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INTEGRATING DESIGN METHODOLOGY, THERMAL SCIENCES, AND CUSTOMER NEEDS TO ADDRESS CHALLENGES IN THE HAIR CARE INDUSTRY

Jaesik Hahn[1], **Tikyna Dandridge**[1], **Priya Seshadri**[1], **Amy Marconnet**[2], **Tahira Reid**[1]*
[1]Research in Engineering and Interdisciplinary Design (REID) Lab
[2] Marconnet Thermal and Energy Conversion (MTEC) Laboratory
School of Mechanical Engineering
Purdue University
West Lafayette, IN 47907

ABSTRACT

Although the hair care industry is a multi-billion dollar industry, there still remains a dearth in the available technologies and research methods to answer one simple question: What temperature and frequency of use will lead to permanent structural damage (i.e. heat damage) to curly hair? Currently, trained professionals in the hair industry cannot predict when heat damage will occur and often rely on heuristics and intuition in their hair care approaches. In addition, scientists that have conducted studies with heat and hair have often used European hair types, which cannot be generalized to all ethnic groups; they have also conducted experiments that are not ecologically consistent with individuals' use context. As a result, a number of lay scientists have emerged whose use contexts are ecologically valid, but are lacking the experimental and quantitative rigor that engineers can provide. In this work, we discuss an interdisciplinary approach to integrating customer needs, design methodology, and thermal sciences for application to the hair care industry. We discuss the formulation of a predictive model, the design of an experimental test-bed for collecting data, and present initial results.

1 INTRODUCTION

It is well understood that hair has religious, cultural, and personal meaning to individuals [1] and promotes positive feelings after professional services [2]. Hair is important to customers. From 2012-2014, customers spent more than $3.2 billion annually on hair care and color related purchases alone [3]. However, when it comes to ethnic hair care and cosmetics $9.5 billion was spent in 2009 alone [4]. Many women have opted to avoid the use of professional services, thus a do-it-yourself (DIY) movement that has emerged among women [5], similar to the Maker Movement.

The DIY movement has emerged in response to a number of issues surrounding personal hair care. Women conduct at-home experiments to identify methods for doing a variety of hair care services. Among the most frequent concerns of this group are those related to the topic of heat damage. Approximately 154,000 videos and channels can be found on YouTube related to the topic of "heat damage on natural hair". Much of the discourse is on ways to completely avoid the use of thermal appliances and/or the best methods for using them while attempting to minimize the damage they cause. One of the limitations is that the results are not generalizable and lack scientific and quantitative rigor. Each video is subject to the viewers' ability to first infer that they have the same hair characteristics as the person on the video, and be able to interpret and replicate the processes themselves. This leads to a cycle of trial-and-error which can

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*Address all correspondence to this author - tahira@purdue.edu.

cause irreparable mistakes and excessive spending on products.

Motivated by the concept of compassionate design by Seshadri et al. [6], we present research to empirically study the effects of heat on hair through the integration of design methodology, customer needs analysis, and thermal sciences. Section 2 presents background information. Sections 3 provides basics of hair along with literature reviews. Section 4 and 5 discuss the preliminary formulation of a predictive model, the design of the test-bed and the experimental procedures used. Sections 6 and 7 discuss initial results, discussion and conclusions.

2 Background

Understanding customer needs is an important part of the solutions engineers generate to address numerous problems [7, 8]. Customer needs have often been assessed through interviews, focus groups, and design ethnography [7, 9] as means of gathering direct information from individuals. Empathic design methods have been used to help engineers identify latent needs of customers [10], and compassionate design helps to sensitize engineers to users' needs [6]. More recently, customer needs have been assessed through the analysis of on-line customer reviews [11, 12]. In this work, we conduct a virtual ethnography [13] to understand customers and their needs through YouTube videos. We specifically focus on women's hair care practices related to the use of thermal appliances, in light of the challenges many have expressed concerning heat damage.

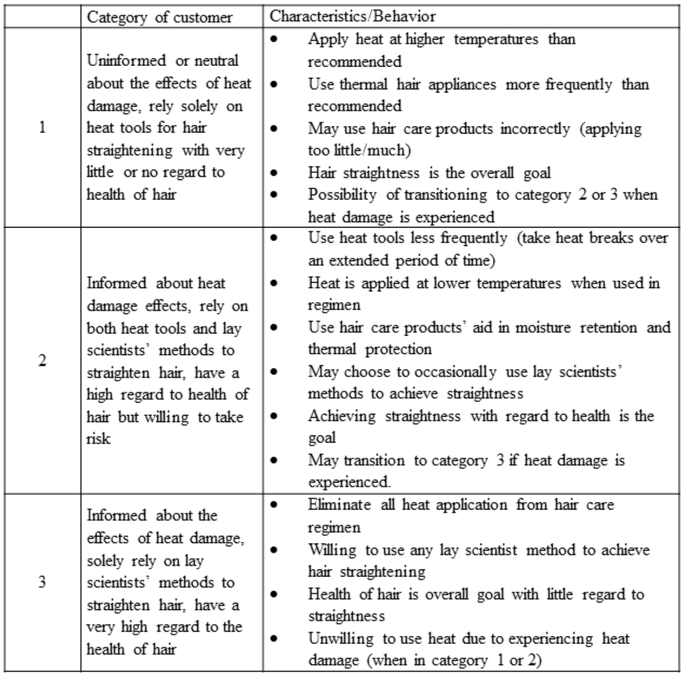
2.1 Profile of Customers

When searching YouTube for the types of customers who use heat to straighten hair, three categories of customers were identified: 1) uninformed, 2) informed but willing to take a risk, and 3) informed and unwilling to take a risk (See Figure 1).

Customer Profile 1 - This customer is one of two things: (1) uninformed about the effects associated with the use of thermal appliances and (2) informed and neutral to the effects associated with heat damage. This customer solely relies on thermal tools to straighten hair, and uses heat more frequently than recommended. If this customer applies thermal protectant, it is often applied incorrectly (the use of too little/much). The main goal this customer wants to achieve is straightness with no regard to the health of hair. It was also noticed that customers in this category can transition into the next categories if they were uninformed and became knowledgeable due to experiencing heat damage.

Customer Profile 2 - This customer is informed about the effects associated with heat damage, and takes precautions to reduce the probability of experiencing heat damage. This customer uses thermal appliances at lower temperatures and less frequently than the previously mentioned customer. In order to protect the health of hair, this customer will sometimes eliminate heat for an extended period of time and use lay scientists' methods to achieve straightness. Although this customer's main goal is to achieve straightened hair, health is a factor. It is noted that if a customer experiences heat damage while in this category, there is a possibility that they will eventually migrate to the interests of Customer Profile 3.

Customer Profile 3 - Due to experiencing heat damage, this customer has chosen to forgo all heat application to eliminate the risk of heat damage. This customer solely relies on lay scientists' methods to achieve straightened hair, with health of hair being her main goal.



	Category of customer	Characteristics/Behavior
1	Uninformed or neutral about the effects of heat damage, rely solely on heat tools for hair straightening with very little or no regard to health of hair	• Apply heat at higher temperatures than recommended • Use thermal hair appliances more frequently than recommended • May use hair care products incorrectly (applying too little/much) • Hair straightness is the overall goal • Possibility of transitioning to category 2 or 3 when heat damage is experienced
2	Informed about heat damage effects, rely on both heat tools and lay scientists' methods to straighten hair, have a high regard to health of hair but willing to take risk	• Use heat tools less frequently (take heat breaks over an extended period of time) • Heat is applied at lower temperatures when used in regimen • Use hair care products' aid in moisture retention and thermal protection • May choose to occasionally use lay scientists' methods to achieve straightness • Achieving straightness with regard to health is the goal • May transition to category 3 if heat damage is experienced.
3	Informed about the effects of heat damage, solely rely on lay scientists' methods to straighten hair, have a very high regard to the health of hair	• Eliminate all heat application from hair care regimen • Willing to use any lay scientist method to achieve hair straightening • Health of hair is overall goal with little regard to straightness • Unwilling to use heat due to experiencing heat damage (when in category 1 or 2)

FIGURE 1. Three categories of customers and their hair care behaviours

Customers from Category 2 and 3 have been among the primary creators of methods for addressing the problems they face in the use of thermal appliances. The next section describes some of the methods they use in an attempt to solve their own problems.

2.2 Methods used by Customers to Straighten Hair without Heat

Achieving straightened hair without the use of thermal hair appliances has become prevalent in women who fit Category 2 and 3, due to the inability to predict when heat damage will occur. Lay scientists (i.e. people who are not formally trained) have developed methods that allow hair to be straightened without compromising the integrity and health of hair. The three most common methods identified were threading, banding, and wrapping methods [14–16]. The threading method is a styling technique that was adopted from the traditional African Threading methods used in Africa. With the use of thread, hair is straightened by wrapping thread along the shaft of hair from root to tip. The banding method is similar to threading, but instead of wrapping thread along the hair's shaft, small elastic bands are used. The wrapping method [17] has been used by professionals for years; however, the natural hair community has adopted and claimed this method by eliminating heat from the traditional process. This method involves wrapping all hair in one direction around the head and securing with bobby pins or hair clips. All of these methods are performed on damp hair, which means that hair has to set and be allotted an extensive amount of time to dry. The straightened styles that are achieved by these methods do not provide the same smooth and sleek appearance as those that are done with the use of thermal heat appliances. Even though these methods require an immense amount of effort and time and do not yield the same results, it is evident from the substantial amount of information provided about these techniques that there is a great desire to achieve straightened hair in the natural hair community.

A limitation of these approaches is the lack of generalizability of the results. As such, research conducted by scientists may provide more insight into this problem. The next sections discusses basics about hair and how scientists explore the effects of heat on hair.

3 Basics about Hair

A human hair fiber can be dissected into three major parts [18, 19]. The exterior shell of the hair called the cuticle is composed of transparent and overlapping, scale-like cells. This shell protects the inner parts from weathering and mechanical damage. Inside this outer layer is the cortex, the structure that accounts for most of the hair fiber's weight, volume and mechanical strength. Finally, the inner most cavity which can be continuous, discontinuous or even absent, is called the medulla. It is known to have little to no contribution to hair structure or function.

The origin of human hair curvature has long been attributed to peculiar cross-sectional shapes among hair of different races [20, 21]. For instance, the cross-sectional shape of straight hair would appear more circular, and as the degree of curvature increases, the cross-section would become more elliptical. However, it was later proposed that the curvature of human hair originates from different shapes of hair follicles, which tend to be relatively symmetrical in Asian and Caucasian population who have straighter hair but asymmetrical in African population with much curlier hair [20–22]. A more thorough review on these theories can be found in [18, 19, 23–26].

Different hair types have often been associated with specific geo-racial groups. However, more recently, various hair typing methods based on the geometry of hair were suggested as alternatives. The method introduced in this paper is Segmentation Tree Analysis Method (STAM) [27]. It was applied to more than 2,400 subjects and Robinson confirmed in his book its robustness for classifying hair types [28]. As of now, the validity of this method only lies in the classification based on geometrical features of hair such as hair diameter, cross-sectional area, and ellipticity.

STAM can classify hair into eight types from Type I to VIII based on its degree of curvature. The hair types are as follows: Type I is straight to slightly wavy hair; Type II is hair with loose waves; Type III is wavy hair; Type IV is curly hair; Type V is very curly hair; Type VI is coily hair; Type VII is tight coils; and Type VIII is zig-zag coils. The typing method requires three measurements: curl diameter, number of crimps (i.e. number of crests on a hair fiber within a certain distance), and the ratio between natural and extended hair length. Using these measurements and given criteria, people can easily figure out which curl type their hair belongs to. Type IV to Type VIII hair has lower tensile properties than other hair types [18, 28–30]. These hair types break prematurely due to high variability in their cross-sectional shapes that yield weak points. Part of its fragility seems to come also from its proneness to be dry. Studies also reported anomalies caused by the use of heat appliances in the population of these hair types [31–35].

3.1 Thermal Characterization of Hair

Studies on the effect of heat on hair have consisted of applying a heat source to single fibers of hair or clusters of fibers. In these studies, the principal metrics that were identified include: changes in tensile properties, amount of protein decomposition, and damage to cuticular layer. Rebenfeld et al. observed that increasing heat reduces tensile properties of hair [36]. Monteiro et al. utilized thermal analysis as a means to observe the change in keratin structure when applied with bleaching and chlorinating agents [37]. Humphries et al. investigated the potential of commercially available thermomechanical analysis for detecting the damage and chemical changes to hair by various treatments [38]. Milczarek et al. closely examined the thermal transition of hair keratin at different stages and its relation to the water content of hair [39]. Cao studied the melting behavior of keratin microstructures in human hair [40]. Harper et al. investigated the efficacy of heat styling with a curling iron by measuring the magnitude of shape retention and the duration for which curl formation lasts [41]. Results yielded that after 100°C, efficacy becomes insignificant, and adverse effects to curling efficacy takes place at temperatures over 200°C. The work proposed by Dussaud et al. was the only experimental research that explores the gradual loss of natural curl pattern on human hair [42]. The authors suggested a technique called "progressive straightening", in which permanent hair straightening occurs as a result of repeated heat treatments. It concludes that the use of silicone heat protectant does not possess an alleviating effect against heat treatment. Other studies examined the effects of heat on the surface properties of the hair [43], discussed various adverse effects [44,45], and the benefits of heat protectants [46–48], though not in all cases were the benefits apparent [49].

Across all these examples, the hairs tested consisted primarily of straight or wavy hair (Type I and II); they do not include hair types characteristic of very curly hair types (Type IV-VIII). In one case, curly hair was studied, but it depicts the loss of curl as a favorable phenomenon, proposing it as an alternative method of permanent hair straightening except for the damage introduced to hair that makes it more fragile [42]. Furthermore, the same study used the curly hair only for general characterization of hair properties and disregarded how the gradual loss of curl with repeated heat treatments was measured. Certainly, the needs of customers, particularly Category 3 customers, are far alienated from the context of academic research.

3.2 Flat Iron Manufacturers

We reviewed manuals for ten different flat iron products to collect the information that is provided to customers in regard to temperature recommendations for different hair types. Low to high priced flat iron manuals were selected in order to examine if the information provided was equal across all models. Manufacturers of high priced flat irons were found to provide greater detail in both temperature recommendation and instruction for use. Although methods to prevent heat damage are not explicitly described in the manual, thermal hair care products are recommended in the instructions. One manufacturer also informed customers why dry hair was important before applying high temperatures. When reviewing medium priced flat irons, temperature recommendations varied among hair types. Some manufacturers informed customers that clean hair and thermal protection were vital for "best results". However, there is no warning against heat damage. When reviewing low priced flat irons, manufacturers were ambiguous. Although heat settings were recommended, specific temperatures were absent. Hair typing for low end products was also vague, which could make it hard for a customer to identify their hair type. Low priced flat irons also had limited detail on instructions, if any information was provided at all. This is an issue for customers who are unable to purchase medium to high priced products. This essentially means that those who cannot afford high end flat irons, are more inclined to experience heat damage due to the lack of information provided by manufacturers of low priced flat irons. All manufacturers provided the same information based on Underwriters Laboratories (UL) standards. Figure 2 provides a summary.

3.3 Summary of Problem and Goals

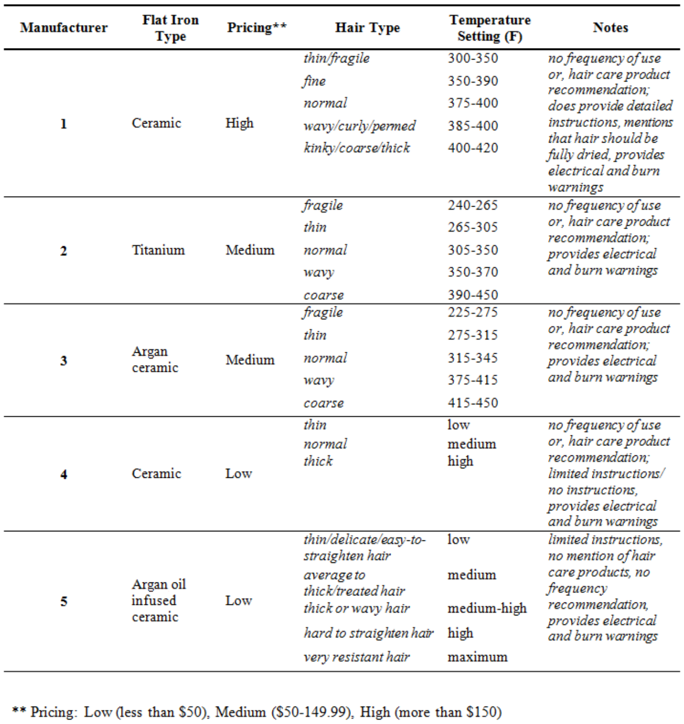
The existing research that examines the effects of heat on hair is based on a limited variety of hair types, and thus overlooks the needs of Category 2 and 3 customers. Secondly, there is no conventional experimental tool that can simulate, and provide a standard measurement for heat damage to hair, which has been acknowledged in other work [50]. Finally, there is a lack of effort to establish a mathematical correlation between heat and hair, and in a way that lay audiences can understand. Current studies focus more on observation and comprehension of underlying mechanism with which heat acts upon to degrade hair. Even though such investigations are valuable and contribute to the body of knowledge, it lacks relevance to the public domain. An engineering perspective on mathematical correlation between heat and hair can help yield more practical and customer-relevant knowledge in the field.

Category 3 customers are avoiding the use of heat altogether because they cannot predict when heat damage will occur. The number of factors to consider in prevention, and the cost of trial-and-error (e.g. hair loss, damage) leaves this group with no choice but to avoid their use altogether. In addition, manufacturers of flat irons are not always clear in the instructions for using their products, and the level of detail varies according to price. Across all product categories, the risk of heat damage is not mentioned in any of them.

Figure 3 shows a flow diagram of a generalized approach to a design problem demonstrated by this work. The unmet needs of customers expressed verbally and behaviorally are identified through observation and interviews. Then, the identified problem is translated into engineering concepts. Once the problem is redefined in engineering terms, reviews of related literature and the current state of the art will be followed to see where the gap is. A system and experiment to address the gap are designed and performed to come up with a viable solution. Finally, the solution will be offered to the customers to address their needs. This could be an iterative process to keep improving on the solution. Furthermore, observing the unmet needs of customers can help the topics of academic research stay more intimate with the contexts of people's lives.

4 Predictive Modeling

As previously mentioned, one of the challenges with the use of thermal appliances on hair is the inability of customers, and even some trained professionals to predict when the onset heat damage will occur. After extensive research on the relevant research, an initial set of parameters was identified based on the literature. The parameters are hair diameter, cross-sectional area, ellipticity, curl type, water content, fibrous protein (FP) to matrix substance (MS) ratio, and composition of cortical cells. In addition to hair related parameters, heat related parameters such as temperature setting of heat appliance, and duration and fre-



Manufacturer	Flat Iron Type	Pricing**	Hair Type	Temperature Setting (F)	Notes
1	Ceramic	High	*thin/fragile*	300-350	*no frequency of use or, hair care product recommendation; does provide detailed instructions, mentions that hair should be fully dried, provides electrical and burn warnings*
			fine	350-390	
			normal	375-400	
			wavy/curly/permed	385-400	
			kinky/coarse/thick	400-420	
2	Titanium	Medium	*fragile*	240-265	*no frequency of use or, hair care product recommendation; provides electrical and burn warnings*
			thin	265-305	
			normal	305-350	
			wavy	350-370	
			coarse	390-450	
3	Argan ceramic	Medium	*fragile*	225-275	*no frequency of use or, hair care product recommendation; provides electrical and burn warnings*
			thin	275-315	
			normal	315-345	
			wavy	375-415	
			coarse	415-450	
4	Ceramic	Low	*thin*	low	*no frequency of use or, hair care product recommendation; limited instructions/ no instructions, provides electrical and burn warnings*
			normal	medium	
			thick	high	
5	Argan oil infused ceramic	Low	*thin/delicate/easy-to-straighten hair*	low	*limited instructions, no mention of hair care products, no frequency recommendation, provides electrical and burn warnings*
			average to thick/treated hair	medium	
			thick or wavy hair	medium-high	
			hard to straighten hair	high	
			very resistant hair	maximum	

** Pricing: Low (less than $50), Medium ($50-149.99), High (more than $150)

FIGURE 2. Summary of the variation in the descriptions provided by different flat iron manufacturers

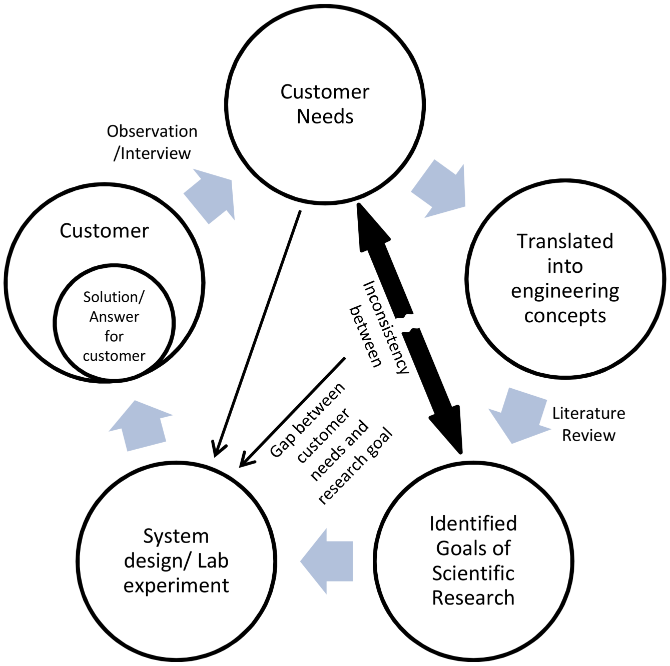


FIGURE 3. Flow diagram of addressing the gap in the ecological consistency between scientific research and customer needs

quency of heat application should be considered as well. Of primary interest would be the characteristics of the curly hair (Type IV-VIII) because both the loss of curl and hair integrity are most conspicuous among this hair. Figure 4 provides a function block diagram indicating the inputs and outputs that are important to consider. Inputs considered are clamping force (F), temperature setting (T), use time (t), etc. Outputs will be either visually assessable indicators such as curl loss and damage to cuticle, or other forms of metrics such as a degree of protein decomposition, change in tensile properties, etc.

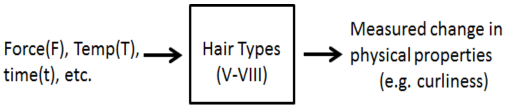


FIGURE 4. Function Flow Block Diagram of the relevant inputs and and outputs that must be considered in the model

This is represented as a function, where the change in the curliness is a function of properties of the hair, and other factors as indicated in Equation 1:

$$\Delta c = f(k, \Delta T, d, t, e, \rho, \sigma) \tag{1}$$

where:

Δc = change in curliness
k = thermal conductivity
ΔT = temperature difference between the environment and heat appliance
d = diameter of hair strand
t = use time
e = ellipticity
ρ = hair density
σ = stress

Creating a database of published results and experimental results from heat transfer experiments will aid in the completion of the model.

5 Heat Transfer Experiments

Heat Transfer experiments were conducted in the Marconnet Thermal Energy Conversion (MTEC) Laboratory at Purdue University. We first describe the design of the fixture used to conduct the studies and then the overall experimental procedure.

5.1 Design of Hair Fixture Apparatus

An automated flat ironing mechanism was fabricated to keep the environmental factors constant and minimize the noise from controlled parameters. Fabrication of the automated experimental tool is a clear distinction and improvement from the other relevant studies that employed manual and often static application of heat [41, 43, 46–49]. The automated mechanism is composed of three parts: the hair fixture, linear stage, and clamp mechanism. The hair fixture is a mount where a hair sample is clamped and stretched for heat application by a flat iron. The temperature distribution on the sample is observed with a high resolution infrared microscope (InfraScope, Quantum Focus Instruments Corporation). The linear stage serves as a means to transport the hair in the hair fixture laterally to simulate the back-and-forth movement of the flat iron in real life usage. Finally, a spring-loaded clamp mechanism securely holds the flat iron and includes a stepper motor used to open and close the flat iron. A GVP Black Ceramic Flat Iron with ceramic plate width of 1" was divided in half at the pin joint for use in the experiment. An Arduino Uno microcontroller and accompanying Integrated Development Environment (IDE) were used to develop a program that controls the speed at which the flat iron glides on the hair sample as well as the rate at which it opens and closes.

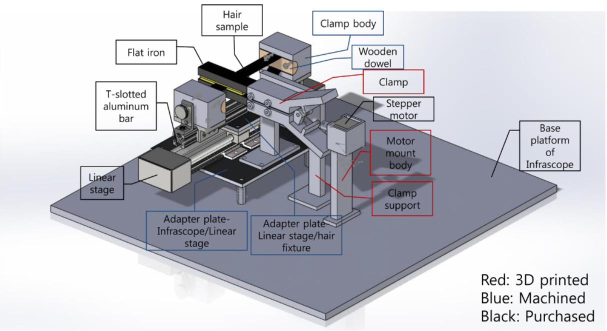


FIGURE 5. Schematics of automated flat ironing mechanism.

5.2 Methods and Materials

The InfraScope high resolution (1.7 to 11.7 μm/pixel depending on the lens configuration and 0.1 K temperature resolution) infrared microscope, manufactured by QFI Corporation, was used for measuring and recording the temperature distribution on the hair sample in real time. The area of view is 1.75 mm^2 at the highest resolution (20x magnification) and 25.7 mm^2 at the lowest resolution (1x magnification).

Prior to characterizing the hair samples, the flat iron itself was characterized. According to the specification provided by the vendor, the temperature ranges from 180°F to 420°F (82.2°C to 215.6°C). However, characterization of the flat iron revealed that the actual temperature range is approximately from 66°C to 178°C. Furthermore, since the temperature was maintained via embedded feedback control, the power turned off and on frequently, which led to fluctuation of temperature on the ceramic plates. The range of fluctuation observed by the InfraScope was between approximately 66°C and 82°C, when it was set for 180°F; it was 165°C and 178°C, when it was set for 420°F.

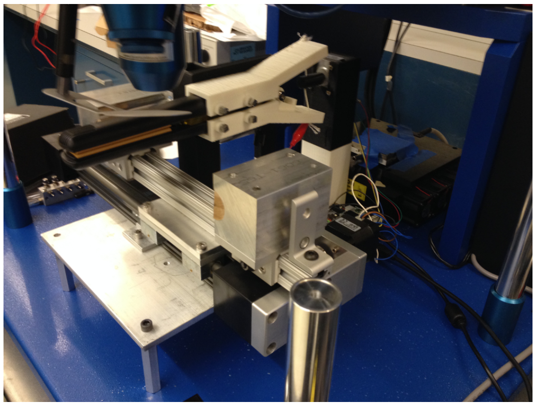


FIGURE 6. Picture of a prototype of automated flat ironing device.

Hair samples from three representative hair types were used: Type I, Type II, and Type V. Each hair sample was collected in the form of a donation. All hair samples were unprocessed, natural hair and kept in an ambient conditions before being used for the experiment. Unprocessed hair was used since previous history with any chemical treatments would have greatly reduced the integrity of hair. Furthermore, if the degree of chemical damage between each hair differs, the inherent difference in reaction to heat application will not be fully captured by the experiment. All hair samples were kept in the same ambient conditions for several days because hair requires at least more than 24 hours to equilibrate under the same relative humidity . In reality, the water content is going to be different for each hair but the intention was to maintain the environmental factor constant rather than setting the water contents the same across hair samples. Each sample was prepared in ten strands of hair except for Type V hair, which was prepared in nine strands. Also, Type V hair samples of loosely packed and densely packed bundles were prepared. Only one set of each sample was prepared and there was no repeated measurement.

The hair sample was mounted on the fixture and stretched straight just enough to prevent it from sagging and to keep the sample in focus. It was also intended to approximate the realistic usage of a flat iron where hair is either pulled by the iron or stretched by a manual force as heat is applied. Two temperature settings were used: low (180°F) and high (420°F). For this work, we focused on comparison of the behavior of heat dissipation between hair samples of different types. Future work will focus on the automated features of the flat ironing mechanism. Thus, heat from the flat iron was applied statically at one location of the hair sample while observing the heat dissipation through the bundle of hairs. The left boundary of the heat map was aligned with the right edge of the flat iron in all figures. The flat iron was in contact with the hair sample during the entire measurement. The temperature distribution on the hair sample was recorded in 100-frame movies with a 10 Hz frame rate.

The experiments were divided into two sets. In the first set, the temperature distribution on a single fiber was closely examined. Multiple individual strands are visible in the images (Figure 7, 8 and 10) in order to observe variations in the heat dissipation between individual fibers. Assuming each fiber is a long fin (extended surface for heat transfer), the temperature is expected to decay exponentially with distance from the heat source. In the second set of experiments, hair bundles of low and high densities were compared to observe the effect of hair bundle density on heat dissipation. This would provide more information that would guide decision of strictly controlling the density of hair bundle in prospective investigations.

6 Results and Discussion

Figure 7 and 8 show results of the first set of experiments. Screen captures of hair samples under low and high temperature settings were taken. Since hair samples were at steady-state and temperature distribution across the hair fiber was kept reasonably constant, one of the 100 frames with highest overall temperature distribution is presented here. To more closely examine how heat dissipates through hair fibers of different types, the temperature profile on one of the fibers in each hair sample was plotted (see Figure 9). As expected, each hair strand acted as a fin and displayed an exponentially decaying temperature profile. To help facilitate the differentiation between each hair fiber's performance on heat dissipation, the thermal conductivity of each fiber was calculated using an infinite fin approximation. The equation for an infinite fin is:

$$\Theta(x) = e^{-mx} \tag{2}$$

where:

$m = \sqrt{\frac{hP}{kA_c}}$

and

$\Theta(x) = \frac{T(x)-T_\infty}{T_b-T_\infty}$

h = convection coefficient
P = perimeter
k = thermal conductivity
A_c = cross-sectional area
T_∞ = ambient temperature
T_b = temperature at base

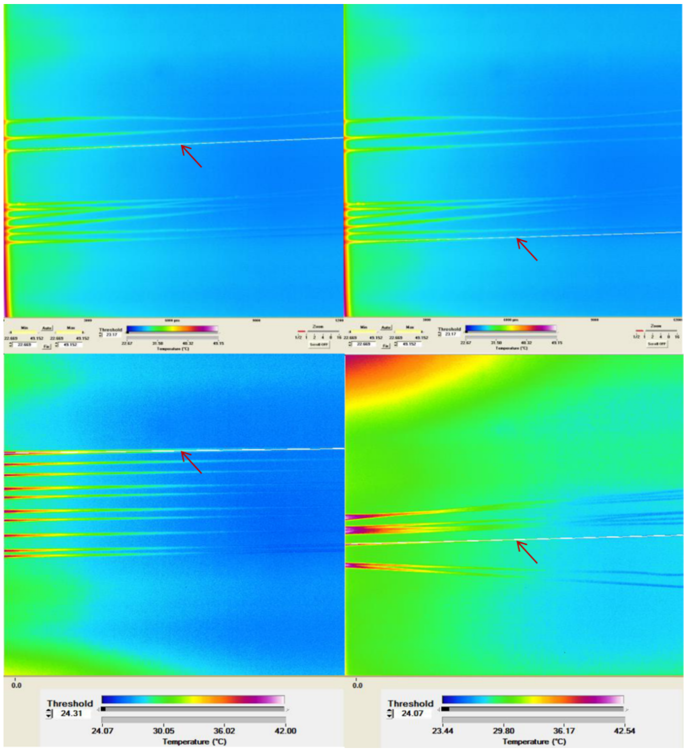


FIGURE 7. Temperature distribution on two hair samples of Type V (top two), Type I (bottom left), and Type II (bottom right) hair at low temperature setting (180°F). The white line (also indicated by red arrow) indicates which fiber was selected to generate the temperature profile.

Since some necessary parameters could not be measured, reasonable assumptions were made. Convection coefficient was considered to be constant across all fibers. For Type I and II hair, average cross-sectional areas for Asian and Caucasian hair were used (5,333 μm^2 and 3,902 μm^2 respectively) [28]. For Type V hair, a regression equation between cross-sectional area and hair type was used (3,337 μm^2) [51]. By assuming circular cross-sectional shape for all fibers, the perimeter was calculated using cross-sectional area. Value for m was found by exponential fit using MATLAB. Then, the ratio between thermal conductivity of each fiber at each temperature setting was calculated using Type V fiber 1 as a reference to capture the variation between hair

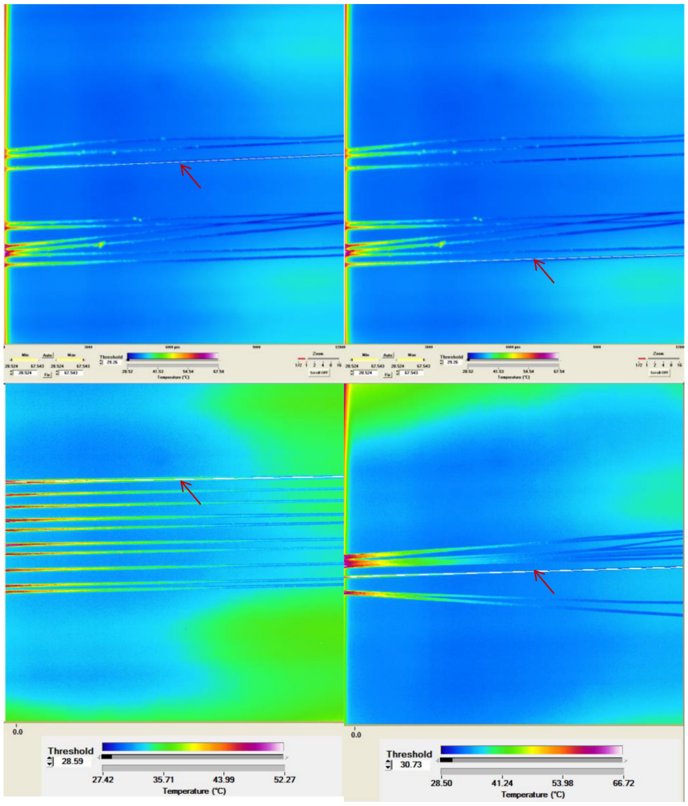


FIGURE 8. Temperature distribution on hair samples of Type V (top two), Type I (bottom left), and Type II (bottom right) hair at low temperature setting (420°F). The white line (also indicated by red arrow) indicates which fiber was selected to generate the temperature profile.

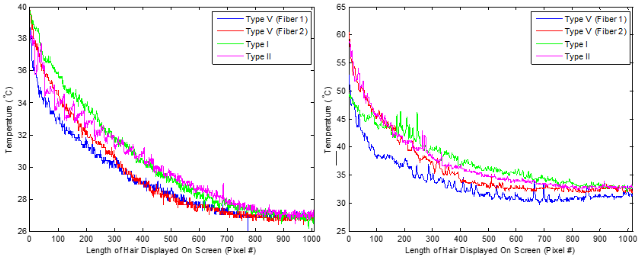


FIGURE 9. Temperature profiles across fibers of different hair types at low (180°F, left) and high temperature settings (420°F, right).

types and between temperatures at the same time. The results are shown in Table 1.

TABLE 1. Ratio of thermal conductivity between different curl types at low and high temperature settings

Temperature setting	Type V fiber 1	Type V fiber 2	Type I	Type II
Low	1	0.8091	1.0623	1.6281
High	0.2988	0.5438	1.4036	0.6509

Looking at Figure 9 alone, it seems as if all the fibers behave similarly when temperature is at low setting. However, according to calculation, Type II hair seems to exhibit the highest thermal conductivity of all at low temperature. When temperature setting is at high, Type I hair dissipated heat better than both Type V and Type II hair. It appears that hair of different types reacts in different ways to the same heat setting. But large fiber to fiber difference was displayed between two Type V fibers. Therefore, variation between fibers of the same hair type should be considered. Table 1 also shows that thermal conductivities of Type II and V decreased when the temperature increased. On the contrary, thermal conductivity of Type I increased with increase in temperature. Also, the amount of reduction in Type V fiber 1 is much larger than Type V fiber 2.

Overall, it seems that there is a lot of variation between different hair types, between different fibers of the same hair type, and between temperature settings, all showing some inconsistencies. To characterize the overall hair behavior associated with heat, a large number of hair samples from numerous types would be required to conduct a more statistically reliable study.

Figure 10 and Figure 11 show the comparison between temperature profiles on loosely packed and densely packed Type V hair bundles. Looking at Figure 10 alone, it seems that the overall temperature level is higher on the densely packed hair. However, it is due to how the software automatically assigns colors for temperature gradient based on the range of temperature observed within a frame. In fact, the red on the left image is hotter than the one on the right image. The difference in the overall temperature level is better shown in Figure 11. The blue line (temperature profile of the loosely packed bundle) clearly sits above the red line (temperature profile of the densely packed bundle). The result is counterintuitive because it was anticipated that the loosely packed bundle would exhibit better heat dissipation due to a larger surface area exposed to the environment. Since an individual hair fiber displays better heat dissipation than the loosely packed bundle, the performance is definitely not only dependent on the number of fibers subject to heat treatment nor the amount of surface area exposed to the environment, but also on how closely the fibers are packed. The density of packing seems to strongly influence heat dissipation. Therefore, for future work, the packing density of hair fibers will have to be carefully controlled to minimize the possible bias.

7 Conclusions

In this work, we present some early stage work for addressing customer needs, particularly those that fit Customer Profile 3.

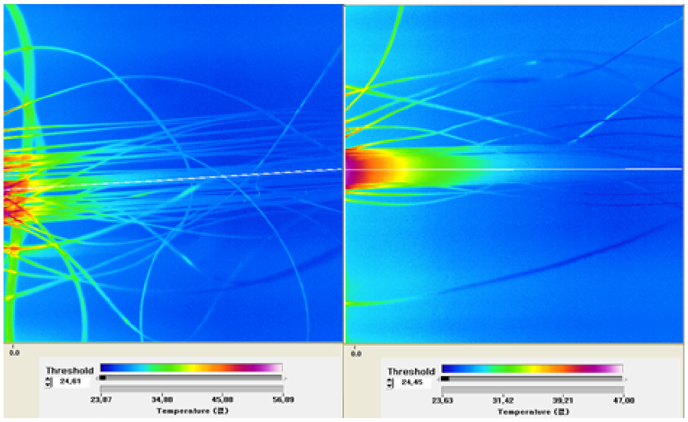


FIGURE 10. Temperature profiles of a loosely packed bundle (left) and a densely packed bundle (right).

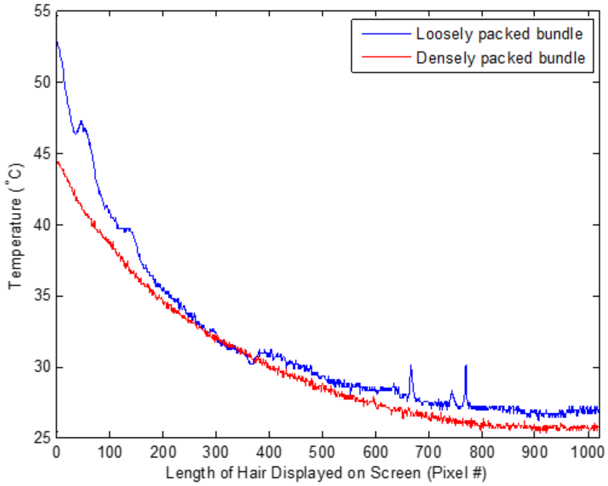


FIGURE 11. Comparison between temperature profiles along the fibers of a loosely packed bundle and densely packed bundle.

We use an interdisciplinary approach for understanding customer needs and integrating design methodology and thermal sciences to explore solutions. Both predictive modeling and heat transfer related experiments were proposed as an approach to address the challenges with trial-and-error and heat damage, respectively. Future work involves a comprehensive review of the literature, and additional tests for a large sample of parameter values to be included in our analysis. In our preliminary results from the heat transfer experiments, we identified some differences in thermal conductivity of the hair samples tested. The results showed that hair fiber behaves like a long fin which displays exponentially decaying temperature profile with increasing distance from the heat source. Type V hair bundles of different densities were compared and turned out to exhibit different behaviors on application of heat, suggesting the importance of careful preparation of hair bundles in the future work. Future work will require gathering hair samples from all 8 categories of hair types, and to refine the automated flat ironing mechanism to ensure minimal contribution of environmental factors and noise from controlled parameters. The main contributions of this work is the integration of design methodology and thermal sciences for gathering more information to address challenges in the hair care industry and to bring this knowledge directly to the customer.

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