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A THERMAL BEHAVIOUR STUDY OF NATURAL FIBER-REINFORCED POLYMER COMPOSITE/HONEYCOMB CORE SANDWICH PANELS

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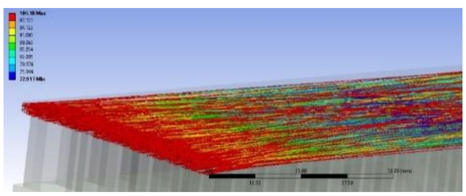
Graphical abstract



Abstract

The unique honeycomb structure has provided good modulus with a lightweight material, especially in aerospace and vehicle applications. Realizing that the thermal analysis of natural fiber honeycomb sandwiches was still lacking in observation, the research needs to investigate thermal transfer characteristics to promote engineering demand. The objective of this research was to investigate honeycomb sandwiches' thermal behaviour by implementing local natural fibers of coconut, oil palm, and sugar cane for sheet plate structure through experimental and numerical analysis. The natural fiber was varied by weight content with the ratio of composite given in a range of 0%wt. - 8%wt. The results have demonstrated that the face sheet plate was paramount part to absorb thermal flow. The study displayed the low thermal conductivity of the face sheet will counter significantly the heat transfer of the honeycomb structure. The experimental investigation found that the coconut fiber successfully performs as an insulator in a honeycomb sandwich which reached 6.78 $W.m^{-1}K^{-1}$ of thermal conductivity which was an 85.86% improvement as an insulator. While palm oil and sugar cane presented at 11.12 $W.m^{-1}K^{-1}$ and 10.59 $W.m^{-1}K^{-1}$, it was slightly higher compared to the coconut. In the numerical investigation, fiber distribution development was successfully performed in a honeycomb sandwich sheet plate composite. The thermal conductivity showed a difference from the experimental, where the higher thermal resistance was shown by palm oil and sugar cane at 8.22 $W.m^{-1}K^{-1}$ and 8.16 $W.m^{-1}K^{-1}$, respectively. This difference was much influenced by the morphology factor in fiber orientation of the experimental study.

Keywords: Honeycomb, sheet plate, composite, fiber distribution, morphology

Abstrak

Struktur sarang lebah yang unik telah menyediakan modulus yang baik dengan bahan yang ringan, terutamanya dalam aplikasi aeroangkasa dan kenderaan. Menyedari bahawa analisis haba sandwic sarang lebah gentian semula jadi masih kurang dalam pemerhatian, penyelidikan perlu menyiasat ciri pemindahan haba untuk menggalakkan permintaan kejuruteraan. Matlamat penyelidikan ini adalah untuk mengkaji perilaku tenaga haba terhadap struktur sarang lebah terapit dengan mengunapakai serat semulajadi buah tempatan iaitu dari buah kelapa, buah kelapa sawit, dan tebu untuk dijadikan struktur kepingan plat melalui ujikaji dan analisis berangka. Serat semulajadi yang beraneka ragam mempunyai kandungan isipadu dengan nisbah komposit antara 0 %wt – 8 %wt. Hasil kajian telah menunjukkan permukaan kepingan plat merupakan bahagian utama yang menyerap aliran tenaga haba. Kajian ini menunjukkan sifat keberaliran haba yang rendah pada permukaan akan beralih secara terus dan ketara terhadap struktur sarang lebah. Kajian ujikaji menemui serat daripada buah kelapa yang diletakkan di dalam struktur sarang lebah terapit berjaya berfungsi sebagai penebat dimana keberaliran haba mencapai 6.78W.m^{-1}K^{-1} seterusnya berlaku kenaikan sebanyak 85.86% penambahbaikan sebagai penebat. Manakala keberaliran haba untuk serat daripada buah kelapa sawit dan tebu lebih tinggi sedikit berbanding serat buah kelapa dimana masing-masing mencapai 11.12 W.m^{-1}K^{-1} dan 10.59 W.m^{-1}K^{-1}. Analisis berangka mendapati pembangunan taburan serat berjaya dilakukan dalam komposit kepingan plat struktur sarang lebah terapit. Keberaliran haba menunjukkan perbezaan dari ujikaji di mana rintangan haba yang lebih tinggi ditunjukkan oleh serat buah kelapa sawit dan tebu masing-masing pada 8.22 W.m^{-1}K^{-1} dan 8.16 W.m^{-1}K^{-1}. Perbezaan ini dipengaruhi oleh faktor morfologi kedudukan serat ketika ujikaji.

Kata kunci: Sarang lebah, plat lembaran, komposit, taburan gentian, morfologi

1.0 INTRODUCTION

In the two last decades, the honeycomb was successful to offer a solution as a lightweight material by promising good performance in the structure. Its performance was demanding attention in several engineering applications such as military purposes, vehicles, airplanes, and aerospace with light weight improvement [1-3]. As an important role in the structural field, the honeycomb sandwich is related to thermal comfort with the characteristics needed to pass the thermal testing system to define conductivity management. Relate to the heat treansfer concept, the thermal source is a significant effect on the surrounding by fluid transfering to the objects. It is interseting to characterize the honeycomb sandwich which some implement for human comfort. The temperature characterization conditions of sandwich honeycomb composite cause challenges due to the unique structure of both the composite and the honeycomb itself. The thermal transfer was characterized by the unique structure of the honeycomb and sheet plate as shown by previous researchers [4-7]. The effectiveness of the face sheet plate was a paramount part of absorbing the thermal flow. The low thermal conductivity of the face sheet improved the heat absorption of the honeycomb structure. Carbon prepreg successfully reduces the thermal conductivity of the honeycomb by constructing a composite face sheet plate as a panel [4]. Other researchers stated that the thermal characteristic was also influenced by composite morphology which thermal conductivity depends on the fiber distribution and fiber content of the face sheet composite [5]. Moreover, thermal loading induced mechanical degradation such as shear buckling and plastic deformation in the honeycomb core. The results showed that the extreme temperature caused a progressive damage response in the composite face sheet [6].

Utilization of face sheet composite in honeycomb structure application is a feasible strategy to increase thermal insulators or vice versa. Adding natural rubber (NR) to increase the thermal insulating properties of composite was a successful strategy of thermal management that has been proposed [8,9]. Typical poor thermal conductivity of NR reduced the ability of the composite to transfer thermal and it has high potential application of advanced semiconductor materials. The other way around, the composite was also capable of increasing thermal conductivity by adding highly thermal conductive polyurethane (PU)-/SiC composites for the advancement of electronic device applications [10]. The fabricated composite sheet to honeycomb sandwich is one alternative for thermal insulation materials to reduce the use of foam plastic. Therefore, a comprehensive study is required to characterize the interaction between matrix and filler.

Natural fiber composites have already been accepted in engineering for several demands especially constructions, even though detailed characteristics still require comprehensive research. The effective natural fiber composite in transverse thermal has been investigated through unique natural fiber characterization [11, 12]. The optimization thermal insulator was achieved by combining the volume percentage of several natural fiber such as Banana, Pineapple and Jute fiber. At the same time, other natural fibers have shown good performance in thermal insulators such as abaca and bamboo fibers to fabricate epoxy composites [13]. The natural fibers of coconut, oil palm and sugar cane are a kind of widely wasted natural fibers in Malaysia that need to characterize in engineering analysis [14-16]. Another researcher has implemented the natural fiber composite as skin in a honeycomb sandwich to investigate the influence of woven glass-fiber prepreg orientation on flexural performance [17].

The numerical simulation gives another solution to counter time and cost consumption regarding the composite investigation. Numerical investigation was capable to measure macrostructure until to microstructures level by mathematical characterization. Optimization of thermal transfer by shapes, volume fractions and various geometric fiber were possibly developed using numerical analysis. Zhao *et al.* have successfully developed a numerical investigation for transverse thermal conductivity of unidirectional natural fiber composites where hierarchical microstructures presented by agglomeration unidirectional fiber [18]. The finite element analysis also introduces in numerical solution to solve thermal conductivity tensor components of carbon-fibre/epoxy composite [19]. The algorithm of tensor components was developed as a core of the computational for determining the thermal conductivity values.

Realizing the composite is a paramount part of the honeycomb and both present a unique structure, the research needs to investigate thermal transfer characterized to promote engineering demand. Furthermore, adding local natural fibers such as coconut, oil palm, and sugar cane fibers are interesting characteristics to study on the framework of the whole honeycomb structure. In this research, the numerical subsequent finite element analysis (FEA) is helping to investigate detail at the macrostructure level to analyze thermal transfer. Varied fiber contents and their distribution are developed in numerical design for evaluating the thermal dissipation capacity.

2.0 METHODOLOGY

2.1 Materials

In the interfacial interaction between matrix and natural fiber study, the Polyester resin was chosen to make composite material. The Polyester resin was made from glycol and unsaturated dibasic acid condensate, while the hardener was the butanox m-50 in a ratio of 100:4. The sodium hydroxide (NaOH) was used to remove impurities from the natural fiber. The last part was natural fibers, three natural fibers were represented in this research; coconut, oil palm, and sugarcane which were prepared as reinforcement composite. The natural fiber was varied by volume content with the ratio of composite given in Table 1.

2.2 Natural Fibers Collection

Malaysia has available and abundance of coconut, oil palm, and sugarcane fibers as waste materials. The collection was simple from local sources with varied techniques depending on the fiber field. The coconut fiber was collected from the field as an unwanted part of the coconut skin. The fibers were shredded to pill out the coconut fibre from impurities part. Then the coconut fibers were embedded and cleaned with distilled water and dried for one day by exposure to sunlight. Meanwhile, oil palm fiber was harvested from the oil palm industry after the milking process. The sugar cane was collected directly from sugar cane water retail traders after the juice was extracted. Both oil palm and sugar cane fibers were also treated with distilled water to remove all those impurities such as oil and sugar contents and dried for one day by exposure to sunlight.

2.3 Mercerization Processing

A 2% content of sodium hydroxide (NaOH) solution treatment was useful to remove impurities from the natural fiber and at the same time increase the flexibility of natural fiber. As shown in Figure 1a, this method was using the NaOH solution to submerge the fiber for soaking it for about 12 hours. To eliminate the NaOH, the distilled water was used for washing the fiber and soaked it for 1 to 2 hours to neutralize it and render it non-alkaline. The last step was the evaporation of the fibers in the oven at 100°C for six hours as shown in Figure 1b.

Table 1 The Composite ratio for varied filler content

Polyester Weight (g)	Hardner Weight (g)	Fiber Weight (g)	Fibers Percentage (%wt.)
336.00	14.00	0.00	0
329.28	13.72	7.00	2
322.56	13.44	14.00	4
315.84	13.16	21.00	6
309.12	12.88	28.00	8
302.40	12.60	35.00	10
295.68	12.32	42.00	12

Figure 1 Natural fiber treatment; 1a) NaOH submerge and 1b) drying process

2.4 Composite Preparation

The grinding and sifting processes were conducted to eliminate some hard impurities and followed by the sieving process to allow impurities collected. Sugar cane fiber as known as bagasse has much cotton attached to the fiber and needs an extra process such as brushing, while oil palm has shell fragments from the fiber to remove as shown in Figure 2. Then the composite construction was ready to fabricate by following Table 1 as a ratio reference. The composite thickness was determined fixed at 5 mm. Before pouring the mold with polyester, an ease-release compound was applied to allow the composite simply release from the mold. The technique chosen was the lay-up method where the composite was applied slowly layer by layer to avoid bubbles trapped in the mold. The sample curing needed at least 4 hours at ambient temperature and the following was by sample cutting in the sandwich honeycomb sample shape. To avoid thermal leaking, the sample required wrapping using foam insulators to cover along thickness as shown in Figure 3.

Figure 2 Impurities removal processing

Figure 3 Composite samples were analyzed in the thermal testing

2.5 Thermal Conductivity Testing

A heat transfer experiment was performed by a linear heat conduction machine to determine the thermal conductivity, *k*. Different temperature measurements from the source troughed the sample can demonstrate the *K* performance by the equation below:

$$k = -\frac{q.x}{A(T_2-T_1)}, \quad \left(\frac{W}{m.K}\right) \tag{1}$$

where *k* is thermal conductivity. *A* is a cross sectional area of sample, T_2 is hot plate temperature and T_1 is cold plate temperature

In this case, the thermal conductivity of the experiment was validated through the copper standard, before conducted the honeycomb panel composite experiment. The validation reported that the thermal conductivity was at 352.97 W/m°K. According J. Carvill, in Mechanical Engineer's Data Handbook, 1994, the value of copper is 385 W/m°K [20].

2.6 Numerical Development Model

The numerical model was developed in two stages for thermal conductivity analysis where the first focused on fibers distribution development by using MATLAB coding version R2021b. The MATLAB version 2021b requires a hardware-accelerated graphics card supporting OpenGL 3.3 with 1GB GPU memory. The random points algorithm were implemented as parameters analysis to develop the fiber points' position. In this stage, the fiber diameter developed was 0.1 mm along a longitudinal direction. The fiber contents were varied by different approaches, 100 fiber numbers represented 1.4 vol.%, 200 for 2.8 vol.%, 300 for 4.2 vol.%, 400 for 5.6 vol.%, 500 for 7 vol.%, and 600 for 8.4 vol.%. In MATLAB coding, the random distribution technique was implemented to produce longitudinal fibers orientation with several providers such as generating domain size, determining launch point, and producing fiber. Alongside was selected as a longitudinal field while the thickness was the area for randomly distributed points. The main rule of random distribution was limited by domain and avoided the repeated point selected. For fiber flow development detail is illustrated in Figure 4. While the second stage was concerned with honeycomb construction for thermal conductivity analysis by using Ansys Workbench. The random fibers distribution was exported to the Ansys Workbench system to analyse the model in thermal. For the honeycomb construction model, the honeycomb cell size and geometry follow the actual aluminium honeycomb size. This investigation considered the honeycomb structure with composite coupling plate method where the heat flux and thermal conductivity of honeycomb sandwich samples are calculated by equation 1. The parameters used in this analysis were the fiber amount algorithm which is used in the composite model. Oil palm, coconut, and sugar cane fiber properties were given in Table 2 for thermal conductivity and density.

Table 2 Single Fiber Properties

Materials (%wt)	Thermal Conductivity, (W/m.K)	Density, (kg/m³)
Oil Palm Fiber	0.059	30
Coconut Fiber	0.062	30
Sugar Cane Fiber	0.061	30

3.0 RESULTS AND DISCUSSIONS

3.1 Experimental Testing

The results were measured from differentiated temperature testing by using linear heat transfer equipment for each honeycomb sandwich natural fiber composite sample. The varied volume content conducted in a range of 0 %wt., 2 %wt., 4 %wt., 6 %wt, and 8 %wt has been measured to determine heat conductivity, *k* of honeycomb sandwich. Figure 5 shows the measurement process for temperature differentiated by linear heat conduction equipment. The sample was presently covered by foam in the middle of linear heat transfer equipment when the heat source was given to allow it throughout the sample. The analysis was recorded based on varied natural fibers which affect thermal conductivity, *k*, of the honeycomb sandwich. Table 3 presents the thermal conductivity of honeycomb sandwich coconut fiber composite in the range of 0 %wt., 2 %wt., 4 %wt., 6 %wt, and 8 %wt. A significant effect on thermal conductivity has been shown in honeycomb sandwich coconut fiber composite by giving a constant power (W) for the source. The thermal conductivity was increased by adding coconut fiber, this was a good deal for thermal insulator purposes. The higher percentage of coconut fiber stated that the lower thermal conductivity resulted which is 6.78 $W.m^{-1}K^{-1}$ for 8 %wt of filler content. The same study has been reported by previous researchers that coconut fiber sandwich for ferrocement panel walls in the sandwich configuration blocks much help schools and houses' roofing in Puerto Escondido, Oaxaca, Mexico for thermal insulators [21].

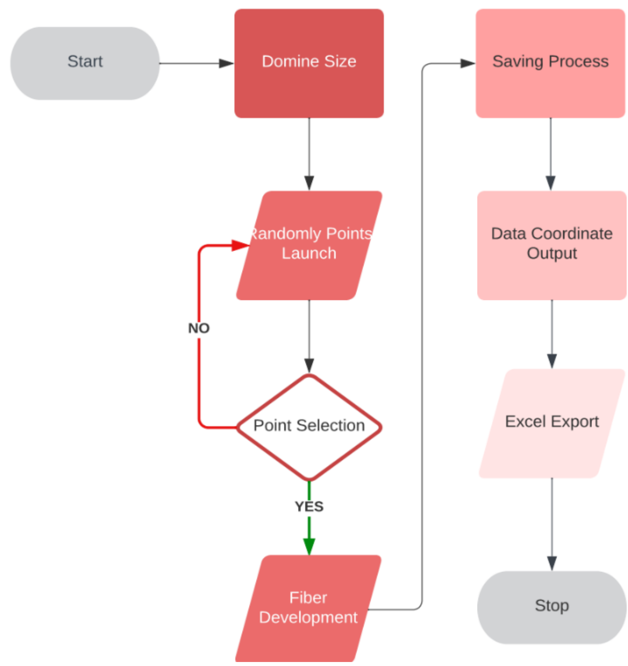


Figure 4 Fiber development flow by using MATLAB software

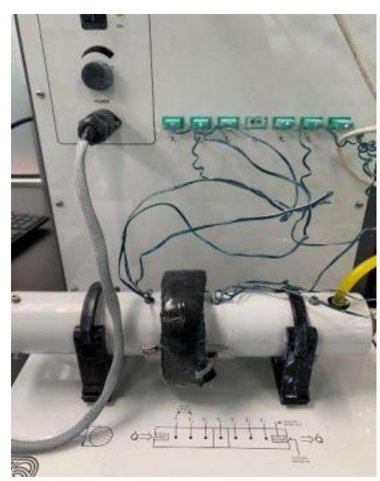


Figure 5 Difference temperature measurement process

Table 3 The thermal conductivity, *k* of honeycomb sandwich coconut fiber composite

Fiber (%wt)	Sample Thickness (m)	Power (W)	Initial Temp. (°C)	Final Temp. (°C)	Thermal Conductivity ($W.m^{-1}K^{-1}$)
0	0.059	30	42	32.4	47.96
2	0.062	30	65.7	29.7	13.44
4	0.061	30	72.3	28.3	10.81
6	0.065	30	83.4	25.9	8.81
8	0.064	30	97.8	24.2	6.78

For the honeycomb sandwich oil palm fiber composite in this research, there were four specimens with varied percentages of fiber measured in a range of 2 %wt, 4 %wt, 6 %wt, and 8 %wt. By giving constant power for 10 minutes, the results were recorded for each sample as presented in Table 4. It has clearly been seen that fiber decreases thermal conductivity which similar results perform by coconut fiber. The higher thermal conductivity was recorded at 33.37 $W.m^{-1}K^{-1}$ for 2 %wt. of filler content. This indicates that by continue adding oil palm fiber promote the thermal insulator. The fiber network successfully counters thermal penetration to form insulating chains. Similar phenomenon has been recorded by previous researcher that oil palm fiber was giving beneficial as composite material insulation because its values satisfy the standard ranges of thermal insulators for buildings [22].

Table 4 The thermal conductivity, *K* of honeycomb sandwich oil palm fiber composite

Fiber (%wt)	Sample Thickness (m)	Power (W)	Initial Temp. (°C)	Final Temp. (°C)	Thermal Conductivity ($W.m^{-1}K^{-1}$)
0	0.059	30	42	32.4	47.96
2	0.055	30	45.3	32.4	33.37
4	0.054	30	50.8	30.1	20.36
6	0.054	30	57.5	26.4	13.42
8	0.057	30	63.6	23.6	11.12

Further analysis was conducted on the honeycomb sandwich sugar cane fiber. Two temperature measurements were carried out on each sample in this study. Fourier's law of heat conduction results is presented in Table 5. Sample 1 to 4 shows a downtrend of thermal conductivity due to an increase in filler loading. Sample 1 with 2 %wt. fiber has the highest thermal conductivity and the lowest thermal resistance. However, sample 4 the lowest thermal conduction with 8 %wt. has been recorded in this study. Materials with lower thermal conductivity networks can be insulator chains, blocking the conduction of heat. Similar reports have been recorded that the thermal conductivity of sugar cane bagasse fibers might promote more insulating material in thermal transfer [23].

Comparison within natural fiber was shown in Figure 6, the figure demonstrates the honeycomb sandwich composite's thermal conductivity under various natural fiber and filler loading. This graph described that adding natural fiber can decrease the thermal conductivity by up to 85.5 %. Adding more natural fiber was increased in order to hold the thermal through the composite due to fiber networks blocking the thermal flow. As a result, the thermal conductivity drops to 49.7 to 85.5 %. The varying natural fiber and filler loading are investigated on the composite material, and varied results were obtained the coconut fiber was dominant to reduce the thermal conductivity then followed by oil palm and sugar cane.

Table 5 The thermal conductivity, *K* of honeycomb sandwich sugar cane fiber composite

Fiber (%wt)	Sample Thickness (m)	Power (W)	ΔT (°C)	Thermal Conductivity ($W.m^{-1}K^{-1}$)
0	0.059	30	32.4	47.96
2	0.093	30	33.9	21.08
4	0.095	30	44.3	14.77
6	0.093	30	54.5	12.31
8	0.095	30	65.7.6	10.59

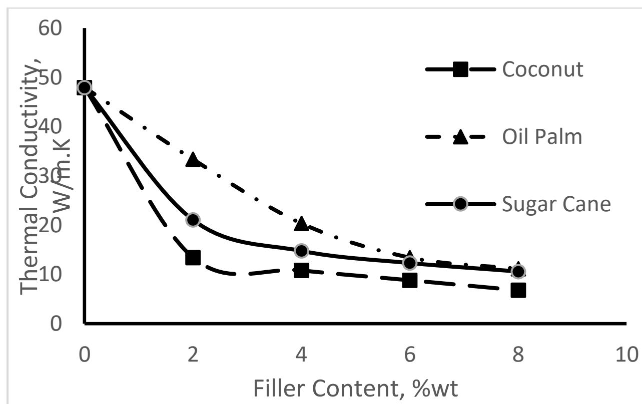


Figure 6 Honeycomb sandwich thermal conductivity, *K* by using experimental

3.2 Numerical Results

Figure 7 shows 600 fibers distributed along the longitudinal of skin honeycomb sandwich. The fiber presents randomly without any overlapping each other to create the longitudinal direction, which random point positioned as one coordinate along sheet thickness. The fiber developed satisfied in thickness along longitudinal with randomly pattern in sheet panel was successful. Further analysis was concerned on thermal analysis which honeycomb sandwich was varied on natural fiber composite.

For validation analysis, the thermal analysis of honeycomb with 0 %wt. shown in Figure 8. The sample size was 0.221 m × 0.076 m × 0.026 m, while 100 and 22°C were set as temperature boundaries. The reading Q = 299.71 W was recorded as a constant value, and the honeycomb conductivity, *k*, was calculated as follows:

$$= \frac{Q \cdot l}{A \cdot \Delta T} = \frac{299.71\mathrm{W} \cdot 0.221\mathrm{m}}{(0.221\mathrm{m} \cdot 0.076\mathrm{m})(100^{o}\mathrm{C} - 22^{o}\mathrm{C})} = 50.55\ \mathrm{W/m \cdot C}.$$

The comparison between the numerical and experimental methods shows an insignificant difference of around 0.51 %.

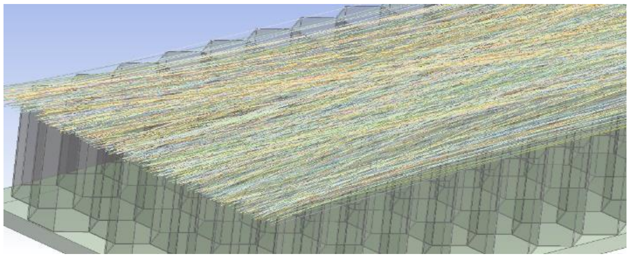


Figure 7 A 600 Fibers distribution number along the longitudinal direction

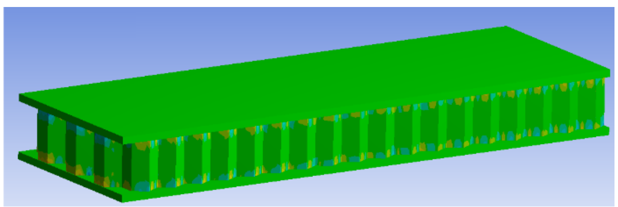


Figure 8 Heat flow distribution

The varied thermal conductivity performance has been presented by simulation, varied natural fiber against filler loading shown in Figure 9. The graph illustrated that the panel sheet composite significantly affected thermal conductivity performance, leading to decreasing trend. It is clearly seen that the natural fibers composite was dominant to determine thermal conductivity, in which oil palm and sugar cane fiber leading to counter thermal transfer was higher. As an insulator, both fibers are suitable for several applications for residential use such as shelter or partition. An improvement in insulator performance has been shown for each fiber, 78.6 %, 83.74%, and 83.86% for coconut, palm, and sugar cane, respectively. The prediction was successful in proving that natural fiber promotes thermal insulators that compete with synthetic foam [24]. The conductivity values predicted by numerical model are then compared to the pattern from each natural fiber, the oil palm and sugar cane fibers were showed similar patterns. It due to the single-fiber thermal conductivity performance in Table 2 shows that both fibers are almost identical. Another reason was due to the numerical fiber model sharing of similar morphology fiber distribution for all fiber types.

Further investigation focusing on the macrostructure level to analyze thermal transfer, the morphology of fiber much influence to protect thermal transfer to flow through sheet plate as shown in Figure 10. It is clearly seen that the natural fibers network stopped the thermal chain due to their low thermal conductivity. The fiber structure is also an important part to block the thermal without allowing any thermal leaking through the sheet panel. By increasing thermal resistance in the panel sheet, the honeycomb sandwich increases temperature absorption. It looks successful to block the thermal network with natural fiber by degrading thermal energy through the aluminum core per unit of time.

Table 2 shows that a single fiber factor affects the thermal performance and the same time can validate computational results of the effective thermal conductivity of the composites. The final conductivity values of the honeycomb sandwich can be shown by insulating properties that were dominant by oil palm fiber. Another effect is determined by morphological factors and the shape of local thermal conductivity.

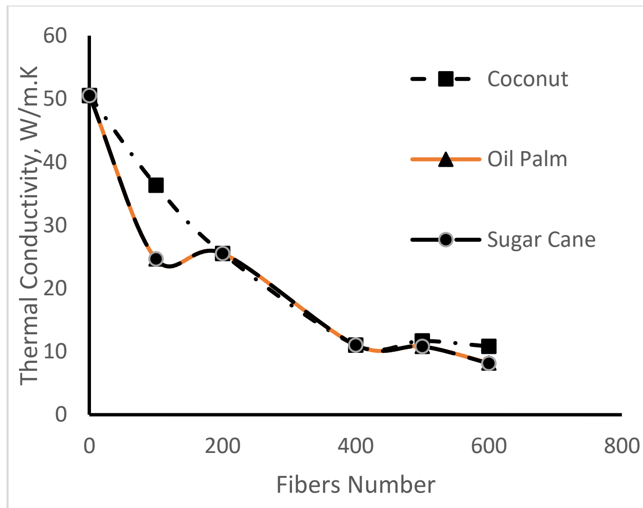


Figure 9 Honeycomb sandwich thermal conductivity, *K* by using numerical analysis

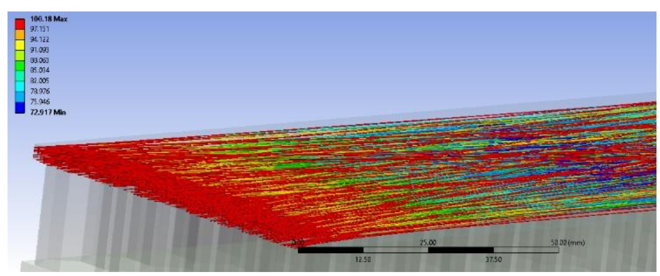


Figure 10 Temperature distribution on 600 fibers of palm oil

4.0 CONCLUSION

The methodology of thermal conductivity performance was successfully presented by experimental and numerical analysis. The study on the natural fiber effects was presented on the behavior of thermal on honeycomb sandwich structures. The thermal energy of the skin sheet sandwich structure is mainly absorbed by the sheet plate composite of the top face sheet. Increasing natural fiber is a paramount part to perform good quality insulators. The experimental investigation found that the coconut fiber successfully performs as an insulator in a honeycomb sandwich which reached 6.78 W.m^{-1}K^{-1} of thermal conductivity and which was an 85.86% improvement as an insulator. While palm oil and sugar cane presented at 11.12 W.m^{-1}K^{-1} and 10.59 W.m^{-1}K^{-1}, it was slightly higher compared to the coconut. In numerical investigation, the fibers successfully developed as a reinforced structure in the sheet plate of a honeycomb sandwich. The observation found that the thermal conductivity had different results from the experimental, the higher thermal resistance was shown by palm oil and sugar cane at 8.22 W.m^{-1}K^{-1} and 8.16 W.m^{-1}K^{-1}, respectively. This difference is much influenced by the morphology factor in the experimental study. Due to the perfect fiber distribution difficult to achieve by the lay-up technique. It allows the thermal chain to flow through the sheet panel therefore localized thermal energy capture in the honeycomb structure. While in numerical, the fiber distribution well disperses causing the thermal energy can counter better. The insulators gradually increase by adding fiber content to the skin sheet, it shown by significant effects. It is a phenomenon captured for all natural fibers study, the honeycomb structure becomes higher thermal resistance by increasing fiber content. It is due to fiber helping to counter the thermal energy as shown in the contour of the numerical method.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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