Thermal Conductivity of Recycled Textile Quilts

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Abstract

Given the detrimental environmental impacts from the fast fashion clothing industry, this research project delves into the recycling of textiles for thermal insulation and energy conservation. The present work includes analyzing recycled fabric samples with varying methods of construction in order to maximize the volume of air—since air resists heat conduction—while keeping the air pockets small enough to minimize thermal radiation and convection. Thermal modeling using resistance networks was done to validate the measurement method and increase the accuracy and replicability of thermal conductivity measurements. Multiple quilt samples were sewn and measured with a thermal conductivity apparatus, with the goal to reduce thermal conductivity as much as possible. Quilt samples varied by the density of top-stitching, where indentations caused by stitching could create air pockets. Preliminary findings show that quilt samples with higher stitch density have a lower thermal conductivity than samples with a lower stitch density.

Background

In 2018, the recycled textile industry was valued at $5.3 billion; it is expected to reach $8 billion by 2026 [1]. Many attribute its growth to the heighted public opinion against fast fashion's reputation of pollution and waste. As of right now, 20% of the world's wastewater comes from fabric dyeing and treatment, and clothing manufacturing is responsible for 10% of the world's CO_2 emissions [1]. Annually, 190,000 tons of plastic microfibers from textiles are dumped into the ocean where they are eaten by sea organisms and introduced into our food chain [2].

Consumers now more than ever are inclined to care about sustainability when purchasing clothes. Online searches for "sustainable fashion" have tripled from 2016 to 2019, and uses of the hashtag #*sustainablefashion* on Instagram has quintupled from 2016 to 2019 [3]. Some clothing companies have adapted to this heightened public awareness by offering store credit for returning a worn out item, or even repurposing it to be resold. A patchwork wool jacket from Eileen Fisher's Resewn collection retails for $298, which was made from discarded customer returns [4].

Due to increased consumer demand and the growing economic leverage of the recycled textile industry, it is worthwhile to investigate repurposing methods for clothing. This research focuses on optimizing insulating clothing made from recycled textiles by reducing the thermal conductivity of the material. Applications from this research can include creating personal insulation to wear at home such as quilts, jackets, and robes, which can also save energy on space heating, which required 43% of residential energy consumption in 2015 [5].

Studies have shown that higher fiber density leads to more conduction between fibers and increase the thermal conductivity of the material. Reducing the density also allows for air to fill the space, which acts as a thermal insulator given air's low thermal conductivity [6].

This paper will continue to explore the relationship between air and thermal conductivity with recycled textiles. Samples were fabricated from t-shirts and shredded t-shirt fibers to create padded quilts with varied amounts of topstitching. The topstitching serves as a method to vary the amount of air pockets per sample. A thermal conductivity measuring apparatus was validated for this experiment and was used for testing.

Materials and Methods

Quilt samples made from t-shirts were sewn and tested for thermal conductivity with a guarded hot plate apparatus. A resistance network model was created to account for heat loss from the apparatus which was factored in the thermal conductivity calculations. This setup was later validated for accuracy by testing styrofoam of a similar thermal resistance to the quilt samples.

Samples consisted of two layers of 100% cotton t-shirt material serged at the edges and stuffed with 10 grams of unraveled t-shirt threads of assorted fiber content (see Fig. 1). To vary the density of air, topstitching was added in a square grid pattern of various sizes, where indentations created by the stitching would provide space for air. In total, 7 samples were tested where side lengths of the stitched squares ranged from no stitching, and 1 cm to 6 cm increasing in 1 cm increments. All samples measured 4.5 inches by 6.5 inches. (see Fig. 2). Higher stitch density quilts (1x1 cm squares) were assumed to have a higher volume of air than lower stitch density quilts (6x6 cm squares).

A guarded hot plate device was used to test for thermal conductivity (Fig. 3). Quilt samples were compressed between a heated plate and a cold plate, and temperatures for both plates were recorded from an Arduino after two hours, allowing time for the system to reach thermal equilibrium. The temperature difference between the two plates, the thickness of the sample, and the amount of power passing through the quilt sample were parameters in calculating thermal conductivity.

Effort was made to increase the precision of measurements. To ensure samples were compressed to the same thickness between the hot and cold plates, four half-inch wide 3D printed spacers of equal thicknesses made out of PETG plastic were used to ensure samples were evenly compressed within the hot plate setup. PETG plastic has a thermal conductivity of 0.29 $W/(m \cdot K)$, much lower than the thermal conductivity of the aluminum heater plate of 205 $W/(m \cdot K)$, minimizing the heat loss through the spacers [7] [8] . Fabric samples were tested with spacers of thickness 8.96 ± 0.004 mm. Four cutouts were made at the edge of each sample to accommodate the spacers. To ensure contact between the spacers and the plates, string was tightly tied around the hot plate and cold plate setup and spacers were adjusted for a snug fit.

Fig. 1. Unraveled T-shirt Fibers

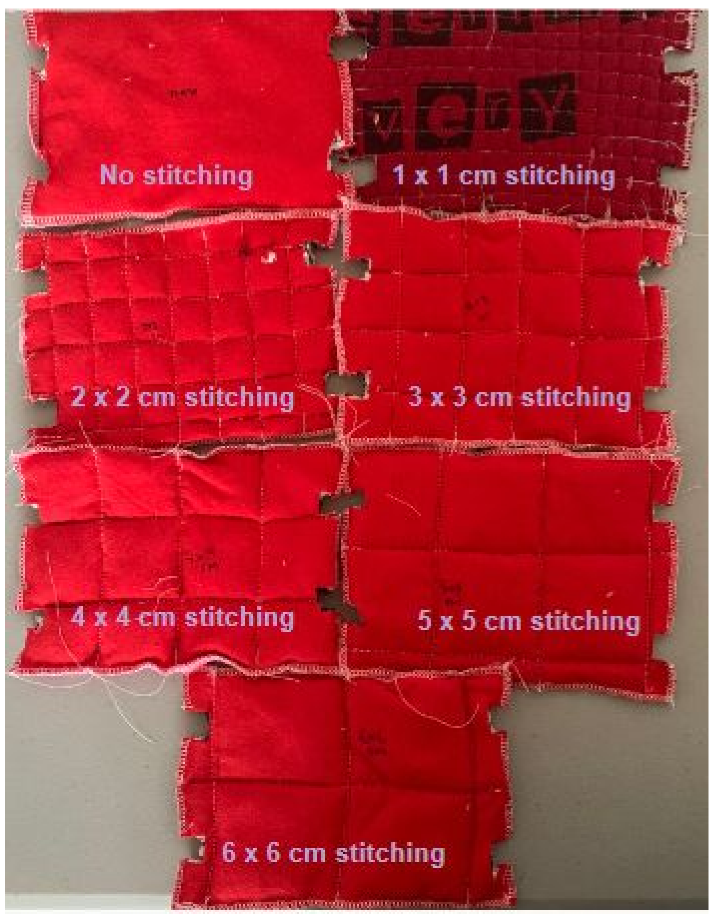

Fig. 2. Quilt samples

Fig. 3. Guarded Hot plate setup

<u>Resistance Network model</u>

To calculate the thermal conductivity of individual quilt samples, a resistance network model was implemented to account for the heat loss through the back of the heater plate.

FOAMULAR polystyrene insulation and four layers of poly/cotton quilter's batting were added on the back side of the heater plate to reduce the amount of parasitic heat loss. Estimated thermal resistances of the polystyrene and batting were integrated in the calculation of heat loss through a resistance network model (see Fig. 4). The resistance network model presents two paths where power from the heater can flow: through the quilt sample or through the back of the heater. The goal was to estimate the amount of power that escapes as heat through the back of the heater in order to estimate the power that flows through the quilt sample.

To judge the accuracy of the resistance network model, batting and polystyrene temperatures were measured and compared against the model's calculated value once the device reached thermal equilibrium for each quilt sample. A difference between measured versus calculated temperatures generally fell between 0-2 K after consistent testing of quilt samples, which falls within the uncertainty of the thermocouple and laser thermometer used to measure the temperatures. Fig. 2 displays locations where this temperature comparison was made. The two points on the figure between Polystyrene insulation and batting connected with a line correspond with measuring the temperature of the polystyrene insulation and the batting individually where they made contact. In reality, air serves as a small layer between the two materials but its effects are negligible in this case.

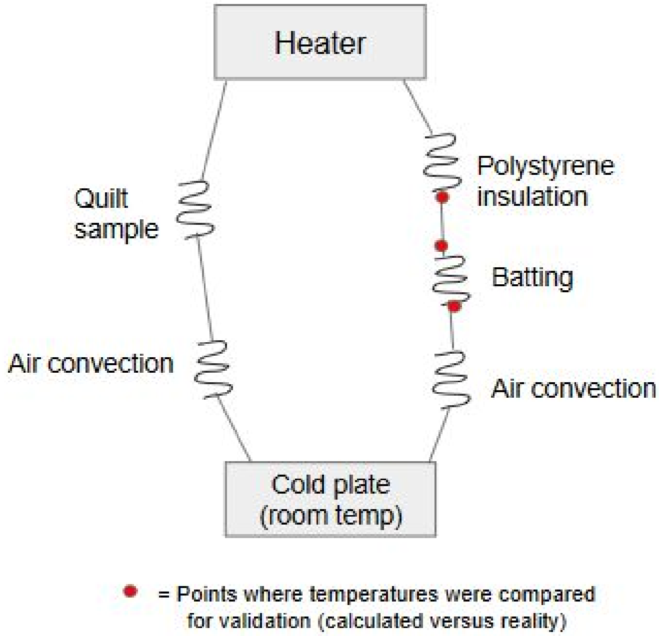

Fig. 4. Resistance network model

<u>Validation</u>

To confirm the accuracy of our thermal conductivity measurements, FOAMULAR polystyrene insulation of known thermal conductivity ($k = 0.029$ W/(m · K)) cut to different thicknesses was tested with the guarded hot plate apparatus (Fig. 5). The measured conductivity increased significantly with increasing sample resistance, suggesting that there was some heat loss not accounted for by the resistance network model. However, the thinnest samples had 5.5% and 4.8% error. The resistances of these two styrofoam samples are 8.7 K/W for 3.9 mm and 10.7 K/W for 4.8 mm. The range of resistances for the quilt samples tested fall in a similar range: between 8.4 K/W and 10.1 K/W. Because the resistances for the fabric samples are in range of the styrofoam, they would theoretically have a similar percent error, so the device was considered to be reasonably accurate in measuring thermal conductivity in samples below about 10 K/W.

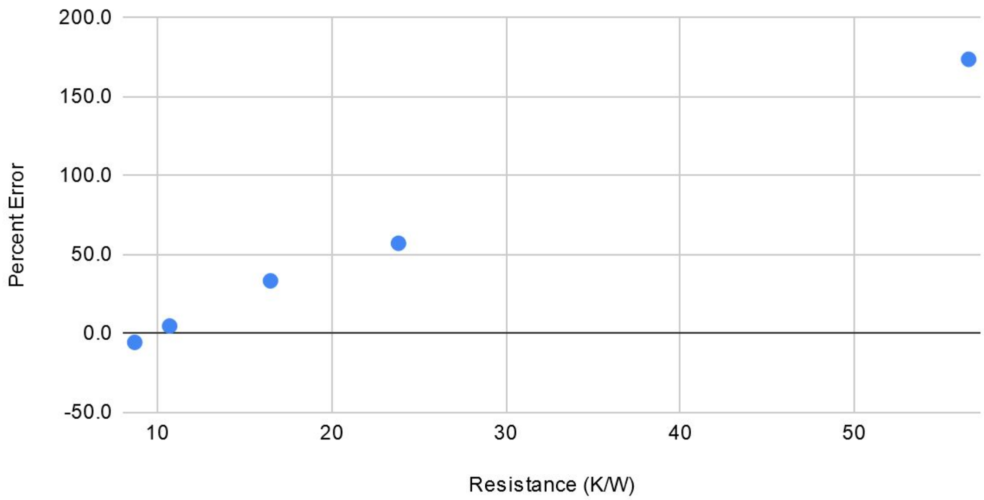

Fig. 5. Polystyrene resistance vs. percent error in calculated thermal conductivity

As Fig. 5 also demonstrates, increasing the thermal resistance of the polystyrene sample increases the percent error of the calculated thermal conductivity value. This was further confirmed with testing poly-cotton batting samples of an unknown thermal conductivity. One-layer, two-layer, and three-layer batting samples were tested to vary the amount of thermal resistance. The calculated thermal conductivity value increased as more layers of batting were added, providing further evidence that testing samples with high thermal resistances would increase the error in thermal conductivity calculations.

Propagation of Uncertainty

The propagation of uncertainty method was used to aggregate various uncertainty elements that factor into the thermal conductivity calculation in order to find the overall uncertainty value for our thermal conductivity data. Table 1 displays the sources that factor into the calculation, the amount of uncertainty, and its partial derivative on final thermal conductivity value with respect to the source. Something to note is that there may be other elements unaccounted for in our uncertainty calculation, such as unknown factors contributing to heat loss from the sensor.

Table 1. Propagation of Uncertainty

Source	**Uncertainty**	**Partial derivative**
Thickness of spacer (m)	4.4 e-06	0
Hot Thermocouple (K)	1	-0.0018
Cold Thermocouple (K)	1	0.0015
Laser Thermometer (K)	2	2.2500e-04

Area of Heater (m^2)	6.3 e-06	0
Total Power (W)	0.2	0.0128
Area of Styrofoam	3.6 e-05	0
Length of Styrofoam	4.4 e-05	0
Area of Batting	0.0022	0.0462
Length of Batting	2.2 e-05	0
H convection air	7.5	-1.3333e-05
Amicivity	0.14	0
Overall uncertainty:		**5.86 %**

Results and Discussion

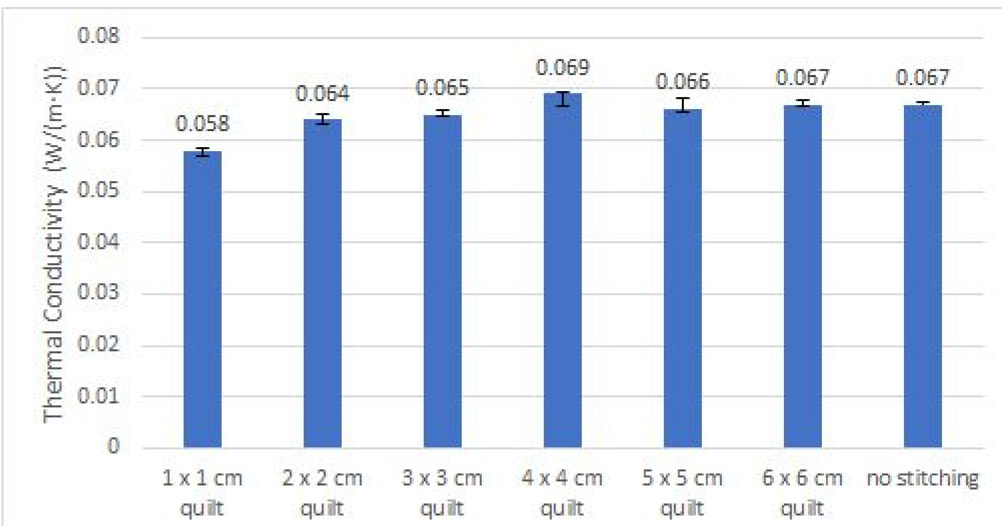

Fig.6. Chart of quilt sample thermal conductivities. Error bars represent 1 standard deviation.

Three tests per quilt sample was taken, and the mean thermal conductivity for each quilt sample was used to create the plot above (Fig. 6). A 1-sample ANOVA test analysis was done for the quilt sample data to see whether there is a statistically significant difference in mean thermal conductivity data. Alpha level 0.05 was chosen. The results gave a P-value of 2.8207×10^{-7}, which is less than the alpha level 0.05. Therefore, There is a statistically significant difference among the means of the groups at error level $\propto = 0.05$. At least one quilt sample's mean thermal conductivity differs from other sample means. However, we cannot determine through the ANOVA test whether there are systematic errors that could affect the data itself. The data may have precise differences among different samples, but it may not necessarily be accurate.

The calculated thermal conductivity values shown in Fig. 5 were similar and vary within 15 percentage points of each other. There is a slight upward trend in thermal conductivity when increasing the size of the quilt sample squares, with the 1 x 1 cm quilt being the least thermally conductive, suggesting that a higher stitch density decreases the thermal conductivity slightly. More data analysis and testing should be done to determine whether the trend is meaningful.

The thermal conductivity of air is 0.026 W/(m·K) while the thermal conductivity of cotton is 0.065 W/(m·K) [9]. Polyester falls within this range as well at 0.05 W/(m·K) [10]. The quilt sample thermal conductivities fall at the higher end of these values which is reasonable because it consists of a mix of air, cotton, and other fibers that may include polyester.

Conclusions

Quilts made from recycled t-shirts with different stitch densities were characterized by thermal conductivity. There is a statistical significant difference in mean thermal conductivities for at least one quilt sample. Higher stitch densities, such as the 1 x 1 cm stitch quilt, tended to have lower thermal conductivities than quilts with lower stitch densities. All quilts had conductivities in the range 0.065 $\pm$ 0.0070 W/(m·K).

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