INDUSTRIAL EXPERIMENTATION ON HANK-DYEING: MODELLING EQUIPMENT AND WATER ECONOMISATION DURING RINSING

Sergio CIGNOLO, Giorgio ROVERO, Mauro BANCHERO and Franco FERRERO

Dipartimento di Scienza dei Materiali e Ingegneria Chimica
Politecnico di Torino,
Corso Duca degli Abruzzi, 24
10129 Torino, Italy
giorgio.rovero@polito.it

Abstract

The hydrodynamics of a dyeing machine affects the exchange mechanisms between a textile material and the liquid medium to a large extent. Namely, the transfer of dyes and chemicals from the dyeing liquor and the release of non-bonded substances during subsequent rinsing steps can be altered by relative movement between phases. Such aspects have not been investigated thoroughly, although the typical approach of chemical engineering can offer a relevant contribution in this view. As a practical result, important benefits may follow in various operations of the dyeing process, aimed at optimising the equipment use or saving resources, in particular water. The attention of this study was focused on hank-dyeing machinery, since this production demands a considerable amount of water due to the large liquor ratios. The experimental study was carried out at a textile industry facility by operating on two units of equipment at significantly different scales. The rinsing operation was monitored by sampling the liquid at several positions along the vertical direction of the liquor: colour, conductivity and other chemical properties were measured in order to devise an optimal production policy aimed at saving water. A mathematical model of the equipment, based on a simple hydrodynamic hypothesis and proper mass balances, was proposed, and its outputs were compared with the experimental results. Both practical considerations and the theoretical analysis suggest that water requirement during rinsing can be halved by modifying the procedure without affecting the final quality of products.

Keywords

hank-dyeing, rinsing, equipment diagnosis, water saving

Introduction

Recently, due to ongoing climate changes, economical considerations regarding the use of water and the new perspectives given to the environment, unlimited consumption of water causes increasing concern among manufacturers. A more rational utilisation of water in productive processes is now pursued by the following steps, in the following strategic order: reduction of use, reuse and recycling. Reducing the water demand could be a benefit from a proper evaluation of the features of the equipment, and reusing water can arise from a more careful analysis of the process. Recycling the resource, however, is definitively a more complex issue; in fact it can be the result of applying waste water refining technologies (tertiary treatment), and the validation of water quality specifications, as well as implementing modifications to the process lay-out.

Concern about the water problem started several years ago thanks to wide-ranging action in the textile production sector; this strategy led to the formation of a large working group (of almost thirty SMEs in the north-west of Italy) which stated the goal of minimising water demand. [Biella, 2000, Aachen, 2001]. Not surprisingly, water was named as an issue for the year 2003 by the World Summit for Sustainable Development.

In this view, the first approach is given by defining the hydrodynamics of equipments, which are typically designed and improved to furnish the best product quality according to operators' practical experience. Nevertheless, only a partial optimisation is generally pursued as far as energy
requirements (heating and pumping) or natural resource demand (water) are concerned. By keeping in mind that rinsing is demonstrated to be the most water-demanding step in the dyeing operation, the equipment can be selected on the basis of its fibre to liquor ratio (R/B) [1]. When equipment is already installed, the rinsing operation can be controlled according to the following factors:

1. time-based feed – the rinsing time is set by operators according to the general process criteria: this method is not optimised at all since only the rinsing time is controlled, while the actual water flow rate depends on the pressure in the mains;
2. volume-based feed – this is a more accurate criterion, since it is independent of the variable pressure in the feed system;
3. continuous overflow – this is sometimes a useful rinsing method to avoid thermal shocks to the product;
4. batchwise operation – a more time-consuming procedure (it is based on the equilibrium between the impregnating liquid and the surrounding bulk), though it can be easily optimised by evaluating the actual liquor outflow with on-line sensors.

Ultrasound technique was used to improve yarn to liquid mass transfer [2]; though effective, a serious concern was raised by operators that the hank yarn structure should not be affected. Rinsing optimisation was studied for other productions, and the results are presented as economical and ecological advantages [3].

Since criteria #1 and #2 are of merely technological interest in the dyehouse, this work specifically investigates water saving by comparing operations #3 and #4. A similar approach to the problem is given by literature in [4], thus confirming the general conclusion of the present work.

To some extent, hank-dyeing can be considered an old-fashioned technology which is characterised by high production cost, chiefly in terms of man-power, required because of difficult automation. Nevertheless, the interest is justified by yarn quality that maintains special features after dyeing.

**Experimental**

As far as the most common equipment is concerned, a hank-dyeing equipment unit consists essentially of a rectangular stainless steel box into which the yarn load is suspended vertically. An upper and a lower assembly of rods keep the hanks in position with a moderate possibility of vertical translation according to the dye-liquor circulation promoted by a reversible propeller installed in the lowest part of the machine. Perforated plates set a few centimetres above and below the rod assembly confine the dyeing chamber and act as distributors ensuring that the liquid has an even circulation.

![Figure 1. Schematic view of the pilot unit](http://www.autexrj.org/No4-2004/0097.pdf)
The whole package of hanks must have a uniform volumetric distribution to assure the best contact between yarn and liquor, which facilitates uniform coloration. Experiments were conducted on two different-scale units, a pilot and a production machine. Each piece of equipment can be divided schematically into three compartments, with capacity given by $V_1$, $V_2$, $V_3$ as model features. Figure 1 presents a scheme of a two-compartment hank-dyeing machine; in this case it represents the pilot unit, which is used in the mill for producing small amounts of highly valuable natural fibres (cashmere, fine wools, silk and their blends). Beside the usual components indicated in the figure, the volume repartition ($V_1$, $V_2$ and $V_3$) is depicted.

The two units used in the industrial experimental runs have the features given in Table 1. Both pieces of equipment were suitably modified to insert sampling tubes. Anyway, most experimental results were obtained by making use of the small unit, where risks to affect production quality were definitely less serious and an easier test scheduling of the experimentation program was possible.

**Table 1.** Main characteristics of hank-dyeing machines used in the tests

<table>
<thead>
<tr>
<th>type</th>
<th>nominal volume / m$^3$</th>
<th>hank load / kg</th>
<th>R/B Fibre to liquor ratio</th>
<th>height / m</th>
<th>width / m</th>
<th>depth / m</th>
<th>compartments / n°</th>
<th>hank assembly / n°</th>
<th>$V_1$ / m$^3$</th>
<th>$V_2$ / m$^3$</th>
<th>$V_3$ / m$^3$</th>
<th>rinsing feed rate / m$^3$/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>pilot</td>
<td>1.0</td>
<td>30</td>
<td>33</td>
<td>0.95</td>
<td>0.92</td>
<td>0.56</td>
<td>2</td>
<td>2</td>
<td>0.25</td>
<td>0.49</td>
<td>0.25</td>
<td>0.27</td>
</tr>
<tr>
<td>production</td>
<td>6.5</td>
<td>250</td>
<td>26</td>
<td>1.50</td>
<td>2.4</td>
<td>1.40</td>
<td>2</td>
<td>4</td>
<td>1.25</td>
<td>5.0</td>
<td>1.25</td>
<td>1.20</td>
</tr>
</tbody>
</table>

The hank load data in Table 1 shows that the scale-up factor in the experimentation was therefore close to 8, which means that a rather large production unit was used from an industrial standard point of view also. The flow rates during rinsing are also given in Table 1, as mean values of several measurement to account for the pressure oscillation; these values can be used to calculate actual water consumption from Figures 3 and 4.

![Figure 2. Sampling point positioning in the pilot unit assembly](image)

According to the stated aims, several sampling points were identified to carry out the measurements and draw the concentration profiles along the vertical coordinate and as a function of the operation time. The original weir configuration at the discharge was modified by inserting a disk containing four sampling 6-mm OD nylon tubes on an additional tee-junction tube to reach the positions indicated in Figure 2 for the pilot unit. The tubing discharged the rinsing liquor continuously, which was sampled by a carousel during the operation. Experimental data showed that the lines caused a time lag of about 20 s; this delay is irrelevant with respect to the experiment's duration. As far as the scheme is concerned, a tube reached the bottom point (b), as a representative of a mean value of the liquid that enters the hank assembly; a second probe was inserted between two adjacent hanks (h); another one was fixed inside the hank, just below the upper rod, as this position is considered critical and most affected by dead zone effects (d); the last probe sampled out the liquor from the top (t), just below the upper grid, to measure the concentration at the exit. Similarly, seven sampling positions were chosen.
for the larger unit in order to increase the definition of the concentration profile in a more complex assembly (lower and upper row of hanks).

Colour and electrical conductivity were identified as the parameters which were most affected by rinsing dilution. Both properties, the first measured by spectroscopy and the second by conductimetry, revealed almost coincident decay ratios. Specifically, a conductivity probe was then used to detect the value relative to the initial time sample \((c/c_0)\), to provide near-on-line monitoring.

Another experiment was carried out to measure batchwise the actual liquor concentration in the dead zone entrapped by the yarn fibres: one or two hanks were withdrawn from the equipment at the end of rinsing, and the impregnation liquid was squeezed out. A clear distinction should be pointed out between continuous sampling (via the \(d\) probe in Figure 2) and the batch measurements mentioned.

**Standard rinsing**

This procedure can also be defined as continuous rinsing, since water from the mains is continuously fed to the hank machine, while it overflows from the upper port. The common practice set for rinsing at the end of dyeing implies, as a first goal, a progressive cooling of yarn carried out by feeding tap water from the inlet at the bottom of the equipment; it is commonly believed that good dyeing practice requires this operative feature, to avoid stains on the yarn. According to step A of the standard operation, Figure 3 demonstrates a rapid decay of salt concentration as a measure of the removal efficiency of the exhausted liquor. By doing this, both thermal capacity and mass hold-up are displaced upward, with good progression of property variation with time. The mixing of the liquid phase was improved by actuating the circulation propeller in step B. The curves provide a number of information:

a) liquid mixing is minimal in step A, since the first set of data is consistently distributed along the machine height;

b) the dead zone effect plays a quite remarkable role after the second sampling, as the concentration at the top (t) is lower than that in the dead zones (d) (i.e. this position could be the most significant for monitoring the effectiveness of rinsing);

c) the very low concentration at the bottom (b) and, to some extent between the hanks (h), rises again once the propeller is started (entering zone B) to promote a more efficient mass transfer between stagnant (d) zones and the liquid bulk;

d) the circulation rate exceeds the transfer rate in step B, as the overlapped profiles demonstrate;

e) the flat concentration profile with time is an indication of a slow release from hanks of non-bound substances, and therefore is a measure of high-water demand to reduce impurities to a few percent of the initial concentration at the end of step B.

![Figure 3. Concentration profiles for a standard rinsing procedure: (A) dilution without propeller action, (B) mixing effect promoted by propeller pumping](http://www.autexrj.org/No4-2004/0097.pdf)
Alternative rinsing

As a consequence of the previous evaluation of the equipment’s hydrodynamic features, it was decided to contrast the effect described by point c) of the above paragraph by discharging the machine completely at the end of a given time in continuous operation. Figure 4 presents the results of a run in the pilot unit: step A was confined to 4 minutes, the machine was then discharged; step C represents the passage of time needed to discharge the system, and B represents the rinsing final step by both actuating the circulation propeller and continuously feeding water.

It is possible to draw the following considerations:

a) the reproducibility of measurements is quite satisfactory, since step A given in Figure 4 differs from step A in Figure 3 for an anticipated sampling only.

b) In the final B step, as in the previous test, mixing seems to be more useful to reach a homogeneous concentration than to actually decrease the impurity concentration.

c) It should however be noted that by comparing data from Figure 3 and Figure 4, the concentration at the rinsing end differs twofold, even though water consumption was decreased by 30% (10 minutes of feeding time in the first test and 7 minutes in the second one).

d) Figure 4 reports a value of liquor residual concentration within the hanks, according to the batchwise experimentation mentioned above. Although the sampling positions are quite close, the noticeable difference between the batch measurement (equilibrium concentration) and the d probe continuous sampling (dynamic concentration) further confirms the slow release of removable substances. The d sampling, however, proves to be the proper position for on-line monitoring of rinsing.

e) The quite large difference in concentration between the actual concentration in dead zones (see the experimental data in Figure 4) and the bulk at the end of step A (t curve value) is a sign that continuous overflowing does not allow equilibrium between the stagnant and the flowing phase to be reached, that is, if this procedure is followed a large amount of water is ineffective.

f) The equilibrium concentration obtained in step B can be confirmed by a mass balance written for the dyeing equipment. After draining and refilling the machine with fresh water (by considering the holdup about 3 l of water/kg of fibre), the residual concentration of the liquor in the hank load (see the experimental data given in Figure 4) and the equipment R/B ratio, the equation representing the mass balance can be solved to give the final concentration.

Batch rinsing

The rinsing operation for equipments characterised by a high R/B ratio is then favourably affected by a thorough replacement of most liquid contained in the prior step: the application of this concept is known as ‘batch rinsing’, and, for a number n of rinsing stages, can be described by the following expression:
The rigorous use of this expression is limited to the equilibrium stages, where the internal and external liquid phases in the textile article have identical composition. In the above expression, \( n \) represents the \( n \)th rinsing stage and \( C_n \) the relative concentration in the liquid after dilution, \( C_h \) the concentration in the hank before starting the rinsing, \( V_h \) its volume after draining, and \( V_r \) the volume of rinsing water fed at each stage and then drained after approaching the equilibrium with the impregnation liquid. It can be easily demonstrated that an optimal rinsing is obtained by subdividing the total volume used in the rinsing operation into the largest number \( n \) of evenly distributed volumetric fractions.

![Figure 5. Batch rinsing and concentration profiles in the hank-dyeing equipment](http://www.autexrj.org/No4-2004/0097.pdf)

Batch rinsing is not always used in common practice, because the operation is believed to be more time-consuming than other rinsing techniques. In fact, the apparatus has to be discharged and refilled, and liquid homogeneity must occur. Additional precautions should be taken to discharge hot liquids and proper infrastructures executed in the mill layout; it is probable that a heat exchange network would make heat recovery more efficient at the same time.

Figure 5 provides the results of a batch rinsing after the exhaust dyeing liquor has been unloaded and replaced with clear water up to the weir overflow (D step). The operations required slightly more than 7 minutes; the circulation propeller was then switched on, and the liquid samples were withdrawn from the equipment. This test has shown that prompt liquid homogeneity was attained in nearly two minutes, with the overall operation time being the same as the usual practice. The concentration distribution in the various positions confirms the results of Figures 3 and 4, the “h” (between hanks) zone acts as a bypass, and the “d” volume is demonstrated to be a liquid slow renewal zone.

The features of the three rinsing procedures are summarised in Table 2, where the operation time, the final \( c/c_0 \) value and the water consumption are given. Quite clearly minor operation time differences do not affect the productivity in the mill, while batch rinsing appears to be quite beneficial both in terms of end concentrations of the discharge and water requirements for this specific operation.

<table>
<thead>
<tr>
<th>type of rising</th>
<th>total time, min</th>
<th>final ( c/c_0 ) -</th>
<th>water consumption, ( m^3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>standard rinsing</td>
<td>10</td>
<td>0.10</td>
<td>2.50</td>
</tr>
<tr>
<td>alternative rinsing</td>
<td>9</td>
<td>0.05</td>
<td>1.75</td>
</tr>
<tr>
<td>batch rinsing</td>
<td>10</td>
<td>0.05</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Quality tests on the product confirmed the full applicability of the suggested technique. Similar results were obtained in the 250 kg hank load production machinery.
Experimentation in the production unit

A number of tests were carried out in the 250 kg production unit to obtain a wider experimental knowledge and validate the conclusions obtained from the extensive work that had been carried out on the small unit. A few modifications to the equipment were required; seven sampling probes were inserted in a way similar to the previously described procedure. Figure 6 gives the concentration profiles vs. operation time. All the curves are positioned in a regular order from the bottom (b), to the intermediate sector (b/t), lower hanks (h₂), top of equipment (t₂), lower dead zone (d₁), upper hanks (h₁) and then the upper dead zone (d₂).

The industrial practice requires about 5 minutes of overflow rinsing (A), followed by an interval of continuous rinsing (B) with the liquid circulation being activated by the propeller. In the first step, the bottom compartment is promptly flushed by clean water, while the slowest bath renewal is detected in the upper dead zone d₂. The rather low concentration of the measured property at the t₂ sampling point is an index of some additional by-pass in the equipment; in this instance draining out the whole exhaust liquor again offers the best way to save rinsing water. The maximum in the curves is caused by the propeller mixing action and generated by a more efficient mass transfer from the dead zones.

Purge test

Aside from the usual rinsing operations, the so-called purge of textile materials is a preliminary step to dyeing, and has the main purpose of eliminating dirt or lubricating oils from the yarn. Since this production step is quite water-demanding, the purge rinsing was evaluated by monitoring the concentration profiles during the operation. The purge step has to undergo strict process specifications which require the elimination of any chemical that has been used, in order not to affect the subsequent dyeing; severe pH control is exerted in the case of wool. Figure 7 depicts the salt, COD and NPOC (non-volatile organic carbon) concentration profiles as a function of the rinsing time after the wool hanks have been purged; depending on substance diffusivity, release from the fibrous material shows different promptness, as given in Fig. 7a, b and c respectively. It is quite clear that the technique of draining out the whole exhaust bath would make a noticeable contribution from the water-saving perspective, or the rinsing time could at least be reduced by some 50% with respect to the usual practice, by still maintaining a good margin as far as pH control is concerned.

Mathematical modelling

The schematic view given in Figure 1 shows that the equipment can be subdivided into three zones, whose capacity can be directly derived from geometrical evaluations: Table I provides the values of V₁, V₂ and V₃, which, in order, are the volumetric portion above the hank assembly, the volume of the equipment actually given to the textile material, and the lower chamber where the propeller is located.

http://www.autexrj.org/No4-2004/0097.pdf
In addition, the intermediate portion can be considered as being formed by at least two parts, one of which is taken by the hank load, and another which permits free liquid circulation.

![Graph a](image1.png)

![Graph b](image2.png)

![Graph c](image3.png)

**Figure 7.** Salt, COD, NPOC concentration profiles in the purge rinsing procedure:

- h (hanks), d (dead zone), b (bottom), t (top)

**Figure 8.** Scheme of the model of the hank-dyeing equipment

From a hydrodynamical point of view, the lower and the upper volumes can be considered well mixed, while the intermediate part has a high liquid renewal zone, characterised by a plug flow, and a dead zone portion given by the liquid entrapped by the yarn structure in the hank assembly. These two parts
are interconnected by cross-flow exchange along their vertical coordinate. Only the intermediate volume is considered in the present model. The aim of the model is to describe the dilution without the propeller action (step A) during standard rinsing. The model provides a physical explanation of the mass transfer phenomena and an estimation of the mass transfer coefficient between the dead and the high liquid renewal zones. Figure 8 provides the scheme of the model and illustrates the main hydrodynamical features.

The following definitions are used to describe the different volumetric portions in the equipment:

- volume of the compartment given to the textiles in the equipment: $V_2$;
- active volume considered in the modelling: $V_2 - V_{ha} = V_P + V_D$,
  where: $V_{ha}$ = volume of the hank assembly, i.e. the actual volume taken by the textile material
- $V_P$ = volume of the high liquid renewal zones
- $V_D$ = volume of the dead zones;
- length of the compartment: $L$;
- impurity concentration in the high liquid renewal zones: $c$;
- impurity concentration in the dead zones: $q$;

The model approach (as in reference [5]) is given by two mass balances which are written for the high liquid renewal zone and the dead zone, respectively:

$$\frac{\partial c}{\partial t} = -v \cdot \frac{\partial c}{\partial z} + k \cdot a^* \cdot (q - c) \quad (2)$$

$$\frac{\partial q}{\partial t} = -k \cdot a^* \cdot \phi \cdot (q - c) \quad (3)$$

with: $\phi = \frac{V_P}{V_D} \quad \text{and} \quad v = \frac{F}{V_P}$

where $F$ is the total flow rate, $v$ is the superficial velocity in the high liquid renewal zones, $k$ is the mass transfer coefficient between the dead and the high liquid renewal zones, $a^*$ is the exchange surface that refers to volume $V_P$.

Equations (2) and (3) are modified by introducing dimensionless terms such as:

$$c' = \frac{c}{c_0}, \quad q' = \frac{q}{c_0}, \quad \xi = \frac{z}{L}, \quad N = k a^* \tau, \quad \theta = \frac{t}{\tau}, \quad \tau = \frac{L}{v},$$

$\tau$ being the mean residence time of the liquid in the high liquid renewal zone.

The dimensionless differential equation system becomes:

$$\frac{\partial c'}{\partial \theta} = \frac{\partial c'}{\partial \xi} + N \cdot (q' - c') \quad (4)$$

$$\frac{\partial q'}{\partial \theta} = -N \cdot \phi \cdot (q' - c') \quad (5)$$

where the boundary conditions are chosen as:

$$\xi = 0 \quad \theta > 0 \quad c' = 0, \quad \theta = 0 \quad \forall \xi \quad c' = 1 \quad \text{and} \quad q' = 1$$

The equation system was solved using a finite element method, and it provided $c'$ and $q'$ values as functions of the vertical coordinate. $\phi$ was estimated from experimental hold-up data and the geometry of the system, while $N$ was obtained as an optimisation parameter from the experimental concentration profiles.

Figure 9 gives the calculated profiles of $c'$ vs. the dimensionless time at different elevations in the equipment. Quite obviously, due to the piston component in the flow and the mass exchange from the dead zone, the rinsing effect is delayed by as much as we move to the hank top. The time scale on the abscissa of Figure 9 (and also in the following figures) ranges from 0 to 1.20. In fact, step A during a standard rinsing usually lasts 5 min, while the average residence time $\tau$ is equal to 4.2 min.
A complete comparison between a concentration profile given by the model at Z=0.5 and the experimental data obtained at the mean vertical position between two contiguous hanks (h position in Figure 2) is given in Figure 10 during the rinsing time for concentration profiles at different axial positions in the machine.

The second model output is given by the q' profiles at different positions. Two curves at the extremes of the hank assembly are presented in Figure 11: the profiles vs. time are rather delayed compared to the corresponding concentrations in the high renewal zone (Figures 9 and 10). The measurements reported in Figure 11 were obtained at the end of rinsing from a batch mode experimentation: the liquid that impregnates one hank was extracted in order to establish the impurity concentration, and the measurement therefore represents a mean value along the axial coordinate.
The N value predicted through model optimisation according to the experimental data leads to a \((ka^*)_{opt}\) value equal to 0.01 min\(^{-1}\). The mass transfer coefficient defines the rate of exchange between the dead and the high liquid renewal zones, thus representing a very important hydrodynamic parameter. Its value was then checked through an experimental estimation, and \((ka^*)_{exp}\) was found from the simple expression:

\[
(ka^*)_exp = \frac{Q}{(V_p \cdot \Delta c)}
\]  

(6)

where Q is the colour or salt flow rate transferred between the dead and the high liquid renewal zones; \(\Delta c\) is the mean driving force between the dead and the high liquid renewal zones. Q and \(\Delta c\) were calculated from experimental concentration profiles, the dead zone volume and the total rinsing time (T) as follows:

\[
Q = (q_0 - q_{fin}) \frac{V_D}{T}
\]  

(7)

\[
\Delta c = q_{mean} - c_{mean}
\]  

(8)

As explained in the experimental section, the dead zone concentrations can be measured batchwise; this allows the values before \((q_0 = c_0)\) and after rinsing \((q_{fin})\) to be known, as well as the mean concentration value \((q_{mean})\). The mean concentration \((c_{mean})\) in the high liquid renewal zones can also be evaluated from experimental profiles obtained from on-line sampling; all the mean concentration values were averaged with respect to both time and space.

\((ka^*)_{exp}\) was found to be equal to 0.0237 min\(^{-1}\), more than twice the value of \((ka^*)_{opt}\). The agreement is satisfactory if we consider that the experimental evaluation was carried out by averaging over space and time. Moreover, the results confirmed that the model is quite robust and reliable due to its simple structure.

**Conclusions**

This research project started as an investigation to promote sound criteria for water saving in high demanding water apparatuses both due to their design structure and to a consolidated industrial practice. The final quality of the products has led to avoiding any overuse of this important natural resource being neglected, and has to some extent hindered the systematic evaluation of equipment performances. From this point of view, this study has highlighted the tangible possibility of saving up to 50% of process water, while guaranteeing a very high dyed product standard at the same time.
The research, carried out on two different-sized units of equipment, can probably be considered an unusual experimentation on an interesting industrial scale, and the results obtained can be considered useful for other operators in the field. At the same time, hank-dyeing equipments have received an insightful evaluation regarding their hydraulic behaviour, thanks to the measurement of the concentration profiles of dyes, salt, acids and auxiliary organic substances during the dynamic rinsing step. Such an approach, which is typical of chemical engineering, offers new scientific information on a standard piece of equipment. The concentration profile evaluation has proved to be a powerful tool for suggesting new rinsing methods, and therefore for saving water.

A mathematical model has been presented to validate the phenomenological description of the equipment; the very good agreement with the experimental data proves the initial hypotheses and soundness of the model.

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