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Thermal Performance Study on Coconut Husk and Kenaf Fibre as Thermal Insulation Materials

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ABSTRACT

Waste heat accounts for 20-50% of industrial energy use, with Southeast Asia processing 40 million tonnes of oil equivalent. Heat losses especially in engines can reduce efficiency, leading to extensive studies to reduce heat loss and improve thermal performance. Heat recovery systems are being studied for recovering lower-grade energy, but not many of them are suitable and economically effective for low temperature waste heat. The objectives of this study are to develop low thermal conductivity agricultural-based material for thermal insulation and investigate the agricultural-based materials' impact on heat transfer rate. The agricultural-based materials that were used in this experiment were coconut husk and kenaf fibre due to their practically low thermal conductivity. The specimens were prepared using two different methods which were needle felting method and fibre-resin blending method. The experiment revealed that coconut husk fibre reinforced with resin (CHER) has the lowest thermal conductivity value of 0.0410 W/m.K and the lowest overall heat transfer rate of 2.85 W, making it an ideal thermal insulation material to be used for low-temperature applications.

1. Introduction

The industrial sector is one of the top three energy consumers in the world. As a result, the volume of industrial waste heat is likely to be significant. This heat can be recovered and utilised in other operations on-site, such as preheating furnace loads and incoming water or combustion air, or being converted into electricity, cold, or another sort of heat. It is estimated that around 20-50% of total industrial energy use is discharged as waste heat [1].

Heat losses to the environment may reduce the efficiency of a machine that generates energy from a heat source. This has become a problem in most types of engines that are using combustion. In regard to this, waste heat recovery is an important technology for strategic energy deployment

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since it may efficiently ease energy shortages and minimize pollution emissions. Waste-heat sources can be loosely divided into three types based on their ability to withstand a wide range of temperatures: low-grade waste-heat (<230°C), medium-grade waste-heat (230-650°C), and high-grade waste-heat (>650°C) [2]. Although there are various waste heat recovery systems available, none are economically effective in the recovery of low temperature waste heat. Although low temperature waste heat accounts for 63% of all waste heat, it is difficult to recover this energy, therefore the problem might be overlooked [3].

As a result, heat transfer improvement is an important technique to improve the heat transfer efficiency of the engine [4]. A significant number of studies have been done in order to decrease heat loss and improve engine thermal performance by adding extra surface heat transfer area, using nanofluid etc. [5-8]. In order to improve engine performance, it has become popular to insulate heat transfer surfaces including the valves, piston, cylinder head, combustion chamber and cylinder wall. In turn, the engine's cylinder walls can get hotter and produce more energy from exhaust gases thanks to insulation that prevents heat from escaping to the cooling system [9]. Thermal insulation is essential for energy management in order to minimise energy waste and increase energy efficiency because thermal energy is diffusive. The lowering of heat conductivity of suitable materials that can be engineered into compositions and structures is the foundation of thermal insulation [10,11].

One of possible solutions is by using natural fibre-based materials derived from sustainable raw material. These types of materials are becoming increasingly popular as thermal insulation materials. This includes natural fibres from agricultural products such as coconut husk, palm fibre and many more. They have very strong sound and heat insulation capabilities, typically better and more beneficial than synthetic fibres, due to their low mass density and cell structure. A significant benefit of natural fibre insulation is not just its low heat conductivity but also the natural quality of the input fibres. Another advantage is that it is a renewable substance that has no harmful impact to the environment. For example, when compared to mineral wool, natural fibre insulation offers equivalent, if not superior, thermal technical properties [12]. According to Dhivar and Patil [13], thermal insulation products made of mineral wool, fibreglass, or polyurethane foams can be harmful to the environment and human health while having low heat conductivity, good moisture protection, and fire resistance. Therefore, natural agricultural insulators are a preferable option to synthetic thermal insulation made of mineral fibres and foam-plastic materials when it comes to environmental concerns. Since they are created entirely of natural materials without the use of chemical binders, these environmentally friendly natural thermal insulators may be able to rival more traditional insulating materials.

Moreover, agricultural by-products have been proven as effective thermal insulators. The greater the heat conductivity, the lower the thermal insulation. The agricultural by-products studied by Dhivar and Patil [13] have excellent thermal insulation capabilities since their thermal conductivity is far lower than that of artificial insulators. All of the specimens examined have low heat conductivity, indicating excellent thermal insulation qualities. Rice husk has the highest thermal conductivity of 0.077 W/mK while sunflower stalk has the lowest thermal conductivity of 0.0378 W/mK. Palm fibre, hemp, banana fibre, bagasse, and coconut fibre are the remaining items in increasing order of heat conductivity.

Another recent study by Nadir *et al.,* [14] investigated the energy efficiency of a solar collector with thermal insulation made of date palm wood and glass wool experimentally. The influence of vegetable materials on the solar collector's air design was examined, and the results showed that a petiole with gypsum can effectively serve as a thermal insulating material for the solar air collector. Compared to the glass wool insulated collector, the thermal efficiency of the Petiole + gypsum insulated collector was found to be 37.7% higher, making it a more effective choice for thermal insulation in the solar air collector.

This paper will eventually concentrate on agricultural by-products such as thermal insulation materials to reduce heat losses which generally occurs in industrial process. The usage of these materials will not only produce a novel agricultural-based product but is also less polluting and environmentally friendly. The effectiveness of these materials will be then evaluated by applying these materials to the outer layer of a cylindrical-wall engine. To the authors' knowledge, there is very little work being done regarding fabrication of this insulation material in a cylindrical pipe form that can represent hydraulic pipes in engines. This is done in fulfilling the primary goals of limiting heat losses to the surrounding environment and, most crucially, in analyzing the heat transfer performance.

2. Methodology

2.1 Data Collection

The materials that were selected for this testing were coconut husk and kenaf fibre, and samples were prepared with two methods which were needle felting method and fibre-resin blending. Sensor calibration was done on the thermocouple and heat flux sensor by applying heat to the system without the specimen until the sensors give consistent readings or the readings do not fluctuate. The system is then heated consistently, and temperature data is collected and logged at regular intervals. Then the different samples were analyzed, and the best insulator based on the thermal conductivity value and heat transfer rate were identified.

Data analysis includes calculating temperature differences and plotting graphs to visualize trends. If the thermal conductivity of the specimens fails to meet the criterion of being below 0.07 W/m.K, then it is necessary to suggest a new material with improved thermal insulation properties. This is because materials with thermal conductivity values equal to or below 0.07 W/m.K are considered the most suitable for thermal insulation applications [13]. The data logger that was used in this experiment was the AGILENT 34970A®. The data logger AGILENT 34970A® allows for precise measurement of a variety of parameters. To provide a more precise and detailed analysis, data is gathered every 10 seconds.

2.2 Materials Preparation

A stainless-steel cylinder pipe was used to represent the hot section or the walls of the heat recovery systems which absorbs heat. The stainless-steel cylinder pipe which measures around one foot was purchased from a hardware store. It is then cut into three, using a circular saw with 10 cm length each. The diameter of the stainless-steel cylinder is 5 cm.

Previous studies revealed that coconut husk and kenaf fibre have low heat conductivity values [13]. Therefore, for this study two different agricultural-derived materials were used and made using two separate procedures. The first process utilized was needle-felting. The needle felting process was done manually by hand due to the small quantity of fibre utilized. The second method that was used is blending the powdered fibres with resin and hardener. For simplicity, the rest of this paper will employ the code below to address the four specimens that will be fabricated and applied in this experiment

(a) Coconut husk needle felted (CHN)
(b) Kenaf fibre needle felted (KFN)
(c) Coconut husk powder reinforced epoxy resin (CHER)
(d) Kenaf fibre powder reinforced epoxy resin (KFER)

The dimension of the thermal insulator was determined by measuring the dimensions of the stainless-steel cylinder. This is done to make sure that the cylinder was covered wholly to ensure a more accurate reading and the heat does not escape from the gaps. The mass was measured using a weighing scale and determined by the amount of fibre that was needed to cover the cylinder. The mass of the thermal insulating materials was different for each material as they have different densities. The dimension and mass of the thermal insulator was also determined by studying previous experiments and the size of stainless-steel cylinders available in the stores. All four specimens have dimensions of 10 cm in height, 22 cm in width and 1.5 cm in thickness. Table 1 shows the mass of every specimen and Figure 1 depicts the illustration of the cylinder with the thermal insulator.

Table 1
Dimension and mass of the specimens

Specimen	Mass, g
CHN	20
KFN	19
CHER	37
KFER	34

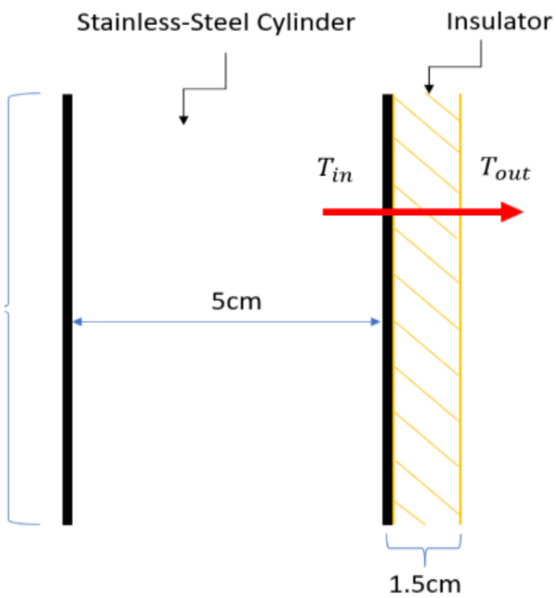


Fig. 1. Illustration of the cylinder and insulator

Next step, in order to remove any moisture, the coconut fibre and kenaf fibre were cleaned and dried in the sun for 5 to 6 hours. Following the drying stage, the felting procedure was performed manually. Figure 2 depicts the final felting outcomes of coconut fibre and kenaf fibre. The fibre is now in sheet form, making it easy to mould into a cylindrical shape to fit the stainless-steel cylinder used in the experiment.

Fig. 2. Coconut husk and kenaf fibre after felting process

For the second part, the coconut husk and kenaf fibres were blended with resin and hardener. The coconut fibre and kenaf fibre were grounded into powder using a pulveriser. The powder is dried in the sun for 5 to 6 hours. After drying, the fibre, resin, and hardener were blended in a 1:2:1 ratio with a mechanical mixer until they were entirely blended. The mixture was then put into a cylindrical mould 10 cm x 7 cm in size, together with the stainless-steel cylinder. The mixture is then cured for a day until it hardens. Figure 3 shows the result of the sample that has been fabricated.

Fig. 3. Coconut husk and kenaf fibre after blending with resin

2.3 Experimental Setup

In this experiment, a type-K thermocouple, and a heat flux sensor model 27160 were employed. The typical Chromel/constant Type K thermocouple has a good operating temperature range and strong corrosion resistance. When compared to other types that have a higher temperature range, it is inexpensive and can endure temperatures of up to 1260℃. It has a partial radiation hardness with a standard accuracy of $\pm$0.75%, a special error limit of $\pm$0.4%, and a typical accuracy of 2.2℃ [15].

In this particular experiment, four thermocouples were utilised and were put in different positions, as shown in Figure 4. Figure 4 depicts the experiment setup for coconut husks with resin as an insulator. One thermocouple was installed in the combustion chamber to measure the temperature of the heat leaving the chamber. Another thermocouple was installed at the cylinder's entrance, one on the insulator material, and the other at the cylinder's end, along with the heat flux sensor. The thermocouple is positioned as shown in Figure 4 to record the temperature of the insulator. This is done to determine the insulator's thermal conductivity and the total heat transfer coefficient of the system. In the combustion process, wood was chosen as the material. Every test involved the usage of 1 kg of wood. To heat the system, the wood was burned with butane gas.

Fig. 4. Setup for the experiment

2.4 Thermal Performance Calculation

Then, the thermal conductivity of the material is calculated using the Eq. (1)

$$q = -k\left(\frac{T_{2-} - T_1}{L}\right) \quad (1)$$

where q is the heat flux, k is thermal conductivity, T_1 and T_2 are the temperature at the hot and cold side and L is the thickness of the thermal insulation material.

Eventually, the heat transfer Q can be calculated using Eq. (2) by dividing the value of heat flux with the area

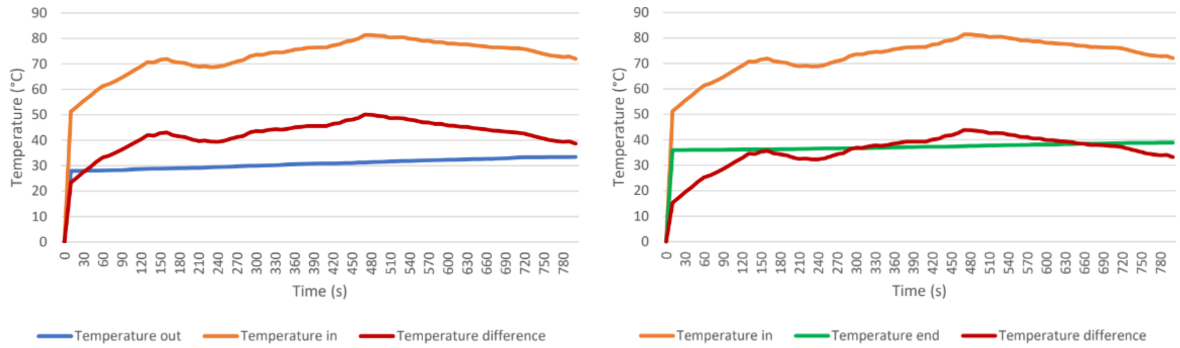
$$Q = qA \quad (2)$$

where A is the total surface area.

3. Results and Discussion

3.1 Temperature

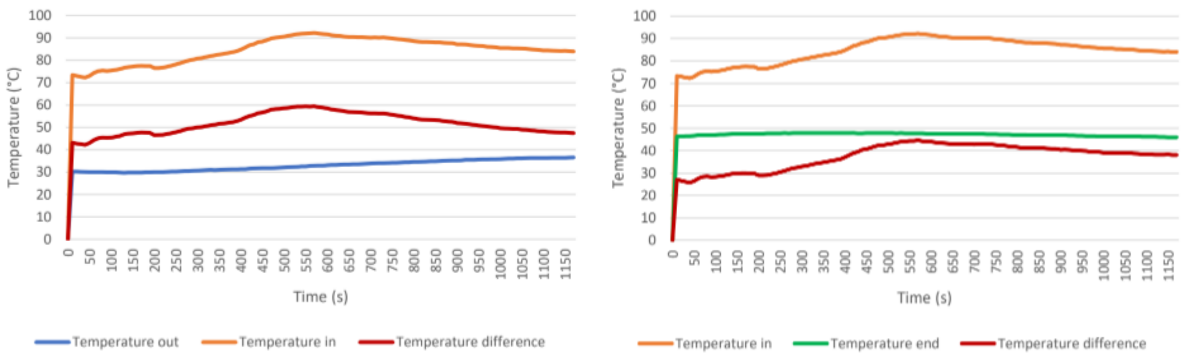
The T_{in} represents the heat that enters the cylinder from the combustion chamber. T_{out} denotes the temperature of the insulating materials, whereas T_{end} denotes the temperature as it departs the cylinder. According to Figure 5(a), the temperature of the insulator remains constant with very little variation as the temperature of the combustion chamber rises. The maximum T_{out} value was 33.4°C. The temperature difference in Figure 5(a) increases until T_{in} starts decreasing. According to Figure 5(b), T_{end} increases in sync with the T_{in}. The maximum value of T_{end} was 38.9°C. The trend for temperature difference in Figure 5(b) is the same as the trend for T_{in} which shows that the T_{end} remains constant.



(a) (b)

Fig. 5. (a) Temperature in and out and (b) Temperature in and end for coconut husk sheet

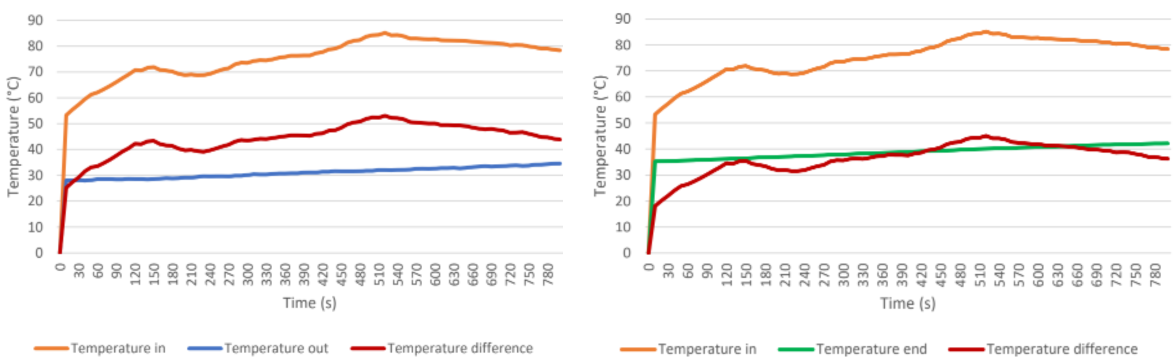
Based on Figure 6(a), the kenaf fibre sheet has some weaknesses in terms of thermal insulating abilities. As the temperature of the heat from the combustion chamber rises, so does the temperature of the insulator. The kenaf fibre absorbs heat from the cylinder walls, as demonstrated by the experiment. The maximum T_{out} value was 36.6°C. The T_{end} is also slightly higher compared to the coconut husk sheet as shown in Figure 6(b). The maximum value of T_{end} was 47.8°C.



(a) (b)

Fig. 6. (a) Temperature in and out and (b) Temperature in and end for kenaf fibre sheet

From Figure 7(a), the T_{out} for the coconut husk with resin insulator shows an increase as the T_{in} reaches maximum. However, the coconut husk with resin insulator shows better thermal insulating properties than the coconut husk sheet as it maintains low temperature as the temperature increases more. The maximum T_{out} value was 34.6°C. Based on Figure 7(b), the T_{end} also shows steady increment as the T_{in} increases. The maximum value of T_{end} was 42.1°C.



(a) (b)

Fig. 7. (a) Temperature in and out and (b) Temperature in and end for coconut husk with resin

According to Figure 8(a), the T_{out} of the kenaf fibre with resin insulator shows slight increase as the T_{in} increases. The maximum T_{out} value was 35.0°C. However, from Figure 8(b), it can be seen that the T_{end} remains almost constant with slight variations when the T_{in} increases. The kenaf fibre with resin exhibits almost similar thermal insulating properties as the kenaf fibre sheet. The maximum value of T_{end} was 47.1°C.

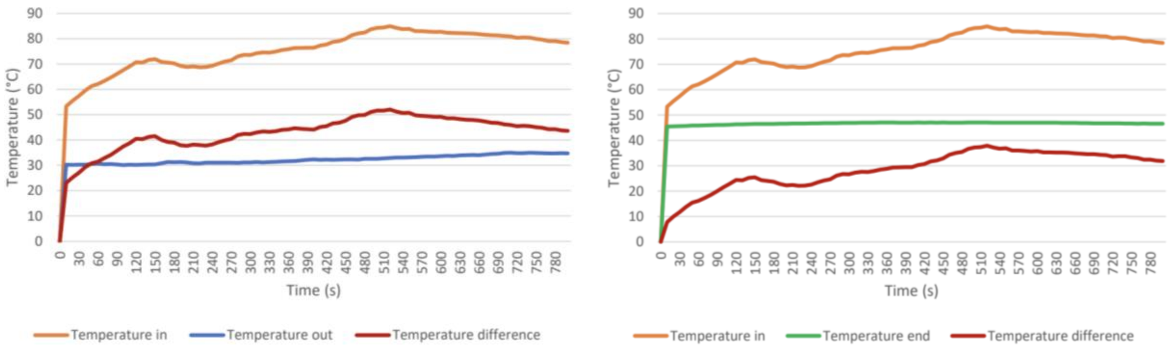


Fig. 8. (a) Temperature in and out and (b) Temperature in and end for kenaf fibre with resin

The temperature difference trend in all the T_{in} and T_{out} against time graphs is consistent with the trend for T_{in}, indicating that the thermal insulator effectively maintains a constant temperature despite variations in T_{in}. Similarly, the temperature difference trend in all the T_{in} and T_{end} against time graphs aligns with the trend for T_{in}, signifying that most of the heat is retained inside the system. Table 2 shows the temperature and voltage values from the conducted experiment that were used in the calculation process.

Table 2
Temperature and voltage values for calculation

Specimens	Temperature In, °C	Temperature Out, °C	Temperature End, °C	Voltage (V)
CHN	81.4	31.2	37.4	3.98×10^{-5}
KFN	92.2	32.8	47.7	5.82×10^{-5}
CHER	85.2	32.1	40.1	3.77×10^{-5}
KFER	84.9	32.9	47.0	5.58×10^{-5}

3.2 Thermal Conductivity

The maximum temperature was chosen as the data for the calculation because it was considered that at the highest temperature, the system begins to stabilize before gradually decreasing in temperature. In addition, all the voltage values have been converted to absolute values in order to disregard the negative value, which simply indicates the direction of heat movement. The heat flux sensor's sensitivity value is 0.26×10^{-6} V/W.m^2 taken from the manufacturer's descriptions of the specific model [16].

Table 3 and Figure 9 display thermal conductivity and heat transfer rate for the four specimens. The values were obtained using Eq. (1) and Eq. (2). Based on previous research, the thermal conductivity value of coconut husk ranges from 0.046 to 0.068 W/m.K [11]. The thermal conductivity of kenaf fibre ranges from 0.051 to 0.058 W/m.K [17]. Table 3 contains the experimental values of thermal conductivity of the materials that were calculated based on the data from the experiment. The table shows that all of the thermal conductivity values are within the range of the reference values. When compared to the other samples, the coconut husk with resin had the lowest thermal conductivity, indicating that it will operate as a good thermal insulator. This is because coconut husk in general has a higher density and porosity compared to kenaf fibre. Moreover, mixing natural fibres with epoxy can contribute to a lower thermal conductivity value and produce stronger and longer lasting thermal insulators. The values at the maximum temperature were used for calculation because it was considered that at the highest temperature, the system begins to stabilize before gradually decreasing in temperature.

Table 3
Experimental values of thermal conductivity

Specimens	Thermal conductivity, W/m.K	Heat transfer rate, W	Overall heat transfer coefficient, U ($W/m^2.K$)
CHN	0.0485	3.01	3.05
KFN	0.0560	4.40	3.76
CHER	0.0410	2.85	2.73
KFER	0.0619	4.21	4.12

It can be also analyzed that kenaf fibre with resin as thermal insulator has the highest heat transfer rate of 4.21 $W/m^2.K$, while coconut husk with resin insulator has the lowest value of 2.85 $W/m^2.K$. As a result of this experiment, the coconut husk with resin has been proven to be the most optimum material to be used as a thermal insulator.

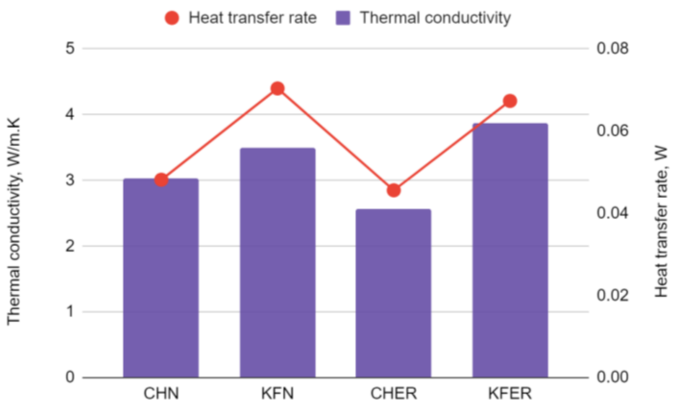


Fig. 9. Heat transfer rate and thermal conductivity for all the four specimens

3.3 Thermal Insulation Materials Applied to Engine's Cylindrical-wall

In this last section, in order to prove the viability of using these insulators, the newly developed thermal insulation materials were applied to an engine's cylindrical-wall and the performance of the engine is analyzed in terms of power output. As demonstrated in Figure 10 and Figure 11, a little increase in engine power output is observed when using natural fibre as a thermal insulation material to retain heat between the engine's cylinder wall, particularly at 450 rpm of engine speed and higher. There might be restrictions on heat transfer between the hot and cold reservoirs at low temperatures of waste heat, which would result in an incomplete heat transfer cycle. Since it is less expensive and a greener solution overall, using this environmentally friendly nature-fiber thermal insulation materials can be a good option to take into consideration.

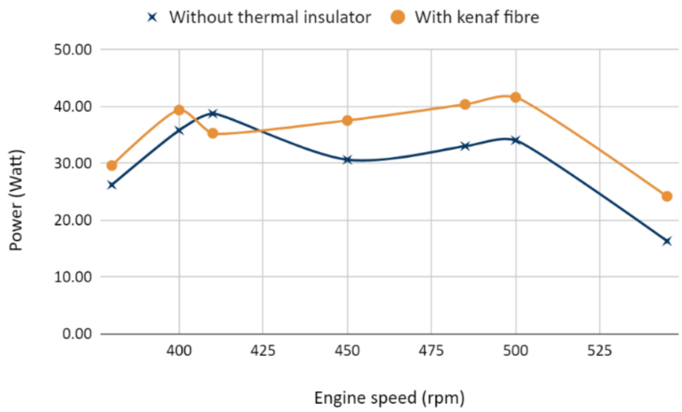


Fig. 10. Power output of engine with kenaf fibre (KFER) acting as a thermal insulator at varying engine speeds

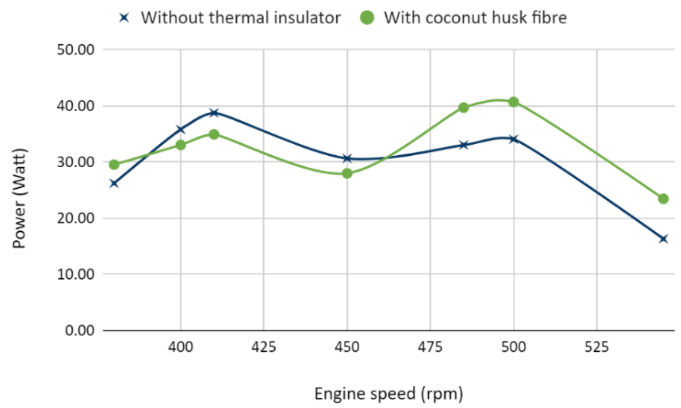


Fig. 11. Power output of engine with coconut husk fibre (CHER) acting as a thermal insulator at varying engine speeds

4. Conclusions

An experiment was carried out using two forms of agricultural waste which are coconut husk and kenaf fibre. The specimens were created utilising two distinct methods: needle felting and resin blending. This experiment was carried out in order to create a low thermal conductivity agricultural-based thermal insulator and examine its effects on the total heat transfer rate. It was possible to select the optimal material to utilize as a thermal insulator. According to the results of the experiment, coconut husk fibre combined with resin has the lowest thermal conductivity value of 0.0410 W/m.K, whereas kenaf fibre reinforced with resin has the greatest thermal conductivity value of 0.0619 W/m.K. This eventually indicates that coconut husk reinforced with epoxy resin is the ideal material to be utilized as a thermal insulator because it has a low thermal conductivity. Eventually, by applying these insulation materials to the engine's cylinder-wall, its performance increases for engine speed starting at 450 rpm and above.

This material could possibly prevent excessive heat absorption from the system and reduce heat losses to the environment which is a common issue in current waste heat recovery systems. Additionally, it demonstrates a low overall heat transfer value, indicating a slower heat transfer rate, which effectively preserves heat inside the system. Thus, by applying this material can significantly enhance the efficiency and performance of a waste heat recovery system.

For future approach, it is recommended to explore different variables and parameters of the insulation materials (thickness, preparation methods, different natural fibres etc.), in order to further optimize its usage.

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