Improvement of Insulation Material for Cool Box Application

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Abstract. Current conventional cool boxes which use expanded polystyrene (EPS) as its insulating material cannot seem to maintain storage at low temperature for long periods. This study aims to determine the effect for different types of insulating materials which can be used in cool boxes to improve its thermal insulation. Using theoretical and simulation approach, three out of six potential insulating materials were chosen in terms of their heat transfer rate, and temperature at the outer wall. The three best insulating materials, polyurethane (PU), expanded polystyrene (EPS) and poly-glass fibre (PGF) were then tested at three different room temperatures experimentally using the thermal insulation test to determine the best insulating material for a cool box. Tensile and density were also conducted to identify the mechanical behaviour and properties of these insulating materials. From the results obtained from the experiment, polyurethane (PU) recorded the longest time taken for ice to change into water at the three different temperatures when compared to other insulating materials. The results showed that when thermal conductivity is low, the heat transferred through the walls of the cool box was also low thus resulting in better thermal insulation of the cool box. This study gives a better understanding in term of thermal insulation and the results obtained from this study can help with the production of better cool boxes with improved thermal insulation.

1. Introduction

A cool box, portable ice chest, icebox or cooler box is an insulated box most commonly used to keep perishable foods or drinks at a relatively cold temperature. The use of cooler boxes ranges from small applications such a family picnics, to large applications such as cold chain logistics. Conventional cool box is made from expandable polystyrene (EPS), can only maintain a cool temperature of its storage for 24 hours with a surrounding temperature of 32°C. To maintain a cool temperature within the cool box, heat transfer to and from the cool box and its surrounding must be relatively low. This can be achieved by providing better thermal insulation for the cool box.

Thermal insulation is the reduction of heat transfer (the transfer of thermal energy between objects of differing temperature) between objects in thermal contact. Heat transfer is all about the transfer of heat from one point to another where heat is transferred from high temperature to low temperature. For example, if a system is at a higher temperature compared to its surroundings, heat will transfer from the system to the surroundings [1]. Thermal insulation provides a layer of protection in which thermal conduction is reduced or thermal radiation is deflected rather than absorbed by the lower-temperature body [2]. The capability of a material to provide insulation is measured by its thermal conductivity ($K$) value. Materials with high insulating capability, resistance ($R$) will have a lower thermal conductivity.
value [3]. In thermal engineering application, besides thermal conductivity, other important properties of material with the purpose of insulation are density ($\rho$) and specific heat capacity ($c$) [2].

Thermal insulation of an object is very much influenced by the insulation material. For this study, six insulation materials have been selected, expanded polystyrene (EPS), polyurethane (PU), glass wool, asbestos, poly glass fibre, and coconut fibre. With regards to these six insulating materials, several studies have shown that they can be used to reduce heat transfer, hence improving the thermal insulation for the object [4, 5, and 6].

Expanded polystyrene (EPS) is the most commonly used insulating material used for cool boxes today. Known for its lightweight, rigidity, and easy for formability, EPS in the form of moulded sheets is also used for building insulation [7] and depending on the density of the EPS board, has a thermal conductivity value ranging from 0.032 to 0.038 W/m.K [8]. EPS performance as an insulating material can be further improved by pairing it with other materials such as aluminium [9].

Polyurethane (PU) as an insulating material has become one of the most important materials that can be used to minimize the energy needed to keep refrigerators and freezers cold [10]. Secondly, PU panels have also been widely used in marine-based and commercial or industrial based projects to build walk-in cold room on board of ships, restaurants, supermarkets and as construction material for factory building and also for applications such as telecommunication cabin shelters, food, fruits, vegetables & meat storage room, marine containers [11]. Similarly, with EPS, PU can also be used as an insulating material for building insulation [12]. When used as insulation, in the case of a fire breakout, PU exhibits two important characteristics which are it produces non-hazardous gasses, and PU foam is completely biodegradable [13].

Fibreglass or glass wool is an insulation material made of glass fibres which are prepared with binders into the same texture similar to wool. Thermal insulation is produced by air between the glasses. Normally produced in the form of rolls or slabs, it can also be produced as a material that can be sprayed or applied in place, on the surface to be insulated [14]. Its application ranges from duct and roof insulation to facings used in metal buildings [15].

Asbestos is a fibrous mineral that has been known since ancient times in resistance to heat. Known for its resistance to heat, wear, alkalis and acids, and its flexibility makes it a suitable material for use as insulation in industrial textiles and many other fields [16]. As reported by Barbalace (2004), asbestos is a very good insulator, strong, resists acid, chemically inactive and it also can be woven into cloth. The thermal conductivity for asbestos is 0.08 W/m.K, and it is readily available at low cost [17].

Poly glass fibre as an insulation material was tested in by following ASTM C518: Standard Test Method for steady-state thermal transmission properties using the heat flow meter. Results showed that when compared with thermal conductivity of typical insulation materials (0.035 – 0.16 W/m.K) or rock wool insulation (0.035 – 0.038 W/m.K) at mean temperatures of approximately 20°C, Poly glass fibre provides low thermal conductivity, meaning they are highly effective in terms of reducing heat transfer [18].

Coconut fibre is also widely as an insulating material. The interest of using natural fibres as reinforcements in polymer composites replacing conventional synthetic fibres have risen due to increasing environmental consciousness and awareness of the need for sustainable development [19]. Other advantages of natural fibres include low cost, low density, unlimited and sustainable availability, and low abrasive wear of processing machinery.

2. Materials and Methods

2.1. Preliminary material selection

Three of the best out of a possible six insulating material which can be used as an insulator for a cool box is determined by using both calculation and simulation method. The best insulating material is judged by its heat transfer rate, $\dot{Q}$ and temperature at the outer wall, $T_o$ of the cool box. The six insulating materials are polyurethane (PU), expanded polystyrene (EPS), glass wool, asbestos, poly-glass fibre (PGF), and coconut fibre. The schematic diagram for the cool box for calculation purposes is shown in Figure 1.
Figure 1. The schematic diagram for conduction and convection analysis, T = temperature, h = convective heat transfer coefficient, L = thickness

For calculation, the conduction and convection formula is used to determine the heat transfer rate, and temperature at the outer wall of the cool box. The formula is as follow:

Heat transfer rate, $\dot{Q}$ [20]:

$$\dot{Q} = \frac{T_{surr} - T_{inner}}{\Delta R}$$

Where;

- $T_{surr}$ is the surrounding air temperature (°C)
- $T_{inner}$ is the inner cool box temperature (°C)
- $\Delta R$ is the overall thermal resistance (K/W)

For $T_{surr}$, three different surrounding air temperatures were used to take into consideration different climate conditions around the world. The temperatures were 20°C, 30°C, and 40°C respectively. For $T_{inner}$, a constant temperature of 15°C was used throughout the calculation. The overall thermal resistance ($\Delta R$) is determined using the following formula:

Overall thermal resistance, $\Delta R$ [20];

$$\Delta R = \frac{1}{h_{inner}A} + \frac{L_1}{Ak_1} + \ldots + \frac{L_n}{Ak_n} + \frac{1}{h_{surr}A}$$

Where;

- $A$ is the surface area of the cool box (m$^2$)
- $h_{inner}$ is inner convective heat transfer coefficient (W/m$^2$.K)
- $h_{surr}$ is surrounding convective heat transfer coefficient (W/m$^2$.K)
- $L$ is the thickness of the insulating and cool box material (m)
- $k$ is the thermal conductivity of the insulating and cool box material (W/m.K)

The values for thermal conductivity, $K$ for the insulating material used were taken for various studies that have been conducted. These values are shown in Table 1.
Table 1. Thermal conductivity, $k$ value for various insulating materials.

| Insulating material         | Thermal conductivity, $k$ (Wm$^{-1}$K$^{-1}$) |
|----------------------------|-----------------------------------------------|
| Polyurethane (PU)          | 0.023 [21]                                    |
| Expanded polystyrene (EPS) | 0.033 [8]                                     |
| Glass wool                 | 0.040 [14]                                    |
| Asbestos                   | 0.080 [17]                                    |
| Poly-glass fiber (PGF)     | 0.035 [18]                                    |

Thickness of the insulating material and cool box, the other parameters are considered constant during the calculation procedure. The values are as shown in Table 2.

Table 2. Constant parameters for thermal resistance, $\Delta R$ calculation

| Parameter                                           | Value                   |
|-----------------------------------------------------|-------------------------|
| Area, $A$                                           | 0.048m$^2$              |
| Inner convective heat transfer coefficient, $h_{inner}$ | 10 Wm$^{-2}$K$^{-1}$    |
| Outer convective heat transfer coefficient, $h_{outer}$ | 30 Wm$^{-2}$K$^{-1}$    |

The following formula is used to determine the temperature at the outer wall, $T_{w2}$ of the cool box,

$$\dot{Q} = Ah_{surr}(T_{surr} - T_{w2})$$

(3)

The results obtained using the conduction and convection formula were then compared using the simulation method. Simulation is achieved by using the ANSYS software. The software specification is shown in Table 3.

Table 3. Simulation software specifications.

| Item                  | Remark                      |
|-----------------------|-----------------------------|
| Software name         | ANSYS Mechanical            |
| Version               | 14.0                        |
| Analysis type         | Steady-state                |
| Thermal modeling      | Conduction and Convection   |

ANSYS software allows the user to simulate the heat transfer rate and temperature at the wall of the cool box. Based on the results from both of these methods, three of the best insulating material is selected.

2.2. Sample, cool box preparation, and testing method

Samples for the best three insulating material based on the calculation and simulation results were prepared to test its performance under actual conditions. Some raw materials used for sample preparation were obtained from a local company, while some were obtained from the local hardware store. Figure 2 shows the example of raw materials used as insulation for this study.

![Figure 2. Examples of raw material a) Polyurethane (PU), b) Expanded polystyrene (EPS)]
To determine the tensile strength, sample materials were cut to a rectangular shape and the dimension follows the standard test method (ASTM). The dimension of sample materials was 250mm (L) x 20mm (w) x 12mm (h). To grip the specimens on the tensile test machine, the end of the specimen was supported with aluminium or sandpaper to avoid specimen fracture at the grip. Example for tensile test specimen is as shown in Figure 3.

![Figure 3. Tensile test specimen a) Polyurethane (PU), b) Expanded polystyrene (EPS), c) Poly-glass fiber (PGF)](image)

Tensile testing is a way to determine how a material reacts when force is applied to it in tension. It is one of the simplest and most widely used mechanical tests. This testing was conducted by using the tensile testing machine INSTRON 3382 Floor Model Universal Testing Systems as shown in Figure 4. This machine ideal is for tension or compression applications for tests up to 100kN (22,500lbf) and provides simplicity, reliability, and affordability for heavy-duty quality control and production testing. The sample of each material must be prepared at least five samples and take the average to get an accurate result. The speed must follow the standard to ensure the accuracy of the results.

![Figure 4. INSTRON 3382 (100kN) floor model universal testing systems](image)

For the density test, sample materials were cut into cubes with a dimension of 30mm (L) x 30mm (w) x 30mm (h). Material samples cut to the required dimension are shown in Figure 5.

![Figure 5. Density test specimen a) Polyurethane (PU), b) Expanded polystyrene (EPS)](image)
The density test was conducted to determine the density of the insulating materials of this project. The weight of the insulating material was obtained using an electronic balance machine as shown in Figure 6. Using the following equation, the density and porosity percentage of the insulating materials were obtained.

For density [23], \( \rho_r \):

\[
\rho_r = \frac{W_{\text{insulating material, air}}}{W_{\text{insulating material, air}} - W_{\text{insulating material, water}}} \times \rho_w
\]  

(4)

For porosity percentage [21], \( \varepsilon \):

\[
\varepsilon = \left( 1 - \frac{\rho_h}{\rho_r} \right) \times 100\%
\]

(5)

The density test was conducted twice for the three best insulating materials and the average value was calculated in order to get an accurate value of the density of the insulating material.

Figure 6. Electronic balance machine

For the thermal insulation test, an inner and outer box was made using an aluminium sheet with a thickness of 0.5mm as shown in Figure 7. The dimension for inner box was 208mm (L) x 208mm (w) x 208mm (h) and for outer box was 220mm (L) x 220mm (w) x 220mm (h). This cubic design was chosen for ease in changing the insulating materials for the testing. The inner box will be placed inside the outer box, and the insulating material will be placed in between the boxes.

Figure 7. Inner (left) and outer (right) cool box for thermal insulation test

Thermal insulation test was conducted at three different temperatures, 20°C, 30°C, and 40°C. For 20°C, the test was conducted in the cold room to obtain a steady temperature reading. For 30°C, the test was conducted inside a standard laboratory room, and for 40°C, testing was conducted by using Memmert Drying Oven as shown in Figure 8.
Using a digital thermometer as shown in Figure 9 via the use of thermocouples, the temperature on the inside and outside of the cool box was recorded. Temperature reading was taken every two hours to record the temperature drop with respect to time for the ice to change into water. Temperature change from cold water to normal water temperature was also recorded.

Figure 8. Memmert Drying Oven for thermal insulation test

Figure 9. Digital thermometer with thermocouples

3. Results and discussion

Using the conduction and convection heat transfer formula, the heat transfer and the temperature at the outer wall of the cool box at different temperature conditions were determined. Table 4 and Table 5 shows the results obtained using the calculation method.

Table 4. Heat transfer across the cool box at different temperature conditions (theoretical).

| Insulating material              | Thermal conductivity, $k$ $(W/m\cdot K)$ | 20°C $\dot{Q}(W)$ | 30°C $\dot{Q}(W)$ | 40°C $\dot{Q}(W)$ |
|---------------------------------|-----------------------------------------|-------------------|-------------------|-------------------|
| Polyurethane (PU)              | 0.023                                   | 0.37              | 1.10              | 1.83              |
| Expanded polystyrene (EPS)     | 0.033                                   | 0.48              | 1.45              | 2.42              |
| Poly-glass Fiber (PGF)         | 0.035                                   | 0.50              | 1.51              | 2.53              |
| Glass wool                     | 0.040                                   | 0.55              | 1.66              | 2.76              |
| Coconut Fiber                  | 0.048                                   | 0.62              | 1.88              | 3.14              |
| Asbestos                       | 0.080                                   | 0.94              | 2.53              | 4.20              |

Table 5. Outer wall temperature of the cool box at different temperature conditions (theoretical).

| Insulating material              | Thermal conductivity, $k$ $(W/m\cdot K)$ | 20°C $T_{\text{outer}}$ (°C) | 30°C $T_{\text{outer}}$ (°C) | 40°C $T_{\text{outer}}$ (°C) |
|---------------------------------|-----------------------------------------|-----------------------------|-----------------------------|-----------------------------|
| Polyurethane (PU)              | 0.023                                   | 19.7                        | 29.2                        | 39.4                        |
| Expanded polystyrene (EPS)     | 0.033                                   | 19.6                        | 29.0                        | 39.2                        |
| Poly-glass Fiber (PGF)         | 0.035                                   | 19.7                        | 29.0                        | 39.1                        |
| Glass wool                     | 0.040                                   | 19.6                        | 28.8                        | 39.1                        |
| Coconut Fiber                  | 0.048                                   | 19.8                        | 29.3                        | 38.9                        |
| Asbestos                       | 0.080                                   | 19.9                        | 29.2                        | 38.6                        |
The results obtained from the calculation method were then verified by using the simulation method. Table 6 and Table 7 shows the results obtained from the simulation method.

| Insulating material       | Thermal conductivity, $k$ (W m$^{-1}$ K$^{-1}$) | $20^\circ$C $\dot{Q}(W)$ | $30^\circ$C $\dot{Q}(W)$ | $40^\circ$C $\dot{Q}(W)$ |
|---------------------------|-----------------------------------------------|--------------------------|--------------------------|--------------------------|
| Polyurethane (PU)         | 0.023                                         | 0.3664                   | 1.0991                   | 1.8318                   |
| Expanded polystyrene (EPS)| 0.033                                         | 0.4829                   | 1.4488                   | 2.4146                   |
| Poly-glass Fiber (PGF)    | 0.035                                         | 0.5040                   | 1.5120                   | 2.5200                   |
| Glass wool                | 0.040                                         | 0.5538                   | 1.6615                   | 2.7692                   |
| Coconut Fiber             | 0.048                                         | 0.6261                   | 1.8782                   | 3.1304                   |
| Asbestos                  | 0.080                                         | 0.9416                   | 2.5411                   | 4.2352                   |

**Table 6.** Heat transfer across the cool box at different temperature conditions (simulation).

| Insulating material       | Thermal conductivity, $k$ (W m$^{-1}$ K$^{-1}$) | $20^\circ$C $T_{outer}$ (°C) | $30^\circ$C $T_{outer}$ (°C) | $40^\circ$C $T_{outer}$ (°C) |
|---------------------------|-----------------------------------------------|-----------------------------|-----------------------------|-----------------------------|
| Polyurethane (PU)         | 0.023                                         | 19.873                      | 29.618                      | 39.364                      |
| Expanded polystyrene (EPS)| 0.033                                         | 19.832                      | 29.497                      | 39.162                      |
| Poly-glass Fiber (PGF)    | 0.035                                         | 19.825                      | 29.475                      | 39.125                      |
| Glass wool                | 0.040                                         | 19.808                      | 29.423                      | 39.038                      |
| Coconut Fiber             | 0.048                                         | 19.783                      | 29.348                      | 38.913                      |
| Asbestos                  | 0.080                                         | 19.952                      | 29.118                      | 38.529                      |

**Table 7.** Outer wall temperature of the cool box at different temperature conditions (simulation).

Overall comparison between theoretical and simulation results for heat transfer rate across the cool box wall and temperature at the outer wall of the cool box is shown in Figures 10 through 15.

![Figure 10. Comparison for heat transfer rate at 20°C](image-url)
Figure 11. Comparison for heat transfer rate at 30°C

Figure 12. Comparison for heat transfer rate at 40°C

Figure 13. Comparison for temperature for outer wall at 20°C
Although there are minor discrepancies between the results obtained from both theoretical and simulation method. It can be concluded that the three best insulating materials across all three temperature conditions in terms of heat transfer were polyurethane (PU), expanded polystyrene (EPS), and poly-glass fibre (PGF). The worst insulating material was Asbestos. The results obtained concurs with [2, 24] who found that the lower thermal conductivity of the material, the lower the rate of heat transfer across the material. Heat transfer across materials of higher thermal conductivity occurs at a faster rate than across materials of low thermal conductivity. As a result, insulating material that has a lower thermal conductivity will have a lower heat transfer rate. The three best insulating material was being further tested experimentally using the thermal insulation test.

During the thermal insulation test, the three best insulating material was placed between the inner and outer layer of the cool box which was prepared previously. By placing ice inside the inner cool box, the time for the ice to change from solid phase to liquid phase (cold) was recorded. Also recorded was the time for the liquid (cold) too reached room temperature (normal). The normal temperature for 20°C condition was also set at 20°C, while the normal temperature for 30°C and, 40°C was set at 27°C. Similarly, with the previous methods, three different temperature conditions were used for the thermal insulation test. The results from the thermal insulation test are shown in Table 8 and Figure 16.
From the results obtained, Polyurethane (PU) recorded the longest time for both scenarios P1 and P2. The time recorded for PU to change from solid (ice) into liquid (cold) for the first scenario, P1, was 630 minutes (at 20°C), 400 minutes (at 30°C), and 240 minutes (at 40°C) respectively. For the second scenario, P2, the time recorded was 445 minutes (at 20°C), 265 minutes (at 30°C), and 110 minutes (at 40°C) respectively. Although there was not much difference in terms of time recorded between expanded polystyrene (EPS) and poly-glass fibre, PGF was seen to be the worst performing insulating material. The reason behind the lengthy time recorded by the cool box insulated with PU is because of its low thermal conductivity when compared to cool box insulated with either EPS or PGF. As calculated and simulated previously, PU heat transfer across the cool box wall insulated with PU is low, which resulted in longer periods for ice to change phases from solid to liquid (cold), and for liquid (cold) to reach normal room temperature conditions. This makes PU a suitable candidate to replace the conventional insulating material, which is EPS used in today’s cool boxes.

A tensile test was conducted on the three insulating materials to determine their ultimate tensile strength. The tensile test involved five specimens for each insulating material to obtain a more accurate result. The mean (average) ultimate tensile strength for each insulating material was calculated. The result for ultimate tensile strength is shown in Figure 17.
Polyurethane (PU) foam has the highest ultimate tensile strength which was 0.317MPa when compared with the expandable polystyrene (EPS), and poly-glass fibre (PGF). The ultimate tensile strength of EPS and PGF were 0.087MPa and 0.046MPa. The PU foam has higher ultimate tensile strength have the highest ability to withstand a pulling (tensile) force and PGF is lowest. The ability to resist breaking under tensile stress is one of the most important and widely measured properties of materials used in structural applications [25].

For the density test, only two insulating material was tested which were, polyurethane (PU), and expanded polystyrene (EPS) this is because, for poly glass fibre (PGF), it tends to dissolve in water [18]. The results from the density and porosity percentage conducted for this study are shown in Table 9.

![Ultimate tensile strength for insulating materials](image)

**Figure 17.** Ultimate tensile strength for insulating materials

### Table 9. Result for density test and porosity percentage

| Insulating material | Mass, m (g) | Volume, V (cm³) | Density, ρ<sub>r</sub> (g/cm³) | Bulk density, ρ<sub>b</sub> (g/cm³) | Porosity percentage (%) |
|---------------------|-------------|-----------------|-------------------------------|---------------------------------|-------------------------|
| PU                  | 27.0        | 27.0            | 1.0000                        | 0.72                            | 28.00                   |
| EPS                 | 24.5        | 27.0            | 0.9074                        | 0.64                            | 29.44                   |

From the results obtained, even though the volumes for both insulating materials were identical, they do differ in mass. As a result, the density obtained for both PU and EPS were different, 1.000g/cm³ and 0.9074g/cm³, respectively. Having a higher density resulted in PU having a lower porosity percentage (28.00%) when compared to EPS (29.44%). For an application involving insulation, a material having a low porosity value is recommended as the increase in porosity percentage will affect the heat transfer rate, by reducing the resistance of heat across the insulating material.

### 4. Conclusion

In this study, improvement of insulating material used in cool boxes was conducted both theoretically and experimentally. Six insulating materials were selected initially which were polyurethane (PU), expanded polystyrene (EPS), poly-glass fibre, asbestos, coconut fibre, and glass wool. Out of the six tested insulating materials, three of the best insulation materials which can be used for cool box application predicted from the calculation and simulation method were PU, EPS, and PGF. These three insulating materials were then tested further experimentally using the thermal insulation test. Experiment results showed that PU was the best performing insulating material in terms of heat transfer rate and recorded the longest time for ice (solid) to change into liquid (cool). The time recorded for liquid (cool) to reach normal room temperature was also longer for PU. Mechanical properties such as ultimate tensile strength, density, and porosity percentage for the respective insulating materials were also determined and results showed that when comparing PU and EPS, PU has higher density and lower porosity percentage.
porosity percentage. Based on these findings, it is apparent that PU has the potential to replace EPS which is the current insulating material used in a conventional cool box today due to its lower heat transfer rate, and resulted in the longer time taken for material (ice) to change from solid to liquid and down to normal room temperature.

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