent fibers. Additional contact points begin to develop in model 2 and by model 3, there are direct paths for heat flow in the through-thickness direction through the carbon fibers. Fibers start to shift in model 4 as a result of further compaction and connect additional heat paths along different directions; this 2D contact network is further enhanced in model 5. Hence, there is an evolution in the heat paths in the through-thickness direction from models 1 to 3, but it does not improve significantly from models 3 to 5. Hence, the trend of diminishing returns with Vf seen in Figs.12-13 indicates that improvements in the fiber contact network through-thickness are significantly less for Vfs above 50%.

Simulation results match the trend observed with experimental data and the last three points are higher than measured values, due to the short line contact between adjacent 24-sided polygons as opposed to contact points between adjacent circles in reality. The simulations clearly simplify reality, but nevertheless they are credible and manage to successfully replicate and explain the trends seen in experimental results for dry fabrics, which cannot be replicated by any published model. Predictions from the Clayton model only agree with simulation results for case 1, Fig.16, because it is only in this case that there is no contact between adjacent fibers.

The success of the simulations accounting for contacts and the discrepancy of predictions made using the Clayton model and simulations without contacts compared to measured values show that the thermal conductivity values and exponential recovery trends in Figs.12-13 is fully a result of the evolution of contact points in the fiber network during the compaction process. This, along with the thermal conductivity of air, is important for predicting the through-thickness thermal conductivity of dry fabrics. Therefore, since both fabrics show a similar behaviour in terms of fiber contact network and have air as the second material phase, the non-crimp and the twill fabric return similar values, Figs.12-13. The effect of cycling is similar to that seen for the in-plane direction as shown again in Figs.12-13.

5 Conclusions

The in-plane and through-thickness thermal conductivity of a non-crimp and a twill fabric were measured within a Vf range of 38.5 to 56.4%. Values suggest that the thermal conductivity of dry fabrics is independent of fabric architecture. Well-defined, reproducible trends showing the effect of Vf on the in-plane and through-thickness thermal conductivity were identified. The effect of the matrix on the through-thickness thermal conductivity was also identified. Through-thickness thermal conductivity simulations of dry fabrics matched experimental results and showed the importance of modelling contact points between fibers.

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References


