GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION SPONSORED PROJECT INITIATION

June 17, 1976 Date: Project Title: Energy Conservation in the Textile Industry (sub-project*E-27-642/Cook/T.E.) A-1853 Project No: Project Director: Mr. James F. Lowry-Sponsor: Energy Research & Development Administration, Oak Ridge Operation Oak Ridge, Tennessee 37830 Dec 7- 1978 November 30; -- 1-976 From June 1, 1976 Until Agreement Period: . 54-76-8-05-5019 • Type Agreement: Contract No. E(40-1)-5099 Amount: \$100,000 Total authorized funding (\$46,853 in E-27-642 and \$46,852 in A-1853-001; A-1853-000 \$6,295)

Reports Required: Quarterly Progress Reports; Final Report

Sponsor Contact Person (s):

Technical Matters

Contractual Matters (thru OGAN) GTRI Mr. Earl Mason Research Contracts, Procedures Reports Branch Contract Division, USERDA Oak Ridge Operations P.O. Box E Oak Ridge, Tennessee 37830 Phone: (615) 483-8611

Defense Priority Rating: None

Assigned to: <u>Productivity & Technology Applications</u> (SN168) (Laboratory)

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GEORGIA INSTITUTE OF TECHNOLOGY OFF **OF CONTRACT ADMINISTRATION**

SPONSORED PROJECT TERMINATION

Date: May 31, 1979 Energy Conservation in the Textile Industry A-1853 097 Project Director: N. W. Carr Sponsor: US Department of Energy Effective Termination Date: _____1/30/78 Clearance of Accounting Charges: all clear Grant/Contract Closeout Actions Remaining: Final Invoice and Closing Documents

- Final Fiscal Report х
- Final Report of Inventions
- Govt. Property Inventory & Related Certificate
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	PROJECT INITIATION 735
heets included Sponsored	PROJECT INITIATION
for reference purposes	Date: June 17, 1976
Project Title: Energy Conservation in	n the Textile Industry
Project No: E-27-642 (Sub-project	to A-1853 PTAL/Lowry)
Project Director: Dr. Fred L. Cook	
Sponsor: Energy Research & Develop Oak Ridge, Tennessee 378	pment Administration, Oak Ridge Operati 30
Agreement Period: From June	1, 1976 Until November 30, 1976
Type Agreement: Contract No. E(40.	-1)-5099
Amount: \$46,853 (Total Authorize \$46,852 in A-1	ed Funding is \$100,000; \$6,295 in A-185 853-001)
Reports Required: Submitted thru A-	1853-000 Y
Sponsor Contact Person (s):	·
Technical Matters	Contractual Matters
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•	See Project A-1853
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Defense Priority Rating: None	
Assigned to: <u>Textile Engineering</u>	(School/Laboratory)
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Security Coordinator (OCA)	Other

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CA-3 (3/76)

Reports Coordinator (OCA)

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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION SPONSORED PROJECT INITIATION

		Date: November 20, 1978
Project Title:	Energy Conservation in the Text	ile Industry Phase III
Project No:	E-27-672 (Sub-project is A-1853)003/Carr/TDL/EED) 4. (d
Project Director	Dr. David S. Brookstein	
Sponsor:	U. S. Department of Energy; Oak	Ridge Operations
Agreement Perio	od: From <u>6/1/78</u>	Until 11/30/79 (Contract Period
Гуре Agreement	Contract No. EY-76-S-05-5099, M	lod. No. A004
Amount:	\$ 63,042 E-27-672 38,442 A-1853-003 \$101,484 Total	
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Reports Require	d: Monthly Technical Status Repor Reprints; Final Report	ts; Publication Preprints; Publication
Reports Required Sponsor Contact	d: Monthly Technical Status Repor Reprints; Final Report Person (s):	y' ts; Publication Preprints; Publication
Reports Required Sponsor Contact <u>Technics</u> Mr. John	d: Monthly Technical Status Repor Reprints; Final Report Person (s): al Matters Rossmeiss1	ts; Publication Preprints; Publication <u>Contractual Matters</u> (thru OCA)
Reports Required Sponsor Contact <u>Technic</u> Mr. John Division Conser	d: Monthly Technical Status Repor Reprints; Final Report Person (s): al Matters Rossmeissl of Building and Industry vation	<u>Contractual Matters</u> (thru OCA) R. A. Fahey, Deputy Director Contract Division
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Reports Required Sponsor Contact <u>Technics</u> Mr. John Division Conser Departme 20 Massa Washingt	d: Monthly Technical Status Repor Reprints; Final Report Person (s): al Matters Rossmeiss1 of Building and Industry vation nt of Energy chusetts Avenue on, D. C. 20545 Rating: n/a	Contractual Matters (thru OCA) R. A. Fahey, Deputy Director Contract Division A. H. Frost, Jr., Chief Research Contracts, Procedures an Reports Branch Contract Division Department of Energy Oak Ridge Operations Oak Ridge, TN 37830 Earl Mason 615-483-8611, ext. 34105

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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION

Date: <u>9/11/80</u>

Project Title: Energy Conservation in the Textile Industry -- Phase III

Project No: E-27-672 (Sub-Project is A-1853-003/Carr/TDL/EED) Project Director: Dr. David S. Brookstein

Sponsor: U.S. Department of Energy: Oak Ridge Operations

Effective Termination Date: _____11/30/79

Clearance of Accounting Charges: <u>11/30/79</u>

Grant/Contract Closeout Actions Remaining:

- X Final Invoice and Closing Documents
- X Final Fiscal Report
- _____ Final Report of Inventions
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Assigned to: Textile Engineering

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Library, Technical Reports Section EES Information Office Project Fila (OCA) Project Code (GTRI) Other_____

Intering Report

RECONSTITUTION AND REUSE OF DYEBATHS

by

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RECONSTITUTION AND REUSE OF DYEBATHS

ABSTRACT

A system for dyeing textiles has been developed which permits reuse of dyebaths for up to fifteen times before the bath is discharged. At the conclusion of the dyeing cycle the bath is analyzed and reconstituted to the dye and chemical concentrations required for the next dyeing. The system has been used on a pilot-scale for dyeing nylon and polyester carpet, nylon hosiery and polyester yarn packages. A plant demonstration of the reuse technology for hosiery dyeing has been completed. Significant reductions in dye (19%), chemical (35%), water (43%), and energy (57%) requirements were achieved with the reuse system. The cost of materials and energy for hosiery dyeing was reduced 37% by reuse of the dyebath.

I. INTRODUCTION

The textile industry uses approximately 125 billion gallons of water annually [1]. Much of this water is discharged with appreciable quantities of organic and inorganic chemicals (dyes, pH control agents, lubricants, surfactants, auxiliaries) which require extensive treatment of the wastewater and which contribute to the pollution problems associated with textile processing. In the past, the problem of pollution resulting from textile processing has been attacked by construction of waste treatment facilities. As requirements became more stringent, the waste treatment plant was expanded or additional treatment processes were added to meet the standards. This approach has consumed large sums of non-income-producing capital and has increased the operating costs of many textile plants.

In addition to problems associated with water supply and pollution control, the increasing cost and decreasing supply of energy represents a major problem for the textile industry. Energy requirements for the United States textile industry in 1971 (most recent comprehensive data) were equal to approximately 67 millions barrels of oil [2]. Industry is heavily dependent on petroleum products and natural gas (the fuel currently in shortest supply) for a major part of process energy requirements. If the industry is to adapt to the shortages or curtailments of energy, new processes or process modifications must be implemented on a broad, industry-wide scale.

Two basic types of procedures are used for textile coloration--pad-fix (continuous) processes and exhaust (batch) processes. Continuous dyeing is used primarily for long runs of a given fabric style. Because of their continuous nature and the use of relatively small volumes of dye liquor,

these processes tend to be more efficient than batch processes. Exhaust processes are generally very inefficient in their use of chemicals, water and energy and generate large volumes of waste that must be treated. Despite these disadvantages, the versatility, ease of control, and short run capability of exhaust processes make them very attractive for coloration of many textile products.

A number of different types of batch dyeing processes (beck dyeing, jet dyeing, jig dyeing, package dyeing, beam dyeing) are used in the textile industry. Batch processes were used for dyeing an estimated five billion pounds of textile fibers and fabrics in 1973 [3]. Batch processes readily lend themselves to process modifications which can reduce energy and materials requirements for dyeing. Such modifications were a major objective of this research project.

II. DEVELOPMENT OF THE REUSE SYSTEM

In the conventional batch dyeing process the dyeing machine is filled with water, the goods to be dyed are entered, and the fabric moved through the bath (or the bath moved through the goods) to saturate the fabric with water. Chemical auxiliaries such as wetting agents, pH control agents, leveling agents, chelating agents, etc., are then added to the bath followed by the dyes. The beck is heated from ambient to the dyeing temperature at a rate usually 30 to 4^{0} F per minute and held at the dyeing temperature for the time required to complete the dyeing. The goods being dyed are checked for proper shade and if on-shade the dyebath is discharged to drain. The goods are then post-scoured and/or rinsed to remove incompletely fixed dye. The goods are removed from the machine and the machine refilled with water for the next load.

If the dyebath is examined before and after the dyeing cycle, two major changes have occurred. First, most of the dye has been removed from the bath by the yarn or fabric and second, the bath is hot rather than cold. Most of the auxiliary chemicals added to the bath are still present in the same condition as they were at the start of the dyeing cycle. When the dyebath is discharged to the drain, large quantities of energy, water and useful chemicals are lost. A more reasonable procedure would be to analyze the spent dyebath for the remaining dye, to reconstitute the bath to the desired strength, and to reuse it for subsequent dyeings. Reuse of dyebaths in this way should significantly reduce the energy, water and chemical requirements in batch dyeing.

A number of technical problems required solution before dyebath reuse could be broadly applied in batch dyeing. First, an analytical system had to be developed to simply, accurately, and economically determine the concentration of dyes remaining in the bath. The analytical technique has to be compatible with existing dyehouse personnel, space, time and equipment constraints. Second, dyeings must be started at elevated temperatures (~170°F). The increased rate of dye adsorption from the bath at these temperatures could lead to spotting and poor levelness in the recycle dyeings. Third, materials handling procedures had to be worked out to give scouring, dyeing, and rinsing cycles compatible with current plant operating procedures. Fourth, evaluation procedures were required to insure that dyeings in recycle baths were equivalent in quality to conventionally dyed products.

A. Analysis System

The very strong absorption of dyes in the visible region of the spectrum provides the simplest and most precise method for determination of dye con-

centration. The absorbance, A, of a dye solution can be related to the concentration by the modified Lambert-Beer equation [4]:

$$A = \log I_0 / I = Kc$$

where I_0 is the intensity of the visible radiation falling on the sample, I is the intensity of the radiation transmitted by the sample, K is a constant including the path length of radiation through the sample and a constant related to the absorptivity of the sample at a given wavelength and c is the concentration of the absorbing species. In mixtures of absorbing species, the absorbance at any wavelength is the sum of the absorbances of each absorbing species and is given by:

$$A_{\lambda} = K_1 c_1 + K_2 c_2 + K_3 c_3 \dots + K_n c_n$$

This characteristic of light absorption by dyes is important in the analysis of dye mixtures of the type found in spent dyebaths. For such dye mixtures, the absorbance can be measured at a number of wavelengths and the concentration of the dyes determined by simultaneous solution of a set of linear equations of the type shown above. The wavelengths selected for the analysis are generally those for which one of the dyes gave a maximum in absorbance.

A second procedure for obtaining dye concentrations from absorbance data was developed for very complex dye mixtures. In this procedure the absorbance of the spent dyebath was measured at sixteen (16) equally spaced wavelengths from 400 to 700 nm. The dye concentrations were determined from a leastsquares fit of the absorbance curve at these sixteen wavelengths. A computer program in FORTRAN IV was developed to determine the concentrations of up to six (6) dyes in a mixture by this technique.

The Lambert-Beer relationship is generally invalid for absorbing species that are not in solution. Most dye classes used in this work (acid, basic, direct, reactive) are soluble in the dyebath and the spectrophotometric analysis could be carried out directly on the dyebath. Disperse dyes, however, are not water soluble and required development of techniques to give true dye solutions. In disperse dye analysis the spent dyebath sample was placed in a separatory funnel, a measured quantity of an organic solvent (benzene or toluene) was added and the mixture shaken to extract the dye into the organic layer. The spectrophotometric analysis was then carried out on the dissolved dye in the organic solvent. Standards for calculation of the K values for disperse dyes were treated in the same way to insure accuracy of the procedure.

Correction for absorbance of species other than dyes (background absorbance) was required also in some cases. For dyebaths containing disperse dyes and using organic solvent extraction, background absorbance presented no problem. The absorbing species other than dyes remained in the water phase. For dyes measured directly in the dyebath, a correction procedure was necessary. Samples of the textile product being dyed were treated in a "blank" bath (a bath containing all chemicals except the dyes) in exactly the same way that the yarn or fabric would be dyed. Samples of the "blank" dyebath were then used to obtain standard absorption data for the blank dyebath and background K values were calculated in the same way as described above for dyes. The background absorbance could then be treated like another dye. Thus, a dyebath with three dyes would be treated as if it contained four dyes with the fourth dye being the background absorbance.

A further advantage of spectrophotometers is the ready availability of

a number of low cost instruments with sufficient accuracy and reproductivity for dyebath analysis. Much of the work in the current study was carried out on a single beam grating spectrophotometer costing approximately \$2,000. The computations necessary in the analysis can be conveniently carried out on low-cost desk calculators or microprocessors. The calculations necessary for a four-dye mixture (or three dyes plus background) can be handled on a system costing less than \$1,000. Even the least-squares fit of sixteen (16) points of the absorption spectrum can be carried out on a \$3,000 minicomputer. Development of these low-cost instrument-minicomputer systems is largely responsible for consideration of dyebath reuse as a practical reality for textile dyeing.

Accurate analysis for dyebath components other than dyes has not been required. These dyebath additives generally control the dyebath environment and are not used up or removed during the dyeing cycle. In general, these components were added to the reuse baths in direct proportion to the quantity of make-up water added to baths between dyeings. For example, if 20% of the dyebath was lost during the dyeing (primarily due to removal with the wet goods) then 20% of the original quantities of pH control agents, wetting agents, etc., was added to the bath being reused. This procedure worked very well for the series of thirteen or fourteen dyeings in the same bath.

B. Evaluation Procedures

Three important characteristics of textile products dyed by the reuse procedure were measured to determine if the dyeings were of acceptable quality--the uniformity, the reproducibility and the stability or "fastness".

The uniformity was assessed by selecting representative samples from the dyed lot and determining the color (tristimulus values) on a standard

colorimeter (DIANO/LSCE Automate System). The difference in color of each specimen from the average color of all specimens was determined using the FMC II color difference formula [5]. In this system one unit of color difference is defined as the minimum perceptible difference in color. Thus, spotting or unlevel dyeings could be readily identified by variations in color difference between specimens from the same dyeing.

Reproducibility of the dyeings was determined by calculation of the color differences between dyed lots and a standard dyeing of the same shade. In this calculation the color difference was determined from average tristimulus values of each dyed lot compared to a conventional dyeing, again using the FMC II equation.

In addition to instrumental measurements, samples dyed by the reuse procedure were examined visually by expert dyers to further assess the color uniformity and color reproducibility.

Dyed samples were also evaluated for resistance to color change by rubbing (crockfastness), exposure to light (lightfastness), and exposure to water (wet-fastness). Standard test methods recommended by the American Association of Textile Chemists and Colorists were used in the fastness evaluations.

III. APPLICATIONS OF THE REUSE SYSTEM

A. Carpet Dyeing

Initial studies of dyebath reuse were carried out on carpet samples. Preliminary bench-scale studies to evaluate the technical feasibility of dyeing in spent baths and to develop the required analytical techniques were carried out as part of a previously reported [6,7] research program. The current work was undertaken to scale-up the dyebath reuse system for

carpet dyeing. All dyeings were carried out in a four-foot beck capable of dyeing thirty to forty-pound carpet samples. This is the same equipment that is normally used in a carpet dyehouse for development work. Two of the carpet experimental trials--dyeing of nylon carpet with disperse dyes and dyeing of polyester carpet with disperse dyes--are reported here.

1. Dyeing of Nylon Carpet With Disperse Dyes

The objective of the first trial run in the pilot-scale experiments was to dye nylon carpet to the same shade five (5) times with reuse of the dyebath. The carpet used in these studies was tufted from Nylon 6 face yarn with a polypropylene primary backing. Both regular nylon and cationic dyeable yarns were used in the carpet but these types of yarns dyed to essentially the same color with disperse dyes. The carpet surface contained both cut pile and loops.

Approximately thirty-five (35) pounds of prescoured carpet were placed in the standard pilot-scale four-foot beck, cold water was added to give a liquor ratio of 25:1 (approximately 100 gallons) and the auxiliary chemicals (leveling agent, 1% owf; complexing agent, 0.5% owf; pH control agent, 1% owf) were added. The carpet was circulated through the bath for five minutes and the dyes required to give a medium green shade (Disperse Blue 7, 0.03% owf; Disperse Yellow 3, 0.35% owf; Disperse Red 55, 0.04% owf) were added over a fifteen-minute period. The bath was brought to the boil at $3^{O}F/minute$ with direct steam injection and held at the boil for forty-five minutes. The carpet removed by hand at 200°F and rinsed three (3) times in a separate machine. The water volume that was removed by the carpet and by evaporation (23 gallons) was added to the remaining bath, and only auxiliary chemicals calculated to bring the added water to the initial concentration of auxiliary

chemicals were added. The residual dye concentrations were determined using the analytical procedure detailed above. A second batch of carpet was placed in the beck after bringing the bath back to 175°F. The dyestuffs were added to the beck over a fifteen-minute period at 175°F, the bath was brought to the boil at 3°F/minute and the cycle continued as in the first run. The reuse sequence was repeated three (3) additional runs to give a total of five (5) dyed batches.

The pilot-scale dyeings of nylon (30-50 pound samples) with disperse dyes were evaluated by color measurement and color difference calculations exactly as described above. Ten (10) random samples were cut from each of the five nylon carpet sections (3' x 38') that were dyed medium green in the reuse sequence on the four-foot beck. Color differences between the samples from the four reuse runs and samples from the initial (conventional) dyeing were calculated. The tristimulus values X, Y, and Z were obtained on the Diano instrument by measuring each sample three (3) times against a white tile standard for a total of thirty (30) color measurements for each carpet length. The tristimulus values were utilized with the FMC II equation to determine the end-to-end shade variation of the carpets by averaging the tristimulus values from the thirty measurements and calculating color differences in MacAdam units between the individual sample positions and the average. The averages of the tristimulus values for all thirty measurements of each carpet section were calculated, and the color difference between those averages and the average tristimulus values for the conventionallydyed standard were calculated in order to determine overall lot-to-lot variation.

Color differences between each of ten (10) individual measurements along the carpet sample and the average for the sample for each of the

pilot-scale dyeings are shown in Table 1. These data indicate that there is little difference in end-to-end color variation between the sample dyed in the conventional manner (Run I) and samples dyed in recycled dyebaths (Runs II to V).

Reproducibility of dyeings in the recycled baths is shown in Table 2. The differences in color between the first run (conventional dyeing) and dyeings in the recycled baths were determined from the difference in the average color of each run and the average for Run I. It is clear from Table 2 that differences in color for samples dyed in recycled baths are well within the acceptable commercial range.

2. Dyeing of Polyester Carpet With Disperse Dyes

The second trial run was conducted on polyester carpet dyed with disperse dyes. In this series three shades in a color line--a light beige, a medium blue and a rust--were selected for dyeing. These colors were actual large volume shades currently being dyed by a leading carpet firm. The objective of this run was to dye polyester carpet seven (7) times (3 beige, 2 blue, 2 rust) in the same dyebath utilizing the reuse technology. In addition, the run was carried out using material handling procedures that were designed to be compatible with in-plant dyeing. The following sequence was used:

- 1) Dye a beige carpet in conventional manner
- 2) Pump dyebath to holding tank
- 3) Rinse carpet 1 in beck
- 4) Remove carpet <u>1</u> from beck
- 5) Clean fiber from rinse water
- 6) Enter carpet 2 for prescour

Position	Run I	Run II	Run III	Run IV	Run V
1	1.68	0.76	2.61	1.81	0.63
2	0.67	1.33	4.02	5.16	0.40
3	1.04	3.90	0.97	3.17	1.30
4	1.99	1.82	1.00	1.90	1.13
5	0.35	3.57	3.75	1.61	2.14
6	1.60	2.38	3.15	2.11	0.69
7	0.72	3.21	1.41	0.76	0.46
8	3.39	0.84	4.17	1.55	1.79
9	0.98	2.53	1.96	3.59	2.09
10	1.10	5.78	1.23	1.52	1.64

TABLE	1

End-to-End Color Differences in MacAdam Units of Nylon Carpet Dyed With Disperse Dyes

TABLE 2

Between Sample Color Differences for Pilot-Scale Dyeing of Nylon Carpet With Disperse Dyes (in MacAdam Units)

Run		Color Difference Versus Control
I	(Control)	-
II		1.3
III		0.4
IV		0.5
v		0.5

- 7) Drop rinse-prescour water
- 8) Pump dyebath to beck
- 9) Dye carpet 2 beige
- 10) Repeat steps 2 through 9 for carpets 2 through 7.

The dyebeck was modified by the addition of a pump and insulated holding tank for this series of runs. It should be noted also that the final rinse bath was used to give the subsequent carpet a short prescour before dropping the rinse bath.

In a typical dyeing in a previously used bath, the beck was full at the beginning of the cycle with the final rinse from the previous run (at 160°F). The carpet was entered and allowed to run for five minutes to partially remove tufting oils and fiber identification tints. The rinseprescour bath was then dropped and the dyebath used for dyeing the previous carpet pumped to the beck from the holding tanks. The dyebath temperature was 170° F. The bath was made up to volume with fresh water to give a 20:1 liquor ratio. The quantities of all auxiliaries (except carrier) were determined from the volume of fresh water required and added to the beck. The carpet was run for five minutes, the pH adjusted to 5.0-5.2, and the required quantities of dyes added to the bath over a fifteen-minute period. The carrier (10% owf) was then added slowly over a fifteen-minute period. The dyebath was raised to the boil at 6^{OF} /minute and run at the boil for one (1) hour. At the end of the dyeing the bath was returned to the holding tank and analyzed for the residual dyes. The carpet was post-scoured, rinsed, removed from the beck, and air dried.

Initial inspection of the dyed carpets suggested that good color reproducibility and uniformity had been achieved. Ten (10) samples were cut

from each of the dyed samples and the color measured on the Diano Colorimeter. Each sample was measured three (3) times to average variations due to instrument changes and sample texture differences. Tristimulus values (X,Y,Z) were calculated from the average of the three measurements.

The base color of each dyed sample was determined by averaging the ten values obtained from the ten different samples cut from each carpet. Color uniformity was evaluated by calculation of the color difference of each of the ten samples from the average value for the carpet. These results for the seven dyed carpets are shown in Table 3. The color difference values were calculated using the FMC II color difference equation.

Color differences between the beck-dyed samples and standards prepared previously in beaker dyeings by conventional dyeing procedures have also been determined. In these calculations the average color for each carpet was determined from ten measurements, and the difference of this average from the average of ten measurements on the standard was determined. These calculations give a measure of the reproducibility of the dyeings in the recycled baths and are shown in Table 4. In addition to the usual FMC II color differences, the color differences in the new C.I.E. 1976 recommended color space, L*a*b*, are shown for comparison. With the exception of the two blue samples, the reproducibility was excellent. Reproducibility in the blue samples was at the outer limit of what can be considered acceptable commercial carpet dyeing. A comparison of the two blue samples with each other showed that they were very close together in color ($\Delta e = 1.44$), but different from the standard. In both blue carpets the yellow was higher than the standard, and the samples were lighter than the standard. Addition of a small quantity of blue dye would have corrected this color difference between the samples and the standard. Since we had elected to do "no add"

TA	B	LE	3
_	-	_	-

			∆e In FM	IC II Uni	ts		
Sample Number	Beige #1	Beige #2	Beige #3	Blue #1	Blue #2	Rust #1	Rust #2
Itanber	··· 1		<u>"0</u>				
1	1.14	1.93	1.97	1.15	2.37	1.16	1.54
2	2.97	2.58	0.97	1.00	0.93	1.51	0.81
3	3.30	0.95	0.87	1.27	0.28	1.00	2.86
4	0.99	3.40	0.99	0.64	0.89	0.76	1.23
5	0.89	1.89	1.26	0.96	1.09	1.42	2.68
6	4.28	1.44	1.70	2.46	1.29	0.53	0.47
7	0.66	0.85	1.27	2.56	0.94	2.77	0.81
8	3.03	0.93	1.73	2.02	1.23	1.39	2.03
9	4.59	1.81	1.33	0.76	1.24	0.89	1.82
10	4.49	1.64	0.74	2.33	2.82	2.92	1.44

Color Uniformity in Polyester Carpet Dyeings With Dyebath Reuse

TABLE 4

Color Reproducibility in Polyester Carpet Dyeings With Dyebath Reuse

Sample	FMC II ∆e	CIE L*a*b* ∆e
Beige #1	0.44	1.22
Beige #2	0.76	0.43
Beige #3	0.27	0.09
B1ue #1	4.85	3.64
Blue #2	3.74	2.50
Rust #1	1.70	1.17
Rust #2	1.80	1.25

dyeing in this series, this dye-add was not made. A slight modification of the dye formula would have corrected the small difference between the blue samples and the standard.

In addition to instrumental color measurements, the dyed carpets have been examined visually by four experienced carpet dyehouse supervisors. All four agreed that both the nylon and polyester carpet dyeings were acceptable as first-quality in both color uniformity and color reporducibility.

Measurement of the fastness properties of the dyeings to light, crocking and water were also carried out. These results are shown in Tables 5, 6, and 7. All dyeings appear to have commercially acceptable fastness properties.

3. Economic Evaluation of Carpet Dyeing With Dyebath Reuse

The energy, materials and cost savings that are possible with reuse of the dyebath are dependent on a number of factors. These include the type of yarns, the shade being dyed, the number of times the bath is used, the type of auxiliary chemicals used, and the temperature of incoming water. All of these will influence the possible reduction in materials, energy and cost. Calculations of these savings have been carried out based on the two pilotscale dyeings of carpet discussed above. These savings are shown in Table 8. The reductions in dye, chemical, and water requirements with recycle of the dyebath were determined directly from the quantities of materials used in the pilot-scale dyeings. Since the beck used was not equipped with energy monitoring devices, the energy reductions were calculated. An example of the energy reduction calculations are given in Table 9.

These results suggest that significant reductions in water use, chemical requirements, energy requirements and cost can be achieved by dyeing carpet with reconstitution and recycle of the dyebath.

Evaluation of Light Fastness for Polyester Carpet										
Dyed by the Reconstituted Dyebath Method										
Color	Dyeing	24 Hours	48 Hours	72 Hours	96 Hours	120 Hours				
Beige	1	5	5	5	4-5	4-5				
Beige	2	5	5	5	4-5	4-5				
Beige	3	5	5	5	4-5					
Blue	4	5	5	5	5	4-5				
Blue	5	5	5	5	4-5	4-5				
Rust	6	5	5	5	5	5				
Rust	7	5	5	5	5	5				

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TABLE 6

Evaluation of	f Fastness to D	ry Crock for Poly	ester Carpets
Dyed	By the Reconst	ituted Dyebath Me	thod
	Dyeing	Rat	ing
Shade	Number	Sample 1	Sample 2
Beige	1	5	5
Beige	2	5	5
Beige	3	5	5
Blue	4	5	5
Blue	5	5	5
Rust	6	5	5
Rust	7	4-5	4-5

TABLE 7

Evaluation	of	Fastness	to	Water	for	Po1y	vester	Carpets
Dyed	by	the Recor	ist	ituted	Dyel	bath	Method	1

Shade	Dyeing No.	Rating
Beige	1	5
Beige	2	5
Beige	3	5
Blue	4	5
Blue	5	5
Rust	6	5
Rust	7	4-5

		Reduction in %
·	Nylon, Disperse Dy <u>5 Cycles</u>	es Polyester, Disperse Dyes 7 Cycles
Dyes	3	7
Chemicals	65	7
Water	34	39
Energy	27	27
Cost	27	12

Reduction in Materials, Energy, and Cost By Reuse of Dyebaths in Carpet Dyeing

TABLE 8

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Cost Summaries for Carpet Dyeing

	Nylon, Dispers 5 Cycles Conventional	se Dyes Reuse	Polyester Disperse Dy <u>7 Cycles</u> Conventional	res Reuse
Dyes (Data and Cost)	2.18	2.11	10.25	9.70
Chemicals (Data and Cost)	1.35	0.47	7.29	6.57
Water (Data and 45¢/1000)	0.45	0.29	0.26	0.07
Energy (Calc. and \$3 per 10^6 BTU)) 3.99	2.91	5.43	3.74
TOTAL COST	\$ 7.97	5.78	22.93	20.08
COST PER #	0.046	0.033	0.094	0.082
SAVINGS %	27.	5	12.4	ŀ
SAVINGS ¢/#	ŧ 1.	3	1.2	2

Energy Savings for Pilot-Scale Dyeings <u>Nylon With Disperse Dyes</u> (5 Cycles)

BASIS: 35# Carpet Samples, 875# Water (105 Gallons), 25:1 Liquor Ratio Incoming Water at 60°F Make-up Water Required Each Cycle ~25 Gallons Dyeing Temperature 212°F, Rinse Temperature 120°F Efficiency of Energy Utilization at Beck 90% Reuse Entry Temperature 170°F Steam Required to Hold at Boil 1#/Gal/Hour Carpet Retains 300% Water Between Processes

Conventional Dyeing

Heat Bath 60°F to 212°F (152° x 875# x 1.11 x 1 BTU/#) = 14.76×10^4 BTU Heat Carpet 60°F to 212°F (152° x 35# x 1.11 x 0.5 BTU/#) = 0.30 x 10⁴ BTU Hold at Boil for 45 min. (105 Gal x 1000 BTU/Lb. x 0.75 Hr) = 7.88 x 10⁴ BTU Rinse at 120°F (60°x 770# x 1.11 - [140# x 92° + 35# x 92° x 0.5] = 3.68 x 10⁴ BTU TOTAL PER CYCLE = 26.62×10^4 BTU TOTAL 5 CYCLES = 1.33×10^6 BTU BTU/POUND CARPET = 7,600Reuse Dyeing Heat Make-up Water 60° to 170°F (110 x 100# x 1.11 x 1 BTU) = 1.22 x 10⁴ BTU Heat Retained Prescour Water 120° to 170°F (50° x 100# x $1.11 \times 1 \text{ BTU}$ = $0.56 \times 10^4 \text{ BTU}$ Heat Bath 170° to 212°F (42° x 875# x 1.11 x 1 BTU/#) = 4.08 x 10⁴ BTU = .18 x 10⁴ BTU Heat Carpet 120° to 212°F (92° x 35# x 1.11 x 0.5 BTU/#) $= 7.88 \times 10^4 BTU$ Hold at Boil 45 min. (105 Gal x 1000 BTU/Gal x 0.75 Hr)

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x 0.5]) = 3.68 x 10<sup>4</sup> BTU
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TOTAL PER REUSE CYCLE = 17.60 \times 104 \text{ BTU}
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TOTAL CYCLES (1 CONVENTIONAL + 4 REUSE) = 0.97×10^6 BTU

BTU/POUND CARPET DYED = 5,543

ENERGY SAVINGS 27% ENERGY SAVINGS 2,057 BTU/POUND CARPET DYED

Rinse at 120°F (60° x 770# x 1.11 - [140# x 92° + 35# x 92°

The estimated cost for a medium size (10 beck) carpet mill to convert 50% of dyeing capacity to the dyebath reuse system is shown in Table 10. The calculation assumes the purchase of new equipment with separate holding tank and pumping system for each of the five becks. At an estimated savings of one cent per pound of carpet dyed (considerably less than indicated in the previous cost analysis) the payback time for the installation is less than one year.

B. Batch Dyeing of Nylon Pantyhose

Hosiery is colored exclusively by batch dyeing processes. The two main types of equipment utilized are the overhead paddle machine and the rotating drum machine. In hosiery dyeing a very limited range of dyes and auxiliaries are employed. Thus, hosiery dyeing presented an excellent opportunity for application of the reuse dyeing technology.

Nylon pantyhose dyeing was selected for initial pilot-scale studies. Both Nylon 6 and Nylon 66 are used in pantyhose and both types are dyed to various shades of brown and black with disperse dyes. The same three disperse dyes are used to produce the majority of shades.

An eight-pound rotary drum machine was equipped with a holding tank and pumping system for the reuse studies. Recipes for three Nylon 66 shades (light, medium, and dark brown) and two Nylon 6 shades (medium and dark brown) were obtained from a leading hosiery manufacturer. Preliminary experiments indicated that these shades could be dyed in any desired order by reconstitution and reuse of the dyebath. The dyeing procedure which was developed for the experimental trial is shown in Table 11. The first cycle is a conventional dye cycle with each reuse cycle after the first essentially identical. Note that in the reuse runs the rinse water from the previous cycle

Payback on Capital Costs

BASIS: Plant with 10 becks--5 to be modified for reuse Capacity 2,000 pounds per cycle, 6 cycles per day per beck No additional personnel required Savings using dyebath reuse, 1¢ per pound of carpet dyed. No productivity increases are assumed

CAPITAL COSTS:	Hold tanks (new)	20,000	each	x 5	100,000
	Pumps	3,000	each	x 5	15,000
	Piping, valves	1,500	each	x 5	7,500
	Analysis Equipment				7,000
				TOTAL	COST 129,500

RETURNS:	Production 5 Becks x 2000#/Beck x 6 Cycles/Day	=	60,000#/Day
	Returns per day 60,000#/Day x 1¢/#	=	\$600/Day
PAYOUT:	\$129,500/\$600	=	216 Days

Procedure for Dyeing Pantyhose With Dyebath Reuse

- I. Dyeing Batch I -- Conventional Cycle
 - 1. Load machine
 - 2. Fill with cold water, raise to $90^{\circ}F$
 - Add auxiliary chemicals (1% dyeing assistant, 1% leveling agent 0.5% wetting agent) run 10 minutes
 - 4. Add dyes
 - 5. Raise temperature 3°F/minute to 170°F
 - 6. Run 20 minutes at 170°F
 - 7. Sample, make adds if necessary
 - 8. Pump dyebath to holding tank, sample and analyze
 - 9. Refill with cold water
 - 10. Heat rapidly to 110°F
 - 11. Add softener and run 10 minutes at 110°F
 - 12. Unload machine
- II. Dyeing Batch II -- Reuse Cycle
 - 1. Load machine
 - Add prescour chemical (1% dyeing assistant) to finish bath in machine
 - 3. Run 5 minutes
 - 4. Discharge finish-prescour bath to drain
 - 5. Pump dyebath from holding tank to dyeing machine
 - 6. Add necessary auxiliaries to reconstitute the bath
 - 7. Add dyes to reconstitute the bath slowly from add tank (~10 minutes)
 - 8. Raise temperature 3°F/minute to 170°F
 - 9. Run 20 minutes at 170°F
 - 10. Sample, make adds if necessary
 - 11. Pump dyebath to holding tank, sample and analyze
 - 12. Finish as above (Steps 9-12)
- III. Dyeing Batches III, IV, V, etc. -- Same as Batch II

was used for a quick prescour of the hosiery before dyeing. This prescour was used to partially remove knitting oils and fiber finish which could build up in the dyebath and affect the reuse dyeing.

The fibers and shades dyed in the pilot-scale run are shown in Table 12. Approximately eight (8) pounds of pantyhose were dyed in each run. All shades were dyed with the same red, yellow, and blue disperse dyes. It should be noted that both fiber types and light and dark shades were randomly mixed during the thirteen runs.

Five (5) specimens were cut from the legs of each of three pair of pantyhose randomly chosen from each of the thirteen runs and the colors of each specimen measured on the Diano LSCE Automate. Color differences were calculated between the samples from each run and plant standards for each of the shades. These color differences (calculated by the FMC II equation) are shown in Table 12. Similar measurements on color tolerance standards used by the plant for two of the shades gave a color difference of 7.8 for the Medium II shade and 2.9 for the Dark II shade. Thus, color differences for the reuse dyeings were well within commercial standards for those shades. In fact, all dyeings were well within normally accepted standards for hosiery dyeing. The dyed hosiery were returned to the participating company and were shipped as first-quality goods.

IV. PLANT DEMONSTRATION OF DYEBATH REUSE TECHNOLOGY

Based on the successful pilot-scale work on dyeing with reconstitution and reuse of dyebaths, a plant-scale demonstration of the reuse technology has been conducted. The demonstration was carried out in the dyehouse of the Ladies' Wear Division of the Adams-Millis Hosiery Company.

Run Number	Fiber Type	Shade*	Color Difference Versus Standard
1	66	Light I	2.0
2	66	Medium I	4.2
3	6	Medium II	2.9
4	6	Dark II	1.9
5	66	Dark I	2.8
6	66	Light I	2.0
7	66	Medium I	3.0
8	6	Medium II	2.2
9	6	Dark II	2.4
10	66	Dark I	2.4
11	66	Light I	3.0
12	6	Medium II	3.4
13	66	Light I	4.2

TABLE 12						
Dyeing	of	Nylon	Pantyhose	With	Dyebath	Reuse

*A total of 5 shades were utilized. The numeral \underline{I} refers to a Nylon 66 shade, and the numeral II refers to a Nylon 6 shade.

A standard 100-pound rotary drum machine was modified by addition of a holding tank, pumping system, water meter and steam measuring equipment. The machine had been equipped previously with a temperature control system and an add tank. Thus, the dyeing machine could be operated in both the conventional manner and in the dyebath reuse mode with monitoring of all materials and energy inputs. In addition to machine modifications, the dyehouse laboratory purchased a Bausch and Lomb Spectronic 100 spectrophotometer and a Hewlett-Packard Model Number 9815A computer for use in dyebath analysis. Cost of the analytical equipment and computer was approximately \$7,000. An interface was constructed so that the computer could read absorbance data directly from the spectrophotometer. Programs were written to permit the computer to calculate and print out the quantities of dyes and auxiliary chemicals needed to reconstitute the spend dyebath to the level desired for the subsequent dyeing.

Before beginning the reuse study, fifteen (15) conventional dye cycles were run to provide baseline data for comparison with the reuse dyeings. Energy, water, dye and chemical requirements for pantyhose dyeings were determined from this fifteen-cycle run.

Following the fifteen conventional dye cycles, three series of dyeings were carried out with reconstitution and reuse of the dyebath. In the first series the dyebath was used five times before discharge to drain. This series served to check out the reuse system and establish operating procedures. The second series consisted of seventeen dyeings in the same dyebath. In this series the rinse water from each cycle was used to prescour the next load to be dyed similar to the laboratory dyeings. The third series consisting of fourteen dyeings in the same bath was conducted in the same manner as Series II except that the hosiery were not scoured before

dyeing. Materials and energy requirements for the reuse dyeings were monitored in exactly the same way as the conventional dyeings.

The sequence of dyeings in the Series II, seventeen-cycle run, is shown in Table 13. It should be noted that both fiber types and light and dark shades were indiscriminately mixed in the run. No problems were encountered in dyeing a light shade following a dark shade.

The materials and energy requirements for the fifteen-cycle conventional dye series and for the seventeen- and fourteen-cycle reuse series combined are shown in Table 14. It is apparent that the reuse dyeings gave substantial reduction in energy, water, chemical and dye requirements. The dye savings are related, of course, to the particular shades dyed in the various runs but reductions in chemicals, water, and energy are essentially independent of the shades being dyed. Cost reductions achievable with reuse dyeing are shown in Table 15. Dyeing costs were calculated using current quoted prices for chemicals, dyes, energy, water and sewer service.

Several important aspects of plant implementation of dyebath reuse were revealed by the demonstration runs. First, the analysis time was reduced during the course of the demonstration from thirty (30) minutes to approximately ten to fifteen (10-15) minutes with no apparent loss in required accuracy. In this time the analysis could be readily completed during the usual rinse cycle and the dyes weighed and ready for the next load.

Second, the third series of dyeings indicated that prescouring of the hosiery was unnecessary. No differences in the analysis of the bath or the quality of the dyeings were detected in the third series. Removal of the prescour step provided a dyeing cycle more compatible with the normal plant operation. About the only difference in Series III runs and conventional runs was that at the conclusion of dyeing the dyebath was pumped to

Series II Seventeen Reuse Cycles

21	Ny1on	66	Light shade
22R	Nylon	66	Medium shade
23R	Nylon	6	Medium shade
24R	Ny1on	6	Dark shade
25R	Nylon	66	Dark shade
26R	Nylon	66	Light shade
27R	Nylon	6	Medium shade
28R	Nylon	66	Light shade
29R	Nylon	6	Medium shade
30R	Nylon	6	Dark shade
31R	Ny1on	66	Light shade
32R	Nylon	66	Medium shade
33R	Ny1on	6	Medium shade
34R	Ny1on	6	Dark shade
35R	Ny1on	66	Medium shade
36R	Nylon	66	Light shade
37R	Nylon	66	Medium shade

Materials and Energy Reduction Reuse Dyeing

ENERGY

Conventional	2.18	Pounds	Steam/Pound	Fiber	Dyed
Reuse	0.94	Pounds	Steam/Pound	Fiber	Dyed
Reduction	57%				

WATER

Conventional	4.08	Gallons/Pound	Fiber	Dyed
Reuse	2.31	Gallons/Pound	Fiber	Dyed
Reduction	43%			

CHEMICALS

Conventional	1.17	Pounds/Pound	Fiber	Dyed
Reuse	0.76	Pounds/Pound	Fiber	Dyed
Reduction	35%			

DYES

Conventional	0.0058	Pounds/Pound	Fiber	Dyed
Reuse	0.0047	Pounds/Pound	Fiber	Dyed
Reduction	19%			

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Energy and Material Cost Reduction in Reuse Dyeings

COST PER DYE CYCLE:

Conventional	\$4.66
Reuse	\$2.98

COST	PER	POUND	OF	FIBER	DYED:	
Conventional					5.25¢	
		Reuse				3.28¢

COST REDUCTION:

37%

a holding tank rather than being discharged to the drain and the beck was filled with used dyebath rather than fresh water in the subsequent cycle.

Careful records were kept of the number of adds required to produce the desired shade in both conventional and reuse dyeings. Savings from dyebath reuse could be rapidly lost if more adds were necessary in reuse dyeings. The fifteen conventional cycles required a total of eleven (11) adds for an add rate of 0.73 adds per cycle. The thirty-one reuse cycles required twelve (12) adds for a rate of 0.39 adds per cycle. Thus, the number of adds required in the reuse dyeings were actually less by 47%.

The hosiery dyeing plant runs clearly demonstrated that reuse dyeing can be incorporated in a commercial operation with no loss in quality or productivity and with substantial savings in materials and energy costs. Additional plant demonstrations of the reuse technology are planned for carpet dyeing and for dyeing of polyester/cotton blend yarn packages. Laboratory work is also being carried out on jet dyeing of knit fabrics.
ACKNOWLEDGEMENTS

The authors gratefully acknowledge the funding of this work by the Department of Energy. Further details on reuse technology will appear in reports issued by the Department of Energy.

The plant demonstration phase of this work was made possible by the generous support and assistance of the management and personnel of the Adams-Millis Hosiery Company.

The substantial contributions to the laboratory phase of the project by Mrs. Lynn Averette and Mr. Jimmy Wadia, student research assistants, are gratefully acknowledged.

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DEVELOPMENT AND DEMONSTRATION OF ENERGY-CONSERVING DRYING MODIFICATIONS TO TEXTILE PROCESSES

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Part II, Phase III Extension of DOE Contract No. EY-76-S-05-5099-004

titled

ENERGY CONSERVATION IN THE TEXTILE INDUSTRY

Submitted to the Department of Energy by

The School of Textile Engineering and The Engineering Experiment Station at The Georgia Institute of Technology Atlanta, Georgia 30332

> Dr. David S. Brookstein Assistant Professor (404)894-2535

> > 30 January 1979

Summary of Effort

The first quarter of this project has been completed with success. The Machnozzle is fully operational and early experiments indicate that significant energy savings can be realized during drying. A visit to the University of Twente in Enschede, Holland was made to discuss the use of the Machnozzle in drying. This trip enabled Dr. David Brookstein to discuss the operation of the nozzle with Professor Van der Linden and Dr. Clemants Theusink. Their advice led to the development of a reel for transporting the fabric through the nozzle. They also provided further insight into the theory of operation for the Machnozzle. The concept of the Machnozzle as a device which imparts significant amounts of kinetic energy through the development of shock waves was dispelled. Instead the Machnozzle is viewed as a vacuum slot acting in reverse, that is a device in which a relatively large pressure differential across the fabric can be obtained.

The problem of steam condensation in the Machnozzle was discussed. This condensation, if allowed to occur, will reduce the effective flow resistance in the nozzle and will result in increased steam usage. The solution to this problem is to allow the nozzle to heat up before it is used and steam measurements are taken.

A mathematical simulation of steam can dryer has been initiated to continue the development of an optimization program for steam can dryers in industrial use. This simulation will lead to an automatic control program for minimizing steam use. Discussions with textile industry representatives indicate that there is an immediate need for this program. A new potential Ph.D. candidate has chosen this area for his thesis research under the supervision of Drs. Brookstein and Carr.

Machnozzle System Modifications

During the last three months there have been several modifications to the Machnozzle system. These include:

- Development of a reel to store and deliver fabrics to the drying unit as needed. This reel eliminates the need for sophisticated fabric guiding equipment which is necessary when the system is operated with a continuous loop of fabric.
- Development of a squeeze roll weighting system.
 This is necessary so that the fabric is conventionally dewatered to as low a level as possible prior to treatment by the Machnozzle.
- Development of a fabric tensioning device Experiments at the University of Twente in Enschede, Holland indicate that maximum fabric tensions result in maximum overpressures and subsequent drying.
- Installation of a vacuum slot to reduce water content on fabric prior to Machnozzle treatment.

During the next quarter, a system for keeping the steam pressure within a tolerance of \pm 1 psi will be installed on the Machnozzle system.

Experimental Results

Experiments conducted during the reporting period have been encouraging. A typical sheeting fabric (3.5 oz/yd² 65% polyester/35% cotton) was tested on the Machnozzle experimental system. Four test conditions were examined. These were:

- Test Condition #1: 140 lbs nip pressure on squeeze rollers, no vacuum, full nozzle width 16 inches operating on 10 inch wide fabric, no additional fabric tension
- Test Condition #2: 180 lbs nip pressure on squeeze rollers, squeeze twice, no vacuum 10 inch nozzle operating on 10 inch wide fabric, no additional tension.
- Test Condition #3: Increased fabric tension, vacuum slot, 180 lbs nip pressure, 10 inch nozzle operating on 10 inch wide fabric
- Test Condition #4: Increased fabric tension, vacuum slot off, 10 inch nozzle operating on 10 inch wide fabric 180 lbs nip pressure.

The average results of these experiments are given in Table I.

The results should be examined in view of the fact that typical thermal drying after conventional mechanical dewatering (squeeze rollers) uses about 2.5 lbs of steam per pound of water removed. For each test condition, the steam usage was independent of fabric speed. This finding is significant since higher fabric speeds result in greater amounts of wet fabric presented to the Machnozzle. However the moisture level after the nozzle increases with the increasing fabric speed.

		IG	our	rs/min.	Ave	rage Moisture	Level,	Weight of Water Weight of Dry Fabrics X 1	.00
	Test Condition	Steam Pressure, PS	Steam Usage, 1bs/h	Fabric Speed, mete	After Nozzle	After Vacuum Slot	After Rolls	Pounds of Steam Used per Pound of Water Removed	
	#1	85-90	82	20	59	-	96	3.81	
				60	73	-	97	1.43	
				80	76	-	98	1.17	
	#2	85-90	50	20	57	-	88	2.02	
				60	67	-	87	1.05	
				80	69	-	90	.75	
	#3	85-90	70	20	50	79	89	3.80	
				60	67	84	90	1.72	
				80	69	87	90	1.22	
<u></u>	#4	85-90	65	20	57		89	2.62	
				60	68		90	1.24	
				80	71		92	.97	

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Table I.

The energy use (lbs of steam per pound of water removed) is calculated in the following manner:

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				Steam Us	e				
Energy l	Jse	=	(Fabric	Speed)(Fa	bric	Width)(Weight	of	Fabric)	х
			(2	• Moisture	Cont	tent)			

From the relationship it can be seen that if the fabric speed increases at a greater rate than the Δ moisture content decreases, the energy use will be reduced. This situation is present for all test conditions.

The results show that the minimum energy use occurs during Test Condition #2 at 80 meters/minute. The energy use here is .75 lbs of steam per pound of water removed.

The energy savings for Test Condition #2 at 80 meters/minute is determined in the following manner.

 $1 - \frac{(.90 - .69)(.75 \text{ lbs of steam}) + (.69)(2.5 \text{ lbs of steam})}{(.90)(2.5 \text{ lbs steam})} = 13\%$

If the Machnozzle is isoenthalpic, as is expected, the energy savings is 23%.

Clearly, energy saved when using a Machnozzle in the drying process is substantial.

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Optimization Program for Steam Can Dryers

The optimization program for steam can dryers has begun. The objective of the program is to determine values of the can dryer input parameters:

- 1.) Fabric weight, construction, and components
- 2.) Fabric throughput speed
- 3.) Can/medium temperature
- 4.) Fabric incoming moisture content

that will optimize:

- 1.) Fabric outgoing moisture content
- 2.) Energy consumption
- 3.) Productivity

Since the input parameters are numerous, a totally experimental approach to optimization would require extensive experimental testing. Therefore, a mathematical model of the can dryer capable of predicting the effects of varying input variables on output variable is needed. Thus, a thorough literature search was made to determine the state of the art in can drying. Although very little information on can drying in the textile industry is available, a considerable amount of work has been published concerning can drying in the pulp and paper industry. However, the mathematical models used to simulate can drying of paper have been oversimplified and do not adequately describe the phenomena controlling drying. Since an adequate can dryer model was not found in the literature, the can drying process is currently being modeled. The governing equations, initial conditions, and boundary conditions have been written. The resulting equations are second order and nonlinear. Approaches for solving the equations are currently being considered. Work on the can dryer model will continue next guarter.

Future Work

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The Machnozzle system will be tested with different weights of fabric to determine its universality. Further, several different operating conditions will be investigated. These include effect of fabric tension, level of predrying and wrap angle on the slot. The steam exhaust from the nozzle will be mixed with fresh water to determine how much heat can be recovered for use in subsequent textile operations.

The installation of a Machnozzle on a commercial scale will be discussed with a large, textile finisher in Georgia. There will be no cost to DOE since this installation can be accomplished under the State of Georgia Industrial Energy Extension Service.

Further work on the simulation of the dryer can operation will be carried out. It is expected that the physics and mathematics of this simulation can be reported in full in the next monthly report.

DEVELOPMENT AND DEMONSTRATION OF ENERGY-CONSERVING

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DRYING MODIFICATIONS TO TEXTILE PROCESSES

Part II, Phase III Extension of DOE Contract No. EY-76-S-05-5099-004

titled

ENERGY CONSERVATION IN THE TEXTILE INDUSTRY

Submitted to the Department of Energy by

The School of Textile Engineering and The Engineering Experiment Station at The Georgia Institute of Technology Atlanta, Georgia 30332

> Dr. David S. Brookstein Assistant Professor (404)894-2535

28 February 1979

Summary of Effort During February

A system for maintaining the steam pressure within a tolerance of \pm 1 psi was installed on the Machnozzle system. Subsequently new runs were completed in which the wrap angle around the Machnozzle was increased to the maximum allowable. The results obtained from these runs indicated that a moisture level of around 20% could be achieved. These values were obtained with a new roll of fabric. Since the results were dramatically different from those reported in last month's report, the fabric was examined. Upon examination it became apparent that the fabric had a surface treatment which prevented adequate wetting.

Accordingly the experimental program was duplicated and at 87.5 yds/minute fabric which entered the Machnozzle at 90.8% moisture content exited at 36.2%. The operating conditions for this experiment were:

minute

Fabric Weight: 3.5 oz/yd^2

Fabric Weight:	3.5 oz/y
Fabric Width:	8 inches
Fabric Speed:	87.5 yds/
Incoming Moisture Content:	90.8%
Exit Moisture Content:	36.2%
Steam Usage:	148#/hr
Moisture removed:	136#/hr
Steam Used Per Pound of Water Removed:	1.08#/hi

The energy savings are calculated in the following manner:

Steam Cans only

2.5 lbs of steam	$x = \frac{.91 \text{ lb of water}}{.91 \text{ lb of water}}$	2.27 Ibs of steam
1b of water removed	lb of fabric	lb of fabric

Machnozzle followed by steam can

$$(1.08 \frac{1\text{bs of steam}}{1\text{b of water removed}}) (.55 \frac{1\text{b of water}}{1\text{b of fabric}}) + (\frac{2.5 \text{ lbs of steam}}{1\text{b of water removed}}) (\frac{.36 \text{ lb of water}}{1\text{b of fabric}}) = 1.49 \frac{1\text{bs of steam}}{1\text{b of fabric}}$$

The savings are

$$1 - \frac{(1.08)(.55) + (2.5)(.36)}{(.91)(2.5)} = 34\%$$

If the Machnozzle is isoenthalpic, as will be determined, the energy savings are 60%.

During the last month, the diffusion model for conduction drying was analyzed. From this study it became apparent that a value for the diffusion coefficient of water in fabric and the effective thermal conductivity of the drying fabric are unavailable. Accordingly, a goal has been set to determine these values during the steam can drying analysis.

Work Scheduled For March

During the month of March a 100% cotton fabric will be evaluated in the Machnozzle. The 100% cotton fabric is usually a difficult material to dry because of its inherent hydrophillicity.

Further optimization work on the condensing system for the Machnozzle will continue. Hopefully within the next month the degree of isoenthalpic behavior will be determined.

Lastly, during March the hot fluid cans will be arranged to dry fabric after treatment by the Machnozzle. This effect will provide an explicit example of the reduction in steam needed to dry fabrics when a Machnozzle is used.

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DEVELOPMENT AND DEMONSTRATION OF ENERGY-CONSERVING DRYING MODIFICATIONS TO TEXTILE PROCESSES

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Part II, Phase III Extension of DOE Contract No. EY-76-S-05-5099-004

Titled

ENERGY CONSERVATION IN THE TEXTILE INDUSTRY

Submitted to The Department of Energy

by

The School of Textile Engineering

and

The Engineering Experiment Station

at

The Georgia Institute of Technology Atlanta, Georgia 30332

> Dr. David S. Brookstein Assistant Professor (404)894-2535

> > 31 March 1979

SUMMARY OF EFFORT DURING MARCH

This month work continued towards completing the experimental program of determining energy conservation with the Machnozzle. The experimental program is focused on determining the residual moisture content and the amount of energy used for the operating conditions listed below.

*

Mach Nozzle Polyester Cotton

Speed (m/min)	Initial Wrap (- ⁹)	100 ⁹ Wráp	60 ⁰ -80 ⁰ Wrap	
(m/min)	Steam Flessure (psig)	**************************************		
20	95	95, 75, 50*	95, 75	
60	95	95, 75, 50*	95, 75	
80	95	95, 75, 50*	95, 75	
110		95		

* depends on results of 75psig runs

Mach Nozzle

100% Cotton	100% Cotton Denim (trouser weight)	100 % polyester
95 psig, 100 wrap	95 psig, 100 wrap	95 psig, 100 wrap
speed (m/min)	speed m/min	speed m/min
20	20	20
60	60	60
80	80	80

During the month of March, further design work on the hot fluid can system was completed. A schematic of this system is included at the end of this report. The experimental can system contains the following features:

- 1. Mobiltherm heating media $100^{\circ}F \rightarrow 350^{\circ}F$
- 2. Centrifugal pump
- 3. Two drying cans each six inches in diameter
- 4. Immersion heater and controller
- 5. Expansion tank
- 6. Temperature monitoring

This system which will be completed by the end of May will allow a determination of a complete family of moisture content/residence time behaviors to be studied for the family of fabrics which are currently being texted with the Machnozzle. An example of how this behavior will be used is provided in the following argument. Consider the drying behavior of a fabric dyed on the can system without having been subjected to the Machnozzle. The residence time can be related to amount of cans needed for drying if the fabric speed is constant. Now if the Machnozzle is used to predry the fabric the drying curve reaches the drying level sooner. This condition will require less drying cans and accordingly less steam. The experimental program will be aimed at determining the energy savings when the dryer can system is optimized.

WORK SCHEDULED FOR APRIL

During April the following efforts will take place:

- 1. Continuation of Machnozzle experimental program.
- 2. Optimization of condensing system for Machnozzle.

- 3. Drying can test stand development.
- 4. Determination of physical constants needed for dryer model.
- 5. A program for testing the Machnozzle under in-plant conditions is being negotiated with the King Finishing Company of Spartan Mills in Statesboro, Georgia.

This program will be at no cost to D.O.E. King Finishing is cooperating with Georgia Tech's Industrial Energy Extension Service. The Machnozzle will be placed in the Number 1 dye range between the last squeeze roll and the steam cans. Currently King uses 45 cans to dry 3.5 oz./yd.² sheeting fabric. The amount of cans which are necessary to dry the fabric after Machnozzle treatment will be determined. From this determination the resulting energy savings will be documented.

EXPERIMENTAL CAN SYSTEM



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> > 30 April 1979

I. MACHNOZZLE PROGRAM

During April the effect of fabric wrap angle on the Machnozzle and the drying potential for 100% cotton fabrics were studied.

A. Wrap Angle Evaluation

Figure 1 illustrates the geometry of the wrap angle and fabric. During April a set of experiments were conducted to determine if the moisture level of a 50/50 blend of polyester and cotton fabric weighing 3.5 oz/yd² could be altered by changing the relative fabric geometry.

The fabric was run by the Machnozzle at 80 meters/minute and the Machnozzle was operated with 95 psig steam. The results of the experiment are given in Table I.

These data show a remarkable dependence of moisture content on wrap angle. In particular when the fabric touches the face of the Machnozzle the moisture content is reduced to 23.9%. At this writing we can only speculate as to why the moisture content is so low, however it is suspected that the pre-heating of the fabric as is touches the face of the Machnozzle reduces the water viscosity and allows more water removal. This phenomena is being further investigated at this time.

B. All Cotton Evaluation

During April Machnozzle drying of a 100% cotton fabric weighing 5.7 oz/yd² (trouser weight) was evaluated. Four processing speeds were investigated, 20, 40, 60, and 80 meters/minute. The results are presented in Table II.

The data at 100 meters/minute indicate that the moisture level can be reduced to 67% using only 1.00 pounds of steam/pound of water removed. Accordingly the total steam use for drying with a combination of Machnozzle and steam can is:



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Figure 1. Wrap Angle

Table I.

Data Summary

(Wrap Angle Experiments) (4/10/79-4/23/79)

Poly-Cotton, 50/50, 3.5 oz/yd² 80 m/Min. Fabric 95 psig Steam (Controller setting 94)

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TEST NO.	(Upstream)	(Downstream) a2	% Moisture in	% Moisture out
11	16.8 ⁰	16.8 ⁰	66.9	55.8
11	28.3	28.3	67.0	55.7
11	47.3	47.3	66.3	48.7
11	50+	50+	63.6	33.4
12	50+	50+	64.7	25.5
13	50+	50+	66.2	27.1
14	50+	47.30	64.5	23.9
14	50+	28.3	65.2	25.6
15	28.3	50+	67.4	40.3
15	47.3	50+	66.5	36.8

^{*}50+ means fabric touches nozzle face.

(1.03 -	.67)	1b	of	H ₂ o	X	1.00	1b	of	steam	
1b c	of fat	orio	2			۱b	of	H ₂ (נ	

.67 1b of H ₂ 0	2.5 1b of steam	2.04 lb of steam
lb of fabric	1b of H ₂ 0	lb of fabric

This represents a significant energy savings since if the Machnozzle was not used the reduction of moisture from 103% to 0% would require 2.58 pounds of steam per pound of fabric dried. With the Machnozzle only 2.04 pounds of steam are required for each pound of fabric which is dried. Accordingly at typical processing speeds an energy savings of about 21% is realized.

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Table II.

Processing Speed, Meters/Min.	Steam Use Lb/Hr	Incoming Moisture, %	Outgoing Moisture, %	Steam Used Per Pound of Water Removed
20	170	103	46	2.9
60	185	103	67	1.65
80	175	103	70	1.25
100	185	103	67	1.00

100% Cotton Fabric - 5.7 oz/yd^2

II. STEAM CAN PROGRAM

The first step in developing a mathematical model of can drying was to make a literature search to determine the state-of-the-art in can drying. The search revealed that almost nothing has been done in the textile area toward developing an understanding of can drying. However, several investigationspertaining to can drying of paper have been conducted. Most of the models used to describe paper drying have been based on a heat conduction model developed by Nissan [1,2,3]. While Nissan's work made a large contribution to the drying field, his conduction model is inadequate because it does not include a description of the mass transfer occurring within the sheet. Nissan's model requires measurements of dryer and sheeting parameters simultaneously, revealing that the controlling drying phenomena are inadequately described.

Studying the effects of system parameters would be greatly simplified by a model capable of predicting energy consumption and drying rates from dryer parameters and fabric parameters measured independently. Such a model of can drying will no doubt include a description of the mass transfer (vapor and liquid water) occurring within the sheeting material.

After reviewing the literature, it became apparent that an adequate model of can drying could not be obtained directly from the literature. However, the basis for a model has been presented by Hartley [4]. In reference 4, a mathematical model for predicting the rate of drying of a paper sheet in air when heated from one side was described. The diffusion mechanism used by Hartley was selected as the basis of the can drying model because the phenomena occurring during drying can be macroscopically described using the diffusion mechanism, while the complications in a capillary-based model are elminated.

A. Objectives

The objectives of the can drying modeling work at Georgia Tech are:

- Develop a can drying model capable of predicting fabric drying and energy consumption rates for various system parameters such as:
 - a. Fabric properties
 - i. weight
 - ii. construction
 - iii. components
 - b. Fabric incoming moisture content and temperature
 - c. Fabric through out speed
 - d. Can shell material and thickness

- e. Distance between cans
- f. Steam pressure and temperature in can
- g. environmental air humidity and temperature
- 2. Use model to:
 - a. Define optimal operating conditions for can dryer
 - Aid in controlling drying process by showing the effects of process upsets for example:
 - variations in incoming fabric moisture content with time
 - (2) variations in steam pressure (and therefore can temperature)
 - c. Determine the magnitude of the effects of various terms appearing in the energy equation--then simplify the energy equation accordingly.

B. Mathematical Model

1. Diffusion Mechanism

A diffusion mechanism with parameters determined from experiment was chosen as the basis for describing the mass transfer occurring during can drying of fabric sheets. When the mechanism is used in writing energy and mass balances, a set of equations describing the general macroscopic phenomena occurring during can drying are obtained. The equations describe the temperature and moisture variations within the sheet.

By using the diffusion mechanism, the widely accepted evaporizationdiffusion-condensation theory explaining moisture movement within a drying sheet was included in our model. According to the evaporation-diffusioncondensation theory, water diffuses from an internal region of maximum moisture content toward the surfaces. Water diffusing through the fabric to the hot can surface is vaporized. The vapor formed in the vicinity of the hot surface diffuses back through the fabric towards the open surface. As the vapor moves back through the fabric, partial condensation can occur because of the decreasing temperature. Thus an evaporation-diffusioncondensation process is partially responsible for heat transfer as well as mass transfer in the the fabric. The diffusion mechanism was used to describe the diffusion of air, water, vapor, and liquid vapor through the fabric sheet.

2. Assumptions

In deriving the set of equations describing the phenomena occurring in the drying fabric sheet, several assumptions were made. The major assumptions were:

- The macroscopic diffusion model adequately describes the diffusion process (eliminates the complications inherent in a capillary-based model, e.g., pore size distribution, short-range hydrogen bonding, and lack of absolute values).
- (2) The web is composed of a network of fibrous material, randomly oriented and containing liquid water, water vapor, and air in the structure voids.
- (3) The fibrous structure is macroscopically uniform and isotropic.
- (4) Variations in the y-direction (width direction are negligible).
- (5) Mass transfer and conductive heat transfer are appreciable only in the x-direction (perpendicular to the fabric sheet).
- (6) Radiative heat transfer is negligible.

(7) Shrinkage and mechanical deformations are negligible.

(8) Void fraction is constant and uniform through sheet.

(9) Densities of fiber and water are constant.

3. Development of Mathematical Model

Development of the mathematical model describing the can drying process was divided into three tasks:

Task 1: Writing the governing equations describing the heat and mass transfer mechanisms in the process.
Task 2: Writing the initial and boundary conditions.
Task 3: Solving the governing equations consistent with the initial and boundary conditions.

Tasks 1 and 2 have been completed, and Task 3 is underway. Brief descriptions of these three tasks follows.

(a) Task 1

The equations governing the heat transfer through the metal shell of the can dryer and the heat and mass transfer in the fabric sheet have been written. The equations were obtained by writing energy and mass balances for the two stationary control volumes shown in Figure 2.

One of the control volumes is located in space through which the can shell rotates. Since only conductive heat-transfer occurs in the shell, the only differential equation needed to describe the temperature variation through the shell is an energy balance equation.

The other control volume is located in space through which the sheeting material flows. The phenomena occurring in this control volume are much more complex since a three phase system (gases (air and water vapor), liquid water, and solid (fibers)) exists there. Several heat-transfer mechanisms operate simultaneously in the drying fabric. The mechanisms include:

conduction, convection, radiation, and evaporation-diffusion-condensation. As a result, six differential equations are needed to describe the heat and mass transfer occurring in the sheet:

- (1) An overall energy balance
- (2) Mass balance on air
- (3) Mass balance on water vapor
- (4) Mass balance on liquid water
- (5) Differential relationship describing diffusion of liquid water on fabric

The equations have been written in terms of two spacial coordinates (x and z) and time (t). However, solutions for steady state cases (time-varying terms neglected) are being sought initially due to the complexity of the governing equations. Solutions are discussed further in the description of Task 3.

(b) <u>Task 2</u>

Solving the governing equations requires initial and boundary conditions for the can shell and the fabric. These conditions are only briefly discussed here; however, they will be presented in detail in the final report.

The initial conditions of the temperature and moisture profiles in the fabric sheet just before the sheet contacts the can must be specified. Prior to contacting the first can, both temperature and moisture content are usually uniform across the fabric sheet.



Figure 2. Schematic Of Can Dryer Showing Control Volumes Used In Deriving Governing Equations

Thermal boundary conditions are necessary for the two surfaces of the can. Since mass transfer is occurring inside the fabric sheet, mass transfer boundary conditions as well as thermal boundary conditions must be specified for the fabric sheet.

As can be seen in Figure 1, fabric is in contact with the surface of the can over only part of the can's rotational cycle. Over the other part of the cycle, the surface is exposed to the surrounding atmosphere. Thus, different boundary conditions must be specified for the two regions. Similarly, one of the surfaces of the fabric sheet is in contact with the can surface for part of the path traveled by the sheet and is exposed to the surrounding atmosphere over the rest of the path. Boundary conditions for the two regions must be known.

As each succeeding can is reached, the roles of the two fabric surfaces are reversed. However, the boundary conditions specified for the first can be easily modified to apply to the succeeding cans.

(c) <u>Task 3</u>

The governing equations are nonlinear partial differential equations with second order terms; therefore, exact solutions would be extremely difficult to obtain, if not impossible. Thus the approach being taken is to solve the equations numerically using a computer.

Time-varying terms as well as spacially varying terms were included in the governing equations. However, computer solutions for steady state cases (all time-varying terms taken as zero) are being sought initially. Since can dryers normally operate under steady state conditions, the steady state solutions will be very valuable in defining optimal operating conditions for can dryers.

The time variations were optimistically included in writing the governing equations. Hopefully, obtaining the steady state solutions will give insight for solving more general time-varying governing equations. Solutions to the governing equations including time variations would be very valuable because they could be used to:

> Aid in controlling drying processes by showing the effects of process upsets such as variations in incoming fabric moisture content or variations in supply steam pressure.

C. Problem Areas

In developing a mathematical model of the can drying process, two problems have been encountered. One concerns a phenomenon that occurs when one of the surfaces of the sheet begins to dry out. The other pertains to transport properties needed for modeling the process.

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1. Drying Front

When one of the surfaces of the fabric sheet dries out, a drying front begins to propagate into the fabric. The front separates a moist region from the dry region. Different phenomena occur in the moist and dry regions; therefore, when a drying front appears, a set of equations must be solved for each of the regions. The solutions for the two regions must match at the interface.

The drying front does present some difficulty in obtaining a computer solution to the governing equations. However, an approach to solving the two sets of equations with matching conditions at the interface is currently being developed.

2. Transport Properties

Several transport parameters appear in the governing equations and boundary conditions and are therefore needed for the mathematical model. The needed transport parameters include:

- Diffusion coefficients (functions of temperature and moisture content) for:
 - i) water vapor-air binary mixture in the fabric sheet

- ii) liquid water diffusing through fabric sheet
- (2) Relative humidity (function of temperature and moisture content) inside of fabric.
- (3) Thermal conductivity of fabric sheet (function of temperature and moisture content).
- (4) Heat-transfer coefficient between can surface and environment.
- (5) Heat- amd mass-transfer coefficients for exposed surfaces of fabric.

A literature search is in progress in an effort to find relationships for the transport parameters. Preliminary results indicate that very little information on the needed transport parameters is readily available due to the scarcity of previous studies to develop an understanding of can drying fabrics. Therefore, it appears that many of the parameters will have to be determined experimentally. Since the transport parameters for the fabric are functions of temperature and moisture content, the experimental determination of the parameters will probably require a great deal of effort.

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- 1. A. H. Nissan, "Drying of Sheet Materials", <u>Textile Research Journal</u>, May 1968, Vol. 38, No. 5, Pages 447-460.
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- 3. A. H. Nissan, "A Theory of Drying of Sheet Materials, By Using Heated Cylinders", <u>Chemistry and Industry</u>, April 7, 1956, Pages 198-211.
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DEVELOPMENT AND DEMONSTRATION OF ENERGY-CONSERVING DRYING MODIFICATIONS TO TEXTILE PROCESSES

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Dr. David S. Brookstein Assistant Professor (404)894-2535 During May the main thrust of the research program was directed towards organizing the in-plant demonstration of the Machnozzle. A trip was made to King Finishing Company and measurements were taken on the finishing line which is to be used in the demonstration. Personnel at King were consulted and a test plan was developed. The plan is included in this monthly report. The essence of the plan is as follows. A determination of moisture content versus residence time on the steam cans will be conducted. This task will be accomplished during five runs. In each successive run an additional stack of steam cans will be charged with live steam.

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The moisture content upon entering and exiting the can system will be measured along with the resulting steam consumptions. Following the first five runs, the procedure will be repeated with the Machnozzle operating. Moisture content and steam consumption will be evaluated. Lastly, a control experiment without fabric will be conducted to determine idle load steam consumption and also production run steam consumption.

The development of a mathematical model for describing the can drying process is continuing. As reported last month, the governing equations describing the heat and mass transfer mechanisms and the corresponding initial and boundary conditions have been dervied. Attempts to solve the governing equations consistent with the initial and boundary conditions are underway. A vexing problem concerning a mathematical singularity has eluded the workers assigned to this task. However, this difficulty should be overcome next month.
TEST RUNS

OBJECTIVES: 1, 2 Initial Conditions: Nozzle Off and Cans Cold

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							AIR CONDITIONS					
					RESPON:	SES	A	mbien	t	E	xhaus	t
RUN	TEST CON	DITIONS	Mois	ture	Steam	Consumption	Т	Т	٧	Т	Т	V
<u>NO.</u>	Heated Stacks	Machnozzle	IN	<u>0UT</u>	Cans	Machnozzle	Dry	Wet	<u>Vel</u>	Dry	Wet	<u>Vel</u>
1	I	Off	х	х	х	NA						
2	1,2	Off	х	х	х	NA						
3	1,2,3	Off	x	х	х	NA						
4	1,2,3,4	Off	x	х	х	NA						
5	1,2,3,4,5	Off	х	х	х	NA						
6	Repeat 1 with Machnozzle on	ON	x	х	х	x						
7	Repeat 2 with Machnozzle on	ON	x	х	х	x			·			
8	Repeat 3 with Machnozzle on	ON	х	х	х	x						
9	Repeat 4 with Machnozzle on	ON	x	х	х	x						
10	Repeat 5 with Machnozzle on	ON	x	x	x	x						
OBJ	OBJECTIVE: 3											
11 12	Without fabric 1,2,3,4,5 Production nun		NA	NA	x	NA	x x	x x	x x	x x	x x	x x

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> Dr. David S. Brookstein Assistant Professor (404) 894-2535

During June hardware was designed and fabricated for the upcoming plant trial of the Machnozzle at the King Finishing Company. A bracket was developed which allowed the geometry of the Machnozzle and test fabric to be altered in virtually any designated fashion. Further, the necessary plumbing for the Machnozzle test was secured. The plumbing includes a pressure regulator and orifice plate for the Machnozzle. The demonstration is scheduled to take place during the week of July 23, 1979.

Mathematical modelling and computer simulation of the steam can drying process progressed during the past month. The solution of the governing differential equations, treated as ordinary differential equations in "x" and "t" (fabric thickness and time) was sought in accordance with the computational scheme presented in the appendix of this report.

As a first step in the solution of the differential equations, the initial value problem was considered. This required specifying five parameters, viz.

- Volumetric void fraction filled with water variable designated as "a".
- 2. The temperature "T".
- 3,4,5. The velocities of air, moisture, vapor respectively at a given coordinate in the fábric assumed to be in contact with the surface of the can.

In addition, the values of the time - derivatives $\frac{dT}{dt}$ and $\frac{da}{dt}$ must be specified at various "points" along the thickness of the fabric. These latter values have to be determined experimentally at a latter stage. However, for the purpose of computation, the values of $\frac{dT}{dt}$ and $\frac{da}{dt}$ were obtained from the experimental work of Han and Ulmanen (1). The computer program was run with the different values of $\frac{dT}{dt}$ and $\frac{da}{dt}$ for different times. The results indicate a fairly good correlation between the model and the experimental data.

In obtaining the above results, other assumptions that are made follow. The model assumes that moisture is only present in the fabric voids i.e., there is no sorption of moisture by the fiber. The diffusion coefficient of moisture is assumed to remain constant. Fiber thermal conductivity and diffusion coefficient for vapor in air k and D_{av} are assumed constant. Future work will examine these assumptions and possibly alter them to represent physical reality more closely.

After obtaining good agreement between the model and the results of Han and Ulmanen (1) using the initial values, the solution of the boundary value problem is being approached.

This solution involves unknown parameters such as heat and mass transfer coefficients. For the present, coefficients used by Hartley and Richards (2) for paper processing are being used.

During June, an improved condensing system has been fabricated for the Machnozzle and results from this will be forthcoming in the next monthly report.

Literature Cited

- (1) S. T. Han and Tapio Ulmanen, Heat Transfer in Hot-Surface Drying of Paper, TAPPI 41: 185-189 (1958).
- (2) Hartley, F. T. and Richards, R. J., TAPPI 57: 157-160 (1974).

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STEADY SEATE ANALYSIS OF CAN DRYING THE FOLLOWING QUARTITIES ARE TREATED AS "CONSTANTS": 1. LE - THE VOLUME OF VOIDS 2. FK - THERMAL CONDUCTIVITY OF FIBER 3. DAV - DIFFUSION COEFFICIENT OF AIR IN VAPOR 4. DW - DIFFUSION COEFFICIENT OF WATER 6. DENF - DENSITY OF FIBER 7. DENW - DENSITY OF WATER 8. CPF - SPECIFIC HEAT OF FIBER 9. CPW - SPECIFIC HEAT OF WATER 10. CPV - SPECIFIC HEAT OF VAPOR 11. CPA - SPECIFIC REAT OF AIR 12. FK - THEAMAL CONDUCTIVITY OF FIBER 13. PATM - ATMOSPHERIC PRESSURE PROGRAM CANDRY4(OUTPUT) DIMENSION A(10) COMMON/CONST/EE, DAV, DENF, DENW, CPF, CPW, CPV, CPA, FK, RV, RA, PATM EE=.B DAR#2.75E-04 BENF=94.9 DE.NW=61.3 CPF=.32 CPV=1. CPV=.456 CPA=.242 FE=1.14E-05 RV=.1103 HA=.0685 PATM=68160.96 ASSIGN INITIAL VALUES A(1)=.0i A(2)=648.2 $\Lambda(3) = 0$. A(4) = 0.A(5) =0. 11=20 NE=5X0=0. XL=.016 GALL RKMO(A, XO, XL, NE, NI) STOP ERD SUBROUTINE RKMØ(A, XØ, XL, NE, NI) DIMENSION A(10), C(10,5), CV(5,5), CX(5) DATA CV. 3333333, -. 1666667, -. 04166666667, .375, -. 33333333, 0., 1 .1666667, -. 1666667, 4*0., .375, -1.875, 1.5, 3*0., 2., -1.333333, 2 .4*0., .16666677, CL/0., .3333333, 0., .1666667, .57 FORMAT(8X, "A - VOLUMETRIC FRACTION OF VOID FILLED WITH WATER"/,8 66 1 X, """ - TEMPERATURE IN DEC. RANKINE"/,8X, "VAX - VELOCITY OF AIR",/ 2 0X, "VMX - VELOCITY OF MOISTURE"/,8X, "VSX - VELOCITY OF VAPOR"/ /) FORMAT(6X, "A", 12X, "T", 10X, "VAX", 9X, "VMX", 9X, "VSX"/ /) 10 20FEREAT(5X, /1P6E12.4) FORMATC5X, "TOTAL MOISTURE CONTENT = ", F10.2, "%"/ /) :10 DN=(NL-XO)/FLOAT(NI) Ха ХО ASUM-0. PRINT 100 PRINT*, " TIME = PRINT*, " " 30 MINUTES " PRINF 110 DO 20 I=1,NI COUNT=FLOAT(I) 17=(1-1)/2+1 XX=.25*FLOAT(IT-1) BO 10 J=1,5 X=X+DX*CX(J) CALL MODEL(X, A, C, J, IT) 00 10 K=1,NE G(K, J) = DX * G(K, J)DO 10 L=1,J 0 $\Lambda(K) = \Lambda(K) + C(K, L) * CV(J, L)$ ASUM=ASUM+A(1) 13 PRINT 120, (A(K), K=1, NE) ASUM1=ASUM/FLOAT(NI)*100. PRHIT*, " " PRINT 139, ASUMI RETORN EnD

APPENDIX

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Monthly reports for July, August, September.

DEVELOPMENT AND DEMONSTRATION OF ENERGY-CONSERVING DRYING MODIFICATIONS TO TEXTILE PROCESSES

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Part II, Phase III Extension of DOE Contract No. EY-76-S-05-5099-004

title

ENERGY CONSERVATION IN THE TEXTILE INDUSTRY

Submitted to the Department of Energy by

The School of Textile Engineering and

The Engineering Experiment Station

at

The Georgia Institute of Technology Atlanta, Georgia 30332

> Dr. David S. Brookstein Assistant Professor (404) 894-2535

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31 October 1979

1. Machnozzle Program

During the past three months, a number of accomplishments have been made in the Machnozzle program. A one day, in-plant test was run at a finishing plant near Statesboro, Georgia. Extensive tests were run to compare the effectiveness of the Machnozzle on three different fabric types at three steam supply pressures. Experiments were also run to determine the importance of fabric tension and temperature on the effectiveness of the Machnozzle. Tests were run with a condensation system to determine the potential for recovering energy from steam used by the Machnozzle.

A. In-Plant Test

The 43.3 inch Machnozzle, purchased by Georgia Tech Engineering Experiment Station for use in its Department of Energy sponsored research in the papermaking industry (Contract No. EM-78-5-05-5961), was installed on a continuous dyeing line immediately before the final steam dyer cans. The Machnozzle was tested for several hours during one shift on 100% cotton, non-production goods. Moisture level samples were taken before and after the Machnozzle. At the same time, the steam flow to the dryer section was monitored. The direct costs to Georgia Tech for this test were paid by the Industrial Energy Extension Service (IEES). The IEES is funded by the State of Georgia Office of Energy Resources to assist Georgia industry on energy related matters.

No useful results were obtained from the one day test. A filter for removal of small particles in the steam was not used for the brief test, and the Machnozzle became partially blocked with pipe scale. As a result, the steam flow through the Machnozzle was appreciably reduced, and the Machnozzle's effectiveness in moisture removal was greatly reduced. To compound the problem, the instrument used to measure steam flow rate was found to be defective at the end of the day. Consequently, all of the steam flow measurements made during the day were questionable. Due to the time limitations on use of the dyeing range, no further testing of the Machnozzle could be conducted on the continuous dyeing range.

B. <u>Comparison of Fabric Types and Steam Supply Pressures</u> - Laboratory Tests

Tests were run on three fabric types; 100% cotton weighing 4.0 ounces/per square yard, 50% cotton - 50% polyester weighing 3.6 ounces per square yard, and 100% polyester weighing 1.8 ounces per square yard; at three fabric speeds and three steam supply pressures. The results of these tests are shown in Figures 1, 2, and 3. For all three fabrics, the fabric moisture content after the Machnozzle (exiting fabric moisture content) decreases with increasing steam supply pressure and increases with increasing fabric speed. As might be expected, the Machnozzle is most effective on 100% polyester fabric. The Machnozzle was able to reduce the moisture content of the 100% polyester from approximately 75% to approximately 7% at a fabric speed of 80 meters per minute with a 95 pounds per square inch gage steam supply pressure. These results compare closely with claims made by the Brugman Company.

Figure 4 shows the steam consumed in removing water from the 100% cotton fabric. The Machnozzle steam consumption increases very little as the fabric speed increases. However, the amount of fabric processed and therefore, the amount of water removed goes up as the fabric speed increases. Therefore, the number of pounds of steam required to remove a pound of water decreases as the fabric speed increases. At 80 meters per minute, the Machnozzle used approximately one pound of steam per pound of water removed at all three supply pressures tested. It should be remembered that the fabric exits at a much lower moisture content with the 95 pounds per square inch gage supply pressure. Steam dryer cans use on the order of 2 to 2½ pounds of steam per pound of water removed.

C. Effect of Fabric Tension and Fabric Temperature

The wrap angle of the fabric around the Machnozzle has a great effect on the drying ability of the Machnozzle. It is especially important for the fabric to touch the upstream face of the Machnozzle. The results of a series of test investigating the effect of fabric wrap angle were reported earlier.

One possible explanation for the importance of the fabric touching the upstream face of the Machnozzle is that the hot face of the nozzle preheats the fabric, thereby reducing the viscosity and surface tension of the water, thus making the water easier to remove. In order to test this theory, 100% cotton fabric was wet out in 200°F water, then run across the Machnozzle at three wrap angles. The moisture removal was still significantly better when the fabric touched the incoming face of the nozzle. Fabric heating does not appear to explain this.

Another possible explanation for the importance of the fabric touching the upstream face of the Machnozzle is that friction across the upstream face increases the fabric tension at the Machnozzle slit, thus opening up the fabric and allowing the Machnozzle to blow the water out more effectively. A test was run to determine the effect of fabric tension on the drying ability of the Machnozzle. Runs were made on 100% cotton at two wrap angles, shown in Figure 5, and at three tension levels, shown in Figure 6. The tension level did have a small effect on the existing moisture level. However, the wrap angle had a much larger effect. It is still not clear why moving the fabric in contact with the upstream face of the Machnozzle has such a large effect on moisture removal.

Condensor System

The new condensor system, has been completed and tested. This condensor uses a series of baffles to increase the mixing time of the steam

and water. Tests indicated that a significant portion of the energy used by the Machnozzle may be recovered as hot water. Water temperatures as high as 130⁰F were reached.

II. Steam Dryer Can Program

The experimental dryer can system has been put into operation. A series of tests has been run on 100% cotton fabric weighing 4.0 ounces per square yard and 50% cotton - 50% polyester fabric weighing 3.6 ounces per square yard. The results of the tests are shown in Figures 7 and 8. The exiting moisture level was measured for various fabric residence times on the dryer cans. Test were run on fabric that had been squeezed-out at 80 meters per minute and fabric that had been run through the Machnozzle at 80 meters per minute with a steam supply pressure of 90psig. The Machnozzle significantly reduces the amount of residence time required to dry the fabric.

III. Conclusions

The laboratory results of this project clearly suggest that the Machnozzle is an excellent device for removing water from fabric subsequent to finishing operations. Further there are significant energy savings which can be realized with the use of the Machnozzle before can drying. However, the accelerated plant trial (one day) did not provide an opportunity to test the Machnozzle under plant conditions. Accordingly, a plant demonstration must take place to convince the textile industry of the energy conservation merits of the Machnozzle.

Based on Phase I data, the research report so far indicates that a potential energy savings of 1 x 10^6 BOE or 20% of the energy used in drying can be realized.



FIGURE 1



1

FIGURE 2



FIGURE 3





WRAP ANGLE FOR TENSION TEST

FIGURE 5



FIGURE 6



FIGURE 7



Traveler: Dr. David Brookstein

Contractor: Georgia Tech Research Institute

Contract Number: EY-76-S-05-5099, Modification No. A004

Visit to Laboratory:

Itinerary of the trip and name of persons with whom discussions were held:

- Atlanta, to Enschede, Holland, Netherlands Laboratory University of Twente
- 2. Dr. Clemants Thevsink and Professor Van der Linden

Discussion Summary:

A visit to the University of Twente in Enschede, Holland was made to discuss the use of the Machnozzle in drying. This trip enabled Dr. David Brookstein to discuss the operation of the nozzle with Professor Van der Linden and Dr. Clemants Theusink. Their advice led to the development of a reel for transporting the fabric through the nozzle. They also provided further insight into the theory of operation for the Machnozzle. The concept of the Machnozzle as a device which imparts significant amounts of kinetic energy through the development of shock waves was dispelled. Instead the Machnozzle is viewed as a vacuum slot acting in reverse, that is a device in which a relatively large pressure differential across the fabric can be obtained.

The problem of steam condensation in the Machnozzle was discussed. This condensation, if allowed to occur, will reduce the effective flow resistance in the nozzle and will result in increased steam usage. The solution to this problem is to allow the nozzle to heat up before it is used and steam measurements are taken.

REPORT OF FOREIGN TRAVEL COST

1.	Name of Traveler:	David Brookstein
2.	Name of Contractor:	Georgia Tech Research Institute
3.	Contract Number:	EY-76-S-05-5099
4.	Inclusive Dates of	ravel: November 8-13, 1978
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6.	Actual Cost of Trip	Charged to AEC Funds: \$1089.16

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Final Report

DEVELOPMENT AND DEMONSTRATION OF ENERGY—CONSERVING DRYING MODIFICATIONS TO TEXTILE PROCESSES

Investigators:

D. S. Brookstein W. W. Carr W. D. Holcombe

Prepared for

U. S. DEPARTMENT OF ENERGY ASSISTANT SECRETARY FOR CONSERVATION AND SOLAR ENERGY OFFICE OF INDUSTRIAL PROGRAMS

GEORGIA INSTITUTE OF TECHNOLOGY SCHOOL OF TEXTILE ENGINEERING

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DEVELOPMENT AND DEMONSTRATION OF ENERGY-CONSERVING DRYING MODIFICATIONS TO TEXTILE PROCESSES

Final Report

Part II, Phase III Extension of DOE Contract No. DE-AS05-76CS40081

Modification No. M004

Prepared By

School of Textile Engineering

and

Engineering Experiment Station

of

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Prepared For:

U.S. Department of Energy Assistant Secretary for Conservation and Solar Energy Office of Industrial Programs

DEVELOPMENT AND DEMONSTRATION OF ENERGY-CONSERVING DRYING MODIFICATIONS TO TEXTILE PROCESSES

1

Final Report

Part II, Phase III Extension of DOE Contract No. DE-AS05-76CS40081

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Covering the Period

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Prepared by

The School of Textile Engineering

and

The Engineering Experiment Station

of

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U.S. Department of Energy Assistant Secretary for Conservation and Solar Energy Office of Industrial Programs

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Special thanks are due to Dr. M. V. Konopasek for his time and assistance in setting up the computational scheme. The authors would like to extend a special word of appreciation to Professor W. F. Ames for his time and advice on the numerical scheme.

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SUMMARY

Textile drying processes are very energy extensive, consuming approximately 24% of the energy used in wet processing of textiles. The purpose of the work under this research program was to develop and to expand procedural and engineering modifications to textile drying processes in order to reduce energy requirements. Research was concentrated in two major areas: 1) an investigation of the potential of a Machnozzle as a fabric predrying device and 2) a program to optimize textile can drying with respect to energy consumption.

Tests were run to evaluate the Machnozzle as a predrying device to be used just prior to final drying. Three types of fabric (100% cotton, 50/50 polyester/cotton, and 100% polyester) were tested. The test results clearly demonstrated that the Machnozzle can significantly reduce the moisture content in fabric. The Machnozzle reduced the moisture content of 100% cotton fabrics weighing 4.0 oz/yd^2 from approximately 97% to 34 and 46% for fabric speeds of 20 and 80 m/min, respectively. The moisture content of 50/50 cotton/polyester fabrics weighing 3.6 oz/yd^2 was reduced from 68% to 7 and 17% for fabric speeds of 20 and 80 m/min, respectively. The Machnozzle was extremely effective in removing moisture from 100% polyester fabric weighing 1.8 oz/yd^2 . The moisture content was reduced from approximately 61% to 3 and 6% for fabric speeds of 20 and 80 m/min, respectively.

The energy consumption of the Machnozzle compares favorably with that for steam can dryers. Typically, steam can dryers require between 1.5 and 2.0 pounds of steam per pound of water removed. The Machnozzle consumes approxi-

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mately 1.0 pound of steam per pound of water removed when processing all three types of fabrics at 80 m/min (which corresponds closely with industrial process speeds). When the energy recovered by the condenser system is considered, the Machnozzle becomes even more attractive as a fabric predrying device. With recovery, the steam consumption of the Machnozzle is approximately 0.3 pound of steam per pound of water removed.

An economic analysis of the Machnozzle as a predrying device was made. The parameter used to judge the economic performance of the Machnozzle was Internal Rate of Return (IRR). The results of the calculations showed that the economic feasibility of using the Machnozzle as a predrying device depends on the cost of energy and process operating conditions. Internal Rate of Return (IRR) was very large (as high as 183%) in some cases, but extremely small in other cases. For some operating conditions (lower fabric speeds), the initial investment would not be recovered in the ten year period used in the analysis.

An Internal Rate of Return (IRR) of 50% is usually considered the lower limit of economically feasible energy-conservation investments in the textile industry. With this constraint on Internal Rate of Return (IRR) and an energy cost of \$3 per million BTU, the economic analysis indicates that the Machnozzle is attractive for 100% cotton fabrics and 50/50 cotton/polyester blend fabrics processed at 80 m/min. All three types of fabrics give favorable Internal Rate of Return (IRR) at an energy cost of \$3 per million BTU plus 10% per year.

The use of steam cans for drying is prevalent in the textile industry. Due to the low cost of energy in the past, low energy consumption has not been a criterion in the design and operation of steam cans. As a result, steam cans are energy inefficient in the drying of textiles. Since textile can

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drying represents an energy-intensive, wasteful process, one of the objectives of this research was to reduce the energy required in textile can drying. An experimental approach to optimize steam can drying with respect to energy consumption is a very tedious and expensive process. Accordingly, a mathematical model describing the physical aspects of the can drying process has been developed to predict drying rates. A numerical scheme for the solution of the governing equations is presented. Due to the lack of available data on drying of textiles, the results were compared with experimental data for paper drying. Comparable temperature-time and moisture content-time profiles were obtained. The importance of critical heat and mass transfer parameters is discussed.
I. INTRODUCTION

Data collected in Phase I of DOE Contract Number EY-76-S-05-5099, "Energy Conservation in the Textile Industry", revealed that predrying and drying of textiles consumes approximately 8.8×10^6 barrels of oil equivalent energy annually or approximately 24% of the total energy consumed in wet processing of textiles(1). Predrying and drying processes have relied heavily on thermal energy to remove water and have been energy inefficient. Therefore, predrying and drying were targeted as processes where research and development in Phase II of the DOE project could lead to significant energy conservation.

During Phase II (2) of the DOE project, methods for combining mechanical and thermal means of moisture removal were investigated. One of the moisture removal techniques involved the use of a novel drying device called a Machnozzle. The Machnozzle is designed to accelerate high pressure steam to sonic speed by passing it through a narrow slot. The fabric is passed across the slot exit where the high velocity steam flow creates a large pressure differential across the fabric. The water is then literally blown out of the fabric. The steam passing through the fabric loses little of its thermal energy and can therefore be mixed with cold water to yield a hot water source for the plant.

The major role of the Georgia Tech research on the Machnozzle was to evaluate and optimize the device while comparing the drying efficiency to the manufacturer's claims. A 16-inch long Machnozzle was purchased, and a test system was built which simulated projected plant conditions of fabric speed and steam pressures. Due to project limitations, no runs were possible on the unit before Phase II termination. Additional funding was granted to Georgia Tech to conduct the drying research reported herein. The purpose of the research was to demonstrate further and to expand procedural and engineering modifications to textile drying processes in order to reduce energy requirements. The modifications were approached cognizant of the requirement of maintaining or improving existing process production efficiency and product quality. Specific objectives of the research were:

1. To develop further and to expand energy-conserving procedural and engineering modifications to textile drying process, in particular, to investigate the potential of the Machnozzle as a predrying device.

2. To demonstrate the developed modifications on a pilot-scale basis.

3. To derive energy savings based on the pilot-scale data and conventional textile process data.

4. To examine cost/benefit relationships of the demonstrated modifications and determine the feasibility of technology transfer to participating plants.

5. To disseminate the results of the research to the industry through short courses, workshops, trade publications and organizations, and relevant Georgia Tech courses.

The research to accomplish these objectives was concentrated in two major areas:

1. An investigation of the potential of a Machnozzle as a fabric predrying device.

2. A program to optimize textile can drying with respect to energy consumption.

II. PILOT-SCALE STUDIES OF A MACHNOZZLE AS A PREDRYING DEVICE

A. BACKGROUND

Textile drying is an energy-intensive process consuming approximately 8.8×10^6 barrels-of-oil equivalent energy annually or approximately 24% of the total energy consumed in wet processing of textiles(1). Drying processes have relied heavily on thermal energy to remove water and have been energy inefficient. During Phase I of DOE Contract Number EY-76-S-05-5099, "Energy Conservation in the Textile Industry", predrying and drying processes were identified as processes where research and development in Phase II of the DOE project could lead to significant energy conservation.

Methods for combining mechanical and thermal means of moisture removal were investigated during Phase II of the DOE project. One of the moisture removal techniques involved the use of a novel drying device called a Machnozzle. A 16-inch long Machnozzle was purchased, and a test system was built which simulated projected plant conditions of fabric speed and steam pressures. Due to project limitions, no runs were possible on the unit before Phase II termination.

Additional funding was granted to Georgia Tech to conduct the drying research discussed in this report. The major part of the research effort was directed at evaluating the Machnozzle as a predrying device to be used just to final drying.

Brugman Machinefabrik of the Netherlands developed the Machnozzle as a moisture removal device to be used in conjunction with washers manufactured by Burgman Machinefabrik. Claims made by Burgman Machinefabrik indicated that the Machnozzle could significantly decrease the moisture content in fabrics and had

a potential for reducing energy consumed in drying textiles(3,4). The claims suggested that the Machnozzle is capable of drying fabrics to lower moisture levels than may be obtained with other mechanical extraction systems such as pressure rolls, while having a much lower energy consumption than is required in thermal drying. However, problems were encountered with the application of the Machnozzle in the washer systems due to lint build up on the Machnozzle and dyeing nonuniformity.

The problems associated with the application of the Machnozzle in the washer systems should not be encountered when the Machnozzle is used as separate unit functioning as a predrying device just prior to final drying. If used in this manner, the Machnozzle could reduce the amount of moisture that must be evaporated in the energy intensive final drying stage. Thus tests were conducted at Georgia Tech to evaluate the Machnozzle as a predrying device.

B. DESCRIPTION OF THE MACHNOZZLE

A cross section of the Machnozzle apparatus is shown in Figure 1. Steam or some other gas if fed by a pipeline to the Machnozzle. The steam flows at very low speed through most of the Machnozzle until it reaches a buffer chamber (the circular chamber located near the tip of the Machnozzle). As the steam leaves the chamber, it accelerates rapidly as it moves through a converging nozzle and then through a very narrow slot (0.001-inch wide). At the exit of the nozzle, the steam velocity is sonic if the input steam pressure is sufficiently high. When fabric is passed across the exit of the slot, the high velocity steam flow creates a large pressure differential across the fabric. Water and residual matter entrained around and in the yarn are literally blown out of the fabric, with little heat transfer occurring. The steam passing



MACHNOZZLE



through the fabric loses little of its thermal energy and can be passed through a condenser where it is mixed with cold water to yield a hot water source for the plant. Thus much of the energy in the steam can be recovered, making the predrying process more energy efficient.

While the Machnozzle may be operated with either steam or compressed air, the study was conducted using steam for two reasons. First, many textile mills may require additional compressor capacity in order to supply air at a sufficient pressure and flow rate to operate the Machnozzle. The total mill steam consumption would be reduced when steam is used to operate the Machnozzle. Second, much of the energy in the steam can be recovered using a condenser, but the energy in the air can not be reclaimed.

C. TEST APPARATUS AND PROCEDURE

A test system for evaluating the Machnozzle's performance was designed and constructed during Phase II (2) of the DOE project. However, several operational problems were encountered when the system was tested. Due to these problems, much of the early effort of Phase III was spent in developing the test apparatus into a workable piece of equipment. Photographs of the Machnozzle and the test apparatus are shown in Figures 2, 3, and 4.

As shown in Figure 5, the 400 mm (approximately 16 inch) Machnozzle is mounted in a framework along with a series of guide rolls. The nozzle jet is directed downward into a plenum which houses the steam condenser. A blower is used to pull the mixture of steam, air, and water through the condenser and to exahust the wet air outdoors. Initially, the plan was to use a continuous loop of fabric which would be dried by the Machnozzle then rewetted and dried again. This proved to be impractical given the limitations of this equipment.



Figure 2. Machnozzle and Guide Rollers



Figure 3. Fabric Being Tested on Machnozzle Apparatus



Figure 4. Rear View of Machnozzle Apparatus



A spool was added at the wet end to hold the wet fabric. A take-up reel was later added at the dry end to ease the job of rewinding the fabric after a set of runs. Weighted squeeze rolls were used immediately before the Machnozzle to reduce the incoming moisture level of the fabric as would normally be the case in a mill. A set of drive rollers was used at the dry end of the machine to pull the fabric through the squeeze rolls and across the Machnozzle.

An electric resistance heated steam boiler was used to provide steam for the Machnozzle. Initial tests were hindered by the relatively imprecise control given by the simple on-off mechanical controllers. The wide variation in steam supply pressures resulted in a wide variation in steam flow rates through the Machnozzle. The mechanical controller was replaced by an electronic, proportional controller which is able to hold the steam supply pressure within less than 1 psi of the set point. This greatly reduced the fluctuation of the steam flow rate.

The normal test procedure was as follows (See Figure 5):

- Wind the fabric through the wet out tank onto the spool at the end of the machine. This operation is shown in Figure 6.
- Thread the fabric through the machine.
- Set the boiler controller at the given steam supply pressure and wait for it to reach that pressure.
- Turn on the steam line to the Machnozzle and allow the Machnozzle to heat up.
- Set the drive roller gear-motor for the given fabric speed.
- Turn on the fabric drive and run fabric through the machine for the specified period.



Figure 6. Wet-Out Set-Up

- Stop the machine and cut out fabric samples before and after the Machnozzle. Record relative humidity and steam flow rate. Sew the ends of the fabric together.
- Weigh the fabric samples then dry the fabric samples overnight in an oven and reweigh them.

A steam condensor system was installed in the plenum chamber below the Machnozzle on the test stand (See Figure 5). The first condenser consisted of two opposed rows of horizontal spray nozzles. Air and steam from the Machnozzle were pulled downward through the cold water spray by a fan which exhausts air from the plenum. Since this system did not work effectively, the two rows of spray nozzles were replaced by a series of baffles. Air and steam from the Machnozzle entered this chamber at the top, and a row of nozzles sprayed cold water into the steam at the top. Mixing of the steam and water continued as the water cascaded down the series of baffles. This condenser system yielded much greater performance than the two rows of spray nozzles.

D. TEST PLAN

The objective of the Machnozzle testing was to determine the performance and drying efficiency of the Machnozzle on common textile fabrics. The effects of the following parameters on the performance of the Machnozzle were studied:

- · Fabric Type
- · Fabric Speed
- Steam Supply Pressure

- Process Parameters
 - 1. wrap angle
 - 2. fabric tension
 - 3. incoming fabric temperature
 - 4. Machnozzle slot width

The tests to determine the effects of fabric type, fabric speed, and steam supply pressure are summarized in Table 1. These three types of fabrics, 100% cotton, 50/50 cotton/polyester, and 100% polyester were tested. Fabric speed was varied from 20 to 80 meters per minute, and steam supply pressures of 50, 75, and 95 psig were tested.

Early test runs during the development of the fabric transport system indicated that the fabric wrap angle (defined in Figure 7) was important in the performance of the Machnozzle. Therefore, a series of tests (see Table 2) were devised to investigate the effect of wrap angle on Machnozzle performance. After the effects of wrap angle on the Machnozzle's performance was established, tests (see Tables 3 and 4) were conducted in an attempt to determine why wrap angle is important. The interacting effects of wrap angle with both fabric tension and fabric temperature were tested.

The effect of Machnozzle slit width on Machnozzle performance was investigated. The tests conducted are summarized in Table 5.

Although the Machnozzle may be operated with either steam or compressed air, all of the tests were run using steam. The major reason for this was that much of the energy in the steam can be recovered, but the energy in compressed air cannot. Tests were conducted to determine how much of energy in the steam can be recovered by passing the steam through a condenser. The condenser

Fabric Type	Fabric Speed (m/min)	Steam Supply Pressure (psig)
50/50 PET/cotton 3.6 oz/yd ²	20 60 80	50, 75, 90 50, 75, 90 50, 75, 90
100% Cotton 4.0 oz/yd ²	20 60 80	50.75,90 50,75,90 50,75,90
100% PET 1.8 oz/yd ²	20 60 80	50, 75, 90 50, 75, 90 50, 75, 90

Table 1. Tests to Determine the Effects of Fabric Type, Fabric Speed, and Steam Supply Pressure



Figure 7. Fabric Wrap Angle

Table 2. Tests to Determine the Effect of Fabric Wrap Angle $\boldsymbol{\alpha}.$

Fabric Type	Fabric Speed (m/min)	Steam Supply Pressure (psig)	Upstream Wrap Angle α_1 (degrees)	Downstream Wrap Angle α_2 (degrees)
50/50 PET/cotton 3.5 oz/yd ²	80	95	17 28 47 50	17 28 47 50
50/50 PET/cotton 3.5 oz/yd ²	80	95	17 28 47	50 50 50
50/50 PET/cotton 3.5 oz/yd ²	80	95	50 50 50	17 28 47

Table 3. Tests to Determine the Effect of Fabric Tension

Fabric Type	Fabric Speed (m/min)	Steam Supply Pressure (psig)	Upstream Angle ^α 1 (degrees)	Downstream Angle ^œ 2 (degrees)	Tension Level
50/50 PET/cotton 3.5 oz/yd ²	80	95	50	50	Low Medium High
50/50 PET cotton	80	95	28	28	Low Medium High

Table 4.	Tests	to	Determine	the	Effect	of	Fabric	Temperature

Fabric Type	Fabric Speed (m/min)	Steam Supply Pressure (psig)	Upstream Wrap Angle (degrees)	Downstream Wrap Angle (degrees)
100% Cotton 5.7 oz/yd ²	80	95	28 47 50 50	130 130 130 70

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Fabric Type	Fabric Speed (m/min)	Steam Supply Pressure (psig)	Wrap Angles ^α 1 ^{= α} 2 (degrees)	Slit Width (inches)
50/50 PET/COTTON 3.5 oz/yd ²	85	95	50	0.001 0.002

Table 5. Tests to Determine the Effect of Slit Width

tests along with the results of the tests will be discussed in the results section of this report.

E. RESULTS

The results of the Machnozzle and condenser tests are summarized in this section. The full set of results for the Machnozzle tests is given in Appendix 1.

1. Effects of Fabric Type, Fabric Speed, and Steam Supply Pressure

The effectiveness of the Machnozzle in removing moisture from the three types of fabrics tested is shown in Figures 8, 9, and 10 for fabric speeds ranging from 20 to 80 m/min and a steam supply pressure of 95 psig. After passing through the squeeze rolls, 100% cotton fabrics weighing 4.0 oz/yd^2 had a moisture content (based on bone dry fabric weight) of approximately 97%. The Machnozzle reduced the moisture content to 34 and 46% for fabric speeds of 20 and 80 m/min, respectively. After passing through squeeze rolls, the moisture content of 50/50 cotton/polyester fabric weighing 3.6 oz/yd^2 was approximately 68%. The moisture content was reduced by the Machnozzle to 7 and 17% for fabric speeds of 20 and 80 m/min, respectively. The Machnozzle was extremely effective in removing moisture from 100% polyester fabric weighing 1.8 oz/yd^2 . The moisture content was reduced from approximately 61% to 3 and 6% for fabric speeds of 20 and 80 m/min, respectively. The results showed that as the fiber in the fabric was changed from cotton to polyester, lower moisture contents were obtained using the Machnozzle. The results were expected since cotton is hydrophilic while polyester is hydrophobic.



Figure 8. Fabric Moisture Content versus Fabric Speed Before and After the Machnozzle for 100% Cotton Fabric



Figure 9. Fabric Moisture Content Versus Fabric Speed Before and After the Machnozzle for 50/50 Cotton/Polyester Fabric



Figure 10. Fabric Moisture Content versus Fabric Speed Before and After the Machnozzle for 100% Polyester Fabric

The effect of increasing fabric speed can be seen in Figures 8 through 13. As fabric speed is increased, moisture removal is decreased slightly. Even though the moisture level exiting the Machnozzle is slightly lower at the lower fabric speeds, the Machnozzle is more energy efficient at the higher speeds. This results from productivity increasing linearly with fabric speed while steam consumption increases only slightly with fabric speed.

The effect of increasing the steam supply pressure on fabric moisture content after the Machnozzle is illustrated in Figures 11, 12, and 13. Plots of moisture contents in each of the three fabrics versus fabric speed are given for steam supply pressures of 50, 75, and 95 psig. As steam supply pressure is increased, moisture content is reduced. For example, for the cotton fabric at a fabric speed of 80 m/min moisture content was reduced from 62 to 46% as steam supply pressure was increased from 50 to 95 psig.

2. Effects of Other Process Parameters

During the early development of the Machnozzle test stand, the importance of the fabric wrap angle on Machnozzle performance became apparent. A series of tests were run to determine the effect of fabric wrap angle on Machnozzle performance. Figure 14 defines the upstream or entering wrap angle and the downstream wrap angle. The wrap angle experiments were run on 50/50 PET/cotton fabric weighing 3.5 oz/yd^2 . All the runs were made at 80 m/min with a steam supply pressure of 95 psig.

The first series of tests were run with equal upstream and downstream wrap angles. Table 6 shows the results of these runs. As the wrap angles



Figure 11. 100% Cotton Fabric Moisture Content Exiting the Machnozzle for Three Steam Supply Pressures



Figure 12. 50% Cotton/50% Polyester Fabric Moisture Content Exciting the Machnozzle for Three Steam Supply Pressures



Figure 13. 100% Polyester Fabric Moisture Content Exiting the Machnozzle for Three Steam Supply Pressures



Figure 14. Fabric Wrap Angle

\propto ,	\propto_2	MOISTURE Content Out (%)
17	17	56
28	28	56
47	47	49
50	50	29

Table 6. Effect of Wrap Angle on Moisture Content

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FABRIC: 50/50 COTTON POLYESTER

WEIGHT: 3.5 oz/yd²

SPEED: 80 m/min

MOISTURE CONTENT IN: 66 %

STEAM PRESSURE: 95 psig

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were increased from 17° to 47° , there was slight improvement in the drying performance of the Machnozzle. As the wrap angles were increased from 47° to 50° where the fabric touches both faces of the Machnozzle, the drying performance improved greatly.

Two series of tests were run to investigate the importance of the fabric touching the upstream and downstream faces of the Machnozzle. Table 7 shows the results of the tests with the fabric touching the downstream face. The drying performance is much better when the fabric touches the upstream face than when the upstream wrap angle is 28° or 47° . Table 8 shows the results of the tests with the fabric touching the upstream face of the Machnozzle. The downstream wrap angle has little effect on the drying performance of the Machnozzle when the fabric touches the upstream face.

One possible explanation for the importance of the fabric touching the upstream face of the Machnozzle is that the drag on the fabric moving across the face of the Machnozzle increases the tension of the fabric at the Machnozzle slot which opens up the fabric, making dewatering easier. To test this hypothesis, a test was run to determine the effect of fabric tension on the drying performance of the Machnozzle. This test was run on 100% cotton fabric weighing 4.0 oz/yd^2 at 80 m/min with a steam supply pressure of 95 psig. Runs were made with the upstream wrap angle at 28° and 50° (i.e., with the fabric touching the upstream face) for three fabric tension levels: low, medium, and high. The wrap angles for this test are illustrated in Figures 15, and the results are presented in Figure 16. The results showed that while fabric tension has a slight effect on Machnozzle drying performance, fabric wrap angle has a much larger effect.

\propto_1	∝₂	MOISTURE Content Out (%)
28	50	40
47	50	37
50	50	29

Table 7. Effect of Upstream Wrap Angle on Moisture Content

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FABRIC: 50/50 COTTON/POLYESTER

WEIGHT: 3.5 oz/yd²

SPEED: 80 m/min

MOISTURE CONTENT IN: 66 %

STEAM PRESSURE: 95 psig

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\propto_1	\propto_{2}	MOISTURE CONTENT OUT (%)
50	28	26
50	47	24
50	50	29

Table 8. Effect of Downstream Wrap Angle on Moisture Content

FABRIC: 50/50 COTTON/POLYESTER

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WEIGHT: 3.5 oz/yd²

SPEED: 80 m/min

MOISTURE CONTENT IN: 66 %

STEAM PRESSURE: 95 psig

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Figure 15. Wrap Angles for Fabric Tension Test



Figure 16. Effect of Fabric Tension on Moisture Content

Another possible explanation for the importance of the fabric touching the upstream face of the Machnozzle is that the hot face of the Machnozzle heats the water in the fabric, thereby reducing the surface tension and viscosity of the water, thus making the water easier to remove. To test this hypothesis, a test was run to determine the effect of incoming fabric temperature on Machnozzle performance. The fabric was wet out in boiling water; however, by the time the fabric reached the Machnozzle, the fabric had cooled to 130° F. The results of this test (see Table 9) indicate that while incoming fabric temperature does have a slight effect on Machnozzle drying performance, fabric wrap angle has a much larger effect.

Thus, test results showed that both hypotheses explaining the importance of fabric wrap angle were inadequate. While the reason for the importance of fabric wrap angle is still unclear, the importance of fabric wrap angle has been clearly demonstrated.

A test was run to determine the effect of the Machnozzle slit width on the drying performance of the Machnozzle. A 0.001-inch stainless steel shim was used to increase the Machnozzle slit width from approximately 0.001 to 0.002 inches. The test was run on 50/50 PET/cotton fabric weighing 3.5 oz/yd^2 , at 80 m/min and with a steam supply pressure of 95 psig. The results of this test are shown in Table 10. Increasing the slit width had little effect on drying; however, the steam flow rate of the Machnozzle was approximately doubled. Therefore, the energy consumption per weight of fabric processed doubled when the slit width was doubled. The results suggest that Machnozzle drying energy
\propto_1	MOISTURE CONTENT OUT %	FABRIC TEMP. IN °F
28	85	130
47	85	130
50	63	130
50	70	70

Table 9. Effect of Fabric Temperature on Moisture Content

FABRIC: 100 % COTTON WEIGHT: 5.04 oz/yd² SPEED: 80 m/min MOISTURE CONTENT IN: 93 % STEAM PRESSURE: 95 psig Table 10. Effects of Slit Width on Moisture Content

SLIT WIDTH (inches)	MOISTURE CONTENT OUT (%)
0.001	26
0.002	27

FABRIC: 50/50 COTTON POLYESTER WEIGHT: 3.5 oz/yd SPEED: 80 m/min MOISTURE CONTENT IN: 66% STEAM PRESSURE: 95 psig

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efficiency could be increased by decreasing the slit width further. However, reducing the slit width below 0.001 inch was beyond the scope of the project since modifications of the Machnozzle would have been necessary.

3. Condenser Tests

The results of one series of condenser tests are summarized in Table 11. Both the amount of energy recovered in the condenser and the temperature of the heated water leaving the condenser depend on the flow rate of cold water fed to the condenser. At condenser operating conditions giving the highest heat recovery (69%), the temperature of the heated water was 118° F. The maximum heated water temperature (130° F) occurred at a lower cold water flow rate. The heat recovery corresponding to the heated water temperature of 130° F was 27%.

Hot water can be used to charge heat conducting cylinders or dryer cans. Water, at temperature between 140 and 180° F, provides significant drying effects (2). One of the objectives of the research reported herein was to determine if the heated water from the Machnozzle condenser system could be used to charge drying cylinders. The maximum temperature of the heated water from the condenser was 130° F which is not sufficient for economical drying. Accordingly, this approach was abandoned. However, there are usually one or more washing steps prior to drying that require warm water at approximately 100° F. The energy recovered from the Machnozzle predrying step can be utilized in many cases in the washing steps.

Cold Water	Exhaust Water	Energy Recovered		
(gal/hr)	w Rate Temperature al/hr) (^o F)	(BTU/hr)	(%)	
29	128	13,180	13	
59	130	27,560	27	
103	116	36,030	36	
189	118	69,530	69	
212	102	49,450	40	

Table 11. Results of Condenser Test

Note: Machnozzle steam flow rate was 90 lb/hr. Machnozzle Rate of Energy Consumption was 100,000 BTU/hr. Cold Water Temperature was 74°F.

F. STEAM CONSUMPTION

The steam consumed in removing a pound of water varies with fabric speed and steam supply pressure as shown in Figures 17 and 18. The steam consumption per pound of water removed decreased as fabric speed was increased even though lower moisture contents were obtained at lower fabric speeds. The reason is that the rate at which steam is consumed by the Machnozzle is nearly constant and independent of fabric speed. As fabric speed is increased, the quantity of fabric processed per unit time by the Machnozzle increases. As a result, steam consumption per pound of water removed decreases as fabric speed is increased. As steam supply pressure is increased, steam consumption increases at low fabric speeds. However, at a fabric speed of 80 m/min, there is little difference in steam consumption per pound of water removed from the cotton fabric. Since more moisture is removed at the steam pressure of 95 psig, the Machnozzle would probably be operated at 95 psig or higher under commercial conditions for 100% cotton fabric. The Machnozzle steam consumption per pound of water removed was significantly higher at 95 psig than at 50 psig for the 100% polyester fabric. The Machnozzle was actually over drying the fabric at 95 psig and would operate at a lower pressure on polyester fabric in a mill.

The steam consumption for a fabric speed of 80 m/min was approximately one pound of steam per pound of water removed. The steam requirements of steam can dryers are normally between 1.5 and 2.0 pounds of steam per pound of water removed. Thus the low steam requirements of the Machnozzle suggest that this device has a potential for saving energy in the fabric drying process.



Figure 17. Steam Requirements for 100% Cotton Fabric

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Figure 18. Steam Requirements for 100% Polyester Fabric

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When the energy recovered by the condenser is considered, the Machnozzle becomes even more attractive as a device for predrying fabrics. The results of condenser tests (see Table 11) indicate that approximately 69% of the energy in the steam used by the Machnozzle can be recovered. If a condenser with a recovery efficiency of 69% is used, the steam consumption of the Machnozzle is shown in Figure 19. At a fabric speed of 80 m/min, the steam consumption of the Machnozzle is approximately 0.3 pounds of steam per pound of water removed.

G. ECONOMIC ANALYSIS

The test results show clearly that the Machnozzle can significantly reduce the moisture content in fabrics. However, if the Machnozzle is to be utilized by the textile industry, the Machnozzle must also be economically attractive. Therefore, an economic analysis of the Machnozzle as a fabric predrying device has been made. The parameter used to judge the economic performance of the Machnozzle was Internal Rate of Return (IRR).

The first step of the analysis was to determine the reduction in energy consumption obtained by utilizing the Machnozzle as a predrying device instead of conventional methods. The two common devices used to predry fabrics are steam cans and infrar-red dryers. Typical energy requirements for steam can and infra-red dryers are 1.5 to 20 and 3.0 to 4.0 pounds of steam per pound of water removed, respectively. For the purposes of the analysis, the Machnozzle has been compared with a steam can system that consumes 1.5 pounds of steam per pound of water removed.

The decrease in the rate of steam consumption (ΔM) obtained with the Machnozzle, assuming no heat recovery, is

$$\Delta \tilde{M} = \rho_{f} V_{f} W_{f} (\gamma_{in} - \gamma_{out}) (E_{S} - E_{M})$$
(1)



Figure 19. Steam Requirements with Heat Recovery for 100% Cotton Fabric

where

is given by the relationship

$$\left(\Delta \dot{M}\right)_{R} = \rho_{f} V_{f} W_{f} \left(\gamma_{in} - \gamma_{out}\right) \left(E_{s} - E_{M}(1-R)\right)$$
(2)

where

R =fraction of heat recovered

The expressions for the annual cash in flow $(CF)_{in}$ generated by using the Machnozzle with and without heat recovery are

$$(CF)_{in} = s(\Delta M)t$$
(3)

and

$$\left((CF)_{in}\right)_{R} = S(\Delta \dot{M})_{R} t$$
(4)

where

S = cost of steam (\$/1b of steam)
t = number of operating hours per year

The annual cash outflow required for maintaining the Machnozzle is simply

$$(CF)_{out} = F$$

where

F = annual maintenance cost

The Internal Rate of Return (IRR) is defined as the discount rate which reduces to equality present values of expected cash outflows to present values of expected cash inflows (5) or

[Present Values of Outflows] = [Present Values of Inflows] (5) The present values of the outflows is the sum of the initial cost of the Machnozzle (and recovery system if used) plus the present value of all the maintenance cost. Thus

 $\left[\text{Present Value of Outflows} \right] = P + F (pwf-i\%-\eta)$ (6) where

P = initial cost of the Machnozzle (and recovery system if used)
pwf-i%-n = uniform series present worth factor which converts a

uniform series of payments (or receipts) continuing for M periods to the entire series' equivalent present worth at a discount rate \underline{i}

If the cost of energy is constant, the annual cash inflow generated by using the Machnozzle is a simple uniform series. Thus, the present value of the cash inflows is given by the simple relationship

 $\left[\text{Present Value of Inflows} \right] = (CF)_{in} (pwf-i^{\circ}-\eta)$ Substituting Equations (3) (or (4) if applicable), (6) and (7) into (5) and rearranging gives $\left(\begin{array}{c} \frac{1}{2} & \frac{1}{2} &$

$$pwf-i\%-\eta = \left(S(\Delta \dot{M})t - F\right)/P$$
(8)

Equation (8) can be used to determine $pwf-i\delta-\eta$. Since η (the life of the Machnozzle in years) will be specified, standard interest tables and the value of $pwf-i\delta-\eta$ can be used to determine <u>i</u> which is equivalent to the Internal Rate of Return (IRR).

The cost of energy for part of the analysis is not uniform, but increases at a rate of 10% per year. For those cases, the cost of energy is given by the equation

$$S = S_0 + 0.1S_0(y-1)$$
(9)

where $S_0 =$ the cost of energy during the first year

By substituting the relationship for S into Equation (3) (or 4) where applicable), the following equation for the annual cash inflow can be obtained

$$(CF)_{in} = S_0(\Delta \dot{M})t + 0.1S_0(\Delta \dot{M})(t)(y-1)$$
(10)

The first term in Equation (10) is a constant, and the second term increases linearly with (y-1). Thus, the annual cash inflow can be separated into two terms. The first term corresponds to a uniform series of cash inflows, and the second to a gradient series that increases by the same amount each year. The total present value of the annual cash inflows can be written as the sum of the present values of the two terms, that is

[Present Value of Inflows] = [Present Value of Inflows of Uniform Series] + [Present Value of Inflows of Gradient Series] (11)

$$\mathbf{or}$$

$$\left[\text{Present Value of Inflows}\right] = \left[S_{0}(\Delta \dot{M})t\right](pwf-i\%-\eta) + \left[0.1S_{0}(\Delta \dot{M})t\right](gpwf-i\%-\eta)$$
(12)

where

 $(gpwf-i\%-\eta) = factor to convert a gradient series to a present work$ The factor to convert a gradient series to a present work, $gpwf-i\%-\eta$, is related to the uniform present worth factor, $pwf-i\%-\eta$, through the expression (6)

$$(gpwf-i\%-\eta) = (gf-i\%-\eta)(pwf-i\%-\eta)$$
 (13)

where

gf-i%-n = factor to convert a gradient series to an equivalent annual series

By substituting Equations (6), (12) and (13) into Equation (5), the following relationship can be obtained

$$(pwf-i\%-\eta) = \frac{S_{0}(\Delta M)t - F + 0.1S_{0}(\Delta M)(t)(gf-i\%-\eta)}{P}$$
(14)

All of the quantities in Equation (14) are known except (pwf-i%-n) and (gf-i%-n). Both of the factors can be considered functions of <u>i</u> alone since <u>n</u> will be specified. The problem is to determine the value of <u>i</u> that will make the left hand side and the right hand side of Equation (14) equal. Since the expressions for (pwf-i%-n) and (gf-i%-n) in terms of <u>i</u> are complicated, the value of <u>i</u> making the two sides equal must be determined by trial and error. The value of <u>i</u> satisfying Equation (14) is equivalent to the Internal Rate of Return (IRR).

The economics of utilizing the Machnozzle to predry three common types of fabrics (100% woven polyester, 100% woven cotton, and 50/50 woven polyester/ cotton) were investigated. The pilot-scale data, summarized in Table 12, were used in this analysis. Several assumptions were made so that the Internal Rate of Return (IRR) could be calculated. The assumptions were:

- 1. The cost of the Machnozzle is \$250 per linear inch.
- The widths of the Machnozzle and the fabric to be processed is 60 inches.
- 3. The cost of the recovery system is \$10,000. If the recovery system is used, 50% of the thermal energy in the steam will be recovered.
- 4. The life of the Machnozzle is ten years, and the salvage value of the Machnozzle and recovery system will be zero at the end of ten years.
- 5. The Machnozzle is utilized 5200 hours per year.
- 6. The maintenance cost of the Machnozzle is \$1000 per year.
- The steam consumption of steam cans is 1.5 pounds of steam per pound of water removed.
- 8. The production of one pound of steam requires 1000 BTU's.
- 9. The boiler efficiency is 80%.

Using the pilot-scale data and the assumptions, Internal Rate of Return (IRR) was calculated for the following four prices of energy:

- 1. \$3.00 per million BTU
- 2. (\$3.00 + 10% per year) per million BTU

Fabric Type	[₽] f Fabric Weight (oz/yd ²)	V _f Fabric Speed (M/Min)	Υ _{IN} Incoming Moisture (%)	YOUT Exiting Moisture (%)	Steam Supply Pressure (psig)	Machnozzle Steam Consumption (lb/hr-inch)	Water Removed by Machnozzle (lb/hr-inch)	E _M Steam Requirement of Machnozzle (1bs of steam/1b of water removed	∆Y (lbw/lbf)
100% woven polyester	1.8	80 60 20	60.5 59.0 68.4	5.9 3.9 2.5	90	17 15.5 13.9	9.0 6.8 2.7	1.9 2.3 5.1	0.55 0.55 0.66
100% woven polyester	1.8	80 60 20	76.0 73.6 75.8	7.0 5.4 1.8	74	14.2 14.1 11.9	11.3 8.4 3.0	1.25 1.68 3.92	0.69 0.68 0.74
100% woven polyester	1.8	80 60 20	77.6 80.6 85.9	14.6 12.7 4.3	50	9.2 8.3 8.1	10.3 8.4 3.4	0.89 0.97 2.42	0.63 0.68 0.81
100% Woven cotton	4.0	80 60 20	96.8 97.3 98.8	46.0 43.8 34.2	90	19.7 20.2 18.1	18.5 14.6 5.9	1.06 1.38 3.07	0.50 0.54 0.65
100% woven cotton	4.0	80 60 20	101.8 99.0 100.0	52.4 49.1 40.6	74	16.2 16.2 14.1	18.0 13.6 5.4	0.90 1.19 2.60	0.49 0.59 0.59
100% Woven cotton	4.0	80 60 20	97.5 99.2 102.6	62.0 59.2 47.4	50	12.2 10.7 9.0	12.9 10.9 5.0	0.94 0.98 1.91	0.36 0.40 0.55
50/50 polyester- c ot ton	3.6	80 60 20	64.9 64.6 70.5	17.3 14.9 7.2	92	18.4 17.9 16.0	15.6 12.2 5.2	1.18 1.47 3.08	0.48 0.50 0.63
50/50 polyester- cotton	3.6	80 60 20	60.6 62.7 70.8	21.5 18.7 9.7	75	15.2 15.1 13.0	12.8 10.8 5.0	1.19 1.40 2.60	0.39 0.44 0.62
50/50 polyester- cotton	3.6	80 60 20	60.9 62.3 69.1	28.4 26.3 16.7	50	11.7 9.5 8.6	10.7 8.8 4.3	1.09 1.08 2.00	0.33 0.36 0.52

Table 12. Machnozzle Pilot-Scale Data Used in Economic Analysis

- 3. \$6.00 per million BUT
- 4. (\$6.00 + 10% per year) per million BTU

The results of the calculations, summarized in Table 13, show that the economic feasibility of using the Machnozzle as a predrying device depends on the cost of energy and process operating conditions. Internal Rate of Return (IRR) was very large (as high as 183%) in some cases, but extremely small in other cases. There were several conditions where the initial investment would not be recovered in the ten year period used in the analysis.

The price of energy greatly affects IRR, as would be expected. For example, when fabric speed is 80 meters per minute and the most economical steam supply pressure is used, IRR for an energy cost of \$6 per million BTU is approximately twice that for an energy cost of \$3 per million BTU. When the price of energy is \$6 per million BTU, the IRR's for fabrics made of 100% polyester, 100% cotton, and 50/50 cotton/polyester are 98, 173, and 129%, respectively. The IRR's for the same three fabrics, but at an energy cost of \$3 per million BTU are 47, 85, and 62%, respectively. The current cost of energy is approximately \$3 per million BTU; however, the time the Machnozzle could be utilized in industry, the price of energy will no doubt be much higher. Thus, the IRR's calculated at \$3 and \$6 per million BTU can be considered as brackets for the actual IRR at plants where conditions are consistent with the assumptions discussed above.

The results of the economic calculations showed that in most cases adding 10% per year to the cost of energy increased IRR by approximately 10%. For example, when the price of energy is \$6 per million BTU and none of the energy

ght Jy				INTERNAL RATE OF RETURN (IRR) (%)							
	YL	ed	COST OF ENERGY PER MILLION BTU								
μ _γ ι	¹²)	upp Tre	Spe (\$3	Plus			\$6	Plus
ic	ic/yo	in S SSU SSig	MIN		\$3	10% P	er Year	\$	6	10%	Per Year
Fabı	Fabr (02	Stea Pre	Fabr (M)	Without Recovery	With Recovery	Without Recovery	With Recovery	Without Recovery	With Recovery	Without Recovery	With Recovery
100% woven polyester	1.8	90	80 60 20	* * *	14 * *	* * *	22 * *	* *	40 13 *	* * *	50 21 *
100% woven polyester	1.8	74	80 60 20	9 * *	41 17 *	17 * *	51 24 *	36 * *	89 47 *	46 * *	98 57 *
100% woven polyester	1.8	50	80 60 20	41 24 *	47 34 *	51 34 *	56 42 *	92 62 *	98 76 *	102 72 *	108 85 *
100% woven cotton	4.0	90	80 60 20	56 0 *	80 51 *	65 5 *	90 61 *	121 16 *	164 107 *	131 25 *	174 117 *
100% woven cotton	4.0	74	80 60 20	77 23 *	85 53 *	87 33 *	94 63 *	162 59 *	173 112 *	172 69 *	183 121 *
100% woven cotton	4.0	50	8 0 60 20	49 36 *	58 47 *	59 46 *	68 55 *	107 82 *	121 100 *	117 92 *	131 109 *
50/50 woven polyester cotton	3.6	92	80 60 20	30 * *	62 39 *	40 * *	72 47 *	71 * *	129 83 *	81 * *	139 93 *
50/50 polyester- cotton	3.6	75	80 60 20	22 * *	50 35 *	32 * *	59 43 *	55 * *	105 77 *	65 * *	114 87 *
50/50 polyester- cotton	3.6	50	30 60 20	24 18 *	42 34 *	34 28 *	52 42 *	62 51 *	92 76 10	72 61 *	101 85 18

Table 13. Results of the Economic Analysis

* For thoses cases, either investment would not be recovered in ten years or IRR is extremely small.

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is recovered, the IRR for the woven 100% cotton fabric (processed using a fabric speed of 80 meters per minute and a steam supply pressure of 90 psig) is 121%. For the same conditions except that the price of energy is \$6 per million BTU plus 10% per year, the IRR is 131%.

Utilization of a heat recovery system with the Machnozzle increased IRR for all the cases considered. However, the magnitude of the increase varied significantly with operating conditions. In some cases, IRR increased only a few percent, but in other cases, IRR increased significantly (as much as 58%).

In general, IRR increased with increasing fabric speed. This was expected since productivity increases linearly with fabric speed while energy consumption of the Machnozzle increases only slightly. The highest fabric speed (80 meters per minute) for which IRR was calculated corresponds closely with process speeds used in industry.

The IRR's, summarized in Table 13, indicate that the Machnozzle can be economically attractive as a fabric predrying device. As mentioned previously, the IRR's are based on pilot-scale data and the assumptions discussed above. For the IRR's in Table 13 to translate to actual commercial conditions, the plant operating conditions must be consistent with those used in this study. Many industrial operations may have squeeze rollers that express water more efficiently that those used to obtained the pilot-scale data. Consequently, if the Machnozzle is used in those plants, the steam usage of the Machnozzle in pounds of steam per pound of water removed would be higher than obtained in this study. On the other hand, many of those plants utilize steam cans that consume more steam than the hypothetical steam system (1.5 pounds of steam per pound of water removed) used as a basis for the energy consumption calculations.

The two effects tend to offset each other.

If 50% Internal Rate of Return (IRR) is the lower limit of economically feasible energy conservation investments in the textile industry, the Machnozzle is attractive for 100% cotton fabrics and 50/50 cotton/polyester blend fabrics (with heat recovery) at an energy cost of \$3 per million BTU. All three types of fabrics give favorable Internal Rate of Return (IRR) at an energy cost of \$3 per million BTU plus 10% per year.

III. MATHEMATICAL MODELING OF STEAM CAN DRYING

A. INTRODUCTION

Heated cans (or drums) have been utilized for at least a century for drying sheet materials and slurries. A series of steam-heated cans are often used to dry textiles, primarily due to the convenience of handling materials on these dryers. Typically, fabrics moving at speeds ranging from 50 to 100 yards per minute pass over a battery of steam cans consisting of 20 to 48 units. The cans are normally charged with steam at pressures ranging from 40 to 70 psig. Due to the low cost of energy in the past, low energy consumption has not been a consideration in the design and operation of steam can dryers. As a result, can dryers are energy inefficient in removing water from textiles. By optimizing can dryers, a large part of the annual energy requirement for drying textiles (estimated 5.6 x 10^6 BOE (1)) could be conserved.

Since textile can drying represents an energy-intensive, wasteful process, one of the objectives of the research reported here was to optimize steam can dryers with respect to energy consumption. The parameters involved in can drying are numerous. Therefore a totally experimental approach to optimization would require extensive experimental testing. Since textile machines are far too expensive to operate for extensive experimentation, the approach to optimize steam can dryers has been to develop a mathematical model of the can drying process than can predict the rate of energy consumption and the corresponding drying rate for various system parameters.

B. BRIEF REVIEW OF STATE-OF-THE-ART IN CAN DRYING

A survey of the literature to determine the state-of-the-art in can drying reveals that almost nothing has been done in the textile area towards the under-

standing of can drying. However, several investigations pertaining to the can drying of paper have been conducted. Most of the earlier models used to describe paper drying have been based on a heat conduction model developed by Nissan (7,8,9). Nissan's model, however, does not include a description of mass transfer occurring within the sheet, and requires simultaneous measurement of dryer and sheeting parameters.

A number of papers dicussing the transport phenomena in porous media have been published. Due to the complex phenomena that can occur during drying of porous media, a single commonly accepted model has not emerged.

Some of the earlier drying models are based on non-isothermal mass transfer processes assuming a single dominant mechanicsm for moisture distribution. In these models, moisture is assumed to migrate by either liquid diffusion or capillarity. Taking into account simultaneous heat and mass transfer, Henry (10) proposed the vaporization-condensation theory with the basic assumption that moisture migrates entirely in the vapor phase. In most cases, these models were too simplistic and could not adequately predict drying rates (11).

The mathematical model proposed by Lyons et al (12), while incorporating both heat and mass transfer, requires that values of porosity, pore diameter, and sticking coefficient be specified.

In the last few years, more complicated models (13,14,15,16) have been developed by using mechanistic reasoning and irreversible thermodynamics. The major difference in the models has been the choice of the dominant driving forces.

The mathematical model presented by Hartley and Richards (17) assumes that liquid flux is a function of moisture content only. The effects of moisture concentration and temperature on liquid flux are important, but neglected by the model.

Fortes and Okos (11) have formulated a drying model by combining mechanistic reasoning with irreversible thermodynamics. Their model assumes that both liquid and vapor fluxes can be expressed in terms of the same driving forces, in particular, temperature and equilibrium relative humidity gradients. The model appears to be based on good assumptions and incorporates most of the accepted features of recent models.

A commonly accepted theory in the contact drying of fibrous materials is that drying begins in a short preheating period in which both the temperatures of the material and the drying rate increase, until they attain some steady state values. This is followed by a constant-rate-of-drying period characterized by vaporization from a surface saturated with free water. As drying proceeds a critical moisture content is reached when the free water concentration at the surface drops to zero and the transition to the falling-rate period of drying begins. Liquid water does not migrate to the surfaces as fast as it evaporates from the surface, and the zone of vaporization recedes into the interior leaving a dry outer layer. In this region the moisture content of the fabric . is obtained from the relative humidity - desorption curve.

The effective thermal conductivity decreases as the dry layer of fabric increases, and as this layer increases, temperatures in the fabric decrease. The flows of heat and water vapor from the hot surface to the plane of minimum temperature in the fabric are concurrent and parallel (18).

C. MATHEMATICAL MODEL

1. Moisture Migration Mechanism

A modified form of Dacry's Law was used to describe the rate of liquid water flow through the fabric. The liquid flux is related to relative humidity, temperature, and their gradients. Under unsaturated conditions liquid moisture movement is negligible.

The moisture moves in the vapor phase by diffusion. The driving force for the diffusion is a vapor pressure gradient. Fick's first law was utilized to relate vapor flux to relative humidity, temperature, and their gradients.

When these relationships for the moisture fluxes were used in writing energy and mass balances, a set of equations describing the general macroscopic phenomena occurring during drying was obtained. The equations describe the temperature and moisture variations within the sheet.

In conjunction with the moisture movement mechanisms, the widely accepted evaporation-diffusion-condensation theory explaining moisture movement within a drying sheet was included in the model. According to the evaporation-diffusioncondensation theory, water flows from an internal region of maximum moisture content toward the surfaces. Water moving through the fabric to the hot can surface is vaporized. The vapor formed in the vicinity of the hot surface diffuses back through the fabric towards the open surface. As the vapor moves back through the fabric, partial condensation can occur because of the decreasing temperature. Thus an evaporation-diffusion-condensation process is partially responsible for heat transfer as well as mass transfer in the fabric.

2. Assumptions

In deriving the set of equations describing the phenomena occurring in drying fabric sheet, several assumptions were made. The major assumptions were:

- The web is composed of a network of fibrous materials randomly oriented and containing liquid water, water vapor, and air in the structure voids.
- (2) The fibrous structure is macroscopically uniform and isotropic, i.e., the system is taken as a continuum.
- (3) Moisture migration takes place in both the liquid and vapor phases. A modified form of Darcy's law is used to relate the liquid flux to relative humidity, temperature, and their gradients.
- (4) The temperatures and vapor pressures of the liquid and vapor phases are in equilibrium.
- (5) The vapor pressure in the voids is equal to the product of the saturation vapor pressure for pure water at the corresponding temperature and the relative humidity.
- (6) Relative humidity is a function of moisture content and temperature.
- (7) Variations in the y-direction (width direction) are negligible.
- (8) Mass transfer and conductive heat transfer are appreciable only in the x-direction (perpendicular to the fabric sheet).
- (9) Radiative heat transfer is negligible.
- (10) Shrinkage and mechanical deformations are negligible.
- (11) Void fraction is constant and uniform through sheet.
- (12) Densities of fiber and water are constant.
- (13) No chemical reactions are assumed to occur.
- (14) Air and steam are treated as ideal gases.

3. Development of Mathematical Model

Development of the mathematical model describing the can drying process was divided into three tasks:

- Task 1: Writing the governing equations describing the heat and mass transfer mechanisms in the process.
- Task 2: Writing the initial and boundary conditions.
- Task 3: Solving the governing equations consistent with the initial and boundary conditions.

Brief descriptions of these three tasks follows:

(a) Task 1

The equations governing the heat transfer through the metal shell of the can dryer and the heat and mass transfer in the fabric sheet were written. The equations were obtained by writing energy and mass balances for the two stationary control volumes shown in Figure 20.

One of the control volumes is located in space through which the can shell rotates. Since only conductive heat-transfer occurs in the shell, the only differential equation needed to describe the temperature variation through the shell is an energy balance equation.

The other control volume is located in space through which the sheeting material flows. The phenomena occuring in this control volume are much more complex since a three phase system (gases (air and water vapor), liquid water, and solid (fibers)) exits there. Several heat-transfer mechanisms operate simultaneously in the drying fabric. The mechanisms include: conduction, convection radiation, and evaporation-diffusion-condensation. As a result, six differential equations are needed to describe the heat and mass transfer occurring in the sheet:





- (1) An overall energy balance
- (2) Mass balance on air
- (3) Mass balance on water vaor
- (4) Mass balance on liquid water
- (5) Relationship describing movement of liquid water in fabric
- (6) Relationship for air-water vapor diffusion in a porous medium (fabric)

The equations are presented in detail in Appendix 2.

(b) Task 2

Solving the governing equations requires initial and boundary conditions for the can shell and the fabric. These conditions are presented in detail in Appendix 2.

(c) Task 3

The governing equations are nonlinear partial differential equations with second order terms, therefore, exact closed form solutions would be extremely difficult to obtain. Thus a numerical scheme was used to solve the equations. The details of the numerical scheme are discussed in Appendix 3.

D. COMPUTATIONAL RESULTS AND DISCUSSION

A lack of experimental data in the drying of fabrics precluded the possibility of any comparison between theory and experiment. However, some experimental data were available on the drying of paper. The experimental results of McCready (19) and Han and Ulmanen (20) were selected for comparison with the predictions of the theoretical model. McCready's data

pertain to the rates of drying of pulp of varying thickness. Han and Ulmanen measured moisture, temperature, and caliper data in the drying of a thick paper sheet at specific points across the thickness of the sheet.

The results of the numerical solution of the reduced and transformed non-dimensional governing equations are plotted in Figures 21 and 22. Neither McCready's nor Han and Ulmanen's data (19,20), independently, contain all the information required for the computer solution. This includes critical parameters such as heat and mass transfer coefficients, and diffusion coefficients. Therefore, only trends are compared. The temperature-time and moisture contenttime profiles show similar trends to those of the experiments.

To study the effect of the sensitivity of the air-vapor diffusion coefficient, the equations were solved first using a diffusion coefficient with a value corresponding to the free stream, second with a value one-half of the previous value, and finally with a value one-tenth of the initial value. The sensitivity of the binary diffusion coefficient is clearly reflected in the plots.





Figure 21. Comparison of Moisture Regain-Time Profiles



Figure 22. Comparison of Temperature Profiles

IV. DISSEMINATION OF RESULTS

Results from this study have been published and presented at a national technical meeting. A paper entitled, "Energy Consumption and Conservation: Textile Drying" by David Brookstein was published in American Chemical Society Symposium Series 107. A presentation "Drying of Fabrics With a Machnozzle" by W. W. Carr, W. Holcombe, and D. Brookstein was presented at the 1979 Textile Conference sponsored by the Textile Industries Division of ASME and the Textile Institute, England.

Technology developed during this project is also included in a course entitled "Energy Conservation in the Textile Industry" taught at Georgia Tech.

V. CONCLUSIONS

The results of the Machnozzle tests clearly demonstrate that the Machnozzle can significantly reduce the moisture content in fabrics. The economical feasibility of utilizing the Machnozzle as a fabric predrying device depends on th cost of energy and process operating conditions, in particular fabric speed. Internal Rate of Return (IRR) increases with fabric speed. For a fabric speed close to plant operating speeds (80 m/min) and a realistic cost of energy (\$3 per million BTU plus 10% per year), the economic analysis indicates that the Machnozzle is economically attractive. All three fabrics (100% cotton, 50/50 polyester/cotton, and 100% polyester) gave Internal Rates of Return (IRR) greater than 50%. Accordingly, the Machnozzle pilot-scale research should be expanded to an in-plant demonstration to prove the technical and economic feasibility of the Machnozzle on a commercial scale.

A mathematical model describing the physical aspects of the textile can drying process has been developed to predict drying rates. The results of the numerical scheme used to solve the governing equations show similar trends to those for experimental paper drying. Many textile fabrics dried on steam cans may be considered as hydrophilic porous media, similar to paper. However, before the model can be applied to the hot surface drying of textiles, critical parameters affecting the heat transfer rates and the mass transfer rates such as the diffusion coefficient and heat and mass transfer coefficients have to be obtained. A dearth of experimental data on these parameters, the diffusion coefficient for instance, has been demonstrated.

Upon the availability of such data, the mathematical model can be used with some refinement, in conjunction with feedback control systems to optimize steam can drying with respect to energy consumption. APPENDICES

APPENDIX 1

Machnozzle Test Results

Fabric	Fabric Speed (M/Min)	Incoming Moisture (%)	Exiting Moisture (%)	Incoming Moisture Range (%)	Exiting Moisture Range (%)	Steam Pressure (psig)	Steam Consumption (1b/hr)	Slot Length (in)
50/50 cotton- polyester 3.6 oz/yd ²	80 60 20	67.2 65.5 67.4	29.0 25.1 16.3	65.6-69.5 62.2-67.9 65.7-68.8	27.7-30.6 24.2-26.8 14.9-17.2	81	140 128	8
50/50 cotton- polyester 3.6 oz/yd ²	100 80 60 20	66.2 65.4 65.8 46.4	29.8 24.3 20.3 20.5	59.7-70.1 63.4-68 60.2-71.4 22.6-72.9	7.3-58.3 7.4-37.3 15.2-23.2 13.6-28.3	94	No Data	8
50/50 (a) cotton- polyester 3.6 oz/yd ²	80 80 80	66.9 67.0 66.3	55.8 55.7 48.7			94	160 160 80	8
50/50 (b) cotton- polyester 3.6 oz/yd ²	80 80 80	63.6 64.7 66.2	33.4 25.5 27.1	61.7-70.8	20.4-36.7	94	153 210 222	8 16 16
50/50 (c) cotton- polyester 3.6 oz/yd ²	80 80	64.5 65.2	23.9 25.6	63.2-67.5 63.2-68.0	23.3-25.4 24.6-27.0	94	172	16

- (a) Wrap angle experiment equal wrap angles
- (b) Slit width experiment using 1 mil shim

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(c) Wrap angle experiment - unequal wrap angles

APPENDIX 1 (Continued)

Fabric	Fabric Speed (M/Min)	Incoming Moisture (%)	Exiting Moisture (%)	Incoming Moisture Range (%)	Exiting Moisture Range (%)	Steam Pressure (psig)	Steam Consumption (1b/hr)	Slot Length (in)
50/50 cotton- polyester	80	67.4	40.3			94	No Data	16
3.6 oz/yd^2	80	66.5	36.8					
100% cotton	100	103.2	67.2	102.7-103.8	66.1-68.2		185	
5.67 oz/vd^2	80	103.6	69.6	101.2-105.5	64.8-86.1		175	
, ju	60	103.0	66.8	102.1-104.7	59.4-91.7	94	185	16
	20	102.5	45.9	100.0-105.0	43.8-48.9		170	
100% (d) cotton		91.8	84.7					
5.67 oz/vd^2	80	92.6	85.0			94	-	16
		93.3	63.4			·		
100%	80	96.8	46.0	94.8-100	44.8-46.9			
cotton 2	60	97.3	43.8	94.4-102.3	40.7-48.4	95	-	16
4.0 oz/yd ⁻	20	98.8	34.2	96.0-102.0	32.7-35.2			
100%	80	101.8	52.4	95.2-121.9	50.3-55.1			
cotton	60	99.0	49.1	96.6-104.4	47.2-51.5	75	-	16
4.0 oz/yd^2	20	100.0	40.6	98.2-101.3	36.3-51.9			

(d) Hot water wet out test

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.
APPENDIX 1 (Continued)

Fabric	Fabric Speed (M/Min)	Incoming Moisture (%)	Exiting Moisture (%)	Incoming Moisture Range (%)	Exiting Moisture Range (%)	Steam Pressure (psig)	Steam Consumption (1b/hr)	Slot Length (in)
100%	80	97.5	62.0	97.1- 98.3	60.4-66.7			
cotton	60	99.2	59.2	98.2-100.9	57.9-60.2	50	-	16
4.0 oz/yd ²	20	102.6	47.4	100.6-105.4	45.1-48.8			
.100% (e)		98.5	46.8	97.7- 99.5	44.7-50.2			
40 oz/yd^2	80					95	-	16
4.0 02/90		100.8	55.2	99.1-103.2	52.1-58.7			
100% (f)		98.3	83.5	93.5-102.2	81.6-85.7			
cotton	80	99.6	84.2	98.3-100.8	81.9-85.0	95	-	16
4.0 oz/ya		100.6	88.5	99.3-101.9	84.7-91.3			
100%	80	60.5	5.90	57.1- 63.8	3.13-8.47			
polyester 1.8 oz/yd ²	60	59.0	3.86	56.9- 61.0	3.23-4.35	95	-	16
	20	68.4	2.47	58.1- 75.5	1.54-1.55			
100%	80	76.0	7.00	73.0- 79.0	5.56-7.84			
polyester 2	60	73.6	5.38	69.7-86.1	3.75-6.54	75	-	16
1.8 oz/yd	20	75.8	1.83	72.3- 78.4	1.09-4.00			
100%	80	77.6	14.55	74.6- 80.0	11.93-17.45			
polyester	60	80.6	12.71	77.7- 82.4	11.45-15.38	50	-	16
1.8 oz/yd-	20	85.9	4.31	83.0- 90.5	3.25 6.92			

(e) Tension test - (high, low)

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(f) Tension test - (high, medium, low)

APPENDIX 1 (Continued)

Fabric	Fabric Speed (M/Min)	Incoming Moisture (%)	Exiting Moisture (%)	Incoming Moisture Range (%)	Exiting Moisture Range (%)	Steam Pressure (psig)	Steam Consumption (lb/hr)	Slot Length (in)
50/50 cotton- polyester 3.6 oz/yd ²	80 60 20	64.9 64.6 70.5	17.3 14.9 7.2	63.4-66.5 63.1-65.9 67.9-73.3	15.7-18.5 13.5-16.4 5.23-8.67	92	-	16
50/50 cotton- polyester 3.6 oz/yd ²	80 60 20	60.6 62.7 70.8	21.5 18.7 9.70	58.5-62.8 56.5-67.0 67.5-73.3	20.8-22.5 18.3-19.6 8.65-10.50	75	-	16
50/50 cotton- polyester 3.6 oz/yd ²	80 60 20	60.9 62.3 69.1	28.4 26.3 16.7	57.1-63.6 60.8-65.1 67.6-70.3	27.8-29.7 25.1-27.0 15.8-17.8	50	-	16

APPENDIX 2

NOMENCLATURE

a	=	volumetric fraction of void filled with liquid
с	-	total molar concentration, mols/ft ³
C _p	=	heat capacity at constant pressure, $BTU/1b/^{\circ}R$
Dav	-	air-vapor binary diffusion coefficient, ft ² /sec
h	=	enthalpy, BTU/lb
h _H	=	convective heat transfer coefficient between can,
		of fabric and surrounding air, BTU/ft ² /sec/ [°] R
h am	=	air mass transfer coefficient, lb/ft ² /sec
h mv	Η	specific latent heat of vaporization, BTU/lb
h _{sm}	=	vapor mass transfer coefficient, lb/ft ² /sec
Н	=	relative humidity
k	=	specific permeability, ft ²
k _{AV}	=	air-vapor mixture thermal conductivity, $BTU/ft/sec/^{\circ}R$
К	=	thermal conductivity, BTU/ft/sec/ [°] R
^K eff	=	effective thermal conductivity of sheet, BTU/ft/sec/°R
L	=	total thickness of fabric/pulp slab, ft
М	=	moisture regain
n	=	mass flux, lb/sec/ft ²
P	ш	pressure, lb/ft/sec ²
Q ₁	H	differential heat of sorption, BTU/lb

.

R	= gas constant, $ft^2/sec^2/^{\circ}R$
t	= time, sec
T	= temperature, [°] R
Tic	= inner surface temperature of can, $^{\circ}R$
^T fab	= temperature of fabric, $^{\circ}R$
Tsat	= saturation temperature of steam in can, $^{\circ}R$
u	= internal energy, BTU/lb
v	= velocity along the z-direction, ft/sec
x	= distance along thickness of fabric, ft
× _A	= mole fraction of air
xv	= mole fraction of vapor
У	= distance along width of fabric, ft
z	= distance along length of fabric, ft

Subscipts

a,A	= air
f,F	= fiber
i	= general species
1	= liquid
m,w	= moisture or liquid water
s,v	= vapor
20	= surrounding air conditions
0	= initial conditions

Greek

αc	=	thermal diffusivity of the can shell, ft ² /sec
$\Delta \mathbf{x}$	=	elemental distance along thickness of fabric, ft
Δy	=	elemental distance along width of fabric, ft
$\Delta \mathbf{z}$	Ħ	elemental distance along length of fabric, ft
٦	=	kinematic viscoscity, ft ² /sec
η	=	dimensionless flux
0	=	dimensionless temperature
τ	=	dimensionless time
ψ	=	dimensionless distance
ρ	=	density, lb/ft ³

APPENDIX 2

Governing Equations In Steam Can Drying

A schematic of the physical process to be modeled is shown in Figure 1. The equations of continuity and energy for the fabric and the can are developed by writing mass and energy balances over a control volume for the fabric, and can respectively, subject to certain assumptions.

The major assumptions in the development of the mathematical model are:

(1) The fabric sheet is consists of a network of randomly oriented fibrous material containing liquid water, water vapor, and air in the structure of the textile voids.

(2) The fibrous structure is macroscopically uniform and isotropic, i.e., the system is a continuum.

(3) Moisture migration takes place in both the liquid and vapor phases. A modified form of Darcy's law is used to relate the liquid flux to relative humidity, temperature, and their gradients. Fick's first law is used to relate vapor flux to relative humidity, temperature and their gradients.

(4) The temperatures and vapor pressures of the liquid and vapor phases are in equilibrium.

(5) The vapor pressure in the voids is equal to the

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Figure 1. Schematic of Can Dryer Showing Control Volumes Used in Deriving Governing Equations

product of the saturated vapor pressure for pure water at the corresponding temperature and relative humidity.

(6) Relative humidity is a function of moisture regain.

(7) Variations across the width are negligible.

(8) Mass transfer and conductive heat transfer are appreciable only in the direction along the thickness of the fabric sheet.

(9) Radiative heat transfer is negligible.

(10) Shrinkage and mechanical deformations are negligible.

(11) Void fraction is constant and uniform throughout the sheet.

(12) Densities of fiber and water are constant.

(13) No chemical reactions occur.

(14) Air and water vapor are treated as ideal gases.

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Governing Equations for Fabric

a) Mass Balance

Consider a control volume of dimensions Δx , Δy , Δz in a section of the fabric as shown in Figure 2. Based on the control volume, mass and energy balances may be written for each of the species entering and leaving the control volume.

The law of conservation of mass for any species i is written as

(2.1)

If ρ_i is the mass per unit volume of species i, then the various contributions to the mass balance are:

time rate of change of mass of i within $= \frac{\partial \rho_i}{\partial t} \Delta x \Delta y \Delta z$ (2.2) control volume

input of mass of i across the = $n_{i|x} \Delta y \Delta z + n_{i|z} \Delta x \Delta y$ (2.3) faces at x and z



Figure 2. Control Volume Used in Deriving Mass Balance Equations

output of mass of i across the faces at $x + \Delta x = n_{i|x+\Delta x} \Delta y \Delta z + n_{i|z+\Delta z} \Delta x \Delta y$ (2.4) and $z + \Delta z$

rate of mass generation =
$$r_i \Delta x \Delta y \Delta z$$
 (2.5)

where $n_{i|x}$, $n_{i|y}$, $n_{i|z}$ are the rectangular components of the mass flux vector given by

$$\mathbf{n}_{i} = \boldsymbol{\rho}_{i} \mathbf{v}_{i} \tag{2.6}$$

 v_i is the velocity of the mass flux in the direction of the flux and r_i is the rate of mass generation per unit volume.

By assumption, the fluxes in and out of the faces at y and y + Δ y are zero.

On substitution of equations (2.2) to (2.5) in equation (2.1), dividing through by $\Delta x \Delta y \Delta z$, and taking the limit as the size of the control volume decreases to zero

$$\frac{\partial \rho_{i}}{\partial t} + \frac{\partial n_{i} | x}{\partial x} + \frac{\partial n_{i} | z}{\partial z} = r_{i}$$
(2.7)

Equation (2.7) is the equation of continuity of species i.

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The species under consideration in this model are

- (1) liquid water
- (2) water vapor
- (3) air

Successive application of the equation of continuity to each of the above species gives

Mass Balance for Water

$$\frac{\partial \rho_{m}}{\partial t} + \frac{\partial n_{m} | x}{\partial x} + \frac{\partial n_{m} | z}{\partial z} = r_{m}$$
(2.8)

Mass Balance for Water Vapor

$$\frac{\partial \rho_{s}}{\partial t} + \frac{\partial n_{s} | x}{\partial x} + \frac{\partial n_{s} | z}{\partial z} = r_{s}$$
(2.9)

Mass Balance for Air

$$\frac{\partial \rho_A}{\partial t} + \frac{\partial n_A | x}{\partial x} + \frac{\partial n_A | z}{\partial z} = r_A \qquad (2.10)$$

Since any generation of water vapor results from conversion of liquid water into vapor and vice versa,

$$\mathbf{r}_{\mathrm{m}} = -\mathbf{r}_{\mathrm{s}} \tag{2.11}$$

and $r_A = \emptyset$, since no air is generated.

The density terms $\rho_{\rm m}$, $\rho_{\rm s}$ and $\rho_{\rm A}$ in equations (2.8) to (2.10) are the apparent densities of water, vapor and air. These may be related to the actual densities $\rho_{\rm w}$, $\rho_{\rm y}$ and $\rho_{\rm a}$ by the following equations

$$\rho_{\mathbf{m}} = \mathbf{a} \in \rho_{\mathbf{W}} \tag{2.12}$$

$$\rho_{\rm S} = (1-a) \, e \, \rho_{\rm Y}$$
 (2.13)

$$\rho_{\rm A} = (1-a) \ e \ \rho_{\rm a}$$
 (2.14)

where

e = volumetric void fraction
a = volumetric fraction of void filled with liquid

$$\rho_w$$
 = density of water
 ρ_v = density of vapor
 ρ_a = density of air
The mass balance equations thus become

$$\frac{\partial (aep_w)}{\partial t} + \frac{\partial n_m}{\partial x} + \frac{\partial n_m}{\partial z} = r_m \qquad (2.15)$$

$$\frac{\partial ((1-a)e\rho_v)}{\partial t} + \frac{\partial n_s |x}{\partial x} + \frac{\partial n_s |z}{\partial z} = -r_m \qquad (2.16)$$

$$\frac{\partial ((1-a)e_{p})}{\partial t} + \frac{\partial n_{A}}{\partial x} + \frac{\partial n_{A}}{\partial z} = 0 \qquad (2.17)$$

b) Energy Balance

The thermal energy entering the control volume at faces x, z and leaving at faces $x + \Delta x$ and $z + \Delta z$ is shown in Figure 3. The general macroscopic energy balance can be written as

The energy in and out of the control volume at faces x and z are due to conduction and convection. No energy is assumed to enter or leave the control volume at face y.

If u_{i} is the energy per unit mass of the species i, then the rate of change of energy within the control volume is given by

$$\frac{\partial \rho_{i} u_{i}}{\partial t} \Delta x \Delta y \Delta z \qquad (2.19)$$

The rate of energy in is

$$q_{\text{cond}} |\mathbf{x}^{\Delta \mathbf{y} \Delta \mathbf{z}} + q_{\text{conv}} |\mathbf{x}^{\Delta \mathbf{y} \Delta \mathbf{z}} + q_{\text{conv}} |\mathbf{z}^{\Delta \mathbf{x} \Delta \mathbf{y}}$$
(2.20)



Figure 3. Control Volume Used in Deriving the Energy Equation

The rate of energy out is

 $q_{\text{cond}|x+\Delta x}^{\Delta y \Delta z} + q_{\text{conv}|x+\Delta x}^{\Delta y \Delta z} + q_{\text{conv}|z+\Delta z}^{\Delta x \Delta y}$ (2.21)

 $q_{cond|x'}$ $q_{cond|x+\Delta x}$ are the energy fluxes per unit where area due to conduction in and out of the control volume at faces x and x + Δx . q and q are the convective conv|x fluxes per unit area into the control volume at faces x and and $q_{conv|z+\Delta z}$ respectively. are the Z $q_{conv|x+\Delta x}$ convective fluxes out of the control volume at faces $x + \Delta x$ and $z + \Delta z$. By assumption the energy fluxes due to conduction at the y and z faces are zero, and the convective flux across the y and $y + \Delta y$ faces is also zero. The rate of energy generation is zero.

Substituting equations (2.19) to (2.21) in (2.18), dividing through by $\Delta x \Delta y \Delta z$ and letting $\Delta x \Delta y \Delta z$ decrease to zero, gives

$$\frac{\partial \rho_{i} \mathbf{u}_{i}}{\partial t} + \frac{\partial q_{cond} | \mathbf{x}}{\partial \mathbf{x}} + \frac{\partial q_{conv} | \mathbf{x}}{\partial \mathbf{x}} + \frac{\partial q_{conv} | \mathbf{z}}{\partial z} = 0 \qquad (2.22)$$

From Fourier's law of heat conduction

$$q_{\text{cond } x} = -K_{\text{eff}} \frac{\partial T}{\partial x}$$
 (2.23)

where T is the temperature and K_{eff} is the effective thermal conductivity of the system in the control volume. Also

$$q_{conv|x} = n_{f|x}h_{f} + n_{m|x}h_{m} + n_{s|x}h_{s} + n_{A|x}h_{a}$$
 (2.24)

and

$$q_{conv|z} = n_{f|z}h_{f} + n_{m|z}h_{m} + n_{s|z}h_{s} + n_{A|z}h_{a}$$
 (2.25)

where h_{f} , h_{m} , h_{s} and h_{a} are the enthalpies of fiber, water, vapor and air respectively. However, $n_{f|x}$ in equation (2.24) is zero since there is no movement of fiber in the x direction.

Thus

$$q_{conv|x} = n_{m|x}h_{m} + n_{s|x}h_{s} + n_{A|x}h_{a}$$
 (2.26)

Now

$$h_{i} = u_{i} + P_{i}V \qquad (2.27)$$

where P_{i} is the the pressure and V is volume. Hence

$$\rho_{i}h_{i} = \rho_{i}u_{i} + \rho_{i}P_{i}V \qquad (2.28)$$

For an ideal gas

$$P_{i}V = R_{i}T \qquad (2.29)$$

and

$$\rho_{i} = \frac{P_{i}}{R_{i}T}$$
(2.30)

$$P_{i}V = \frac{P_{i}}{\rho_{i}}$$
(2.31)

Equation (2.28) may therefore be written as

.

$$\rho_{i}h_{i} = \rho_{i}u_{i} + P_{i} \qquad (2.32)$$

Thus

$$\rho_A h_a = u_a h_a + P_a \tag{2.33}$$

$$\rho_{sh_{s}} = u_{sh_{s}} + P_{v0}$$
 (2.34)

where ${\tt P}_{\rm v0}$ is the saturated vapor pressure and ${\tt P}_{\rm a}$ is the pressure due to air.

Adding equations (2.33) and (2.34) and differentiating with respect to t

$$\frac{\partial (\rho_{s}h_{s} + \rho_{A}h_{a})}{\partial t} = \frac{\partial (u_{A}h_{a} + u_{s}h_{s})}{\partial t}$$
(2.35)

since

.

$$P_{atm} = P_{v0} + P_{a}$$
 (2.36)

and the derivative of P with respect to t is zero. Also

$${}^{\rho} f^{h} f \stackrel{\simeq}{=} {}^{\rho} f^{u} f \stackrel{+}{=} {}^{\rho} f^{P} f^{V}$$
(2.37)

$$\rho_m h_m \stackrel{*}{=} \rho_m u_m + \rho_m P_m V \tag{2.38}$$

where P_{f} and P_{m} are the pressures on the fiber and moisture respectively, and

$$P_{f} = P_{m} = P_{atm}$$
(2.39)

Adding equations (2.37) and (2.38) and differentiating with

respect to t

• *

$$\frac{\partial (\rho_{f} u_{f} + \rho_{m} u_{m})}{\partial t} = \frac{\partial (\rho_{f} h_{f} + \rho_{m} h_{m})}{\partial t}$$
(2.40)

Combining equations (2.35) and (2.40)

$$\frac{\partial (\rho f^{u} f + \rho_{m} u_{m} + \rho_{s} u_{s} + \rho_{A} u_{A})}{\partial t}$$
$$= \frac{\partial (\rho f^{h} f + \rho_{m} h_{m} + \rho_{s} h_{s} + \rho_{A} h_{a})}{\partial t} \qquad (2.41)$$

Thus the energy balance may be written as

If $n_{f|z}$ is assumed to be constant, the derivative with respect to z vanishes.

Grouping terms, using equations (2.15) to (2.17) and simplifying:

$${}^{\rho} f \frac{\partial h_{f}}{\partial t} + \rho_{m} \frac{\partial h_{m}}{\partial t} + \rho_{s} \frac{\partial h_{s}}{\partial t} + \rho_{a} \frac{\partial h_{a}}{\partial t}$$

$$+ n_{m} |x \frac{\partial h_{m}}{\partial x} + n_{s}|x \frac{\partial h_{s}}{\partial x} + n_{s}|x \frac{\partial h_{a}}{\partial x} + n_{f}|z \frac{\partial h_{f}}{\partial z}$$

$$+ n_{m} |z \frac{\partial h_{m}}{\partial z} + n_{s}|z \frac{\partial h_{s}}{\partial z} + n_{a}|z \frac{\partial h_{a}}{\partial z}$$

$$= \frac{\partial}{\partial x} \left(\begin{pmatrix} K eff & \frac{\partial T}{\partial x} \end{pmatrix} + r_{m} (h_{s} - h_{m}) \right) \qquad (2.43)$$

The enthalpy h is a function of temperature T and pressure P thus

$$h = h(T, P)$$
 (2.44)

and

$$dh = \left(\frac{\partial h}{\partial T}\right)_{P} dT + \left(\frac{\partial h}{\partial P}\right)_{T} dP \qquad (2.45)$$

Since the derivative with respect to P is negligible,

$$dh = C_{p} dT$$
 (2.46)

where h is the enthalpy and $\ensuremath{C_{\mathrm{p}}}$ is the heat capacity at constant pressure.

Therefore

$$\frac{\partial h_i}{\partial t} = C_{pi} \frac{\partial T}{\partial t}$$
(2.47)

$$\frac{\partial h_{i}}{\partial x} = C_{pi} \frac{\partial T}{\partial x}$$
(2.48)

$$\frac{\partial h_i}{\partial z} = C_{pi} \frac{\partial T}{\partial z}$$
(2.49)

The enthalpy of water in the control volume h_m is the enthalpy of water h_1 minus the heat of sorption Q_1 of the fibrous material the fabric is composed of. Hence

$$h_{m} = h_{1} - Q_{1}$$
 (2.50)

The latent heat of vaporization is given by

$$h_{mv} = h_s - h_1$$
 (2.51)

Substituting equations (2.47) to (2.51) in (2.43) the energy equation becomes

$$(\rho_{f}C_{pf} + \rho_{m}C_{pm} + \rho_{s}C_{pv} + \rho_{A}C_{pa})\frac{\partial T}{\partial t}$$

$$+ (n_{m}|xC_{pm} + n_{s}|xC_{pv} + n_{A}|xC_{pa})\frac{\partial T}{\partial x}$$

$$+ (n_{f}|zC_{pf} + n_{m}|zC_{pm} + n_{s}|zC_{pv} + n_{A}|zC_{pa})\frac{\partial T}{\partial z}$$

$$= \frac{\partial}{\partial x} \binom{K_{eff}}{2} \frac{\partial T}{\partial x} + r_{m}(h_{mv} + Q_{1})$$

$$(2.52)$$

The effective thermal conductivity of the system is taken as a function of the proportion of each constituent and moisture content in the control volume. The "resistances" to heat flow are taken to be in parallel. Hence

$$K_{eff} = (1-e)K_{f} + aeK_{w} + (1-a)e(\omega_{s}K_{v} + \omega_{a}K_{A})$$
(2.53)

where

$$\omega_{a} = \frac{P_{a}}{P_{atm}}$$
(2.54)

$$\omega_{\rm s} = \frac{{\rm H P_{\rm v}}}{{\rm P_{\rm atm}}}$$
(2.55)

$$P_{atm} = P_a + H P_v \qquad (2.56)$$

 K_f , K_w , K_v and K_A are the thermal conductivities of fiber, water, vapor, and air. P_a and P_v are the pressures at saturation due to air and vapor and H is the relative humidity.

A modified form of Darcy's law is used to describe the liquid flux $n_{m|x}$ through the fabric. The liquid flux becomes important only when then the moisture content in the fabric drops below the saturation regain of the fiber/fibers the fabric is composed of.

Darcy's equation relates the velocity of the flux (flow per unit area per unit time) to the hydrostatic pressure difference Δp , specific permeability k, thickness Δx and the kinematic viscosity of the liquid n_1 . Thus

$$v_{\rm m} = -\frac{k}{\eta} \frac{\Delta p}{\Delta x}$$
(2.57)

The hydrostatic pressure difference or the water potential

is composed of both the capillary and osmotic potentials [18]. Fortes and Okos [11] have shown that the water potential p can be expressed as

$$p = R_v T(\ln H)$$
 (2.58)

where R is the gas constant for vapor. Hence

$$n_{m} r_{x} = -\rho_{m} \frac{K}{\eta_{1} R_{v}} \frac{d}{dx} (T \ln H)$$
 (2.59)

Plots of relative humidity versus regain can be found in the literature [21,22,23]. The moisture regain M is related to a - the volumetric fraction of void filled with liquid thus

$$M = \frac{ae\rho_{w}}{(1-e)\rho_{F}}$$
(2.60)

The air-vapor binary diffusion equation is given by Fick's first law

$$n_{A|x} = n_{s|x} \frac{\rho_{A}}{\rho_{s}} - \rho_{s} D_{av} \frac{\partial}{\partial x} \left(\frac{\rho_{A}}{\rho_{s}} \right)$$
 (2.61)

where D is the binary air - vapor diffusion coefficient.

Governing Equation for Can

The heat transfer through the can may be described by writing an energy balance on a control volume taken in the shell of the can. The resulting equation is the Fourier Heat Conduction Equation

$$\frac{\partial \mathbf{T}}{\partial t} = \alpha_{\mathbf{C}} \frac{\partial^2 \mathbf{T}}{\partial \mathbf{x}^2}$$
(2.62)

where α_{c} is the thermal diffusivity of the can shell.

INITIAL AND BOUNDARY CONDITIONS

The initial and thermal boundary conditions required for the solution of the governing equations are presented in this section.

Thermal Boundary Conditions for the Can Shell

The inner surface temperature T_{ic} of the can is assumed to be equal to the temperature at the saturation pressure of the steam in the can. Hence

$$T_{ic|t} = T_{sat}$$
 for all t. (2.63)

There are two boundary conditions for the outer surface of the can because the fabric is in contact with only a part of the can during its cycle of rotation (see Fig. 1).

The rate at which heat is conducted from the can surface is equal to the rate at which heat is convected away by the surrounding air. Therefore, the boundary condition for the region where no fabric is in contact with the can is

$$q_{sc} = h_{H} (T_{sc} - T_{\infty})$$
 (2.64)

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The heat conducted out of the can shell is equal to the heat flow into the fabric. Hence the boundary condition for the region where the fabric is contact with the can is

$$T_{sc} = T_{fab}$$
(2.65)

Boundary Conditions at the Can-Fabic Interface

The surface of the can is impervious to flow and therefore, the fluxes due to liquid water, water vapor, and air are zero. Hence

$$n_{m|x} = 0$$
 (2.66)

$$n_{s|x} = 0$$
 (2.67)

$$n_{A|X} = 0 \tag{2.68}$$

Boundary Conditions at the Free Surface of Fabric

The net rate of energy leaving the fabric sheet at the free surface due to conduction and mass fluxes of vapor and air is equal to the rate at which energy is convected away from the surrounding environment, thus

$$q_{|_{X=L}} = h_{H} (T-T_{\infty})_{|_{X=L}}$$
 (2.69)

and the heat transferred out of the surface is

$$q_{|x=L} = (-K_{\text{eff}} \frac{\partial T}{\partial x} - n_{\text{s}}h_{\text{s}} - n_{\text{A}}h_{\text{a}})_{|x=L}$$
(2.70)

The mass transfer boundary conditions at the free surface are

$$n_{s|x=L} = h_{sm} (P_{v0} - HP_{v\infty})$$
 (2.71)

anđ

$$n_{A|x=L} = h_{am} (P_a - P_{a\infty})$$
 (2.72)

Also

$$n_{m|x=L} = 0$$
 (2.73)

since no liquid water flows out of the surface.

Initial Conditions

The initial conditions of the temperature and moisture profiles in the fabric sheet just before the latter contacts the can are assumed to be uniform across the fabric sheet.

The initial conditions are

$$T|_{x,t=0} = T_0$$
 (2.74)

$$a_{x,t=0} = a_0$$
 (2.75)

As each succeeding can is reached the roles of the surfaces of the fabric sheet are reversed. However, the boundary conditions specified for the preceeding can are easily modified to apply to the succeeding can. The temperature and moisture profiles in the fabric sheet just before contacting the succeeding can are the initial conditions for that can.

APPENDIX 3

NOMENCLATURE

a	Ŧ	volumetric fraction of void filled with liquid
c	Ħ	total molar concentration, mols/ft ³
с _р	n	heat capacity at constant pressure, $BTU/1b/^{\circ}R$
Dav	#	air-vapor binary diffusion coefficient, ft ² /sec
h	=	enthalpy, BTU/1b
h _H	=	convective heat transfer coefficient between can,
		of fabric and surrounding air, $BTU/ft^2/sec/^{\circ}R$
h am	8	air mass transfer coefficient, lb/ft ² /sec
h mv	=	specific latent heat of vaporization, BTU/lb
h _{sm}	Ħ	vapor mass transfer coefficient, lb/ft ² /sec
н	N	relative humidity
k	=	specific permeability, ft ²
^k AV	H	air-vapor mixture thermal conductivity, BTU/ft/sec/ ⁰ R
K	N	thermal conductivity, BTU/ft/sec/ ⁰ R
^K eff	n	effective thermal conductivity of sheet, BTU/ft/sec/°R
Ĩ.	=	total thickness of fabric/pulp slab, ft
М	=	moisture regain
n	Ξ	mass flux, lb/sec/ft ²
P	T	pressure, lb/ft/sec ²
Q ₁	=	differential heat of sorption, BTU/lb

R = gas constant, $ft^2/sec^2/{}^{\circ}R$ = time, sec t = temperature, $^{\circ}R$ T = inner surface temperature of can, ^oR Tic = temperature of fabric, $^{\circ}R$ Tfab = saturation temperature of steam in can, $^{\circ}R$ Tsat = internal energy, BTU/lb u = velocity along the z-direction, ft/sec V = distance along thickness of fabric, ft х = mole fraction of air ×A = mole fraction of vapor $\mathbf{x}_{\mathbf{v}}$ = distance along width of fabric, ft У = distance along length of fabric, ft Z

Subscipts

a,A	= air
f,F	= fiber
i	= general species
1	= liquid
m,w	= moisture or liquid water
s,v	= vaper
.0	= surrounding air conditions
0	= initial conditions

Greek

°c	= thermal diffusivity of the can shell, ft ² /sec	
Δx	= elemental distance along thickness of fabric, f	t
Δy	<pre>= elemental distance along width of fabric, ft</pre>	
∆ z	<pre>= elemental distance along length of fabric, ft</pre>	
٦	<pre>= kinematic viscoscity, ft²/sec</pre>	
ŋ	<pre># dimensionless flux</pre>	
θ	= dimensionless temperature	
τ	= dimensionless time	
ψ	= dimensionless distance	
ρ	= density, lb/ft ³	

APPENDIX 3

Numerical Scheme

The governing equations are quasi-linear parabolic differential equations with two partial derivatives in space and one in time. In their existing form the equations are **very** complex and do not lend to an easy solution.

A lack of experimental data in the drying of fabrics comparison between theory and experiment extremely makes difficult. A comparison is made, therefore, with experimental results pertaining to the drying of paper; in particular, with the work of McCready [19] and Han and [20]. Ulmanen McCready's data pertains to the rate of drying of pulp slabs of various thicknesses. Han and Ulmanen measured moisture, temperature and caliper data in the drying of a thick paper sheet, at specific points across its thickness.

The numerical scheme is written for steady-state conditions. Since the governing equations are written from an Eulerian point of view, the derivatives with respect to time at steady-state are zero. However, time measured from instant the fabric first contacts the the can is an important parameter, and readily identifiable in can drying.

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A transformation is made therefore, from the z - coordinate to the t - coordinate. The resulting equations now contain one space and one time derivative. This corresponds to the Lagrangian point of view.

The transformed equations are:

Mass Balance for Water

$$\frac{\partial \rho_m}{\partial t} + \frac{\partial n_m | \mathbf{x}}{\partial \mathbf{x}} = r_m$$
(3.1)

Mass Balance for Vapor

$$\frac{\partial \rho_{s}}{\partial t} + \frac{\partial n_{s}}{\partial x} = -r_{m} \qquad (3.2)$$

Mass Balance for Air

$$\frac{\partial \rho_{\mathbf{A}}}{\partial t} + \frac{\partial n_{\mathbf{A}}}{\partial \mathbf{x}} = \emptyset$$
(3.3)

Energy Balance

$${}^{(\rho}f^{C}pf + {}^{\rho}m^{C}pm + {}^{\rho}s^{C}pv + {}^{\rho}A^{C}pA)\frac{\partial T}{\partial t} + {}^{(n}m|x^{C}pm + {}^{n}s|x^{C}pv + {}^{n}a|x^{C}pw + {}^{n}a|x^{C}pm + {}^{n}s|x^{C}pv + {}^{n}a|x^{C}pw + {}^{n}a|x^{C}ph + {}^{$$

Binary Diffusion of Air-Vapor

$$n_{A|x} = n_{s|x} \frac{\rho_{A}}{\rho_{s}} - \rho_{s} D_{av} \frac{\partial}{\partial x} \left(\frac{\rho_{A}}{\rho_{s}} \right)$$
 (3.5)

Moisture Diffusion

$$n_{m|x} = -\rho_{m} \frac{k}{\eta_{1}} R_{v} \frac{\partial}{\partial x} (T \ln H)$$
(3.6)

The nature of the one-dimensional equations at first prompted the use of the Runge-Kutta numerical integration technique. A solution for the initial-value problem was first sought. For this purpose the partial differential equations were reduced to ordinary differential equations with derivates with respect to x, and the derivatives with respect to time were substituted with estimates obtained from Han and Ulmanen's data. The governing equations were
integrated along the x-axis after the the initial values of a, T, $n_{m|x}$, $n_{s|x}$, and $n_{A|x}$ had been specified at the hot surface, together with the estimates of the derivatives of a and T with respect to time t, at fixed points across the thickness. The fibrous material of the fabric sheet was assumed to be all-cotton, and the surface temperature of the can, constant.

A Newton-Raphson iterative scheme was utilized in conjunction with the Runge-Kutta method to improve the values of the initial estimates of the time derivatives $\frac{\partial T}{\partial x}$ and $\frac{\partial a}{\partial x}$.

9 X

The solution failed to converge due to mathematical instability. Therefore, the Runge-Kutta approach was abandoned in favor of a finite difference scheme to approximate the partial derivatives with respect to both x and t.

In order to apply the finite difference scheme, the equations are first non-dimensionalized. The following dimensionless quantities are defined:

dimensionless temperature
$$\theta = \frac{T-T_0}{T_s-T_0}$$
 (3.7)

dimensionless time
$$\tau = \frac{V t}{L}$$
 (3.8)

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dimensionless distance
$$\psi = \frac{x}{L}$$
 (3.9)

dimensionless flux
$$\eta = \frac{n_s | x}{\rho_w V}$$
 (3.10)

The approach is to solve the governing equations from the time the fabric first contacts the hot surface. At this stage the relative humidity is unity and hence the moisture flux and the heat of sorption are zero. The relative humidity drops below unity when the regain drops to a value of about 0.29 from the initial value. The former value corresponds to the saturation regain value of cotton.

Adding equations (3.1) and (3.2), using equations (2.12) to (2.14) and rearranging

$$(1-a)e \frac{\partial \rho_{v}}{\partial T} \frac{\partial T}{\partial t} + e(\rho_{w} - \rho_{v}) \frac{\partial a}{\partial t} + \frac{\partial n_{s}}{\partial x} = 0 \qquad (3.11)$$

Upon non-dimensionalizing, equation (3.11) becomes

$$\frac{(1-a)}{(\rho_{w}-\rho_{v})} \frac{\partial \rho_{v}}{\partial T} (T_{s}-T_{0}) \frac{\partial \theta}{\partial \tau} + \frac{\partial a}{\partial \tau} + \frac{\rho_{w}}{e(\rho_{w}-\rho_{v})} \frac{\partial \eta}{\partial \psi} = 0 \qquad (3.12)$$

If C_{pi} is the volumetric specific heat, then

$$C_{pi} = (1-e)\rho_F C_{pf} + ae\rho_W + (1-a)e(\rho_V C_{pV} + \rho_a C_{pa})$$
 (3.13)

Non-dimensionalizing equation (3.4) gives

$$\frac{\partial \theta}{\partial \tau} - \frac{e \rho_{W}}{C_{pi}(T_{s}-T_{0})} \frac{\partial a}{\partial \tau} = K_{eff} \frac{\partial^{2} \theta}{\partial \psi^{2}}$$

$$+ (1-a) e D_{av} \left(\frac{\partial \rho_{a}}{\partial T} - \frac{\rho_{a} \partial \rho_{v}}{\rho_{v} \partial T}\right) C_{pa} (T_{s}-T_{0}) \left(\frac{\partial \theta}{\partial \psi}\right)^{2}$$

$$- \eta \frac{\rho_{W}}{C_{pi}} (C_{pv} + \frac{\rho_{a}}{\rho_{v}} C_{pa}) \qquad (3.14)$$

and the non-dimensional form of equation (3.3) is

.

$$\frac{\partial n_{a}}{\partial \psi} = \frac{\rho_{a}}{\rho_{v}} \frac{\partial a}{\partial \tau} - (1-a)e \frac{\partial \rho_{a}}{\partial T} (T_{s}-T_{0}) \frac{\partial \theta}{\partial \tau}$$
(3.15)

The unknowns a, T, $n_{s|x}$, and $n_{a|x}$ are evaluated by solving equations (3.5) to (3.6) and (3.12) to (3.15) together with the initial and boundary conditions. Details of the initial and boundary conditions are given in Appendix 4. Some of the boundary conditions are reproduced here for convenience.

$$n_{m|x=0} = 0$$
 (3.16)

$$n_{s|x=0} = 0$$
 (3.17)

$$n_{A|X=0} = 0$$
 (3.18)

$$q_{|x=L} = h_{H} (T-T_{\infty})_{|x=L}$$
 (3.19)

$$q_{|x=L} = (-K_{eff} \frac{\partial T}{\partial x} - n_{s}h_{s} - n_{A}h_{a})|_{x=L}$$
(3.20)

$$n_{s|x=L} = h_{sm} (P_{v0} - H P_{v\infty})$$
 (3.21)

The explicit finite difference scheme is illustrated in Figure 1. The values of a, T, $n_{s|x}$, and $n_{A|x}$ are evaluated at 10 points across the thickness of the fabric. Point 1 corresponds to the part of the fabric in contact with the can, and point/represents the free surface. The initial values of a, T and $n_{s|x}$ are specified at time t = 0, at all points. The size of the grid is selected such that the stability criterion $\Delta \tau / \Delta \psi^2 < 1/2$ is satisfied.

The computational scheme is as follows. The heat transfer coefficient is calculated from McCready's mass transfer coefficient using the Chilton-Colburn analogy:

$$h_{\rm H} = \left(\frac{\rho C_{\rm p}}{c}\right)_{\rm f} \left(\frac{k_{\rm AV}}{\rho D_{\rm av} C_{\rm p}}\right)_{\rm f} h_{\rm sm}$$
(3.22)

where ρ , C_p , and c are the density, specific heat, and



Figure 1. Finite Difference Grid showing the explicit molecule

molar concentration of the mixture of air and vapor respectively. The subscript f denotes that the properties are evaluated at the "film temperature" [24] given by

$$T_{f} = \frac{(T_{\infty} + T_{|x=L})}{2}$$
(3.23)

and \mathbf{k}_{AV} is the thermal conductivity of the air-vapor mixture given by

$$(k_{AV})_{f} = (x_{A}K_{A})_{f} + (x_{V}K_{V})_{f}$$
 (3.24)

and \mathbf{x}_{A} and \mathbf{x}_{V} are the mole fractions of air and vapor respectively.

Also

$$(C_p)_f = (x_A C_{pa})_f + (x_V C_{pv})_f$$
 (3.35)

and

$$(\rho)_{f} = (\rho_{s})_{f} + (\rho_{A})_{f}$$
 (3.23)

The values of a and T at τ + $\Delta \tau$ and points 2 to 9 are evaluated from equations (3.12) to (3.14). The values of a and T at point 10 should simultaneously satisfy boundary conditions (3.18) to (3.20). This is accomplished by combining equations (3.18) to (3.20) with equation (3.5) and using equation (3.14) at point 10 to solve for a and T at that point.

The value of <u>a</u> at the hot surface is obtained by applying equation (3.14) at the hot surface, together with the boundary conditions (3.17) and (3.18) at the hot surface. The explicit molecule for this computation is shown in dotted lines.

The values of $n_{\mathbf{S}|\mathbf{x}}$ and $n_{\mathbf{A}|\mathbf{x}}$ at points 2 to 9 are obtained from equations (3.15) and (3.5).

The entire procedure is repeated to evaluate a, T, $n_{s|x}$, and $n_{A|x}$ at $\tau + 2\Delta \tau$ $\tau + n\Delta \tau$.

APPENDIX 4

Physical Properties

The expressions used in the computational scheme for the evaluation of certain physical properties are given in this Appendix.

Saturated Vapor Pressure

The saturated vapor pressure is obtained from Antoine's Equation

$$\log_{10} P_{v0} = A + \frac{B}{C + T_{c}}$$

where P_{v0} is the pressure in mm. of Hg., T_{c} is the temperature in degrees Centigrade and A, B, and C are constants:

$$T_{C}$$
ABC< 608.107651750.286235 \geq 607.966811668.21228

Density of Air and Water Vapor

Since both air and water vapor are treated as ideal gases,

$$\rho_a = \frac{P_a}{R_A T}$$

and

$$\rho_{\rm v} = \frac{P_{\rm v0}}{R_{\rm v}T}$$

 $P_{\rm v0}$ is the pressure due to air and T is the temperature in degrees Rankine. $R_{\rm A}$ and $R_{\rm v}$ are the gas constants for air and vapor.

Latent heat of Vaporization of Water

$$h_{mv} = 1093.3 + 4.563095 \times 10^{-6} T_F - 1.726 \times 10^{-4} T_F^2 - T_F$$

where h_{mv} is the latent heat of vaporization of water in BTU/lb and T is the temperature in degrees Farenheit.

Thermal Conductivity

The thermal conductivities given below are for the temperature range 80 $^{\rm 0}F$ to 300 $^{\rm 0}F.$

Water

$$K_{w} = R_{0}T^{2} + R_{1}T + R_{2}$$

 K_{ω} is the thermal conductivity of water in BTU/hr/ft/⁰F and

Rø	z	-2.0238x10	BTU/hr/ft/	⁰ F
Rl	Ħ	2.93285x10	BTU/hr/ft/	⁰ F
^R 2	-	9.08334x10	BTU/hr/ft/	⁰ F

Water Vapor

$$K_v = R_3 + R_4 T$$

 K_v is the thermal conductivity of vapor in BTU/hr/ft/ 0F and

 $R_3 = 8.29 \times 10$ BTU/hr/ft/ °F $R_4 = 2.39 \times 10$ BTU/hr/ft/ °F

$$K_{A} = R_{5} + R_{6}T_{F}$$

 $K_{\underline{a}}$ is the thermal conductivity of air in BTU/hr/ft/ ^{0}F and

R₅ = 1.347x10 BTU/hr/ft/ ⁰F R₆ = 1.930x10 BTU/hr/ft/ ⁰F

Enthalpy of Air

$$h_a = h_{ar} + (T - T_r)$$

where T_r is a reference temperature in degrees Rankine and h_a and h_{ar} are the enthapies of air in BTU/lb at temperatures T and T_r respectively.

Heat of Sorption

The heat of sorption for cotton is obtained from the experimental results of Guthrie [25] and Rees [26].

H	Q ₁
0.1	$W_1(exp(W_2 H) \times 1.8$
Ø.1	(-1630 x H + 300) x 1.8

where \boldsymbol{Q}_1 is the heat of sorption and

W₁ = 155.13 BTU/1b W₂ = -1.2426

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