COMMUNICATIONS IN
DEVELOPMENT AND ASSEMBLING OF TEXTILE PRODUCTS

Heat transfer test method development: Consideration for design and safety of household oven mitts

Adriana Petrova*, Semra Peksoz, Aditya Jayadas

Department of Design and Merchandising, Oklahoma State University, Stillwater, OK, USA
*Corresponding author *E-mail address:* adriana.petrova@okstate.edu

INFO

CDATP, ISSN 2701-939X
Peer reviewed article
2024, Vol. 5, No. 2, pp. 207-221
DOI 10.25367/cdatp.2024.5.p207-221
Received: 16 July 2024
Accepted: 01 November 2024
Available online: 29 December 2024

ABSTRACT

The purpose of this study was to develop a test method – an apparatus and a protocol for evaluating the rate of heat transfer across a sample of layered materials commonly used in oven mitts. Using the apparatus, effects of contact temperature and pressure as well as design features such as quilting stitching pattern of the sample on heat transfer were examined. The apparatus featured a round wooden base with three silicone-covered wooden "fingers" equipped with thermocouples where the test samples were mounted. The device was lowered with the samples down onto a hot plate kept at stable high "pan" contact temperature. Upon contact, changes of the "skin" contact temperatures (at the "fingers") were recorded at 10 Hz for 300 s. Tests were carried out at six levels of pressure on the sample (exerted by variable weights), 3 levels of "pan" contact temperature, and 3 different quilting stitch patterns of the material. Time to reach critical skin threshold temperature was affected by stitch pattern; it decreased exponentially with increasing pressure and increasing hot plate contact temperature. The shape of the temperature-time curve indicated how the material configuration of the sample affects the transfer of heat.

Keywords
textile testing,
heat transfer,
oven mitts,
burn injuries

1 Introduction

Manufacturers and designers must ensure that products such as household oven mitts and potholders meet mandated performance standards and that they are effective in preventing burn injuries related to food preparation at home. Burns can be prevented through engineering design of heat source systems, through use of personal protective equipment when handling such systems, or through administrative control. For instance, ovens can be designed to automatically turn off the heating element or actuate a heat guard if a hand moves too close to the heat source. Additionally, it is imperative that established safety operating procedures and product warning labels are strictly followed.

The United States Consumer Product Safety Commission (CPSC), which evaluates the risk of injury or death associated with consumer products, estimates that the costs associated with deaths, injuries, and property damage from consumer product-related incidents is one trillion dollars annually [1]. Burns resulting from poor products are a serious problem concerning health and wellbeing of individuals. A burn is defined as an injury to the skin, primarily caused by heat from radiation, radioactivity, electricity, friction or contact with chemicals [2]. Burns can result from hot liquids, leading to scalds; hot solids, causing contact burns; or flames, resulting in flames burns. The American Burn Association reported that 398,000 individuals were treated for burn injuries in 2021 [3]. Occupational burn incidence reported was 26.4 per 10,000 workers, with wrist and hand injuries accounting for the majority. Specifically, 8.9 females and 6.7 males per 10,000 workers experienced some degree of burn, with cooks and food service workers among the higher risk occupations [4]. The World Health Organization (WHO) estimates over 180,000 deaths worldwide caused by burns [2]. Non-fatal burn injuries, which are leading cause of morbidity, require generally expensive care. Lost wages and long-term care, including mental health support, greatly contribute to the economic impact of burn injuries. According to WHO, females have slightly higher rates of death from burns than males, primarily due to cooking, unsafe cookstoves and their handling, and ignition of loose clothing [2]. WHO points out that lack of proper safety measures and policies is a major risk factor for burn injuries and recommends increasing awareness, enforcing policies, and providing burn prevention programs [5]. While statistics for non-occupational burn injuries are difficult to estimate, considering that at least one member per household worldwide is involved in daily food preparation and handling heat sources, the risk of burn injuries among the general population is probably very high. Therefore, addressing the design of oven mitts, potholders, and other products to prevent burn injuries is crucial.

Design considerations for such products include the selection of materials, their assembly into a composite sample, and their appropriate placement over the hand depending on the product's usage. To be used for protection against high ambient (oven) and surface temperatures (hot pots/pans, burners), materials used for oven mitts and potholders need to block heat so that the surface that is in contact with the skin does not reach temperatures that can cause burn injury for the duration of the exposure. The ability of a textile material or a multi-layer composite material to block heat is described by its thermal resistance. The thermal resistance is measured in controlled conditions by determining the temperature drop across a sample when a heat source is applied on one side of it. A common apparatus for measuring thermal insulative properties of textiles, such as the sweating guarded hot plate, measures the power necessary to keep the temperature on one side of a sample at skin temperature while the other side is being kept at a constant (air) temperature. All values necessary for the calculation of thermal resistance are taken once a steady state is reached. While thermal resistance is a good descriptor of insulation and allows for comparison of fabrics, evaluating the ability to block heat to prevent burns requires knowing how fast heat propagates across the material's thickness upon contact with high temperatures and how the temperature on the other side (skin contact side) changes with time.

ASTM C1055-20 Standard Guide for Heated System Surface Conditions that Produce Burn Injuries [6] establishes a method of determining acceptable operating surface temperatures to prevent serious injury to the skin for certain exposure times. The method is based on plots of temperature versus exposure time, defining the thresholds for reversible injuries and for total necrosis (death of tissue). The plots determine the ranges of temperatures and exposure times that are safe or where particular injuries can be expected. The reference points are given with respect to injuries commonly defined as 2nd and 3rd degree burns, i.e. reactions of the skin to heat exposure where either complete necrosis of the epidermis but no significant damage to the dermis occurs or significant damage to the dermis occurs, respectively. Data show that at higher temperatures the exposure time before 2nd or 3rd degree burns occur shortens exponentially: contact temperature of about 70 °C (160 °F) is critical as burn injuries are practically instantaneous and irreversible (death of tissue occurs). ASTM F1060-18 Standard Test Method for Evaluation of Conductive and Compressive Heat Resistance [7] uses the same data on tissue tolerance to heat as ASTM C1055-20 to determine the “thermal protection” of a material, defined as the exposure time necessary for sufficient amount of heat to flow and accumulate across a sample as to cause pain or to cause a 2nd degree burn. In this test, a sample is placed onto a plate heated to a specified temperature (up to 600 °F, or 316 °C) appropriate for the end use. The sensor assembly consists of a calorimeter weighted to create a pressure of 0.5 psi on the sample and equipped with thermocouples to measure temperature. The sensor unit measures the transferred heat as well as the temperature on the other side of the sample. The measurement of the exposure time begins when the sample is placed in contact with the heated plate and it stops when the skin-side temperature reaches the point when pain is felt or 2nd degree burn occurs according to the curve of the model for tissue tolerance to heat, also called Stoll’s curve [8]. A similar method for measuring thermal protective performance (TPP) of materials exposed to radiant and convective heat was established by NFPA 1971 Standard on Protective Clothing for Structural Fire Fighting [9], which uses an apparatus where the heat source is a flame.

Comparison and selection of materials for protective oven mitts and potholders can be guided by results of testing based on the ASTM F1060 method. To determine the test conditions, the specifics of the end use need to be analyzed. Typically, oven mitts are used to transfer a hot pot or pan to or from an oven or burner heated to a temperature range of 120 °F to 660 °F (50 °C to 350 °C). When the pot/pan is lifted, fingers are in contact with its surface, with contact temperature initially being the same as the oven or burner temperature reached during cooking. The heat quickly starts dissipating as the pot or pan is taken away from the heat source. The higher the contact temperature, the greater the temperature gradient across the mitt will be, resulting in a higher speed of heat transfer across the material. Therefore, it should be expected that at higher contact temperature, the time to reach critical temperature on the skin side of the mitt will decrease, and the thermal protection will be lower.

Another factor influencing heat transfer is the pressure exerted on the mitt by the pot or pan. Commonly, household oven mitts and potholders are made with cotton fabrics as shell and lining layers and cotton or polyester batting as fill material. This material combination generally has higher thermal resistivity due to the air trapped in its layers. When the material is compressed under the weight of the pot or pan, the trapped air is displaced, thereby locally changing the properties of the assembly. Localized compression also occurs along the various types of quilting stitches typically used to hold all materials together. The compression of the material due to stitches may be further increased by the compression due to the weight of the pot or pan if that section of the material happens to be between the finger and the pot or pan surface. Under increased pressure, it is expected that heat will transfer across the sample faster, shortening the time to reach critical skin threshold temperatures. Considering the importance of contact temperature and pressure on heat transfer, investigating the effect of these factors on fabric thermal protection, particularly in relation to stitch patterns and placement design, is needed. Such an investigation would inform not only the selection of appropriate materials for oven mitts for the typical temperature and pressure ranges but also inform mitt design in terms of stitching designs and their placement across the mitt to protect the hands of the wearer during typical mitt use.

2 Purpose of the study

The purpose of this study was to develop a test method, including an apparatus and a test protocol, to measure the rate of heat transfer across a sample of layered textile materials as applicable to oven mitts and potholders. The test needed to allow for (a) accurately and precisely measuring the temperature on both the skin-contact and the hot surface-contact sides of a textile sample; (b) varying the hot surface temperatures in a range typical for cooking; (c) applying pressures that are typically exerted by a full pot or pan; (d) determining the time of contact of the sample with the hot surface and recording the contact temperatures with the hot surface for several minutes thereafter.

The developed apparatus was intended to investigate the following hypotheses: (1) the heat transfer rate will increase with increasing contact surface temperature, shortening the time to reach critical temperatures; (2) the heat transfer rate will increase with increased pressure on the sample, shortening the time to reach critical temperatures; and (3) the heat transfer rate will increase for locations with higher number of quilting stitches due to compression of the layers, shortening the time to reach critical temperatures.

3 Test method development

The development of the apparatus and the protocol of the test method for measuring the rate of heat transfer across a sample were carried out in stages, with multiple trials and testing of ideas, involving major and minor modifications of the experiment setup. The goal was to design an experiment that mimics the process of using an oven mitt, such as lifting a hot heavy pan, taking it out of an oven, and transporting it to a flat surface nearby. The procedures had to be sufficiently generalized and simplified to create a consistently reproducible laboratory test that yields meaningful results. In general terms, the experiment setup had to feature (a) a method of mounting test samples to allow contact with a heat source on one side, (b) sensors measuring the temperature on either side of the sample that is connected to a data recording system, (c) a heat source, and (d) a system simulating the pressure that the pot or pan exerts on the mitt and fingers.

3.1 Apparatus

3.1.1 Mounting samples

A small experiment was carried out to investigate the shape and size of the area where the hand contacts a pan. It was observed that one of the common ways to lift a pan was to use the fingers to support the pan's weight. The pan was often held either by its handles or by supporting it on the bottom (Fig. 1). A generic 4 Qt glass pan with handles with weight of 2.090 kg was filled with water to reach total masses of 3 kg, 4 kg, and 5 kg. The finger imprints of smaller and larger hands were taken, and the contact areas measured using tools in Adobe Photoshop. Fingerprints were smaller by area and rounder when the pan was held by the handles and larger, more oval and showing imprints from the intermediate phalanges at higher weights.

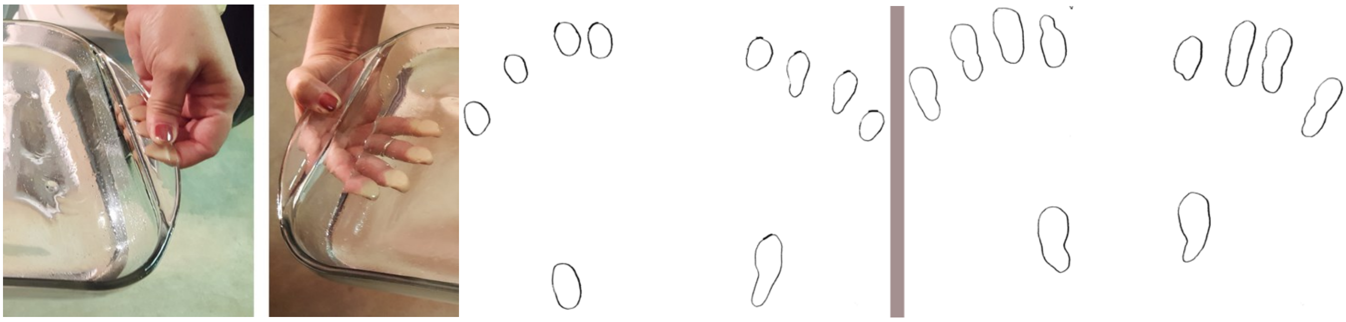

Fig. 1 Estimating size of mounts in apparatus – lifting pan by holding handles (left) and by supporting on the bottom (right). Finger imprints transfer for 2 kg pan (left) and 5 kg pan (right).

Results and analysis of the experiment led to the decision to simulate holding a pan by using protruding "fingers" that will serve as mounts for the textile test samples and will be brought in contact with a flat heated surface. Three short wooden cylinders with a flat top were used to form the "fingers". The cylinders were arranged in an equilateral triangle centered over a round wooden base ensuring stable support and uniform distribution of any round load applied symmetrically over the wooden base (Fig. 2). This symmetry was necessary to achieve uniform heat flow all around and identical conditions for each of the three textile samples, allowing for averaging their data. Considering the variability of the fingerprint area measurements, a contact area of 1 inch in diameter was deemed appropriate for each "finger". To keep the sample in place on top of the “finger”, two small elastic bands with a hook at the end were attached across the base of each “finger” stretching up to hold the sample with the hook.

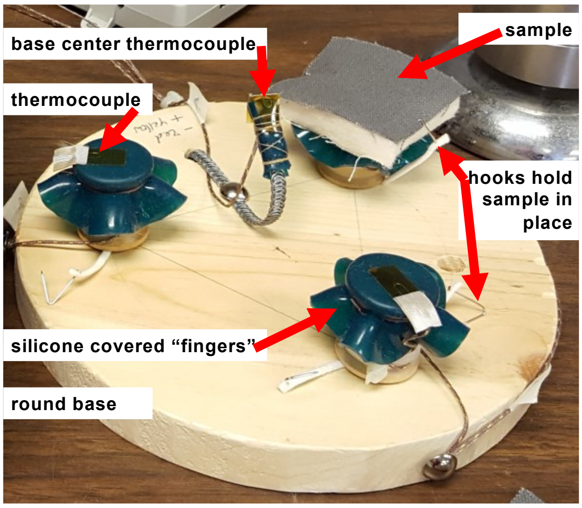

Fig. 2 Sample mounting of apparatus.

3.1.2 Temperature sensors

The “fingers” were covered with silicone that had skin-like thermal properties and were equipped with thermocouples as temperature sensors (Fig. 2). Omega K-type thermocouples (Model: SA1XL-K-SRTC) with 30AWG fiberglass lead wire capable of withstanding 482 °C [10], were attached on top of each “finger” to measure “skin” contact temperature. The same thermocouples were used to measure the temperature of the heat source as discussed in next section. A DataQ data acquisition board (Model DI-D008) was used to record temperature data [11]. The data logger was connected to a computer. Using proprietary software, voltage signals from each thermocouple were collected, recorded, and converted to temperature readings. The data were stored as Excel files for subsequent processing and analysis.

3.1.3 Heat source

The surface of a pan heated in an oven should, at a steady state, reach the temperature to which the oven is set. When one reaches into the oven to take the pan out using mitts or a potholder, the initial contact temperature should be equal to the oven temperature. However, as soon as the oven is opened, the temperature starts to drop, cooling even faster when the pan is taken out into room temperature. This cooling can be significant, depending on the size, shape, and mass of the pan, as well as on the ambient temperature and humidity conditions. The cooling of the pan can greatly affect the rate of heat transfer from the plate through the protective material to the skin because it depends on the temperature gradient across the textile sample. Figure 3 shows an experimental setup where, mimicking the real situation of a pan held with fingers, the “fingers” with the mounted samples are facing up to support the heated round glass plate, which had just been taken out of an oven, and placed over the samples. The graph shows the first 300 seconds of the change of the temperature measured in the middle of the glass plate. (An additional mass of 500 g placed in the middle of the plate during the experiment is not shown in Fig. 3 but can be seen in Fig. 5.) The plate cools down considerably from about 210 °F at 20 seconds to about 170 °F at 300 seconds. While a temperature drop would help protect the hand as the contact temperature drops down on its own, such behavior would be difficult to replicate consistently in data collection meant for a rigorous test method. Repeating the test conditions would be possible if the apparatus were equipped with a mechanism that takes the pan out of the oven, transports it, and places it over the arrangement of test samples. A mechanized apparatus would certainly produce data with high validity in comparative studies of protective materials because the scenario where cooling is taken into account would be representative of the real situation. However, building such apparatus may be cost-prohibitive and not warranted by demand.

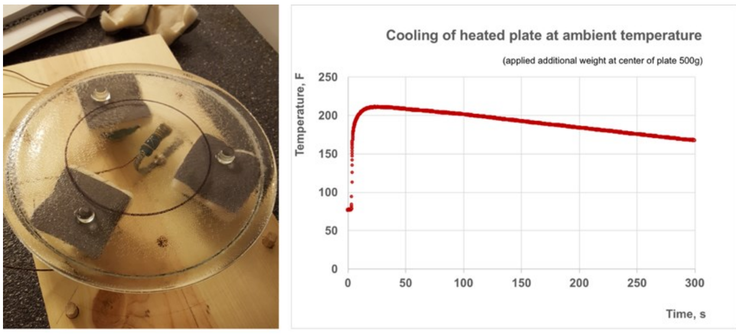

Fig. 3 Apparatus configuration with heated plate as a heat source (left). Temperature drop on the heated plate in the first 300 seconds (right).

Alternatively, achieving validity and reliability of the test is possible by using a heat source that is kept at constant temperature such as a hot plate. Typically used in test methods design, maintaining a constant temperature allows test conditions to be reproduced accurately, giving validity to comparisons of samples. The constant temperature method would produce more conservative results for a given initial contact temperature than the cooling heated plate, but test conditions are easier to reproduce and therefore preferable for designing a test.

An important advantage of this method is that building the apparatus would be easier, as no specialized robotic mechanisms need to be designed and produced at this stage. To use a hot plate as a constant heat source, the test apparatus featured a flipped arrangement. As shown in Fig. 4, the wooden base holding the samples is flipped with the samples facing down to be lowered onto the heated hot plate. In laboratory conditions, this process can be done manually.

Fig. 4 Apparatus configuration with a heat source at constant temperature.

A portable solid single round burner (Oster Table Stove Model CKSTS8100-B) was used as the heat source. The adjustable temperature control allowed for continuous adjustment of the temperature in the operating range. Setting the desired contact temperature required time for temperature stabilization and several back-and-forth adjustments of the temperature control knob. Temperature was monitored via thermocouples, as previously described. Initially, only one thermocouple was attached to the heating plate to record its temperature. An experiment mapping the temperature across the heated plate revealed an uneven heat distribution of up to ± 20 °F that was due to the geometry of the heating element typical for burners. To address this, three thermocouples were added on the surface of the hot plate to monitor the average temperature of the burner. The three thermocouples were placed in the same configuration as were the samples on the apparatus' base ensuring that the samples are exactly over the thermocouples on the hot plate. A small time variation of the hot plate temperature was observed, caused by the temperature control electrical feedback circuit, which switches the electricity to the burner on and off to compensate for overheating and cooling of the heating element. The time variation of the burner was ± 5 °F with a period of 65 seconds. Considering that our experiment focused on the first 30-40 s after contact, this time variation of the burner was acceptable. The added expense of acquiring a professional hot plate with better parameters was not justified at this time of the development of the prototype apparatus.

3.1.4 Loading – application of pressure

Figure 5 shows the method of applying variable weights. Appropriate numbers of round weights were installed on a stand with a central pole to achieve the desired weight. The stand was centered over the arrangement of the round base with the samples, applying pressure symmetrically. To ensure symmetrical placement of the loading pole, a circle with appropriate diameter was drawn on the back of the round base to guide the pole's placement. Regardless of the way the base with the samples was arranged facing up to contact the cooling heated plate or facing down to make contact with the constant-temperature hot plate, the stack of weights was always placed on top of the arrangement, exerting pressure on the samples. The configuration of the final apparatus prototype is the one shown on the right side in Fig. 5.

Fig. 5 Method of application of variable weights (center) for two cases of heat sources – cooling heated plate (left) and constant-temperature hot plate (right).

3.2 Data acquisition protocol highlights

- **Preparing the data monitoring and recording system:** Ensure that the data recording system is ready for data collection and prepare the software to monitor temperatures on the three fingers and the hot plate prior to and during the test.
- **Preparing test samples:** Cut samples of the same size from areas representing typical quilt stitches of the materials tested, using new samples for each test. Ensure samples are large enough to cover the finger of the apparatus and for the tested stitching to center over the thermocouple. Face the sample with its skin side towards the thermocouple; attach samples with hooks ensuring the hooks not to touch the heated surface. Orient samples over the fingers to ensure consistent alignment of the stitching pattern with respect to the center of the round base. Weigh samples prior to mounting and record the mass to the nearest 1 g.
- **Preparing the heat source:** The hot plate should be heated to the desired temperature in the range appropriate for the end use. The temperature must be stabilized by adjusting the temperature control dial of the apparatus as many times as necessary and waiting for the temperature to steady again after each adjustment.
- **Preparing the load:** Stack the necessary number of round weights on the loading pole and weighed to reach the desired level of pressure for the end use. Adjust the load to achieve the desired pressure, considering the contact area of the fingers of the apparatus is $3\pi r^2$, for radius r = 0.5 in.
- **Preparing the base for testing:** Ensure the hot plate and the fingers are at the appropriate temperatures. While one researcher holds the base with both hands with the samples facing down, an assistant should place the loaded pole in the middle of the base. Place the loaded base down onto the hot plate with a sudden movement.

- **Conducting the test:** Monitor the samples for any signs of failure such as smelling, fuming, or burning, and stop the test if necessary. Continuously monitor all temperatures. Stop the test when all finger sensors reach a predetermined critical temperature or when the testing time (e.g. 300 s) is over. Record all details of the test.
- **After the test:** Extract and review the collected data to verify the test's success and repeat if necessary. Remove samples from the base, label, and store them. Condition the base with the fingers back to room temperature using a fan and ice packs to cool the fingers.

3.3 Data processing highlights

Because the goal of the test is to measure a very short period of time, determining the starting point of the heat transfer process precisely is crucial for data processing and analysis. When the base with the samples is lowered onto the hot plate, the temperature rises rapidly. A procedure to quantify that starting moment was devised in order to calculate accurately the time to reach a certain temperature as the difference between the logged time when that certain temperature was reached and the starting moment.

The starting moment was found by making a plot of the difference (on the y-axis) of the temperature T at moment t_i and the temperature 0.5 seconds later at moment t_i+0.5 vs. time t on the x-axis. Plotting the changes between adjacent time points at 0.1 seconds interval produces a similar plot but the changes have greater variability. The results for the starting moment are the same. Such plots (Fig. 6, right panel) exhibited a straight sloped segment, indicating a rapid temperature change. The vertical mid-level of that segment was found by subtracting the lowest and the highest values at the beginning and the end of the segment and finding the middle. The time at which that mid-level occurred (reading off the horizontal time axis) was interpreted as the starting point of the temperature rise. All raw data files were processed in this way. The starting point was used also as an offset point for aligning graphs for visual comparison in data presentation. Data were processed in Excel, and macros were written to allow multiple files to be processed faster, including extracting data, performing calculations, reorganizing data, and plotting necessary figures.

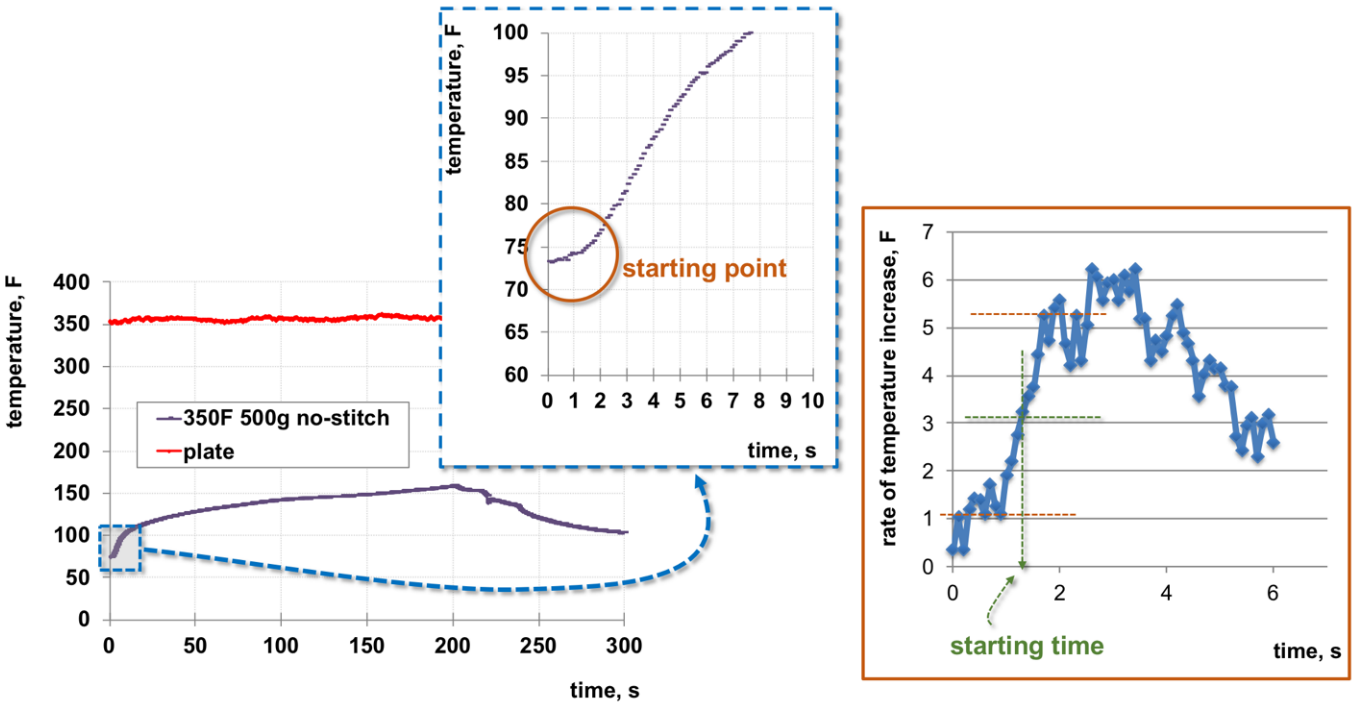

Fig. 6 Determining the starting point of the time to critical temperature. Close up of the starting point (left). Plot of rate of temperature increase with time shows the starting point as the midpoint of the time interval of the steepest increase (right).

4 Application of developed test method

4.1 Testing procedures and details

To test the performance of the developed apparatus and measure the rate of heat transfer through textiles used for oven mitts, such material was selected for testing. It was plain weave grey, medium weight 100% cotton shell with 100% cotton batting. Batting fabric was quilted with approximately 1" squares with both sides covered with very light weight non-woven polyester fabric, which held the batting in place. The square-shaped quilting pattern formed three types of stitching that could be up against the skin when a mitt made of this fabric was used: no stitch, one-stitch, and cross-stitch, as shown in Fig. 7. Samples with size 2 inch x 2 inch were cut for each of the three stitch types. These samples were arranged and mounted to the base with the fingers, as previously described. An example of the symmetry of the alignment of the stitches over the base is shown on the right side in Fig. 7.

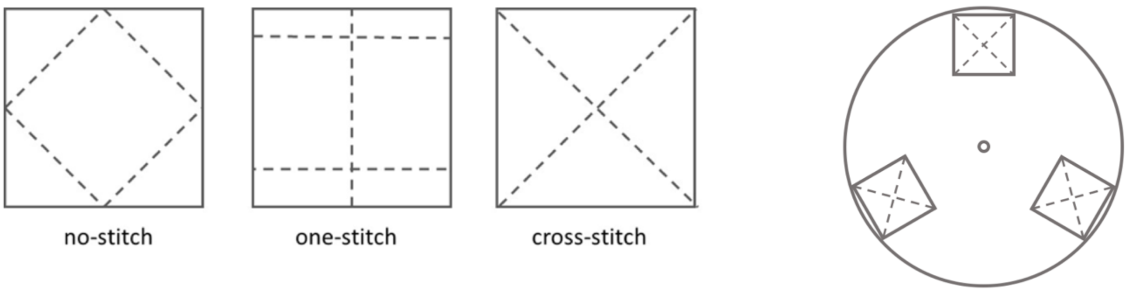

Fig. 7 Common quilting stitching patterns (left). Example of arrangement of test samples on the round base (right).

Testing was completed at 3 levels of "pan" contact temperatures, setting the hot plate at typical cooking temperatures of 250 °F, 350 °F, and 450 °F. To represent the pressure exerted by a reasonable range of common baked items, loads ranging from 0.5 to 5.0 kg were applied, approximating a full cookie sheet to a medium sized glass tray of a casserole dish. Heavier loads such as a whole thanksgiving turkey were not considered for this stage of the development. Tests were conducted at six levels of pressure – 0.5 kg, 1 kg, 2 kg, 3 kg, 4 kg, and 5 kg.

Upon contact with the hot plate, recording of "skin" temperatures at the "fingers" began at a sampling frequency of 10 Hz, using the DataQ data acquisition board [11]. Temperatures of the sensors on each "finger" and on the hot plate were monitored continuously. Contact temperature of 70 °C (160 °F) where injuries are instantaneous and irreversible [8] was used as the critical skin temperature where the test was to be stopped. If the critical temperature was not reached, the test was run for 5 minutes because (a) by this time the skin temperature was observed to have stabilized, and (b) by this time the hot pan would have been brought to and placed on a nearby surface. So, the test was run until (a) 300 seconds were up, (b) one of the "fingers" reached 160 °F, or (c) a sample started fuming or scorching.

The first step in data analysis was to find the starting point for each test, following the previously described procedure. Temperatures of the three "fingers" were averaged and plotted against time to visualize the process of heat transfer. To quantify and tabulate the process of heat transfer, times to reach critical skin threshold temperatures of 100 °F, 110 °F, 120 °F, 130 °F, 140 °F, 150 °F were extracted from the data for each test condition and plotted to reveal dependencies on weight, "pan" contact temperature, and quilting stitch type. These critical temperatures were also based on the findings of Moritz and Henriques [12] (as cited in ASTM C1055 [6], p. 5), who established that the lowest temperature at which damage to the epidermis occurs at long exposure (6 h) is 44 °C (111 °F) and that the first reaction felt as pain is at 47.5 °C-48.5 °C (117 °F-119 °F). While it is unlikely that injury will occur at 100 °F, tabulating the data over a wide range of temperatures provides clarity about the nature of the heat transfer process over time.

4.2 Results of heat transfer testing and discussion

4.2.1 Effect of pressure and contact temperature at no-stitch level

The effect of pressure and contact temperature on heat transfer is presented through time-to-threshold temperature charts for the no-stitch condition of the test material. Data are presented in two ways: Figure 8 shows the changes in the time to reach the threshold skin temperature levels of 100 °F, 110 °F, 120 °F, 130 °F, 140 °F, and 150 °F at contact temperature 250 °F, 350 °F, and 450 °F, respectively, showing all six weight conditions side by side. Figure 9 shows the changes in the time to reach threshold skin temperature levels of 100, 110, 120, 130, 140, and 150 °F at pressure levels of 0.5 kg, 1 kg, 2 kg, 3 kg, 4 kg, and 5 kg, respectively, showing the pressure conditions side by side. It is evident that the heavier the load and the hotter the hot plate surface, the faster the skin side of the sample reaches the threshold temperatures. This indicates a lower thermal protection by the material under these conditions.

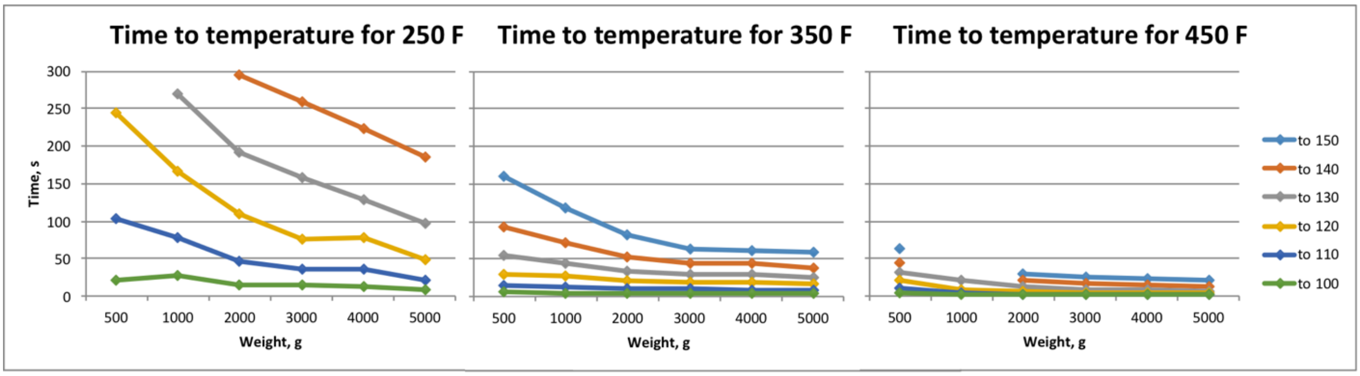

Fig. 8 Time-to-threshold skin temperature by weight and temperature conditions for no-stitch condition.

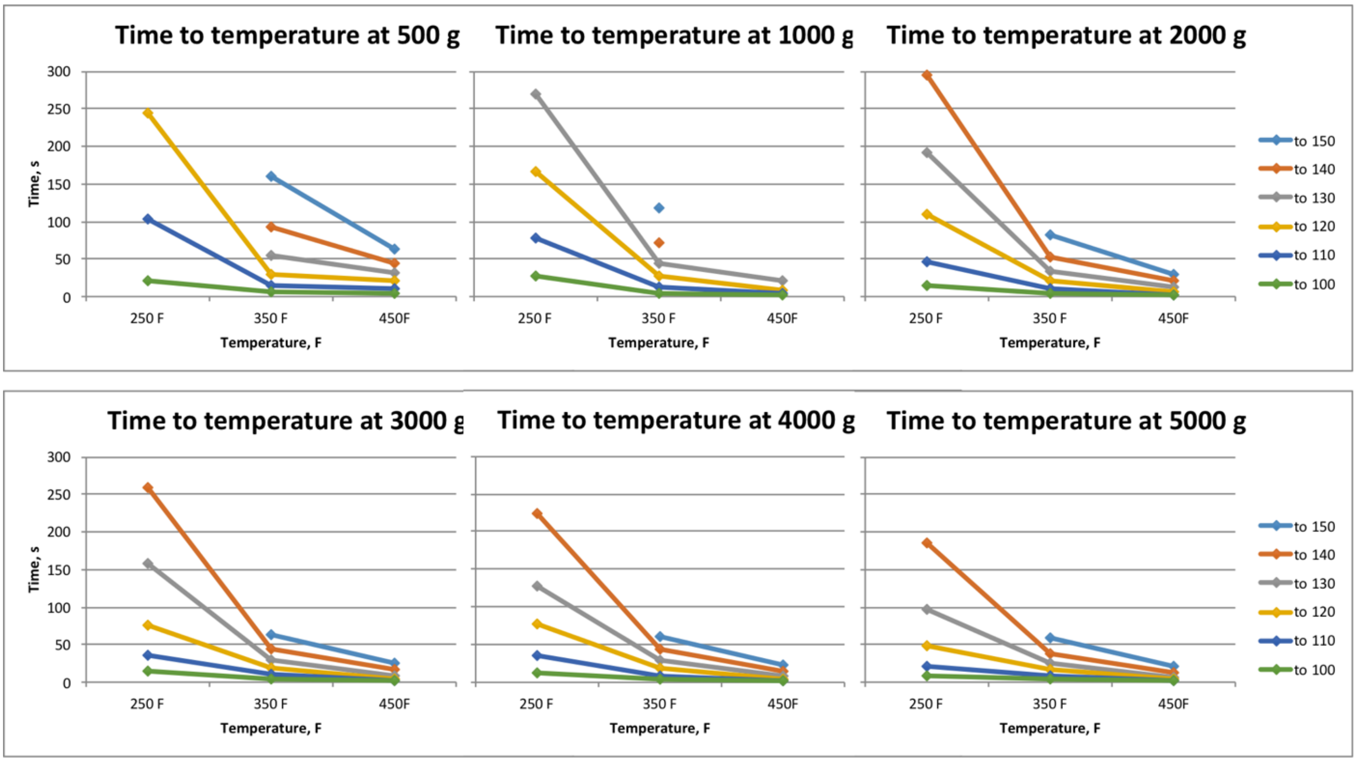

Fig. 9 Time-to-threshold skin temperatures by temperature and weight conditions for no-stitch condition.

The absence of some points on the graphs is due to the fact that the particular value of the threshold temperature was not reached within the test period at that specific combination of load and temperature, or, because the test was terminated to prevent burning of the sample. For example, at a 250 °F contact temperature and 500 g load, the “skin” temperature never reached 130 °F and beyond within the 300 s of testing time. At a 450 °F contact temperature, data are missing at 140 °F and 150 °F for 1000 g because the experiment was terminated at 30 seconds to prevent burning of the samples at contact side. For the lowest load of 500 g at 250 °F, the temperature on skin side reached 120 °F in 244 s but did not reach 130 °F within the 300 s test time (Fig. 9).

According to the ASTM C1055-20, the temperature at which the burn injuries become irreversible is 140 °F. At a contact temperature of 250 °F, a skin temperature of 140 °F was reached in 294 s at a 2000 g load, dropping to 185 s for the 5000 g load. At contact temperature of 350 °F, which is a typical oven temperature for baking cakes, cookies, some meats, casseroles, skin temperature of 140 °F was reached in 92 s at the 500 g load (the mass of a typical cookie sheet), dropping to 52.3 s for the 2000 g, and 38.7 s for the 5000 g load. At a contact temperature of 450 °F, which is typical oven temperature for roasting, a skin temperature of 140 °F was reached in 45.5 s at the 500 g load, dropping to 20.9 s for the 2000 g load, and 13.9 s for the 5000 g load.

Figure 8 also demonstrates that the higher the contact temperature the quicker the threshold skin temperature is reached, even at lower loads. For example, we see the threshold skin temperature of 140 °F level off at about 3000 g for the 350 °F contact temperature, taking 44 s, but it levels off at lower loads around 2000 g for the 450 °F contact temperature, taking only 20.9 s. That means that the heavier the pan and the higher the oven temperature, the faster the cook needs to let go of the pan to avoid possible injury.

As previously discussed, data on exposure times to heat (ASTM, 2020) provide information on the safe and dangerous zones for burn injuries. According to these data, it would take only about 4 seconds of exposure time at 140 °F (60 °C) to have a 2nd degree burn and about 8 seconds to get a 3rd degree burn. The textile layer of a protective mitt or potholder should be able to keep the temperature on the skin side of the mitt or potholder below the 2nd degree burn threshold for at least the time it takes to transport a pan from the oven to a table or nearby surface. Considering that the time to reach threshold temperatures also depends on the load, it is important to rate mitts and potholders for particular uses based on their material properties and design.

4.2.2 Effect of stitching and pressure at 350 °F

In this set of tests, samples were cut for each of nine conditions: three load conditions (1000, 3000, and 5000 g), and three stitch conditions (no-stitch, one-stitch and cross-stitch). This introduced additional variability due to variations in sample weight and thickness. Threshold temperatures were reached within the first 150 seconds. As expected, when the load increased, the time to reach the threshold temperature decreased (Fig. 10).

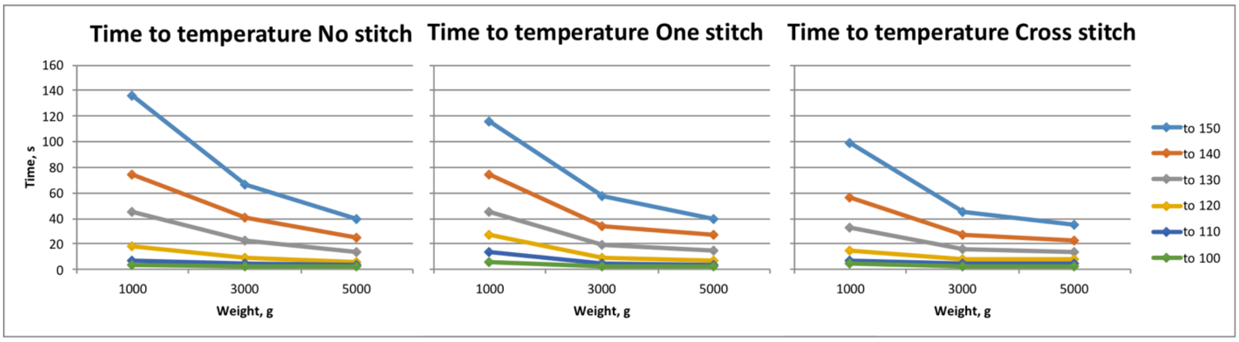

Fig. 10 Time-to-threshold skin temperature by weight and stitch conditions for 350 °F contact temperature.

The effect of stitching on heat transfer is shown in Fig. 11. The effect of pressure is as expected – the time-to-threshold decreases with increasing load. However, the effect of the amount of stitching is not always consistent. For example, we see the threshold skin temperature of 140 ˚F for no-stitch drops from 74.1 s to 40.6 s, and to 24.4 s for 1000 g, 3000 g, and 5000 g respectively. For one-stitch, the time decrease is from 74.3 s to 34.4 s and to 27 s, and for the cross-stitch, the time decrease is from 56.6 s, to 27.3 s, and to 23.1 s for 1000 g, 3000 g, and 5000 g, respectively.

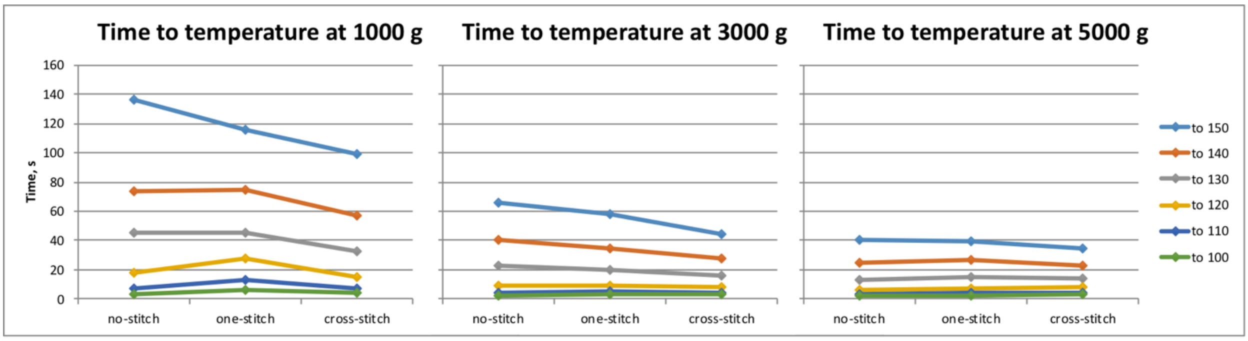

Fig. 11 Time-to-threshold skin temperature by stitch and weight conditions for 350 °F contact temperature.

It appears, however, that for the one-stitch condition, the time-to-threshold slightly increases compared to the no-stitch data. The effect is more prominent at the 1000 g load level than at the 3000 g and 5000 g loads. The effect also seems stronger at the lower thresholds of 100 °F, 110 °F, and 120 °F for the 1000 g load. While time-to-threshold was always shorter for the cross stitch than the other two cases (no-stitch and one-stitch), many one-stitch cases showed equal or longer time-to-threshold than the no-stitch samples in the same experiment. In the first graph, it is easy to see the bend in the line for 110 °F, 120 °F, 130 °F and 140 °F, where the one-stich condition diverges from the expected trend. We hypothesized that the cause of this behavior could be that the stitch of the sample aligns exactly with the thermocouple, allowing the stitching to form a line of indentation that prevents direct contact with the thermocouple and simultaneously creates a tiny micro-environment with an insulating air pocket (Fig. 12). It is likely that this amount of insulation might have delayed the time-to-threshold. Additionally, the channel formed along the stitch may have acted as a conduit for air flow, allowing heat to escape sideways rather than through the sample to its skin side.

The effect of load on the time-to-threshold skin temperature for one-stitch sample suggests that the load may be influencing the system in a way that eliminates the cause of the increased insulation. Consistent with the hypothesis offered above, the insulative air channel would become shorter as the sample flattens under higher pressure and the time to threshold would drop again. At the higher loads of 5000 g, the one-stitch sample is quite compressed, eliminating the effect of the long sideways channels and having similar time-to-threshold times as the no-stitch and cross-stitch samples.

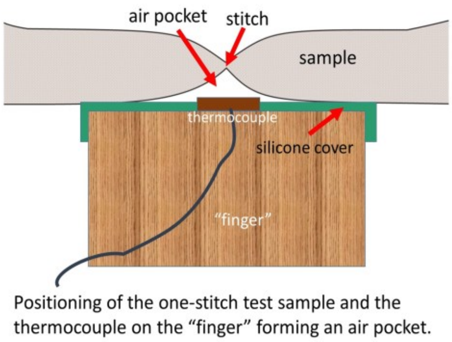

Fig. 12 Air channel forming under stitch.

The cross-stitch sample, while having two channels, did not have the improved insulation property seen in the one-stitch sample. The effect of stitching obviously requires more investigation, as it has the potential to affect insulation quite effectively.

5 Discussion of test development and application

The developed apparatus produced meaningful data, allowing the effects of contact temperature, weight (pressure exerted), and stitch type to be evaluated for materials used in oven mitts and potholders. The method enables comparisons among materials. The effects of stitch types need to be investigated further because stitching has direct implications for design. Our testing revealed that the temperature increases most rapidly within the first 30 seconds. Literature is clear that burn injuries happen within 5-6 seconds of exposure to heat, so it is crucial to examine the first minute of contact more carefully.

The test apparatus developed for this study worked well; however, the apparatus is delicate, and the procedure is labor intensive and time consuming. There is definitely room for improvement in terms of maintaining a uniform and steady temperature of the hot plate and controlling the pressure to include incremental increases of the load. Additionally, after each test, the “fingers” had to be cooled down to ambient temperature which was about 23 °C (73 °F). We used fans and directed the airflow towards the base to speed up the cooling. This process slowed down the testing considerably. To speed up the testing, a faster way to cool the equipment or an alternative method of assembling the apparatus could be used, such as using exchangeable modular sets of “fingers” (with or without a modular base). For example, one set could be used for testing while the other cools down.

The scorching phenomenon needs to be further investigated because, although it is not very frequent in real life, it does occasionally occur when the user accidentally makes contact with the heating source. Similar testing protocols followed by retail companies require the contact duration to be 300 seconds, which we adopted in our protocol. In reality, contact with the hot object (i.e. the hot pot or tray) is shorter than a minute, and the hot objects do not keep generating heat after removing them from the heat source but instead start to cool down immediately. In this regard, the developed test yields more conservative results.

6 Limitations of the study

A major limitation of the test developed in this study is that it tests the materials in dry conditions, which is highly unlikely in any kitchen. It is well-established that water is a far better conductor than air and will hasten heat transfer. Even a partially wet pot holder or oven mitt presents a more serious burn hazard than a dry one. Hence, mitt and pot holder evaluation testing should incorporate wetness.

The proposed apparatus maintains a constant temperature throughout the experiment, which does not reflect real life, as a pan or pot immediately starts cooling after being removed from the heat. However, this is not a significant drawback because the test provides a reliable way to control for temperature, making it more adequate for comparing materials. Trying to mimic a cooling pot or pan would introduce more variables, such as ambient temperature and humidity, thermal conductivity, of the material, shape, size, and mass of the pot or pan.

The study was limited only to one fabric at this stage because the objective of the study was to evaluate the developed method and apparatus. At this stage, physical characteristics of fabric and fabric systems, such as thickness, permeability, or wicking were not measured, nor was the amount of compression and recovery under different load conditions taken into account.

At this stage the test has not yet addressed the issue of the microclimate created by larger amount of fabric covering the hand, although some experiments are underway. An improved evaluation protocol could include the effect of microclimate inside the mitt, which would help with design improvements.

7 Conclusions and future work

Examination of the existing testing protocols suggests that a standardized protocol where temperature and pressure are controlled should be used in a test of heat transfer for materials used for oven mitts. As demonstrated in this study, pressure is essential to the rate of heat transfer and it is crucial that the effect of pressure is clearly described and taken into account in the design process.

Furthermore, while heat transfer is affected by the fiber content and structure of the materials, it is also affected by the design of the mitt/potholder through features such as shape and size, seams, quilting stitches and patterns. These aspects should be investigated. Additionally, user habits, practices, pot/pan grabbing/holding patterns, aesthetic perceptions, usage (oven vs. stove top vs. grill) should be studied to fully evaluate the product's function in situ and the expected performance.

The process of developing the testing apparatus and protocol unveiled many issues related to the equipment itself and its efficient use. Ideas on how to improve the efficiency and ease of use of the developed instrument were generated, giving good prospects for developing the next prototype, possibly with the ability to evaluate oven mitts as well as other hand coverings as a whole.

Thermal imaging of the mitts could prove valuable as it would help visualize heat transfer between a hot object, like a pan, and different points on the oven mitt and fingers inside the mitt. This could be instrumental in improving the testing apparatus by informing designers where sensors should be placed. Time lapse thermal images could provide even further insight into understanding the thermal exchange between the user and the hot equipment.

A major next step would be exploring the effect of water on heat transfer. Investigating the effect of water on heat transfer is of great importance, with possible impact both on design and regulation of mitt and potholder use.

Another valuable direction for future research would be to conduct user testing, as different individuals use oven mitts in various settings. User testing will provide good insight into when and how individuals use oven mitts and/or potholders and what implications that information might have for the design of such products and for suggestions for their safe use.

Author Contributions

A. Petrova: conceptualization, methodology, data collection, analysis, writing, visualization, project administration; S. Peksoz: conceptualization, methodology, data collection, analysis, writing, visualization, project administration; A. Jayadas: conceptualization, methodology, data collection, analysis, writing. All authors have read and agreed to the published version of the manuscript.

Acknowledgements

The project was partially funded by JVC LLC.

Conflicts of interest

The authors declare no conflict of interest.

References

1. United States Consumer Product Safety Commission. About CPSC.
2. World Health Organization. Burns, 2023.
3. American Burn Association. Burn Incidence and Treatment in the United States, 2023.
4. Islam, S. S.; Nambiar, A. M.; Doyle, E. J.; Velilla, A. M.; Biswas, R. S.; Ducatman, A. M. Epidemiology of Work-Related Burn Injuries: Experience of a State-Managed Worker's Compensation System. *J. Trauma Acute Care Surg.* **2000**, *49*(6), 1045-1051.
5. World Health Organization. *A WHO Plan for Burn Prevention and Care*. World Health Organization: Geneva, 2008.
6. ASTM. C1055-20 Standard Guide for Heated System Surface Conditions That Produce Contact Burn Injuries.
7. ASTM. F1060-18 Standard Test Method for Evaluation of Conductive and Compressive Heat Resistance (CCHR), 2018.

8. Stoll, A. M.; Chianta, J. R.; Piergallini, M. A. Thermal Conduction Effects in Human Skin. *Aviat. Space Environ. Med.* **1979**, *50*(8), 778-787.
9. National Fire Protection Association. NFPA 1971 Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting, 2006.
10. OMEGA. The “All-in-One” Surface Thermocouple Fiberglass-Insulated Thermocouple Wire Leads.
11. DATAQ Instruments, Inc. DI-2008 Thermocouple and Voltage Data Acquisition System, 2020.
12. Moritz, A. R.; Henriques, F. C. Studies in Thermal Injury II, The Relative Importance of Time and Surface Temperature in the Causation of Cutaneous Burns. *Am. J. Pathol*. **1947**, *23*(5), 695-720.