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EFFICACY OF FABRIC THICKNESS IN PROTECTING AGAINST HIGH HEAT

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Abstract

Fire-spinners often wear denim fabric to protect against accidental contact with a burning prop. Most spinners do not purchase specialty fabrics and would be interested in information gained about off-the-shelf single-layer fabrics. How much protection do different fabrics actually afford? A heat source was applied to several samples of common cotton denim fabric in five different thicknesses, and temperature was measured across the fabric. For each experiment, the time taken for the far side of the fabric to reach a normalized temperature of 60°C was recorded. A strong correlation was found between increased fabric thickness and increased time of protection: increasing fabric thickness from 0.382 ± 0.007 mm to 0.676 ± 0.035 mm, or by about 0.3 mm, increased time of protection by 5.9 ± 3.0 seconds. Additionally, even the thinnest fabric was able to offer 5.2 ± 1.2 seconds of protection from 100°C heat.

1. Introduction

From bakers pulling trays out of the oven with mitts to fire-spinners allowing their props to hit their bodies to perform tricks, people trust fabrics every day to prevent burns from intense heat. However, most research on fabrics and heat transfer deals only with specialty layered fabrics and long-term applications. For the layperson looking to buy a better pair of jeans for firespinning, it is important to know how a single-layered fabric will behave when heat is applied for only a few seconds.

This paper intends to quantify the effect fabric thickness has on the rate of heat transfer through fabric exposed to a high-temperature source. Thereby, the amount of time it takes for a certain amount of heat to conduct through fabrics of different thicknesses can be determined.

Five different weights of cotton denim fabric will be tested: 14 oz/yd^2, 12 oz/yd^2, 10 oz/yd^2, 8 oz/yd^2, and 6 oz/yd^2. These weights were chosen as they are common, commercially available weights of denim fabric. In each test, a heat pad was applied to one side of a swatch of fabric while a thermocouple collected data from the other side. Initial analysis observed the temperature over time graphs produced by each thermocouple for each of five samples per weight. By defining a threshold temperature with a nominal value of 60°C, the graphs of each thermocouple provided a defined time to reach the threshold. Further analysis averaged the time values for each fabric weight and used those five new values to draw conclusions about fabric weight and its effects on rate of heat transfer through denim.

This paper will expand upon existing research into the thermal properties of fabrics of various types[1,2] and effective models for measuring fabric heat transfer[3,4] which focused on multi-layer fabrics and steady-state applications. In contrast, this research is on transient heat transfer on single-layer fabrics of varied thicknesses. While much prior research has gone into specifically-designed safety fabrics, such as firefighter's clothes, this research will be applicable to standard clothing fabrics and their use in daily or amateur hobbyist life.

2. Background and Theory

Prior research into heat transfer through fabrics has mainly been limited to steady-state applications. Fabric is also useful as a home insulator, or as clothing for people to wear in high-temperature environments, including firefighting. Experiments on such environments have been performed investigating the efficacy of multi-layer fabric in providing heat insulation [2,5]. Though this paper only investigates single-layer fabric, it is supported by other papers agreeing that thicker fabric provides better insulation[2]. Other research has also determined thermal properties of cotton fabric[1], which allows the data taken in this paper to be compared to thermal-fluids heat transfer models. Prior modelling supports the use of the heat diffusion equation to model fabric heat transfer[3], and thermal-fluids engineering models support the simplification of the heat diffusion equation into a solvable 1D slab equation, as the sample can be modelled as homogenous and has a much greater length along the surface than its thickness[4]. The 1D slab equation will be used in this paper to support the choice of fit model for the data, and the same normalization of temperature used in this equation will be used to normalize temperature across all experiments.

The physics of heat transfer that this paper focuses on are outlined in the 1D slab equation, written below:

$$\frac{T(x,t) - T_i}{T_s - T_i} = erfc\left(\frac{x}{\sqrt{4\alpha t}}\right)$$

Equation 1

This equation is a variation of the generic heat transfer equation to be used on an object (or "slab") which is very wide and long compared to the depth of measurement. The slab is exposed to a constant temperature at its surface, and the equation describes the temperature $T(x,t)$ of any depth of point x at any time t, measured in seconds after exposure begins. The temperature is non-dimensionalized by the surface temperature T_s and the initial temperature of the object T_i. The temperature relates to depth and time by the complimentary error function $erfc\left(\frac{x}{\sqrt{4\alpha t}}\right)$. The value α is determined the material properties of the object, being equal to an object's thermal conductivity divided by its density and specific heat[4].

3. Experimental Design

3.1 Sensor Validation

Prior to running the experiments, it was important to ensure that the thermocouples, which have relatively slow response times, would respond fast enough to capture useful data. In a sensor test-run, water was boiled so that it was 100°C. Then, data was recorded as the sensor was quickly placed into a cup of boiled water and kept there until the sensor reached a steady temperature. When moving from room temperature to 100°C, it was found that the sensor took less than 3 seconds to reach the final measured temperature during every test experiment run. When data from the fabric experiment was all found to involve longer times, it was concluded that the thermocouples were providing accurate accounts of how long it took to reach the specified temperature. Furthermore, during experiments, one thermocouple was experiencing the same instantaneous change measured here while another went through a lower-temperature transient process, and the instantaneous change thermocouple always reached high temperatures well before the transient thermocouple measured its target temperature. Therefore, it can be assumed that the response time of the thermocouple is fast enough to accurately report the times and temperatures studied in this experiment.

3.2 Experiment Setup

For each experimental run, a 2.5” by 2.5” fabric sample was cut and clamped into the experimental setup system. A 2” square heat pad was used so that its entire surface would be in contact during the experiment. The thermocouple and heat pad wires were taped to their respective acrylic surfaces, but no other adhesive was used. The heat pad, thermocouples, and fabric were kept in contact with each other during the experiment with the application of force, as shown in the diagram on the next page.

Acrylic was used to support the fabric and head pad and protect any surrounding objects from heat. This material was chosen for its ease of acquisition and machining as well as its relatively similar thermal coefficient to skin[4,5], suggesting that an experiment performed on acrylic would more closely mimic results for denim in normal (worn) use.

Five samples were cut from each weight of fabric and each sample was tested once for a total of twenty-five experiments performed. In Figure 1, the setup of each fabric sample is shown.

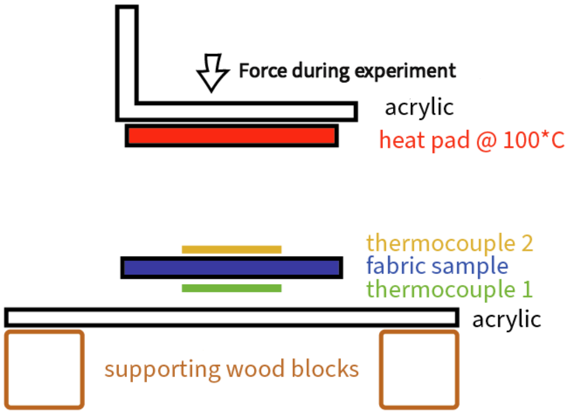

Figure 1: A diagram of the experimental setup. The heat-pad portion of the assembly is initially separated from the fabric sample portion of the assembly. The thermocouples used here are Vernier TCAs and the heat pad is a 2” x 2” electrical heat pad.

3.3 Procedure

Each sample was measured with a micrometer and then clamped into the assembly as seen in Figure 2.

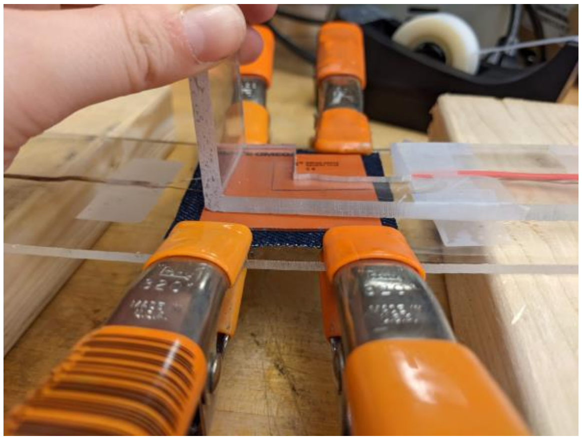

Figure 2: Photograph taken during one experiment showing very heavyweight fabric clamped into the assembly and force being applied by hand to the acrylic.

The heat pad was placed off to the side to heat up to a steady temperature. Before each experiment, any parts not touching the heat pad were cooled to ambient temperature.

Once the heat pad reached steady state, the heat pad was quickly applied to the fabric and held there until the collection of data was finished.

The software used for data collection detected the heat pad's presence by the top thermocouple rising above 30°C but kept a second of data from before that point. Actual ambient temperature was taken from the thermocouple's measurements before that point. Actual heat pad temperature was taken from the top thermocouple's measurements after it reached the steady temperature, about three seconds into the experiment. Time to reach nominal temperature was calculated when the experimental data were analyzed.

4. Results and Discussion

Graphs from each experiment were consistent in their shape, with variation in small bumps attributed to jostling as the heat pad was set down. Each experimental run was analyzed for the time it took to reach a normalized temperature. The normalized temperature was calculated using the same normalization as the heat equation with nominal values as shown below:

$$\frac{T_{target} - T_{i,\,meas}}{T_{s,\,meas} - T_{i,\,meas}} = \frac{60 - 25}{100 - 25}$$

Equation 2

When this equation is rearranged, it shows T_{target} in terms of other measured and nominal values (all values in Celsius):

$$\frac{(60 - 25)(T_{s,\,meas} - T_{i,\,meas})}{100 - 25} + T_{i,\,meas}$$

Equation 3

In both of these equations, T_s is the surface temperature of the heat pad and T_i is the ambient temperature, taken between the fabric and acrylic surface.

When graphed as a line onto the raw data from both thermocouples, the normalized temperature shows the target time in seconds, as seen in Figure 3.

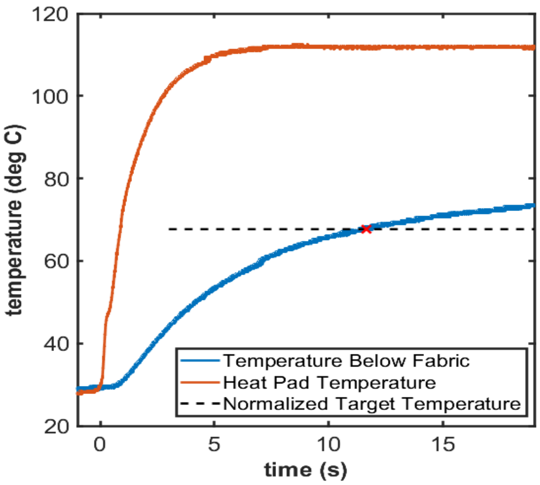

Figure 3: Graph of raw data from one experiment corresponding to a midweight fabric. The measured 'skin' temperature, shown in blue, crosses the normalized target temperature 11.65 ± 0.05 seconds into the experiment.

From this same experimental run, it is shown in Figure 4 that the graph of the raw temperature data from below the fabric is visually similar to a graph produced using the 1D slab heat equation.

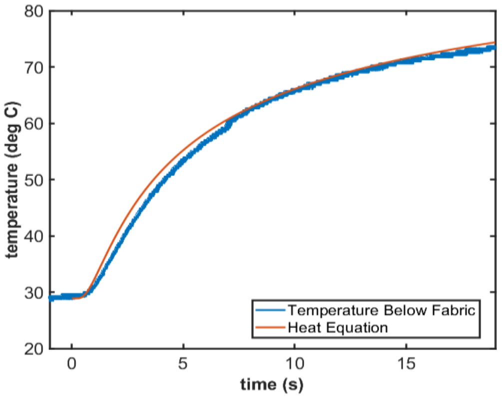

Figure 4: Graph of raw data from one fabric experiment shown alongside a graph of data produced by the 1D slab heat equation using estimated values of x and α. The shapes of the two graphs are similar.

This similarity supports the usage of the 1D slab equation in analysis of the experimental data. Actual values of x and α were not determined.

When the data points are extracted for each experimental run and graphed together, they show a clear positive correlation. To determine which equation should be used to fit the data, the heat equation can be rearranged to solve for time, as shown in equation 4.

$$\frac{T(x,t) - T_i}{T_s - T_i} = erfc\left(\frac{x}{\sqrt{4\alpha t}}\right)$$

$$t = \left(\frac{x}{erf\left(\frac{T(x,t) - T_i}{T_s - T_i}\right)}\right)^2 * 4 * \alpha$$

Equation 4

Given that every temperature and α are constants, (4) can be simplified for fitting:

$$t = b * x^2$$

Equation 5

Data taken from all samples was plotted and fitted with the $t = b*x^2$ equation, producing the graph in Figure 5.

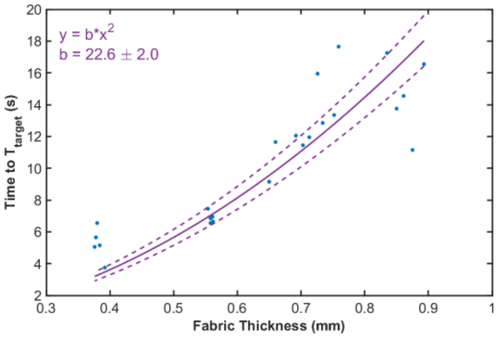

Figure 5: Graph of fabric thickness versus time taken to reach T_{target} for every experimental run. The graph is fitted with the line $y = b*x^2$ where $b = 22.6 \pm 2.0$ with 95% confidence.

The $y = b*x^2$ model, derived from the 1D slab equation (1), proves to be a good fit from the data and shows there is a positive correlation between thicker fabric and longer time until T_{target}.

It is also useful to group these fabric samples by the sheet of fabric they were cut from, even though it introduces further uncertainty into the results, as seen below in Figure 6.

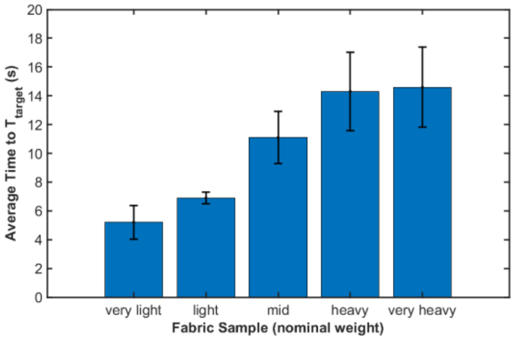

Figure 6: Graph of fabric nominal weight versus time taken to reach T_{target} where fabrics are divided into five weight categories ranging from very light weight to very heavy weight.

The words used here correspond to the words used in sales listings for fabric, and sometimes sales listings for clothing items. This graph may be a more useful informational format for those looking to purchase a pair of jeans for their effective protection who don't have a micrometer on hand.

There are a few limitations on the conclusions presented in this paper. Because all temperatures were normalized, it is easier to compare different experimental runs to each other without concern for the ambient or heat pad temperature being different between experiments. However, in a physical situation, a person would likely feel pain faster if the surface temperature is increased. Therefore, the scope of this analysis is limited to applications where the hot item being contacted is exactly 100°C.

This analysis is also limited by a lack of fabric variety, and only applies to denim fabric, which may have a tighter weave than other types of cotton fabric. It is unknown how the weave density of the fabric alters the protectiveness of the fabric.

Finally, though the 1D slab equation was referenced to and used in this analysis, it was not conclusively determined that the 1D slab equation is the best model for fabric contacting an external heat source while laying on skin or a skin-like surface. If future analysis was to be conducted, it may be useful to determine what model is most useful so that safety information might be determined for a wider variety of fabrics, fabric thicknesses, and temperatures.

5. Conclusions

Based on the results presented in this paper, there is a clear correlation between thicker denim fabric and longer protection time. Even very lightweight denim will protect skin from experiencing a 60°C temperature due to a 100°C heat source for about 5.2 ± 1.2 seconds, but extremely heavy weight denim fabric offers a protection time for the same temperatures of 14.6 ± 2.8 seconds, an increase of 9.4 seconds of protection time just in commercially available fabrics.

Heavier weight denim fabric is more effective at protecting from burns and pain due to heat than lighter weight denim fabric. It is interesting to see, however, that even the thinnest commercially available fabric appears to provide protection for several seconds, which is long enough to pull one’s hand from a hot surface, for example.

This paper also suggests that the 1D slab model could be analyzed for use in modelling single-layer fabric, as it appeared to visually correlate with results in this paper. Future research may pursue this model, or otherwise expand upon the temperatures, thicknesses, and fabrics used here to provide a more holistic view of heat transfer through single-layer fabrics.

Acknowledgments

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