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ELECTROTECHNOLOGY APPLICATIONS IN TEXTILE MANUFACTURING (S92-6)

PERSONNEL

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GOAL

This project consists of a series of interrelated subprojects which focus on three major electrotechnologies: infrared, dielectric (radio frequency) and acoustics/ultrasound to solve energy, environmental, and quality problems.

ABSTRACT

Three electrotechnologies; infrared, dielectric (radio frequency), and ultrasound are studied in the attempt to improve productivity, increase process efficiency, and enhance the quality of textile products. Some activities seek to improve existing processes such as drying, conventional batch dyeing, and conventional continuous dyeing. Other tasks concentrate on generating fundamental knowledge about properties of electrical energy which affect textile processes and understand the mechanisms involved in ultrasound-assisted wet processing. Another area involves modeling infrared dryers to better understand the drying process so costly production errors can be avoided. Finally, the effects of acoustic energy on the continuous dyeing and drying of tufted nylon carpet is being studied.

MODELING OF INFRARED AND CONVECTION DRYING OF TEXTILE MATERIALS

Suresh V. Pullela submitted a thesis titled "Analysis of drying operation of wet fibrous structure using IR (infrared radiation) and convection" to the Graduate Faculty of NCSU in partial fulfillment of the requirements for the Degree of Master of Science in the Department of Textile Engineering, Chemistry, and Science and the Department of Mechanical Engineering. The following is a summary of this work.

In order to plan drying schedules and determine the capacity of the equipment, it is necessary to know the time required to dry the material from the initial moisture content to the desired moisture under specified conditions. The design of the related equipment is dependent on the mechanism of the drying process. However, it is found necessary that the specific nature and conditions related to the specimen to be dried are incorporated in the theoretical studies and the practical design of the machinery. The capacity of any dryer depends on the rates of both heat and mass transfer. The latter depends on the distribution of the moisture on and through the solid material, and the mechanism by which moisture migrates from the interior of the material to the vapor/liquid interface where it may be vaporized. Since little information is provided in literature regarding the drying of textile materials using IR radiation and convection, the present investigation is undertaken.

Three important dimensionless groups, π_{qm} (heat flux parameter), π_{hm} (mass transfer parameter), π_s (vaporization parameter) are derived and their influence on drying time is studied. Further, it has been observed that radiative heat flux, q_r, and fabric velocity, V, are important governing parameters in the prediction of drying time. The influence of ambient air temperature, T_a, on evaporation for different values of radiative heat flux has also been studied. The influence of the flow rate of air was found to be negligible in the computation of total time required to dry the material. Thus, air could be looked upon to serve only as an evacuating agent for the water vapor.

Figure 1 shows a comparison between theory and experimental data. The correction factor (C.F) is used to account for the emissivity of the emitters, re-radiation for the wet fabric surface, and the view-factor. Radiation absorption of water vapor being negligible. There appears to be a reasonable agreement between theory and experimental results within a range of 10% as can be observed from Figure 2.

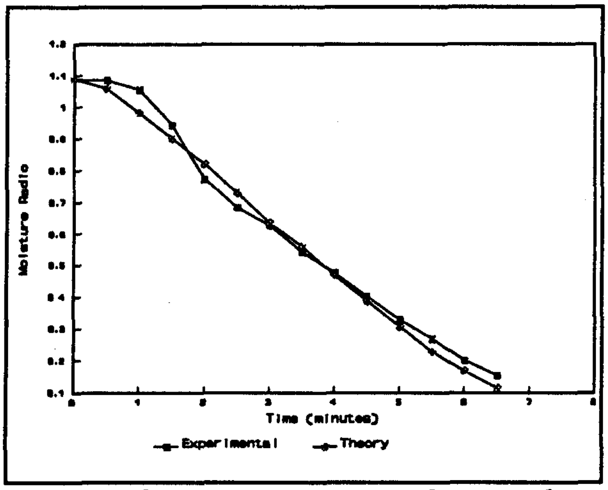


Figure 1: Comparison Between Theory and Experimental Results of Cotton Fabric Dried in an Infrared Oven.

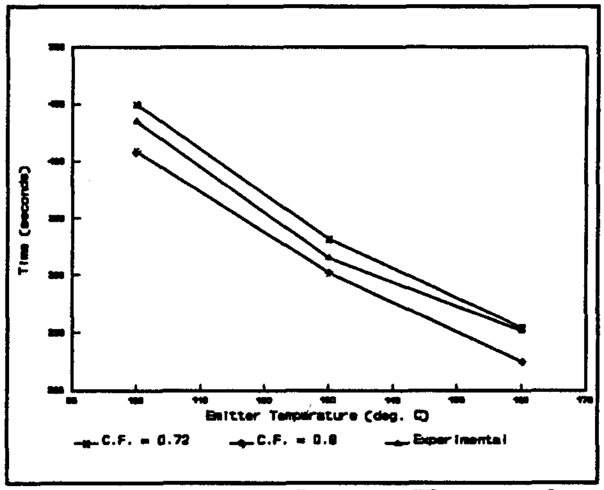


Figure 2: Comparison Between Theory and Experimental Results of Cotton Fabric Dried in an Infrared Oven.

ULTRASOUND-AIDED WET PROCESSING

Ultrasound-Aided Exhaustion Dyeing

David Klutz submitted a thesis titled "Ultrasound-Aided Exhaustion Dyeing" to the Graduate Faculty of NCSU in partial fulfillment of the requirements for the Degree of Master of Science in the Department of Textile Engineering, Chemistry, and Science, North Carolina State University. He received his diploma in December 1993. The following is a summary of this work and a brief explanation of his future work.

This work began by examining the current dyeing machines and processes to determine which could most easily be modified to use ultrasound as a mechanical accelerant of the dyeing process. The concerns addressed in selecting a machine to use were: could the ultrasound be applied evenly, could the ultrasound penetrate a thick mass of fabric, and would the distance between the substrate and the ultrasound horn have an effect the dyeing process. Because of these concerns, the most promising machine to be modified for ultrasound seemed to be the atmospheric beck.

To simulate an atmospheric beck, a metal parts cleaning tank manufactured by Blackstone Incorporated was used. This machine had six 800 watt ultrasound generators with 107 transducers mounted on the bottom of the tank. A circulation system was added to this tank to maintain a homogeneous dye solution and to allow use of a flow-though heater to reach temperatures near the boil. Transport of the substrate was achieved via an installed roll system.

Once a machine was selected the dye and substrate to be used had to be determined. The three most common substrates (cotton, nylon, and polyester) were chosen along with the more common dye class for each substrate, ie direct dyes on cotton, acid dyes on nylon, and disperse dyes on polyester. The next step was to survey the dye manufacturers to determine which dyes in each class were the most commonly used. After collecting this data, screening trials were conducted in an Ahiba Texomat dye machine to determine which of these most commonly used dyes might best be suited for ultrasound dyeing. The goal of these screening trials was to select dyes requiring either high temperatures or high chemical additives to achieve desirable exhaustion levels. From this work two direct dyes, Solophenyl Blue FGL 220 and Solophenyl Scarlet BNL 200, and five polyester dyes, Dianix Blue FBLN FS 200, Dianix Red HBLA, Dianix Yellow R3G 200, Resolin Blue FBL, and Resolin Orange F3RN, displayed the high temperature and/or high auxiliary chemical concentrations requirement indicating they were good candidates for ultrasound aided dyeing. All of the acid dyes screened exhausted well even at low temperatures so the addition of ultrasound would be of little benefit with the acid dye on nylon combination.

The substrates used were jersey knits of either 100% upland cotton supplied by Cotton Incorporated or 100% polyester supplied by Dupont. With the selection of machine, dye class, and substrate the next step in the research process was to design the experiments to test the hypothesis that ultrasound could be used to replace auxiliary chemicals and/or heat in dyeing process. Direct dyes on cotton was the first substrate to be studied with the goal of reducing the amount of electrolyte (salt) required or reducing the temperature required to achieve exhaustion. In all of the experimental trials, the dye manufacturer's recommended procedure was followed except for the two manipulated variables of electrolyte concentration and temperature. Also, for each trial one sample was dyed following the dye manufacturer's recommended procedure exactly. This one sample was used as a baseline for comparing all the other dyes. For the experimental trials, three electrolyte levels (0%, 5%, and 10% on weight of fabric) and three temperatures (120°F, 150°F, and 190°F) were studied. Under each set of experimental conditions one sample was dyed with ultrasound and one was dyed without ultrasound.

From all of these trials it was found that the effect of ultrasound decreased as the temperature increased. It was found that ultrasound could be used to replace electrolyte in that the electrolyte concentration could be reduced by as much as 50% without decreasing exhaustion when ultrasound was used at 120°F. Furthermore, as shown in Figure 3, using ultrasound at 150°F achieved the same exhaustion levels as the baseline dyeing. As shown in Figure 4, ultrasound can reduce the dyeing cycle by approximately 25 percent. The main drawback of ultrasound dyeing found from these trials was that ultrasound either reduced or left unaffected the fastness properties of the finished goods.

Two other areas studied briefly were the effect of turning ultrasound off during the dyeing process and the effect of fabric tension and fabric thickness during dyeing. This work indicated that turning ultrasound off during the dyeing process could be the optimum procedure for ultrasound dyeing because the effect of ultrasound on exhaustion decreased as the dyeing proceeded. Holding the fabric under tension had little effect on the dyeing. The thickness did make a difference and indicated that the ultrasound had little effect on any thickness greater than a single layer of fabric.

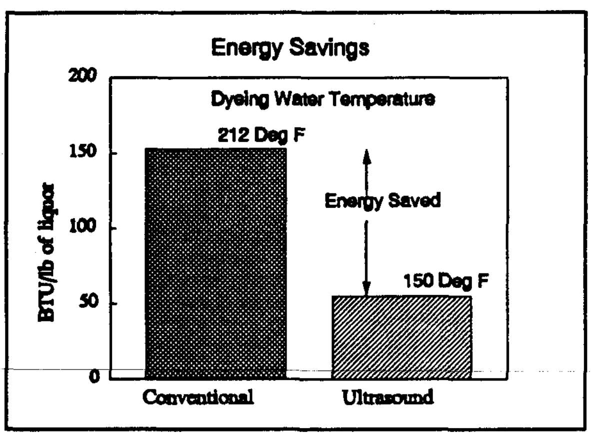


Figure 3: Energy Savings with Ultrasound-Assisted Direct Dyeing of Cotton.

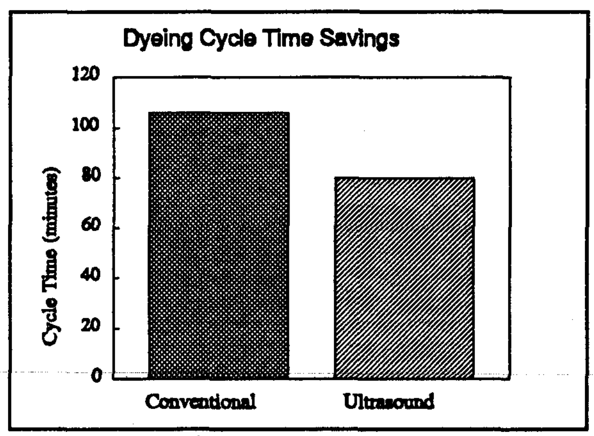


Figure 4: Time Savings with Ultrasound Assisted of Direct Dyeing of Cotton.

The research currently being planned and conducted deals primarily with the fundamental interactions of ultrasound with the dye and with the fiber. The effect of ultrasound on the dye liquor will be determined using a filtration method to determine ultrasound's effect on dye solubility. Laser light scattering will be used to study ultrasound's effect on the size of dye agglomerates in the dye bath. Ultrasound's effect on the fiber properties such as swelling will be examined by suspending the fiber in an electrolyte solution between two electrodes and measuring the conductivity of the fiber.

Ultrasound-Aided Batch Dyeing of Polyester

In other ultrasound research, batch dyeing of polyester fabric with a disperse dye using two horns (round and square) and two boosters (1.0 and 2.5 gain) has been done at 170°F, 190°F, and 212°F, with variations in dye concentration, leveling agent, and carrier. At 212°F, the ultrasound retards the dye transfer from the solution to the fabric. At lower temperatures, the ultrasound accelerates the dye transfer to the fabric. The goal is to determine the shade curves and where the maximum benefits of ultrasound occur in batch dyeing.

Ultrasound-Aided Continuous Dyeing

Cotton fabric was dyed to significantly darker shades on a continuous basis using ultrasound generated by the Nearfield Acoustical Processor which was loaned by Advanced Sonics. The dye application was the initial stage in vat dyeing of cotton, the application of the pigment to the fabric. The material was passed through the NAP unit into a pad, and then dried. The reduction and oxidation operations were performed separately. The samples were then analyzed for color shade difference. While running through the NAP unit, ultrasound power was run for several meters at each of three levels, no power, 50% power, and 100% power. As shown in Figure 5, results show that as the ultrasound power is increased, the color shade becomes darker. On four different dyes, the maximum increase in depth of shade was 29%, 51%, 102% and 103% for full ultrasound power. The increase in shade due to ultrasound depends on the intensity of ultrasound, amount of dye in the pad, and type of dye. The most significant results of these test was shade changes were made simply by adjusting the intensity of ultrasound. This is the first step in real time shade control.

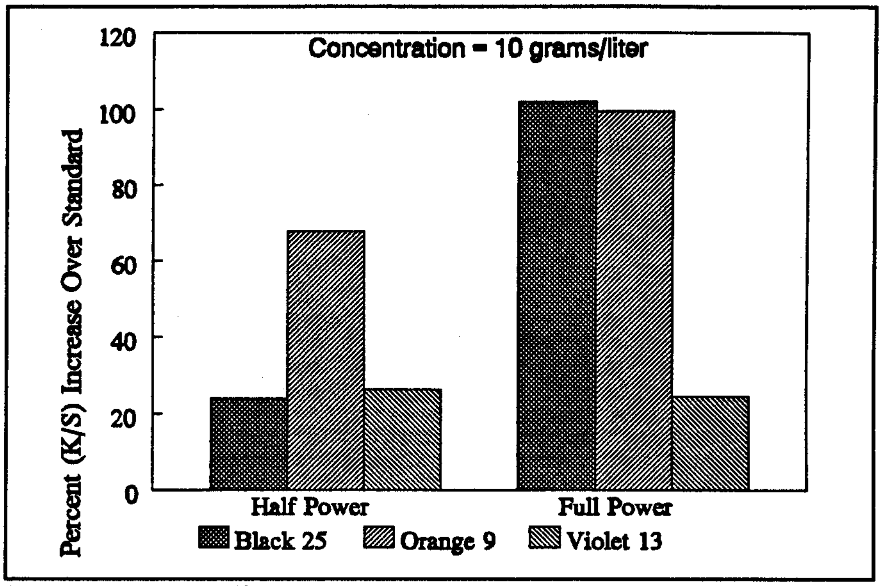


Figure 5: Percent K/S Increase with Ultrasound.

Design of an Ultrasound Based Continuous Dye Padder

Syed Zafar Kazmi submitted a thesis titled "Design of an Ultrasound Based Continuous Dye Padder" to the Graduate Faculty of NCSU in partial fulfillment of the requirement of a Master of Science degree in the Department of Textile Engineering, Chemistry, and Science and the Department of Textiles and Apparel Management. The following is the abstract from this thesis.

A comprehensive study of continuous dyeing process is done to investigate the possibilities of application of ultrasound power in the dye application. The continuous dyeing process is reviewed and the problems identified. On-line sensors for the measurement of ultrasound power and fabric color are studied and experiments were conducted. Effort is made to produce a closed loop model of the control system for the dye padder and a simplified control algorithm is suggested.

INFRARED

The successful utilization of infrared radiation is highly dependent on the spectral characteristics of the material being processed and on how well the spectral output of the infrared source matches those of the material being heated.

There are three phases to this study:

1. Installation and testing of an FT-IR spectrometer.
2. Development of software to manipulate the spectral data.
3. Collection of spectral data from a wide range of textile samples under various experimental conditions.

A BioRad FTS-60A spectrometer was acquired during the first year of this project. After installation, thorough testing was performed to ensure that the instrument was functioning according to design specifications. Numerous adjustments and equipment expenditures were required to bring performance up to the consistent level of accuracy required for quantitative data collection. During this time, the data collection process was also optimized to provide the greatest efficiency possible for data collection while maintaining the necessary high performance standards.

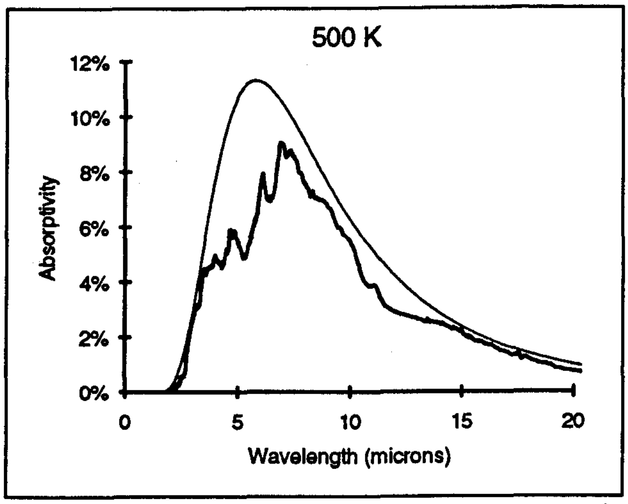
Midway through the first project year, development of the necessary spectral manipulation software began. In addition to maintaining high performance standards for the equipment, it was also necessary to perform several spectral corrections in the software to adjust for experimental conditions.
In addition to performing spectral corrections, the software was to perform three important functions:

1. Approximate emissions from practical and theoretical IR sources at user-specified temperatures
2. Calculate the spectral and average absorptivity of these emissions by the textile sample being analyzed
3. Approximate the efficiency with which the textile sample could be heated by the selected emitters at various temperatures. This would allow for the best match between emitter and operating conditions and the spectral properties of textiles.

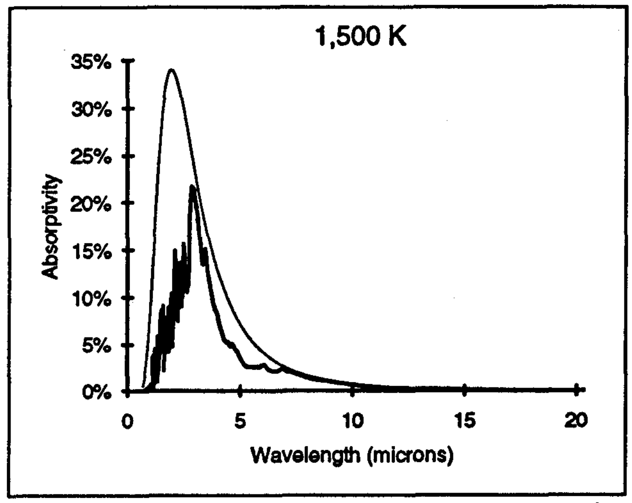
Initially, black body emissions were used as an approximation of common IR sources. However, as the software was further developed, methods of incorporating data on real emitters were included. The software now can use tables of IR emission data taken at various emitter temperatures to interpolate emission information at the user-specified temperature. To provide greater flexibility, the user can also select from a number of common filters in order to better approximate realistic conditions (such as a tungsten filament enclosed in a quartz glass bulb).

Once the IR emissions are approximated, the software can then multiply the spectral absorptivity of the textile sample, shown in Figures 6 and 7, by the spectral emissions of the IR source to determine the fraction of the emitted energy that would actually be absorbed by the sample. By integrating this curve, the average absorptivity of the IR emissions by the sample is computed as shown in Figure 8. This value is presented as a ratio of absorbed energy over the amount of energy emitted.

The final step is to adjust this average absorptivity according to the radiant efficiency of the emitter at that temperature. It is well known that black body type emitters convert electric or thermal energy to IR radiation more efficiently at higher temperatures. For example, while the radiant efficiency of a tungsten lamp may be only 30% at 500K, it may be as high as 90% at 3,000K. Figure 9 shows that while a textile may absorb 85% of the light emitted at 500 K, this represents a total efficiency of only 25%.



(light: black body emission, dark: absorption by rayon)
Figure 6: Normalized spectral absorptivity of emissions from a black body at 500 K by rayon fabric.



(light: black body emission, dark: absorption by rayon)
Figure 7: Normalized spectral absorptivity of emissions from a black body at 1,500 K by rayon fabric.

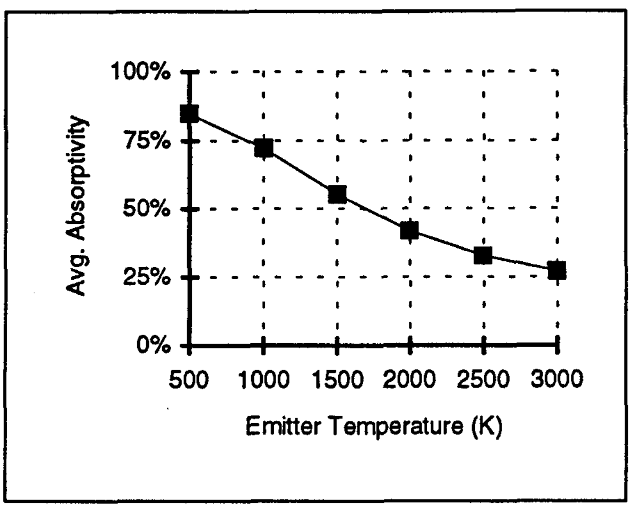


Figure 8: Average absorptivity of black body emissions versus emitter temperature by rayon fabric.

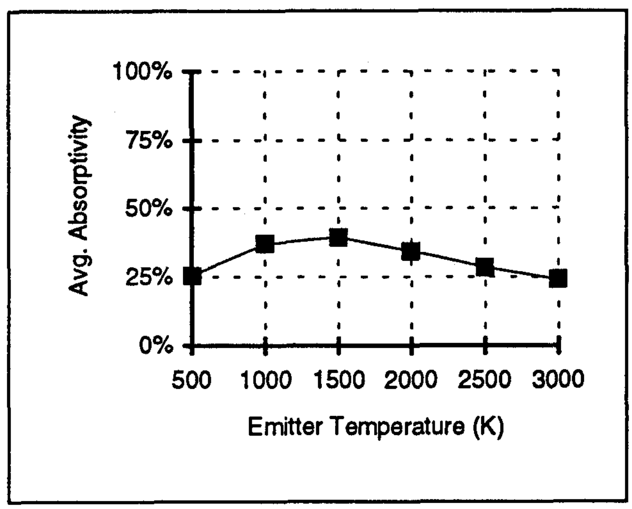


Figure 9: IR heating efficiency versus emitter temperature of the rayon sample described in Figure 8.

The software developed to perform these functions was designed to meet one other criterion: to be user friendly. While performing high speed calculations and allowing for a strong balance between efficiency and flexibility, the software presents an intuitive user interface.

DATA COLLECTION

The final phase of this project is to apply the hardware and software tools toward the detailed infrared spectral analysis of textiles. The collection of spectral data began immediately after phase I (installation and testing of the FT-IR spectrometer) was completed. To date, 114 spectra of 17 widely used fabrics have been taken under numerous experimental conditions.

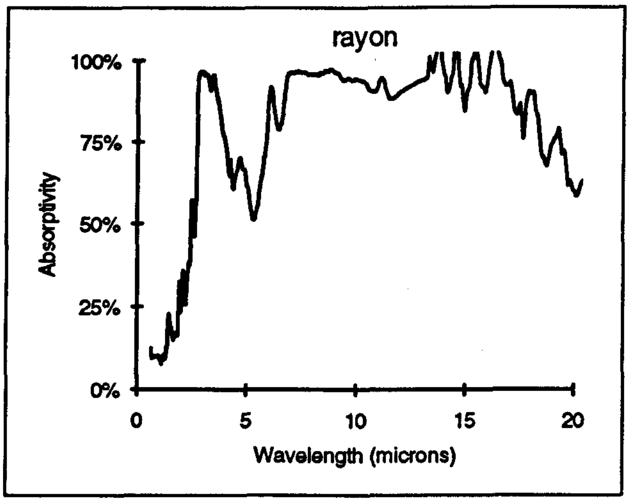


Figure 10: Spectral absorptivity of rayon.

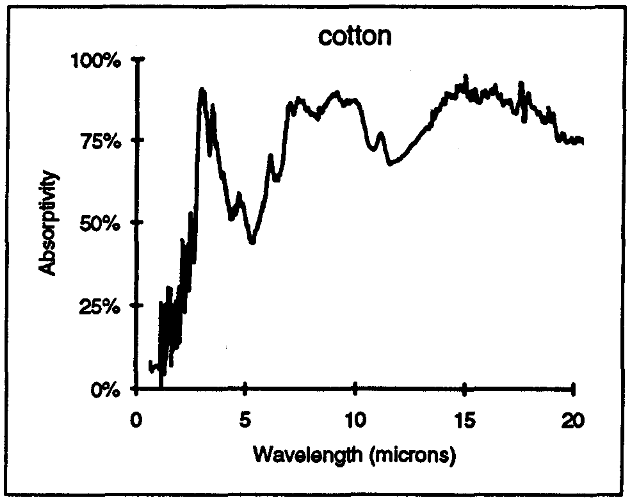


Figure 11: Spectral absorptivity of cotton.

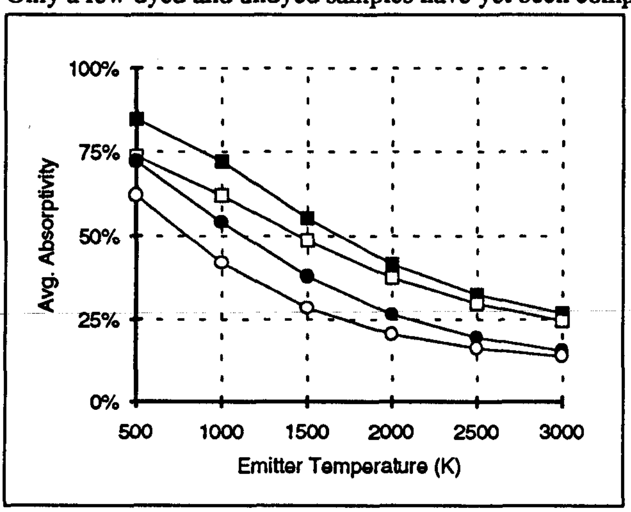
Since the completion of the software development phase, analysis of this data has now begun. Although more data is required to draw definite conclusions, initial results have provided many interesting insights into understanding the effects of fiber type, dyes, fabric weight, and moisture content.

Fiber Type

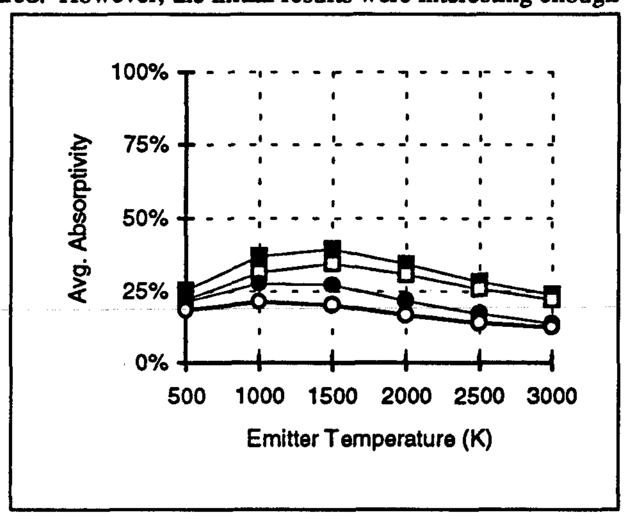
As can be seen in Figures 10 through 11, fiber type plays a significant role in determining the effectiveness of infrared heating. However, the spectral absorptivity of each fiber type alone does not clearly demonstrate how the material will respond to infrared heating. Three of the four fibers tested (polyester, cotton, rayon, and nylon) share peaks in the regions from 3 to 4 mm and 7.5 to 10 mm. Only by actually computing the average absorptivity of black body radiation does it become apparent just how different these similarities are. By then calculating the efficiency of infrared heating, it is evident that the optimum emitter temperature can be found in the 1,000 to 1,500 K range shown in Figures 12 and 13.

Dyeing

Only a few dyed and undyed samples have yet been compared. However, the initial results were interesting enough

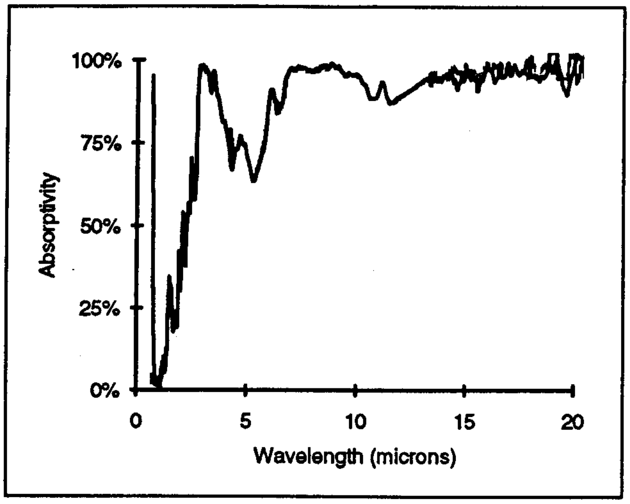


(■ rayon, □ cotton, • nylon, ○ polyester)
Figure 12: Average absorptivity of black body emissions versus emitter temperature by common textile fibers.

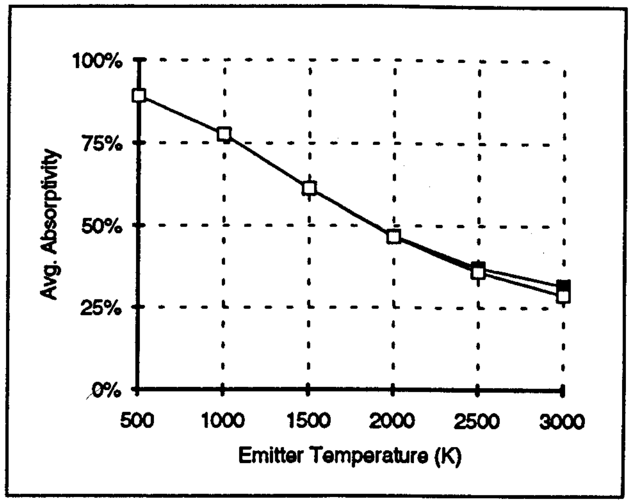


(■ rayon, □ cotton, • nylon, ○ polyester)
Figure 13: IR heating efficiency versus emitter temperature of common textile fibers.

to report here. Of the samples tested, the dyed samples showed virtually no change except in the very near infrared. (Notice how difficult it is to distinguish the dyed from the undyed in Figures 14 and 15, except below 1mm where the absorptivity of the dyed sample rises sharply.) It appears that these dyes are limited in their influence to the visible and near infrared regions, beyond which they are virtually invisible. Despite what one might find intuitive--that a black material would absorb infrared very well--it becomes clear that these samples, in fact, do not absorb infrared light significantly more than undyed samples under similar conditions.



(dark - dyed black, light - undyed)
Figure 14: Spectral absorptivity of dyed and undyed cotton fabric.



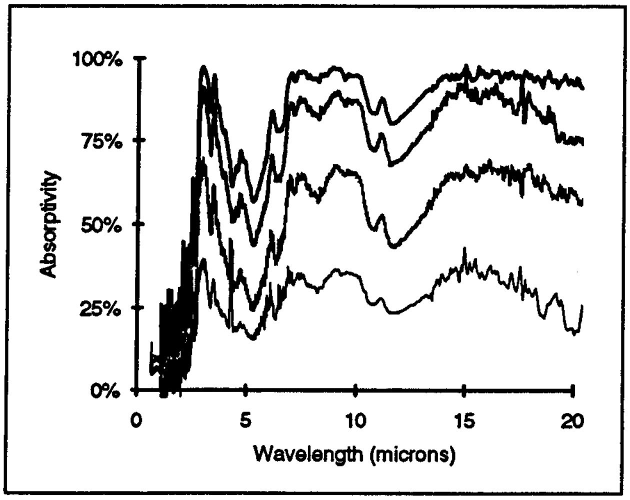
(■ dyed black, □ undyed)
Figure 15: Average absorptivity of black body emissions versus emitter temperature by dyed and undyed cotton fabric.

Fabric Weight

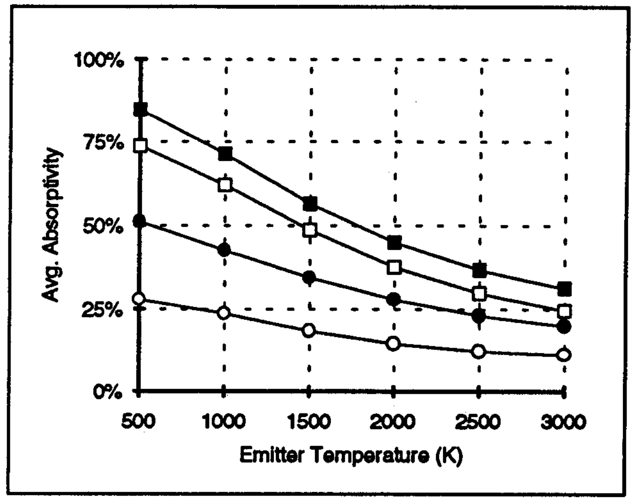
When samples of the same fiber type but different fabric weights are compared, we find that low-weight fabrics can have significantly lower infrared absorption. However, as fabric weight increases, a threshold is eventually met at which further increases in weight cause no further change in absorptivity. This appears to be primarily due to decreasing transmissivity as weight increases. The absorptivity threshold is the point where transmissivity becomes zero through most of the infrared region. Thus, all of the light incident upon the surface of the sample is either absorbed or reflected, neither of which appears to be affected by further increase in fabric weight.
Figures 16 and 17 show the effect of increasing weight of cotton fabrics. In the spectral absorptivity plot, the appearance of the curve remains similar from one sample to the next, but the baseline shifts as thicker materials are analyzed. Notice, however, that between the samples of 2.22 and 6.92 $^{oz.}/_{sq.\ yd.}$, there is relatively little change in comparison to the difference between 0.63 and 2.22 $^{oz.}/_{sq.\ yd.}$

Moisture Content

Whether dealing with cotton, rayon, nylon or polyester, the presence of moisture causes a significant increase in the infrared absorption of textiles. Increasing the moisture content of cotton causes a "flat-lining" effect across the infrared spectrum from approximately 2.5 to over 20 mm. As a result, the average absorptivity of the material increases proportionally for short, medium, and long wavelength infrared emitters. One interesting note, however, is that in many samples the presence of moisture will cause an increase in the transmissivity in near infrared region. However, this effect is typically balanced by a corresponding decrease in reflectivity in the same region resulting in relatively small changes in absorptivity.



(dark to light: 6.92, 2.22, 1.54, 0.63 oz/sq. yd.)
Figure 16: Spectral absorptivity of cotton fabric at varying weights.



(dark to light: ■ 6.92, □ 2.22, ● 1.54, ○ 0.63 oz/sq. yd.)
Figure 17: Average absorptivity of black body emissions versus emitter temperature by cotton fabric at varying weights.

The interesting spectral behaviors described above show why this type of spectral characterization is necessary. In many cases, the data did not conform to simple intuition, suggesting a complex set of interactions. These properties must continue to be studied to better optimize infrared heating applications to best suit the materials commonly used in industry.

ACOUSTICS

The study of acoustic augmentation of textile drying and dyeing processes began with a research effort referred to as the flow-through dryer project. This project was originally intended to investigate the effect of humidity on the drying rate of carpet. The results of this study could then be used to optimize dryer exhaust rates from industrial dryers that typically follow a dyeing, steaming and washing operation. The project expanded to include a total of four objectives:

1. Measure drying conditions for tufted nylon carpet in a flow-through dryer at temperatures up to 300°F and humidity levels from ambient to 100% relative humidity. (This is to optimize exhaust rates of existing dryers and investigate the economic advantages of steam drying.)
2. Measure drying conditions for tufted nylon carpet as they may be enhanced by the presence of an acoustic field of intensity near 160 dB and frequency range from 350 to 4,000 Hz.
3. Investigate enhanced aesthetic qualities, such as yarn bloom, in tufted nylon carpet as would be caused by the presence of a strong acoustic field during drying.
4. Investigate enhanced dye fixation in textiles, and especially hard-to-dye textiles such as Nomex and Kevlar, as is caused by a strong acoustic field.

Fulfillment of these goals requires obtaining the testing equipment, performing the tests, analyzing the data and reporting the results. It was decided that testing on an industrial scale would be prohibitively expensive. Further, the appropriate experimental setup did not exist. Thus, it became necessary to design and build a laboratory scale flow-through dryer that allows continuous weighing of a carpet sample and the application of a controlled acoustic field. The equipment was designed with the flexibility to test dye fixation as well as drying conditions and effects.

The project can be divided into four phases as previously mentioned:

1. Building the test equipment.
2. Testing.
3. Analyzing the data.
4. Reporting the results.

The first phase of the project is nearing completion. Since there have been numerous encumbrances, it is tentatively declared that construction will be complete by the end of September 1994.
Further, the construction phase can be broken down into four tasks:

1. Design and construction of the dryer tunnel and support structure.
2. Preparation of the data-acquisition and control system.
3. Wiring of the electrical power supplies.
4. System performance testing.

The design phase is complete and construction has begun. Final construction requires the arrival of parts due within the month. The second task, preparing the data-acquisition and control system, is complete except for integration with the dryer unit. The final two tasks also await full assembly of the structure. However, since the design and construction phase represents a majority of the work required to construct an operational dryer unit, work is reported to be 80% complete.

PUBLICATIONS / PRESENTATIONS

1. Carr, Wallace W. "Radio Frequency Drying of Latex on Carpets," presented at the Textile Electrotechnology Conference sponsored by EPRI and CRI, Dalton, Georgia, June 7, 1994.
2. Carr, Wallace W. "Infrared Drying and Curing of Textiles and Carpet," presented at the Textile Electrotechnology Conference sponsored by EPRI and CRI, Dalton, Georgia, June 7, 1994.
3. Carr, W. W., Williamson, V. A., Johnson, M. R., and Do, B. T., "Matching of Infrared Emitters with Textiles for Improved Energy Utilization," Proceedings of the Sixteenth National Industrial Energy Technology Conference, April 11 & 12, 1994, Houston, Texas.
4. O'Dell, D. R., "The Drying Behavior of Carpet Tiles in a Medium of Superheated Steam," M.S. Thesis, Georgia Institute of Technology, March 1994.
5. Williamson, V. A., "Characterization of the Infrared Absorption Properties of Polymeric Materials," M.S. Thesis, Georgia Institute of Technology, March 1994.
6 P.V. Suresh, H. Hamouda, M. J. Cato, "An approximate analysis of drying operation of wet fabric," Wärme-und Stoffübertragung, 1994, Volume 29, p 441-446.
7. Cato, M. J., "Radio Frequency Drying in Textiles", Presentation to the Design for the Environment Dry Cleaning Project Technical Workgroup Meeting, January 27, 1994.
8. Hechmi Hamouda and Mike Cato, "An Analytical Model for the Combined Convective and Radiative (IR) Drying of Fabrics", the 28th Microwave Power Symposium in Montreal, Canada July 12-14, 1993.
9. Mike Cato, Perry Grady, and Gary Mock, "Radio Frequency Drying of Textiles: A Global Perspective", the 28th Microwave Power Symposium in Montreal Canada July 12-14, 1993.
10. Hechmi Hamouda and Mike Cato, "A Precise Model for RF Drying of Yarn Packages", the Microwave and High Frequency 1993 International Conference in Goteborg, Sweden, September 28-30, 1993.
11. David Klutz, "Ultrasound-Aided Exhaustion Dyeing", Master of Science, Department of Textile Engineering, Chemistry, and Science, North Carolina State University, December 1993.
12. Rick Ingham, "Design for Assembly of Ultrasonic Squeeze Roll System for the Application of Direct Ultrasonic Energy to Textile Materials in the Dyeing Process", Master of Integrated Manufacturing Systems