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EFFECTS OF OPERATION CONDITIONS ON DYEING BEHAVIOR OF ROPE FABRICS*

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The simulation model offered in the previous paper was extended and effects of operation conditions on levelness of rope dyeing were investigated in more detail.

From the analysis, effects of operation conditions on degree of dyeing levelness were arranged apparently, and in addition, following suggestions were obtained in relation to level dyeing:

- 1) Unlevel dyeing occurs strongly in a certain stage of dyeing.
- 2) Degree of dyeing levelness depends on the parameter β which relates to flow conditions of dye liquor.
- 3) In the stage of constant end point temperature, it is suggested that to suppress flow of dye liquor is desirable from the view point of preventing unlevel dyeing.
- 4) From 1) to 3), an optimal flow condition of dye liquor is suggested.
- 5) Temperature rising rate dT/dt also gives strong effects on degree of dyeing levelness.
- 6) If dyeing is performed under a constant dT/dt , lower end point temperature is suitable to avoid unlevel dyeing.

INTRODUCTION

As pointed out in recent papers,^{1,2)} dyeing industries have been changed their form from labor intensive one to capital intensive one. And besides, recent remarkable developments of electronic computer system will force them to introduce "mechatronic devices" and computer control of production.

To realize such a metamorphosis smoothly, much more investigations should be given on the phenomena in each process unit from the view points of dyeing engineering to obtain data of design and operation conditions.

In the previous paper, a simulation model was offered and several fundamental considerations were given on the dyeing behavior of rope fabrics for a polyethyleneterephthalate (PET)-disperse dye system.³⁾

From the analysis, several important suggestions were derived to prevent unlevel dyeing of rope

fabrics.

In this paper, effects of some model parameters and operation conditions are investigated.

It might be possible to some extent to determine design and operation conditions from these considerations rationally, not empirically.

1. BRIEF DESCRIPTION OF THE MODEL

The model offered by the author is as follows:

In a rope dyeing, unlevel dyeing will occur when some quantity of low temperature dye liquor are enclosed in a mass of fabrics in a rapid rising stage of dye bath temperature and are kept for a sufficiently long time. The rate of generation of low temperature spots and the duration of the state depend on operation conditions.

In the case where a quantity of low temperature dye liquor is enclosed in an entangled part of the fabrics at time t_1 and remains as it is, and is mixed stepwise with bulk dye liquor at time t_2 , the degree of dyeing levelness ϵ on the spot after t_2 is expressed by the equation:

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$$\epsilon = C_f^i(t)/C_f^{av}(t) = (A^i(t)/A^{av}(t)) (1 - A^{av}(t_2) + A^i(t_2)) \quad (1)$$

(C_f : dye concentration in a fiber, A : degree of dye exhaustion, i : unlevel spot, av : average or standard part)

One of the most important problems for formulating the model is how to express generation rate of low temperature spot n and its duration distribution $p(\xi)$.

As a first approximation, here, let's express them, respectively,

$$n = n_0 \cdot f(T(t)) \cdot g(dT/dt) \quad (2)$$

$$p(\xi) d\xi = 2\beta\xi \exp(-\beta\xi^2) d\xi \quad (3)$$

(n_0 : generation rate of unlevel temperature spots under a standard condition, f and g : correction factors relating to dye bath temperature T and its rising rate dT/dt respectively, ξ : duration of unlevel state, β : parameter relating to dye liquor flow)

The following simple form of dyeing rate equation was selected exclusively to determine A in the equation:

$$dA/dt = kD(A_\infty - A) \quad (4)$$

In Fig. 1, an example of change of dyeing levelness on one of unlevel spots is shown.

Fig. 1 Change of dye exhaustion and degree of dyeing levelness (Example)

2. RESULTS OF MODEL CALCULATIONS AND DISCUSSION

2.1 Effects of duration of temperature unlevelness

As shown in Fig. 1, on the unlevel dyeing spot,

dyeing proceeds a little more slowly because the temperature on the spot is lower than that of any other parts, and ϵ goes down promptly. But after the time when the temperature unlevelness vanishes due to the mixing of the unlevel dye liquor with bulk dye liquor, ϵ recovers to some extent gradually.

In a PET-disperse dye system, it is well known that, the lower the temperature is, the smaller the dyeing rate is, and at the same time the more the equilibrium exhaustion is. Hence, if the motion of the fabrics is suppressed and the duration of lower temperature unlevelness is long, degree of levelness on this spot will be beyond the threshold value of unlevel dyeing (for example, $\epsilon_{crit} = 0.9$). And if the duration is much longer, the dye exhaustion on the spot will be even higher than that of other standard parts (refer Fig. 2).

Fig. 2 Effect of duration of temperature unlevelness

In this model, it is assumed that after the dye bath temperature reaches the upper limit, no temperature unlevelness occurs in the fabrics. Then, after the time, dyeing can be considered in the stage of recovery to level dyeing, namely, it is desirable to suppress the motion of the fabrics or dye liquor flow to obtain level dyeing.

2.2 Stage of generation of unlevel dyeing

In a dyeing unit, the fabrics and the dye liquor are forced to move vigorously, and as a result, low temperature spots appear in the fabrics at a certain rate (Eq. (2)). The spots are never kept in the constant state to the end point.

Statistically, they contact with bulk solution gradually, and the temperature of which goes back to the standard one (Eq. (3)).

Though, when dyeing proceeds very slowly during those processes, unlevel dyeing may seldom appear, almost all of the unlevel dyeing spots may be fixed as unlevel dyeing specks when dyeing rate is very large.

In the initial stage, the rate of dyeing is small, then becomes larger, and finally approaches zero again, because a dye exhaustion curve is generally S-shaped as shown in Fig. 1. In addition, most of the unlevel temperature spots generated in the initial stage will fade out without being fixed as unlevel dyeing. It is imagined that there will be a certain stage for unlevel dyeing to occur relatively easily. Therefore, facilitating fabrics-dye liquor contact at that stage will be effective for preventing unlevel dyeing.

Meanwhile, it is possible to improve dyeing levelness by suppressing the motion of fabrics after the dye bath temperature reaches the end point temperature as mentioned in the previous section.

Fig. 3, 4 show examples of probability for unlevel temperature spots appearing at a certain stage to be fixed as unlevel dyeing.

As shown in Fig. 2, an unlevel low temperature spot will be an unlevel dyeing speck when the unlevelness continues for longer than the critical duration ξ_{c1} , but if it continues even more longer than another critical value ξ_{c2} under certain conditions, the unlevel spot goes back again to standard level dyeing.

Then, the probability can be expressed by the following equation:

$$P_c = \int_{\xi_{c2}}^{\xi_{c1}} 2\beta\xi \exp(-\beta\xi^2) d\xi \quad (5)$$

Fig. 3 corresponds to the case where the bath temperature changes from 40°C (30min.) through linear rising stage (30min.) to 100°C (60min.). From the figure, it is clear that unlevel dyeing generates so much at around 55 minutes from the start point of dyeing.

β in the equation is a measure of rate of vanishment of low temperature unlevelness and relates to the frequency of fabrics-dye liquor contact. Values of β , 0.0102, 0.0230 and 0.0409 correspond to the case where 90% of temperature unlevel spots fade out in 15, 10 and 7.5 minutes, respectively. The effect of β is very strong, and

Fig. 3 Probability of unlevel spot fixation-1

Fig. 4 Probability of unlevel spot fixation-2

it can be guessed that if β is set large (namely, facilitating contact between fabrics and dye liquor) near 55 minutes, unlevel dyeing will be able to be suppressed remarkably.

Fig. 4 shows the results for different temperature profiles, 10–100, 40–100 and 70–100°C, for the same value of β .

In the case where the initial temperature is high, e.g. 70°C, remarkable unlevel dyeing does not occur at a certain stage because dyeing proceeds fast just from the start point. This seems to mean that it is desirable to start dyeing at high temperature from the view point of preventing unlevel dyeing.

According to the assumption that temperature unlevelness in the fabrics generates mainly in a temperature rising stage, dyeing operation at a constant high temperature might be by nature effective to prevent unlevel temperature spots from generating, and besides, as mentioned above, low temperature spots also will not easily be fixed

as unlevel dyeing specks.

Hence, to do such an operation is desirable. In such a case, however, it is intrinsically necessary to take the elementary processes into account. If the dyeing rate equation (4) can be applied throughout the dyeing process, the dyeing should be operated under the condition suggested above. But practically, the fabrics should take up dye solution on itself homogeneously first of all, and hence, it is necessary to keep the dye liquor temperature low and to facilitate the contact between rope fabrics and dye liquor just at the initial stage.

Thus, to prevent unlevel dyeing, it is important to give adequate conditions for each stage of dyeing, grasping the rate determining step.

In addition, relating to dyeing rate, the followings should be pointed out. Though in this paper, dyeing rate is given by a simple equation like Eq. (4), any forms of rate equation are allowed to apply to model calculations, as being understood easily. Namely, whichever the rate determining step is, the calculation procedure is similar. That means at the same time the procedure is applicable to any substrate-dyestuff system, for example even to cotton-direct dye system. The model calculation offered here is applicable universally.

2.3 Effect of β

To apply the simulation model practically, β must be expressed in such a form relating to operation conditions, for example,

$$\beta = a \bar{u}^b \quad (6)$$

($\bar{u}$: average flow rate or circulation rate of dye liquor, a, b : parameters determined empirically)

At present, no attempts are found on the treatment, especially for rope dyeing.

In Fig. 5, a relation between the final number of dyeing specks (N), and the parameter β is shown. In all cases, the dyeing time is set by 2 hours and the threshold value of levelness ϵ_{crit} is 0.9.

From the figure, it can be seen that the order of the value N decreases by one according to the increment of the order of the value β by one. This relation seems to be applied to wide range of temperature profiles, though not strictly. Hence, it is desirable to operate keeping the value of β high. But under high value of β , the energy consumption is estimated to be large, because the motion of fabrics and dye liquor is vigorous and

Fig. 5 Effect of parameter β on the number of dyeing speck N

at the same time the heat loss from the wall of a dyeing unit increases. Therefore, considering the suggestions mentioned in 2.2 that there is a certain stage for unlevel dyeing to generate, to operate under high value of β at that stage only is energy saving without failure of level dyeing.

Here, let's consider the case where

$$\beta = a \bar{u}^2 \quad (7)$$

If the value $\bar{u}$ can be set by three times, β increases by ten times. And according to Eq. (5), degree of dyeing levelness would decrease by about one-tenth.

Thus, to express the parameter β quantitatively relating to operation conditions is essential not only for preventing unlevel dyeing but also for energy saving.

2.4 Effect of initial and endpoint temperature

In all cases considered in this paper, temperature profiles are as follows: First, 30 minutes dyeing under a certain initial temperature T_0 , then 30 minutes linear temperature rising to a certain endpoint temperature T_f , finally 60 minutes dyeing under T_f . Hence, change of T_0 or T_f results in change of temperature rising rate.

From Fig. 6, effects of T_0 on N can be seen under the conditions of constant T_f .

Fig. 6 Effect of initial temperature

The lower T_f is better for level dyeing, but under lower T_f , the longer dyeing time is needed. Then, there should be an optimal endpoint temperature T_f from the view point of practical operation.

Meanwhile, under higher initial temperature conditions, degree of dyeing levelness does not fall for higher T_f . Though as mentioned in 2.2, elementary processes of initial stage of dyeing should be investigated and the energy consumption for such an operation should be taken into account, higher temperature-short time dyeing after careful preparation of rope fabrics and dye bath would be effective for level dyeing.

2.5 Effect of temperature rising rate dT/dt

Here, let's consider the effects of temperature rising rate, which is often used as a measure of level dyeing, on the final number of unlevel dyeing speck N .

N is expressed by the following equation:

$$N = \int_{30}^{60} n \cdot \left(\int_{\xi_{c2}}^{\xi_{c1}} p(\xi) d\xi \right) dt \quad (8)$$

n in this equation is given by the Eq. (2), ξ_{c1} and ξ_{c2} are determined from such figures as Fig. 2.

N is estimated by nature as an integral of a certain temperature profile as shown by the equation. Thus the problem is how to define the temperature rising rate, especially for such a practical temperature profile as the rising rate changes with time.

Fig. 7 shows change of N with the temperature

Fig. 7 Effect of temperature rising rate

Fig. 8 Effect of endpoint temperature

rising rate under constant T_f . The effect of the rate seems roughly linear for practical operation conditions. As mentioned previously, T_0 changes widely for the cases in Fig. 7. So roughly speaking, the average temperature rising rate might be useful as one of a measure of level dyeing even for practical cases where the temperature rising rate is not constant.

Fig. 8 shows the effect of endpoint temperature T_f for constant temperature rising rates. The tendency that N depends strongly not only on the rising rate but also on T_f can be recognized clearly. The results that N reaches maximum near $T_f = 120^\circ\text{C}$ is interesting. It seems to occur due to the phenomenon that dyeing proceeds smoothly from just the beginning for the case of higher initial temperature, since the initial temperature T_0 increases with T_f under the condition of constant temperature rising rate.

2.6 General considerations

1) In recent years, the concept of "isoreactive dyeing" (linear exhaustion) has been offered by Carbonell and et al. as a measure of level dyeing.⁴⁾ And, several considerations have been given on the concept.⁵⁻⁷⁾ However, as pointed out by themselves, the concept was offered only as an approximate guide to establish level dyeing and the basic reason why level dyeing can be obtained by linear exhaustion has not been elucidated so far. Besides, some modifications should be given for rope fabrics since the concept is mainly for fixed fiber loads.

The dyeing behavior of rope fabrics must be investigated taking two rate, namely dyeing rate and rate of fabric motion, into account.

The simulation model developed by the author seems one of the most actual solutions to the problems.

2) Fundamentally, in the model, unlevel temperature spots are assumed to appear only at a temperature rising stage of dyebath and low temperature unlevelness are kept constant for a certain period. These assumptions are not intrinsic. If a suitable temperature unlevelness is defined, any temperature unlevel spots at any stages of a dyeing process can be followed quantitatively. Unlevel dyeing spots will occur also at a temperature falling stage, and sometimes a certain part of the fabrics is not dipped in the dyebath. Hence, the rate of generation of unlevel temperature spots are desirable to be expressed in such a form that those mechanisms mentioned above are included.

Eq. (2) is one of the forms which fulfil the requirements, and can correspond to various generation mechanisms of temperature unlevelness.

3. CONCLUSION

The simulation model of rope dyeing assuming that unlevel dyeing is due to entanglement of the fabrics is investigated in more detail, and following conclusions are obtained:

1) At the stage of constant endpoint temperature, it is suggested that to suppress flow of dye liquor

is desirable from the view point of preventing unlevel dyeing.

2) In a given temperature profile, there will be a stage where unlevel dyeing will occur mainly. Hence, at the stage, vigorous circulation of dye liquor is desirable.

3) By setting the initial temperature high, it would be possible to prevent the phenomenon mentioned in 2), because dyeing proceeds smoothly to some extent from the beginning. Though such an operation is not suitable to homogeneous adsorption of dyestuff, the suggestions will be useful to select the optimal preparation procedure of fabrics and dye liquor.

4) The parameter β which relates to dye liquor flow (or directly to motion of fabrics) is much effective for level dyeing. If some rational relations are given between β and $\bar{u}$, the optimal value of β and $\bar{u}$ will be easily determined so as to avoiding unlevel dyeing.

5) To set the endpoint temperature as low as possible has some effects for obtaining level dyeing.

6) It is desirable to operate under a small temperature rising rate. The average value of temperature rising rate is effective but not sufficient as a measure of level dyeing.

In addition, the model developed here is useful not only to follow the dyeing behavior precisely but also to arrange which and how physical properties should be controlled. So, the treatment may be valuable for designing dyeing units.

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ロープ状布染色のシミュレーション-2 — 運転条件の影響 —

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前報で提案したロープ状布染色のシミュレーションモデルについて考察を進め、均染度におよぼす運転条件の影響を検討した。

検討の結果、運転条件の定量的評価が可能となり、さらに均染性を得るための条件について、次のような結論が得られた。

- 1) 不均染は、染色操作のある段階で特に強く発生する。
 - 2) 均染度は、染液流動条件に関連するパラメーター β に強く依存する。
 - 3) 一定の終端温度条件下では、染液流動を抑制する方が均染性の点からは望ましい。
 - 4) 上述の点から、染液流動条件の最適化に関する知見が得られた。
 - 5) 染浴温度上昇速度は、均染性に非常に強い影響を与える。
 - 6) 昇温速度を一定にするなら、終端温度を低くすることが望ましい。
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