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APPLICATIONS OF ELECTRO-OSMOTIC TRANSPORT IN THE PROCESSING OF TEXTILES

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We report development of a pilot process for the industrial rinsing of fabrics. This process combines hydraulic (pressure-driven) transport with electro-osmotic transport. It reduces the total amount of water required in certain rinsing operations by a factor of about five. Cotton exhibits an electro-osmotic transport coefficient of about $6x10^{-9}$ m^2/s-V resulting from a partial ionization of hydroxyl groups on the cellulose polymer substrate. This process applies a field transverse to the fabric to effect the movement of water in the spaces between the 10 μm cotton fibers which constitute the yarn. The field strength is adjusted so that the induced electro-osmotic flux is comparable to a pressure-driven flux, which moves preferentially in the more open channels between the yarns. For a fixed current density, solution conductivity and electro-osmotic transport vary inversely. The process is most practical for removal of liquids of relatively low conductivity (<500 μS/cm). For removal of solutions of conductivity greater than 1200 μS/cm, the rate of electro-osmotic flow may be too low to benefit the rinsing process if current densities are restricted to practical levels of about 30 mA/cm^2. Electro-osmotic transport may have important applications in wet processing of extremely fine textiles, such as micro fiber fabrics. In addition to rinsing, electro-osmotic transport may also be used to speed the penetration of chemicals and dyestuffs that are applied to the surface of wet textiles.

INTRODUCTION

Large amounts of water are used in the production of textiles for cleaning and wet processing—including washing and rinsing following dyeing, chemical treatments and mercerization. About 3 million tonnes of cotton fabrics are processed annually in the US. Water required for this production is factored at about 20 kg per kg of cotton—a total annual usage of 60 million m^3. To protect the environment, the industry reprocesses and recycles this water, often at considerable expense and energy use. This situation motivated development of a process that might greatly reduce water usage. [1,2]

In cotton, the fiber consists of chains of saccharide rings linked with oxygen atoms (Figure 1). Hydrogen bonding between hydrogen and neighboring oxygen atoms weakens the O-H bond, causing a partial ionization of the substrate. The fiber develops a net negative surface charge, which is counter balanced by a dispersed positive charge in the diffuse part of the double layer (roughly 10 nm thick). If an electric field is applied tangential to the fiber surface, positive ions in the double layer will drift in the direction of the field, dragging along additional water molecules and inducing a flow in the bulk of the electrolyte. [3-5]

Most cotton textiles consist of tightly bound bundles of fibers (or "yarns") woven into larger matrices. In hydraulic rinsing, most of the water travels through the more open spaces between the yarns, while exchange of material between the interior of the yarns and the hydraulic flow is slow and diffusion controlled. In theory, if the field is adjusted to produce a flow equal to the hydraulic flow, then the entire volume of liquid held within the fabric can be displaced with an equal volume of rinse water—giving rise to a cleaning effectiveness, Q = 1, where as Q is defined as the weight of water used per unit weight of fabric.

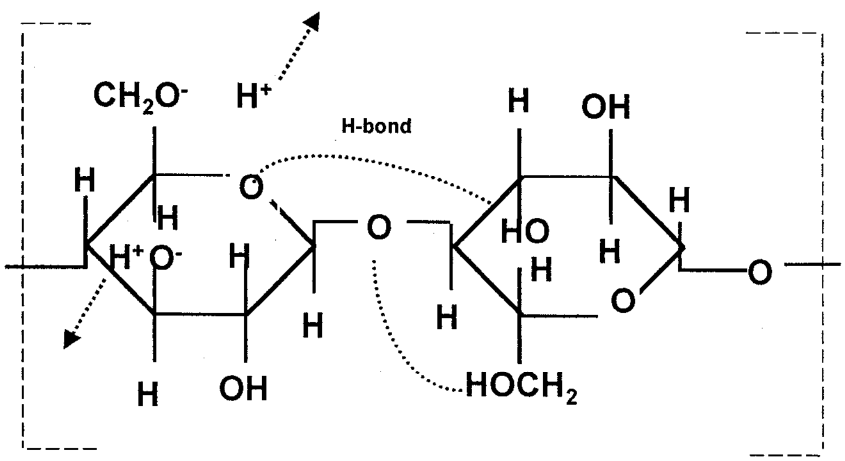

Figure 1. Cellulose consists of chains of saccharide units. Hydrogen bonding between neighboring hydroxyl groups weakens the O-H bond, allowing partial ionization of the polymer. This creates a negative surface charge on the fiber balance by a positive space charge dispersed in the adjacent liquid.

Newman [5] gives a general discussion of the theory of electrokinetic transport phenomena, while Neal [6] reports early experimental work on transport in cotton fabrics. The value of velocity of the flow outside the diffuse layer, v_o, for an applied field E is given by

$$v_o = -\frac{\varepsilon\zeta E}{\mu} \tag{1}$$

where the zeta potential, ζ, can be roughly associated with the potential at the inner surface of the diffuse layer. For cotton, values of $\zeta = 0.1$ V have been reported. Epsilon (ε) is the permittivity of the solution, and μ is the solution viscosity. For a tangential field strength of 400 V/cm (typical in our application), $\varepsilon/\varepsilon_o = 78.3$, and a viscosity of 0.01 g/cm-s, a value of $v_o \sim 2.7$ mm/s can be expected for the electro-osmotic flow velocity for cotton. These velocities are generally achieved in our system.

The form of equation (1) allows us to define an empirical relation between potential drop across the fabric (ΔV) and volume flow rate G (measured externally to the surface of the textile) through an electro-osmotic transport coefficient, k_{eo}:

$$G = (Af_v)k_{eo}\frac{\Delta V}{s} \tag{2}$$

Here, s is the fabric thickness, f_v is the liquid fraction of the fabric, and A is the geometric surface area of the fabric.

MEASUREMENT OF ELECTRO-OSMOTIC TRANSPORT COEFFICIENTS

Electro-osmotic transport coefficients were measured by applying a voltage across a fabric plug comprised of 10-20 fabric layers (area, 2.85 cm^2) separating an anode and cathode chamber, and measuring the displacement rate of the electrolyte (at zero hydraulic head) through a narrow tube (4 mm diameter) connecting the two chambers. This tube has a hydraulic resistance which is very low compared with that of the fabric sample. Voltage drop was measured with reference probes at each surface of the fabric plug. A bubble was injected into the connecting tube, which just spanned the inner diameter. The velocity of the bubble was measured with ruler and stopwatch. This configuration, called a "bubble cell," is widely used to measure electro-osmotic transport in low-porosity plugs.

Figure 2 shows the measured values of k_{eo} for diverse electrolytes and concentrations, which are clustered at about $0.7 \pm 0.3 \times 10^{-8}$ m^2/s-V. The concentrations of caustic range from 0.125 mM to 0.25 M. Versatint Red Tint No. 2 (Milliken and Company, Spartanburg SC) is a non-staining tint of proprietary composition, used by the industry to temporarily mark fabrics. This tint has a measured electrolytic conductivity of 370 μS/cm at 1% dilution and its color is unaffected by changes in pH or by the presence of a strong oxidant such as hydrogen peroxide that might develop during electrolysis. It has an ionic electrolyte base and a neutral pH.

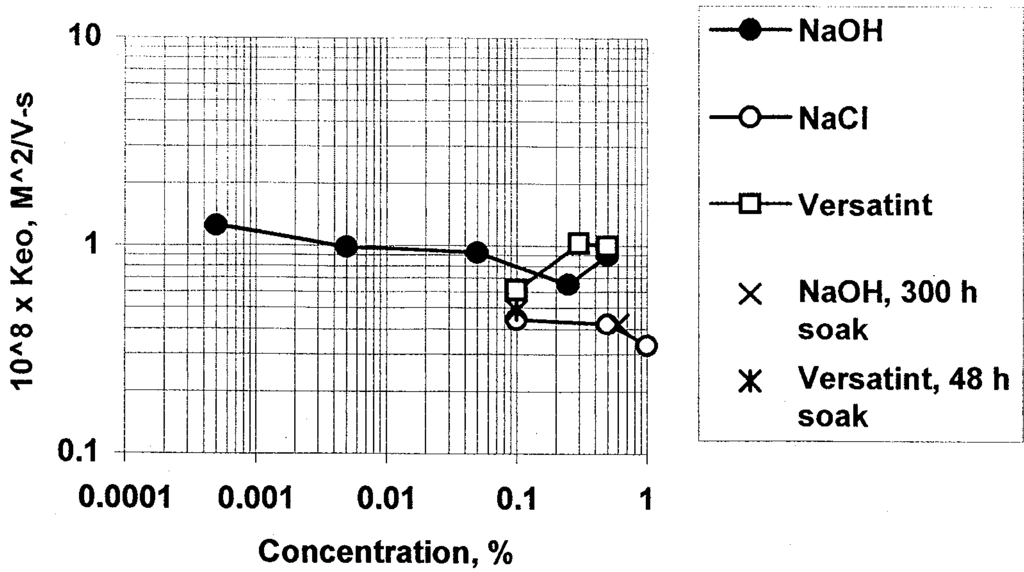

Figure 2. Measured electro-osmotic transport coefficients using the bubble cell at high electrolyte concentrations for caustic (NaOH), Versatint Red No. 2 tint, and sodium chloride.

TESTS IN A PLANE-PARALLEL CELL

Simulated rinsing studies were conducted in flow channel by translating a fabric of 30-cm width between plane-parallel nickel electrodes (Figure 3) that were perforated to allow electrolyte flow parallel to the field. The cell was provided with input and output wells to prevent water leakage. Each electrode measured 15 cm in direction of flow by 15 cm in width. Two identical cells with separate electrical connections were placed side by side in the flow apparatus, such that a voltage could be applied across one cell while the other cell supported the same hydraulic flow without applied voltage. The inactivated cell provide an internal control against which the effect of electro-osmotic transport was measured.

Color changes upon rinsing out a red tint provide a direct and dramatic indication of the electro-osmotic rinsing enhancement. The fabric was saturated with a solution of the tint (foreground, Figure 4). The fabric exiting the cell after passing between charged electrodes is lightest in color (left side); the fabric passing through the other half of the cell is intermediate, showing the effect of hydraulic rinsing alone. The relative concentrations (pre-treatment, and with and without applied field) were measured photometrically, using a digital camera and series of standard concentrations. The digital image was deconvoluted by image processing software into red, green and blue components; the difference in saturations of the red and green components were correlated with a set of standard concentrations on the same fabric sample.

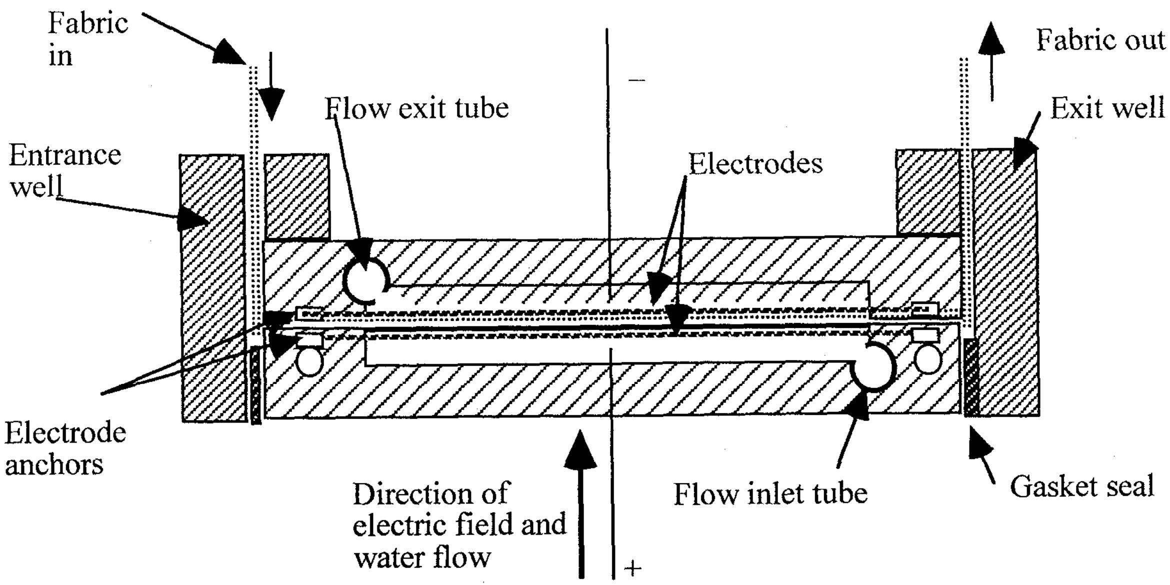

Figure 3. A plane-parallel cell was used in studies of rinsing on fabrics (30 cm width, speeds 3-15 m/min). Electrolyte flows is upwards through porous Ni plates across which a potential of (typically) 10 V was applied.

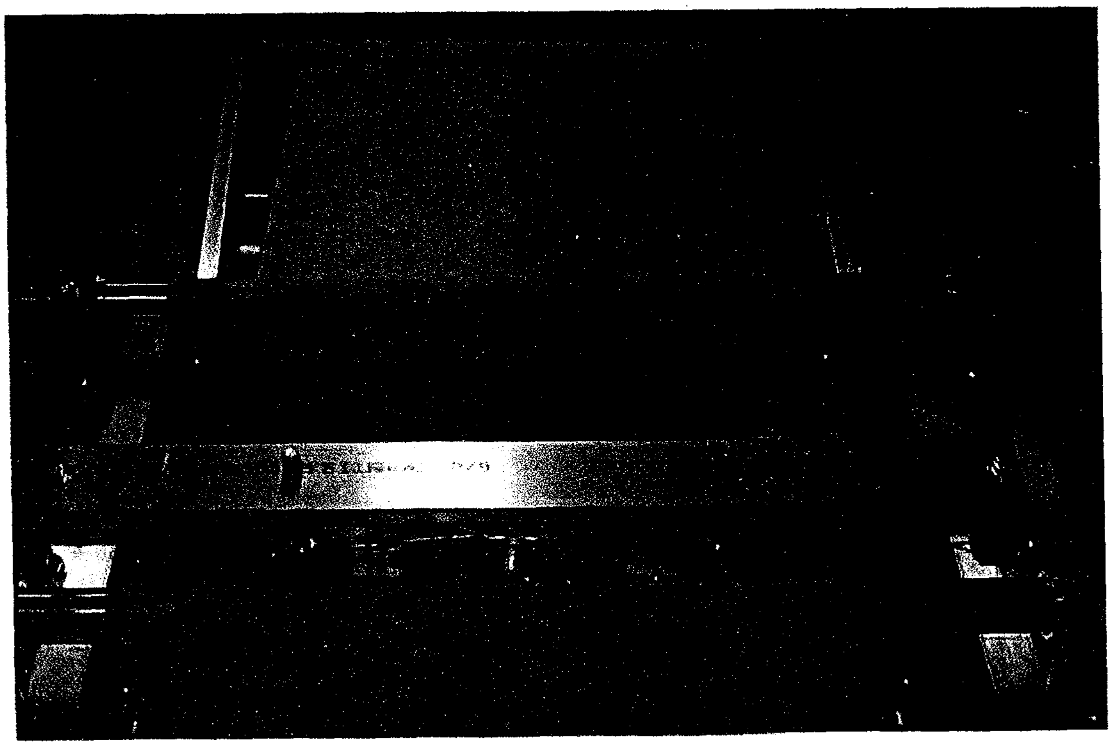

Figure 4. The effect of electro-osmotic enhancement of rinsing is shown on a Versatint-saturated cotton twill fabric entering the cell (foreground) and exiting with hydraulic rinsing only (right) and with identical hydraulic conditions but with field-driven electro-osmotic transport (left).

Figure 5 compares the amount of tint remaining on a fabric (Industry standard cotton twill) after rinsing with and without the electric field. For this fabric, thickness varies in the range 0.4-0.5 mm, depending on source and tension. The concentrations are normalized to the initial concentration of tint (a 1% solution of the Versatint). For an electrolysis time of 5 seconds (fabric velocity of 1.8 m/min), the electro-osmotic transport reduced tint retention by a factor of 3. The voltage drop (10 V) across the 0.4 mm thick fabric produces a field strength of 25 kV/m, and should produce an electro-osmotic flow rate (equation 3) of about 0.25 mm/s for $k_{eo} = 1 \times 10^{-8}$ m^2/s-V. The curves appear to converge rapidly below 1-s low residence times in the cell, where the electro-osmotic flow distance becomes comparable to the thickness of the yarn (one half the thickness of the fiber in twill). The hydraulic flow velocity (0.44 mm/s) is about 3.5 times that of the electro-osmotic flow measured externally to the fabric (0.25*f_v, where the liquid fraction $f_v \sim 0.5$).

The data from this and other experiments are given in Table 1. The ratio of attenuations are given for fixed flow rates, showing benefits of up to 5-6. The actual benefit of the process is more clearly seen by comparing water usage (Q) for fixed levels of attenuation. For an attenuation of 10 (fraction of tint remaining = 0.1), the water usage falls by a factor of 15.

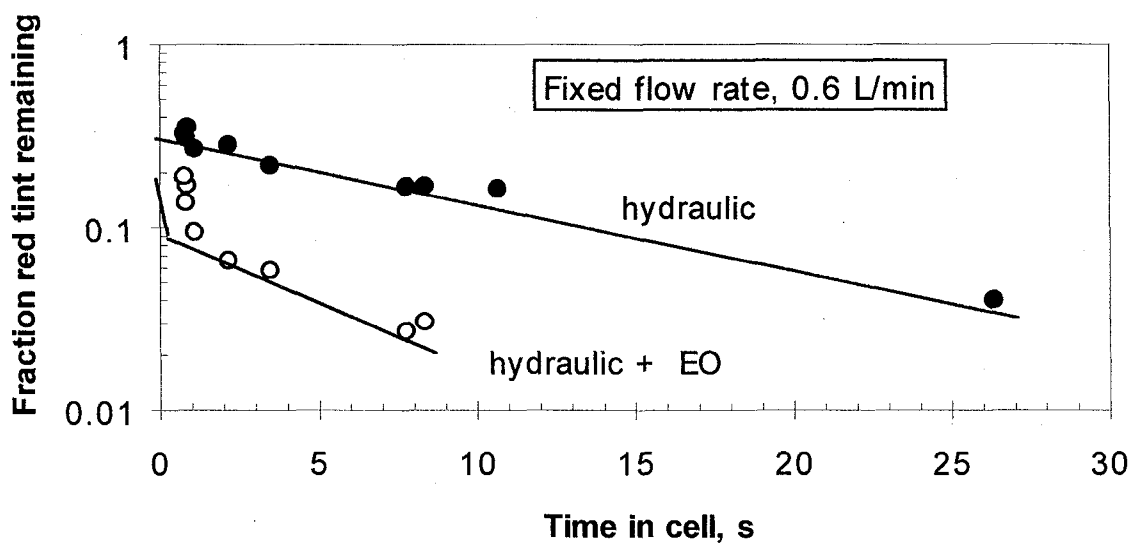

Figure 5. These curves compare the relative attenuation of tint for hydraulic rinsing (solid points) and hydraulic rinsing enhanced with electro-osmotic (EO) transport (open points), for fixed hydraulic flow rates of 0.6 L/min per electrode (external velocity v = 0.44 mm/s).

Table 1. Rinsing data for plane parallel cell, Versatint Red Tint No. 2 (Milliken and Company)

Q kg-water/ kg-fabric	hydraulic	Hydraulic plus electro-osmotic	cell voltage, V	Ratio: hyd/ (hyd+eo)	V m/min	Dwell time s
0.6	0.3306	0.1905	25	1.7	13.3	0.8
0.7	0.31	0.1373	25	2.3	12.5	0.8
0.7	0.3531	0.1706	25	2.1	12	0.8
0.9	0.2692	0.0947	25	2.8	9.4	1.1
1.4	0.2812	0.1154	25	2.4	12.5	0.8
1.7	0.2832	0.0661	25	4.3	4.7	2.1
2.0	0.3115	0.1289	25	2.4	9.4	1.1
2.0	0.2623	0.1169	25	2.2	9.4	1.1
2.8	0.2196	0.0582	25	3.8	2.9	3.4
6.3	0.1674	0.0271	25	6.2	1.29	7.8
6.8	0.1692	0.0306	25	5.5	1.2	8.3
8.7	0.1631	--	var.	--	0.94	10.6
21.5	0.0402	--	var.	--	0.38	26.3

PILOT PROCESS STUDIES USING A DRUM AND BELT TRANSLATOR

A drum and belt fabric conveyor was chosen for scaleup studies because this configuration allows minimum spacing between electrodes and therefore maximum fields for a fixed inter-electrode potential drop. Also, drum and belt systems are commercially available as efficient hydraulic rinsers, and can be readily adapted for electrification.

System configuration and operating conditions

The drum and belt translation system entrains a 40-cm wide fabric between a metal mesh belt and each of two insulated, porous drums. (Normally, the fabric bypassed the first drum and studies were conducted with the second drum.) Roles up to 50 m long could be accommodated. The belt was a continuous stainless steel chain mesh commonly used in food processing. The drums were two perforated cylinders (46 cm wide and 46 cm diameter) of 6 mm thick stainless steel sheet rolled over perforated disk bulkheads. A 1.5 mm thick stainless steel screen was welded to the cylindrical surface of the perforated drum; two layers of porous rip-stop nylon (each 0.003 cm thick) were attached to the surface of the screen to serve as an insulating separator and a diffusion barrier. This separator isolated the belt (grounded) from the drum anode (25-50 V positive to ground).

The drums were supported on stainless steel tubing that was perforated to allow the rinse water to be pumped into the drums and through the fabric. .

The belt was driven by a 3 hp DC controllable speed motor at speeds of 5-40 m/min. A mercury-wetted rotating feed through allowed current flows up to 500 A. Because of the poor conductivity of the stainless steel mesh, a stationary grounded copper screen (6 mm spacing) was pressed against the lower surface of the belt in the area of contact with the drum. The power supply was a welding unit, rated at 100 A at 100 V.

Operating conditions and procedures

The hydraulic flow rates were chosen to match the range of accessible electro-osmotic flow rates. Water flow was controlled between the levels of 30- and 190 ml/s over the submerged surface of the fabric (0.44 m^2). At 190 ml/s, the linear flow rate is 0.43 mm/s (or 0.86 mm/s through the interstices of a 50% void-fraction fabric). For an electro-osmotic coefficient of $1x10^{-8}$ m^2/V-s and fields of 40 kV/m, interstitial flows of 0.4 mm/s are expected. Since the yarns of the 0.4 mm thick fabric are about 0.2 mm diameter, then the electro-osmotic enhancement should be seen for dwell times > 0.5 s, as obtained at fabric velocities < 40 m/min.

The range of translation velocities (up to 40 m/min) is comparable to that of many industrial fabric rinsing operations. The fabric was first passed though a padding tank with a submerged stainless steel bar as a bearing surface. Upon exiting the padding tank, the fabric was passed over two knife scrapers to remove excess liquid. Tint attenuation was measured by digital photometry. A digital image was taken of the fabric. The image was deconvoluted into red, green and blue components. As with the plane parallel cell, the difference between red and green signals for the tests were compared with a standard set of tint concentrations on the same fabric, as imaged under identical conditions.

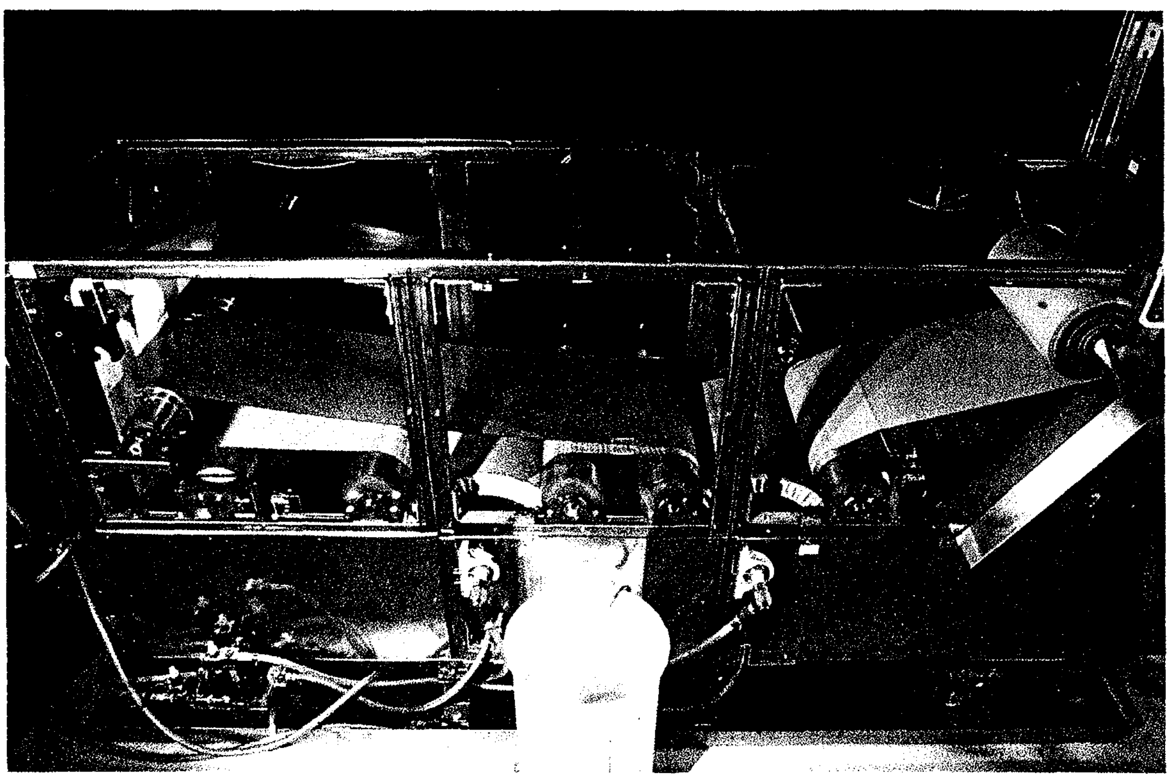

Figure 6. Drum and belt conveyor system provided speeds of 6-40 m/min for a 40-cm wide fabric. Fabric from feed role (left) is fed through second of two drums

(right) and taken up by driven spool on the extreme right. The 30 gal drum collects water effluent from the sump surrounding the drum.

Results

Summary results of the drum and belt system are compared with the corresponding data for the plane parallel system in Figure 7. In each case, the relative attenuation of the tint for hydraulic rinsing (upper branch) is linear on the semi-logarithmic plot against flow rate. Because wide ranges of water flow and fabric speeds are plotted here, the flow rate is represented as the ratio of water flow to fabric speed, Q, in units of kg-water/kg-fabric.

The hydraulic rinsing data for plane-parallel cell and drum and belt are parallel, but that for the drum and belt is displaced to lower values. This may reflect the greater efficiency of rinsing in the drum and belt system, which provides for a uniform and quantitative transfer of the water through the fabric. The drum and belt system shows a much stronger effect of electro-osmotic transport, with an attenuation of 10 at Q = 6.

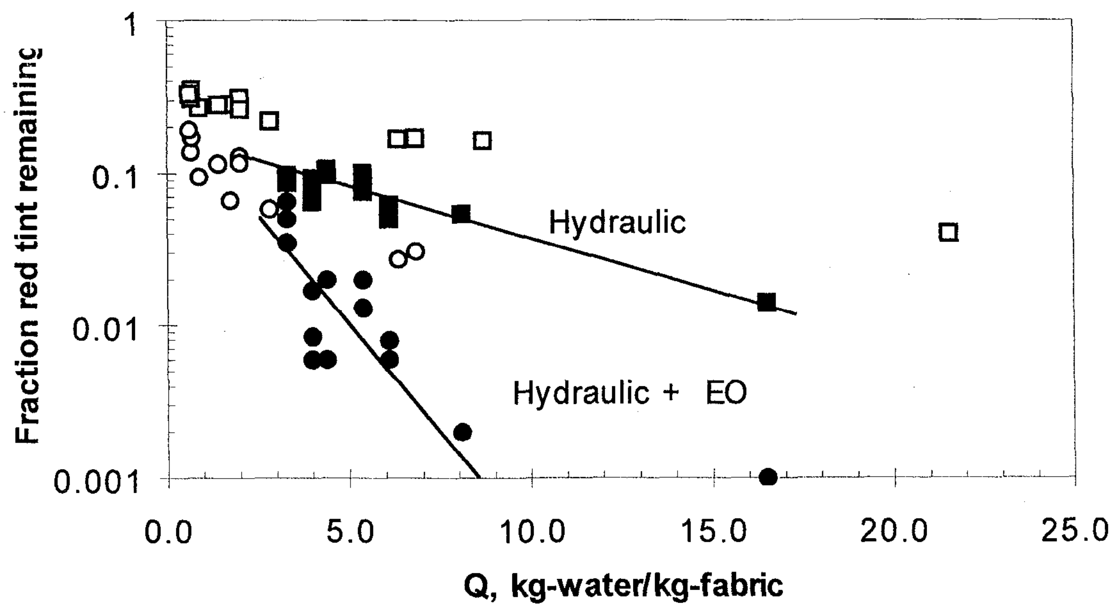

Figure 7. Attenuation of tint as function of Q, for plane parallel cell (open data symbols) and drum and belt system (solid symbols). The upper branch of each set (square points) represents hydraulic rinsing, while the lower branch represents combined hydraulic and electro-osmotic transport.

The drum and belt system showed no substantial benefits from using the electric field in rinsing dilute caustic from cotton fabrics at initial concentrations of 0.1-0.5%. These results were obtained despite the fact that solutions of tints and caustic showed similar electro-kinetic effects in the bubble cell that was used to measure electro-osmotic transport coefficients (Figure 2).

Discussion

One expects that the applicability of this process will depend on the relative magnitudes of electro-osmotic transport and electro-migration (*i.e.*, ionic current flow). The electro-osmotic flow and electrical current can be expressed as analogous functions of field strength, F:

$$G = (Af_v)k_{eo}F \tag{3}$$

$$I = (Af_v)\sigma F \tag{4}$$

where F is defined as the voltage drop ΔV across the fabric of thickness s and geometric area A. Here flow and current are measured externally to the fabric, the geometric cross-sectional area of which is reduced by the liquid fraction, f_v. The current density, i, measured external to the fabric is given by:

$$i = \frac{I}{Af_v} \tag{5}$$

Similarly the electro-osmotic flow velocity measured external to the fabric is given by

$$v = \frac{G}{Af_v} \tag{6}$$

Combining (3-6) and eliminating F yields a relation between current density and electro-osmotic flow velocity:

$$i = \frac{\sigma v}{k_{eo}} \tag{7}$$

For a fixed current density (limited to a practical level by the overall resistance of the circuit), the far greater conductivity of the caustic solution (relative to hat of the tint) results in a greatly reduced electro-osmotic flow velocity, despite nearly equal values of k_{eo}.

Table 1 gives the electrical conductivity of several of the test solutions. The thirty-fold increase in caustic conductivity (relative to tints) results in a thirty-fold decrease in the electro-osmotic flow rate v, for a current density fixed at a practical level.

Table 2 compares calculated and measured flow rates for the 0.25% caustic solution (0.0625 M) for the same fabric (Industry standard twill, thickness 0.5 mm). In the bubble cell, with an applied voltage of 1.4 V across a 10 ply sample, an electro-osmotic flow rate of 1.1 μm/s was measured while the current density was recorded at 12.3 mA/cm^2. The calculated field strength was 274 V/m, from which an electro-osmotic transport coefficient was derived (Figure 2), $k_{eo} = 0.65 \times 10^{-8}$ m^2/V-s. For the drum and belt system, voltages of 50 V (an apparent field of 100 kV/m) yielded a reasonable current density of 22 mA/cm^2, but the resultant electro-osmotic flow rate (1.1 μm/s) is far to low. Since the fabric is 500 μm thick, this low electro-osmotic flow velocity should have little measurable effect on the cleaning of the fabric which resides in the cell for only 8.1 s at the lowest velocity (8 m/min) tested in the drum and belt system. For the tint, the lower conductivity should increase the transport rate by a factor of >35, for conductivities below 380 μS/cm. Thus, at 40 μm/s the lower speed allows a transport distance of 40 μm/s x 8.1 s = 320 μm—significantly greater than the thickness of the yarn (250 μm).

Table 1. Electrical Conductivity of the Test Solutions

Solution	*Electrical conductivity, [$10^{-6}/\Omega$-cm]*
Deionized water (rinse)	3
Versatint Red, 1%, as applied to test fabrics	380
Caustic: 0.25% (0.0625 M)	13,130

Table 2. Comparison of calculated and measured flow rates for 0.25% caustic having conductivity of 13130 μS/cm

Cell	*Applied voltage, V*	*Measured current density, mA/cm²*	*EO velocity, μm/s*	*Apparent field, V/m*	*Actual field V/m*
bubble	1.4	12.3	0.7	274	274
Drum & belt	50	22.2	1.1*	100,000	209**

*calculated from equation (7), from measured current density, σ = 13130 μS/cm, and k_{eo} = 0.6 x 10^{-8} m^2/V-s.

**calculated from equation (4) , for measured current density, assuming f_v = 0.4.

Conclusions

Electro-osmotic transport can be used to enhance the efficiency of fabric rinsing in certain cases where the conductivity of the solution entrapped in the yarns is sufficiently low. Industrial rinsing occurs over a wide range of fabric velocities and hydraulic flow rates. If we limit the current density to a value < 300 A/m^2 (30 mA/cm^2) to limit waste heat generation and electrolyte composition change, and require that the electro-osmotic flow velocity be > 25 μm/s, then from equation (7) we require an electrolyte conductivity of <1200 μS/cm. Within these constraints, the fabric should show the benefit of electro-osmotic rinsing for residence times of greater than about 1 s. Unfortunately, we have found no way to use electro-osmotic transport to enhance the rinsing of caustic solutions or other high conductivity solutions.

We have not reported here the effect of diffusion potentials across the interface between the advancing front of low-conductivity water (3 μS/cm) and the high conductivity electrolyte solutions within the yarn (13000 μS/cm) , under the extreme conditions applied in this technique (fields to 100 kV/m). This will be reported in a later communication.

As reported elsewhere [2], this process also may be applied to synthetic fibers which support an electro-osmotic transport phenomenon because of hydrolysis of the fiber surfaces. In addition to rinsing cotton, the process may also be used to speed the penetration of chemicals, wet-proofing agents, inks and dyestuffs applied to the surface of a wetted fabric.

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KEYWORDS

textiles, electrokinetics, electro-osmosis, cotton