Vapor Phase Dyeing of Synthetic Fibers with Disperse Dyes

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Synopsis

Dyeing of synthetic fibers by the heat transfer process of disperse dye vapors is performed by contacting white receptor polyester or polyamide fabric with other dyed polyester fabrics (donor) under the influence of heat. The dye vapours flowing away will diffuse across the very slight air gap enclosed between the inner donor and receptor surfaces under the applied pressure. It is found that the dye uptake by the receptor fabric is dependent on the original dye content of the donor fabric, transfer temperature and dwell time. The released dye from the donor fabric under the influence of heating is found to be dependent on the original dye content of the donor fabric as well as the transfer temperature. The efficiency of the dye transfer is also attributed to the original shading of the donor fabric. Evaluation of the imparted colors on the receptor fabric (polyester, polyamide) obtained by heat contact with the same donor fabric showed visually the same colour level up to the 13th run. Thermodynamic interpretation of the standard affinity (Δu^0) and heat of dyeing (ΔH^0) as well as the partition coefficient of the dye show that the dyeing process has an exothermic character. The rate controlling step in this dyeing process is found to be dependent on the diffusion of the dye vapors into the fiber phase.

INTRODUCTION

It has been known that fabrics can be color decorated by heat transfer methods using sublimable dyes.[1–3] The thermal migration of disperse dye into synthesic polymers has been thoroughly investigated.[4–7] The mechanism of coloration printing of synthetic fibers by transfer of dyestuffs from an inert supportlike paper was established as a vapor phase process.[8–12]

A new transfer way to dye white polyester fiber bits in wool blends was recently mentioned.[13] The method is of the vapor phase type. A deeply dyed polyester fabric is considered as a reservoir from which it partitions only on the receptive white polyester bits. There is no deposition on the wool, for example, since it has no affinity for disperse dye vapors. This principle was recently tackled and extended as a new approach to dry dyeing of synthetic fabrics in a very short time of heat contact with a dye-donor fabric.[14,15] This technique is reported to have the advantages of avoiding subsequent washing and/or reduction clearing of blends, no water usage, no effluent problems, and no solvents or carriers needs. It has a remarkable potential for efficient and economic comparison with the traditional methods.

In the present work, we aim to study in some details the capacity of generalizing this dry dyeing and/or printing technique as a continuous process for various synthetic fabrics. A kinetic investigation of the dyeing parameters is also tried.

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EXPERIMENTAL

Materials

Polyester knitted fabric (210 denier/34 filament), polyamide 66 fabric (70 denier/35 filament yarn), density 1.14 g/mL, the fabrics soaped at 70°C, thoroughly washed, and air dried at room temperature.

Dyestuffs: Commercial disperse dyes were used in this investigation such as C.I. Disperse Red 15, C.I. Disperse Orange 3, and C.I. Disperse Violet 1.

Dyeing Procedure

Polyester fabrics were dyed in a dyebath prepared by raising the temperature of 400 mL water to 45°C and adding 0.25 g dispersing agent (Irgasol DA gran., Ciba-Geigy) and then acetic acid to adjust the pH value to 4.5. When the temperature had reached 60°C, a proper amount of the disperse dye (based on the weight of the sample) was added portion-wise. The contents of the dyebath were continuously stirred for about 20 min. A polyester fabric, 10 g, was immersed in the dye liquor. The dyeing temperature is raised to 125°C in ¾ h and kept at 125°C for a further hour. Dyeing was performed in an Ahiba Turbomat dyeing apparatus. Dye liquors were circulated at a moderate rate. After a predetermined dyeing period, the dyebath was regularly cooled and the dyed sample was then removed, soaped, washed out under running water, and then air dried.

Transfer Dyeing

The previously dyed polyester fabric was used as a dye reservoir (donor) in the heat transfer technique in place of the printing paper. Another white synthetic fabric designated as receptor fabric was brought into contact with the donor fabric either from one side or to be contacted by two donor fabric surfaces from both sides under the heater of the transfer equipment. Dye transfer from donor to receptor fabric under constant pressure was performed using The Double A, Manual Heat Transfer Press, supplied by Philipps-Faire Ltd., England. The operating conditions, dwell time and temperature, ranged between 10 and 120 s and 190–220°C, respectively. The donor and receptor fabrics system was enveloped with tinfoil to avoid soiling of the heater plate with sublimed dye and spoiling successive works.

Measurements

The dye uptake on the receptor fabric was completely extracted in dimethylformamide and measured spectrophotometrically and expressed as g dye/100 g fibers.

The dye content on the donor fabric was similarly extracted and expressed as g dye/100 g fibers.

Calculations

$$\%\ \text{dye release from donor fabric} = \frac{\text{original dye content—dye content after time } t}{\text{original dye content}} \times 100$$

$$\%\ \text{color transfer efficiency}^{12} = \frac{\begin{pmatrix}\text{color strength of donor}\\ \text{fabric before use}\end{pmatrix} - \begin{pmatrix}\text{color strength of donor}\\ \text{fabric after use}\end{pmatrix}}{\text{color strength of donor fabric before use}} \times 100$$

$$\text{partition coefficient } (k') = \frac{\text{dye uptake by receptor fabric (g dye/kg fiber)}}{\text{dye vapor concentration (g dye/L)}}$$

$$\text{Dye vapor concentration}^{16} = \frac{P_s M}{RT}$$

where P_s is the saturation pressure (atm), R is the ideal gas law constant, M is the molecular weight of the gas, and T is the transfer temperature (°K).

$$\text{standard affinity}^{12,17} - \Delta u^0 = 2.3\, RT \log k'$$

$$\text{heat of dyeing}^{17} = \left[\frac{\Delta u_1^0}{T_1} - \frac{\Delta u_2^0}{T_2}\right] \Big/ \left[\frac{1}{T_1} - \frac{1}{T_2}\right]$$

color difference (ΔE)[18]:

$$\Delta E = [(L - L_0)^2 + (a - a_0)^2 + (b - b_0)^2]^{1/2}$$

where L, a, and b denote the Hunter Color values of the tested sample and L_0, a_0, b_0 are the corresponding ones of the reference sample of the same color hue.

The measurements were performed on a Hunterlab Colorimeter model D 25 M-2:

$$L = 10\, Y^{1/2}, \qquad a = 17.5 \frac{[(X/0.98) - Y]}{Y^{1/2}}$$

$$b = 7.01 \frac{[Y - (Z/1.18)]}{Y^{1/2}}$$

$$X, Y, Z = \text{C.I.E. Tristimulus values}$$

RESULTS AND DISCUSSION

Dye Transfer Process

In the heat transfer process of dye brought about by contacting the receptor with the dye-donor fabric, some variables may influence this operation. These are the heat transfer temperature, time of contact, and dye content originally present in donor fabric. In case of no application of heating source, the vapor pressure in this combined system can be considered very small. Consequently, the concentration of the dye vapor will equal zero. As the heating source is

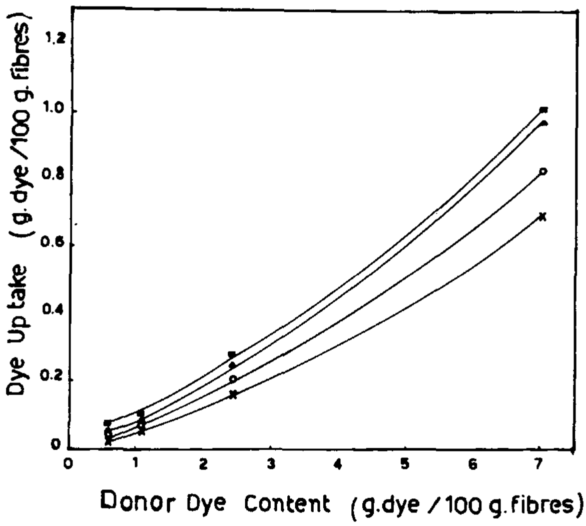

Fig. 1. Dependence of the dye uptake by the receptor polyester on the original dye content of donor fabric. (C.I. Disperse Red 15; time = 30 s; (X–X) 190°C; (O–O) 200°C; (Δ–Δ) 210°C; (□–□) 220°C).

subjected to the system from the backside of the donor fabric, a temperature gradient is set up across this system. The resulted heat flux is dependent on the prevailed temperature of the heating source, thickness of contacted layers, su-

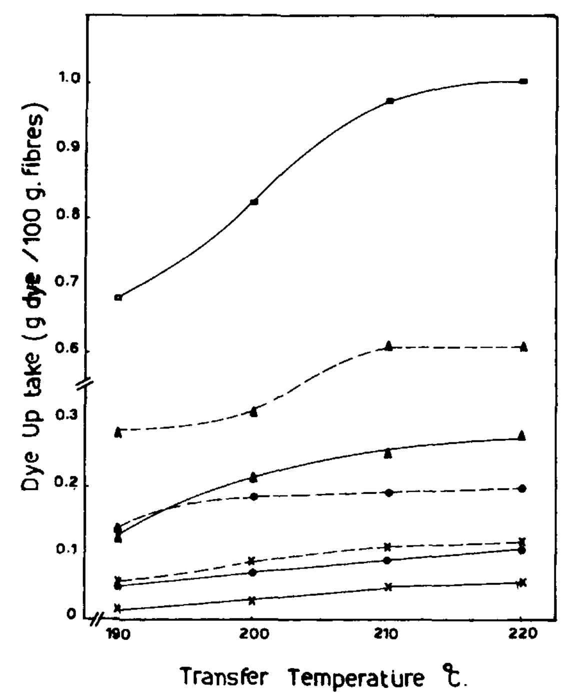

Fig. 2. Dependence of the dye uptake by the receptor fabric on the heat transfer temperature using donor fabrics of different dye content. (C.I. Disperse Red 15; time: (—) 30 s; (- - -) 120 s; (X–X) dye-donor content 0.6 g dye/100 g fibers; (O–O) dye-donor content 1.04 g dye/100 g fibers; (Δ–Δ) dye-donor content 2.40 g dye/100 g fibers; (□–□) dye-donor content 7.00 g dye/100 g fibers.

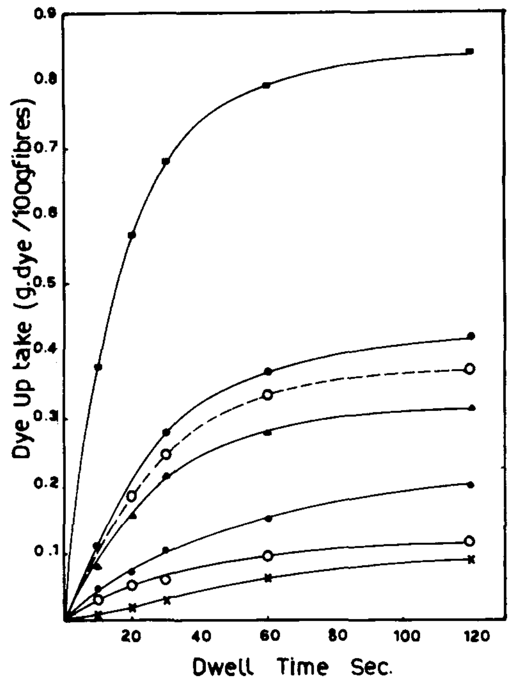

Fig. 3. Dependence of the dye uptake by the receptor fabric on the dwell time using donor fabrics of different dye contents and at various temperatures. (C.I. Disperse Red 15; (—) polyester receptor fabric; (- - -) polyamide receptor fabric; (X–X) 200°C, 0.6 g dye/100 g donor fibers; (O–O) 220°C, 0.6 g dye/100 g donor fibers; (●–●) 220°C, 1.04 g dye/100 g donor fibers; (△–△) 200°C, 2.4 g dye/100 g donor fibers; (●–●) 220°C, 2.4 g dye/100 g donor fibers; (□–□) 190°C, 7 g dye/100 g donor fibres.

blimation energy of the dye molecules, heat capacity, weight, and denier of the substrate.

Receptor/Donor Fabrics Interrelationship

The vapors of the dye sublimed by the effect of heat flow into the interior of the donor fabric structure until it approaches an equilibrium. In the same time the dye molecules flowing away would diffuse across the very slight air gap enclosed between the inner donor and receptor fabric surfaces under the applied pressure of the press.

Dye Uptake

Figure 1 shows the dependence of the dye uptake of the polyester receptor fabric on the amount of dye carried out by the donor fabric as well as on the transfer temperature. It can be observed that the dye uptake has increased as the original dye content of the donor fabric is increased. Higher transfer temperatures favor dye uptake by the receptor fabric.

Figure 2 presents the dependence of the dye uptake by the polyester receptor fabric on the transfer temperature. Raising the temperature from 190°C to 210°C reveals an increase in the dye transfer tendency. Further increase of temperature to 220°C enhances relatively the dye uptake, but the handle of the fabric is badly affected.

Figure 3 depicts the relation between the dye uptake and the dwell time. Application of donor fabrics carrying various dye contents (0.6–2.4 g dye/100 g fibers) has confered a progressive dye uptake by the receptor fabric. This progression is levelled off after 1 min. Further prolongation of dwell time will establish a dynamic equilibrium, where the molecular adsorption and desorption rates will be equal.

Figure 4 is a three-dimensional diagram which illustrates the interrelationship between the dye uptake by the receptor fabric and the temperatures of both dye transfer and the original dye content of donor fabric. It is well to emphasize that increasing the temperature to 210°C give rise to an increment in dye uptake. This increase is found to be relative to the amount of dye originally present in the donor fabric.

Dye Release

The released dye from the donor fabrics is also investigated with respect to the original dye content of the donor fabric. It can be seen (Fig. 5) that at a relatively short time (30 s, first run), the released dye from the donor fabric is slightly less with rich-dye donor fabric than the poorer ones. The released dye is progressively sublimed by temperature increase of the heating system (Fig. 6).

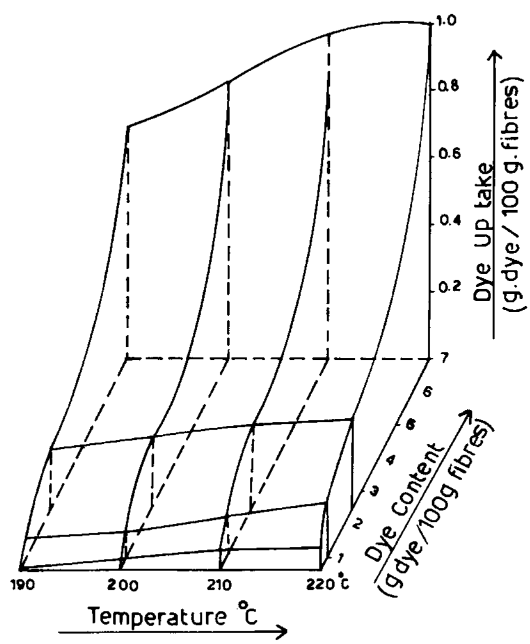

Fig. 4. Dependence of the dye uptake by the receptor fabric on both temperature and dye content of donor fabric (dwell time = 30 s).

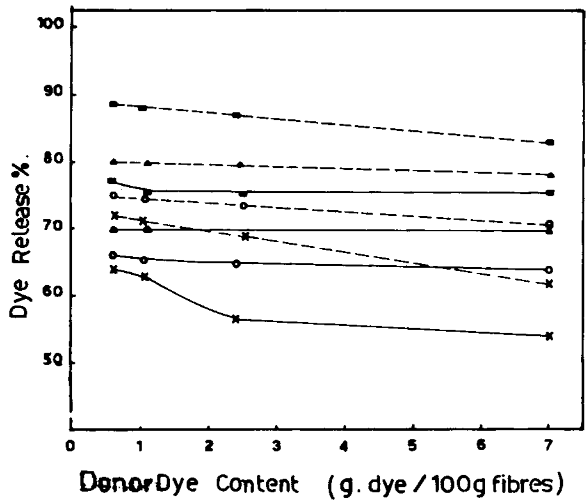

Fig. 5. Dependence of released dye from the donor fabric on the original dye content of the donor fabric. (—) 30 s; (---) 120 s; (X–X) 190°C; (O–O) 200°C; (△–△) 210°C; (□–□) 220°C.

Efficiency of Dye Transfer

The efficiency of transfer of the dye at different temperatures for 30 s from the donor fabrics carrying various amounts of dye is correlated with the resultant dye uptake by the receptor fabric (Fig. 7). It can be observed that in the case of light-shaded donor fabrics, the transport of dye from donor to receptor fabric has reached such an equilibrium. The residual dye retention on the donor fabric may be due to the partition of the dye between the vaporized phase and the donor fabric. In case of medium to deep-shaded donor fabric, the effect of increrased dye retention on the donor fabric and the dye transfer percentage are nearly the same as in the case of light-shaded one. The dye uptake has increased to nearly

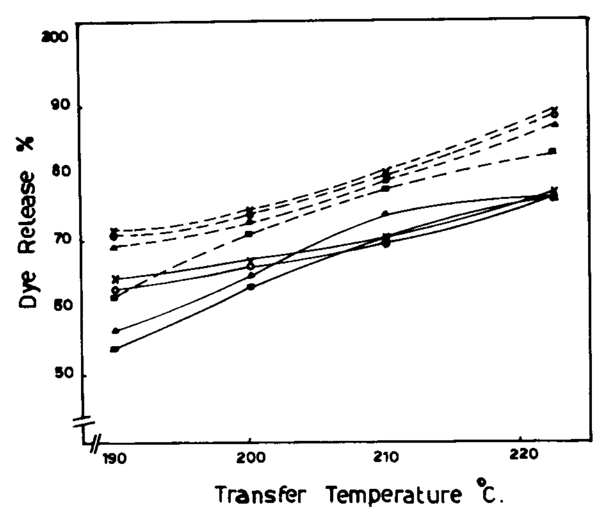

Fig. 6. Dependence of the released dye from the donor fabric on the heat transfer temperature. (—) 30 s; (---) 120 s; (X–X) 0.6 g dye/100 g donor fibers; (O–O) 1.04 g dye/100 g donor fibers; (△–△) 2.4 g dye/100 g donor fibers; (□–□) 7 g dye/100 g donor fibers.

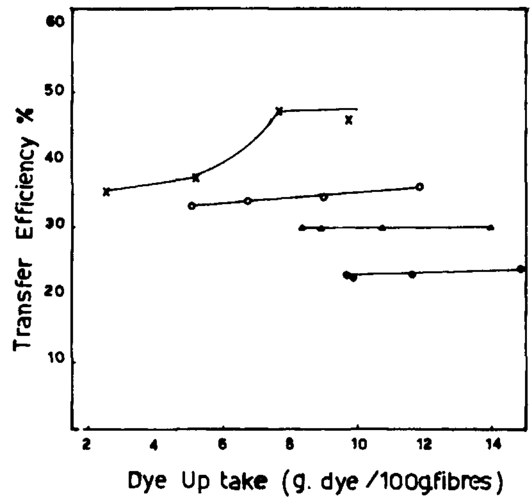

Fig. 7. Correlation of the transfer efficiency of the dye from the donor fabric with dye uptake by the receptor fabric at various temperatures. Dwell time = 30 s; (X–X) 190°C; (O–O) 200°C; (△–△) 210°C; (●–●) 220°C.

double. In case of extra deep-shaded donor fabric (7 g dye/100 g fibers), the oversaturation of the fabric with dye reveals a very slight increment in percentage transfer efficiency and a consequent dye uptake by the receptor fabric of nearly double as that given by the light-shaded donor fabrics.

Continuous Technique

The principle of continuous dyeing of synthetic receptor fabrics by disperse dye vapors is also tried. The same dye donor fabric is brought into contact successively with white receptor fabrics under the heat-transfer system at 210°C for a short dwell time of 30 s. The trial reveals the capability of imparting colors on the receptor fabrics which are visually of the same level. Table I presents

TABLE I
Color Difference Values (CIE Units) between Synthetic Receptor Fabrics Colored Successively by Heat Transfer from Same Dye-Donor Fabric at 210°C, 30 s and First Contacted Receptor Fabric

Receptor/donor contact no.	Polyester receptor fabric			Polyamide receptor fabric		
	ΔE^a	ΔE^b	ΔE^c	ΔE^a	ΔE^b	ΔE^c
2	0.1	0.06	0.12	0.10	0.12	0.14
4	0.15	0.10	0.16	0.12	0.16	0.18
6	0.20	0.12	0.18	0.18	0.20	0.20
8	0.28	0.25	0.30	0.26	0.22	0.24
10	0.30	0.32	0.42	0.30	0.28	0.32
12	0.35	0.34	0.46	0.32	0.37	0.38
16	0.60	0.80	0.70	0.72	0.75	0.78
20	1.04	1.20	1.28	1.40	1.50	1.35

[a] Using donor fabric dyed with C.I. Disperse Red 15.
[b] Using donor fabric dyed with C.I.Disperse Orange 3.
[c] Using donor fabric dyed with C.I. Disperse Violet 1.
Note: Each value of the mentioned color difference is an average of six samples.

the evaluation of the color difference between the various successive runs of the receptor fabrics and the first run contacted the donor fabric.

The color on the donor fabric is significantly faded after the 13th run. Recharging the same reservoir fabric by repeated dyeing and reusing it again as a dye-donor fabric for coloration of white receptor synthetic fabrics is also successfully performed.

Standard Affinity and Heat of Dyeing

Dyeing of polyester fibers by the above-mentioned heat transfer system using C.I. Disperse Red 15 at 210°C is prolonged to a practically true equilibrium so that the receptor fabric is uniformly penetrated by the vapors of the sublimed disperse dye, and its adsorption and desorption will take place at the same rate. The partition coefficient is determined by calculating the ratio of the concentration of the dye into the receptor fabric to that in the air gap trapped between the receptor and donor fabrics, the affinity ($-\Delta u^0$) of the dye at different temperatures, as well as the heat of dyeing can be also therefrom calculated.[19]

Calculation of Δu^0 and the heat of dyeing (ΔH^0) reveals that these parameters are negative values, indicating that dyeing of polyester with disperse dye vapors is an exothermic process. The increase in the dyeing temperature has decreased the partition coefficient as well as the affinity of the dye to the fibers. Polyester fiber has acquired $-\Delta u^0$ values of 25 kJ/mol and 22 kJ/mol at 190°C and 210°C, respectively. The heat of dyeing (ΔH^0) is found to be in the order of 94 kJ/mol.

Rate Controlling Step

It was reported that the transport of the dye through the vapor phase is the rate controlling step.[19] Recent arguments[20,21] revealed that diffusion of dye either in vapor phase or the receptor phase may be the rate controlling step. Simplified tracing of the controlling step is given based on the application of Levich hydrodynamic diffusion analysis.[21,22] The partition coefficient of the dye between the receptor and gas phases as well as the diffusion coefficients of the dye in the gas phase D_g and receptor phase D_f at 210°C are calculated and found to be in the order of 10^6, 10^{-1}, and 10^{-9} cm²/s respectively.[12,20]

It is found that the partition coefficient is smaller than the difference between the supply rate of molecules to the surface and their transport to the fiber interior. Based on the foregoing conclusion and in accordance with the Gorondy analysis,[12] it can be assumed that the rate controlling step in this vapor phase dyeing system is the diffusion of the dye vapors into the fiber phase.

References

1. British Celanese, Brit. Pat. 293,022 (1928); Brit. Pat. 349,683 (1930).
2. Agfa-Gevart, Ger. Pat. 928,423 (1951).
3. Filatures Proavost-Masurel, Fr. Pat. 1,223,330 (1958).
4. K. V. Datye, S. C. Pitkar, and U. M. Purae, *Textilveredlung*, **8**, 262 (1973).
5. H. Fujito, A. Kishimoto, and K. Marawama, *Trans. Faraday Soc.*, **56**, 424 (1960).
6. Imperical Chem. Industry, Brit. Pat. 1,271,372 (1969).
7. M. R. Fox and N. Parsons, *J. Soc. Dyers Coll.*, **85**, 478 (1969).
8. R. A. Fenglio and E. J. Gorondy, *Text. Chem. Colorist*, **7**, 84 (1975).
9. F. Jones and R. Seddon, *Text. Res. J.*, **34**, 374 (1964); **35**, 334 (1965).
10. J. Griffiths and F. Jones, *J. Soc. Dyers Col.*, **93**, 176 (1977).
11. U. Beck and F. Hoffman, *Textilveredlung*, **12**, 193 (1977).

12. E. J. Gorondy, *Text. Res. J.*, **47,** 604 (1977).
13. M. E. Fielding, Brit. Pat. 1,432,197; *Textilveredlung*, **12,** 32 (1977).
14. M. E. Fielding, *Am. Dyestuff Reptrs.*, **66,** 46 (1977).
15. A. Bendak, Egypt. Pat., 12819 (1979).
16. H. S. Green and F. Jones, *Trans. Faraday Soc.*, **63,** 1612 (1967).
17. R. H. Peters, *Textile Chemistry, The Physical Chemistry of Dyeing*, Elsevier, New York, 1975.
18. D. B. Judd, and G. Wysezcki, *Color in Business, Science and Industry*, 3rd ed., Wiley, New York, 1975.
19. C. J. Brent, T. D. Flynn, and H. H. Summer, *J. Soc. Dyers Coll.*, **85,** 606 (1969).
20. H. Gerber, *Textilveredlung*, **8,** 449 (1973).
21. W. McDowell, *Melliand Textilber.*, **11,** 1265 (1972).
22. V. G. Levich, *Physicochemical Hydrodynamics*, Prentice-Hall, Englewood Cliffs, N.J., 1962.

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