A Novel High Temperature and High Pressure Yarn Dyeing Machine with Ultra-Low Liquor Ratio

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Abstract — In recent years great many novel technologies have been investigated to improve the production efficiency and reduce the pollution and energy consumption of dyeing machines. However, these new methods are still unavailable for industry. It is known that ultra-low liquor ratio dyeing machine based on mature technology can effectively reduce pollution and energy consumption. In this paper, an ultra-low liquor ratio yarn dyeing machine is developed. The dyeing machine adopts non-immersing dyeing mechanism involving a special pump and pulsating current control system. A prototype was set up to validate the dyeing machine. Experiments show that this 1:3 liquor ratio dyeing machine has a minimum dyeing time of 2 hours and saves 33.3% dyeing time comparing to traditional one.

Keywords - Ultra-low liquor ratio; Dyeing machine; pulsating current

I. INTRODUCTION

Dyeing is a traditional industry that is notorious for its high pollution, high energy consumption and high water consumption. It is reported that more than 40% of dyeing production comes from China where high pollution and energy consumption but low production efficiency dyeing machines are dominant. A typical dyeing machine immerses the yarn in a large amount of dyeing liquor. In this investigation, dyeing liquor is directly sprayed on the yarn, which aims at reducing the liquor ratio so that it can cut down the pollution, water and energy consumption.

In recent years great efforts have been made to improve the production efficiency and reduce the pollution and energy consumption of dyeing machine. All kinds of new methods are utilized such as supercritical carbon dioxide [1,2], ultrasonic washing [3,4], electrochemical techniques [5], radiant energy techniques [6], etc. Unfortunately, these novel methods are still available in lab instead of the industry though great progress has been made. In order to turn around the high pollution and energy consumption situation in dyeing industry as soon as possible, less water technology has been developed, including cold-pad-batch dyeing[7,8], low liquor ratio[10], etc. Comparing to other methods, low liquor ratio dyeing machine can be easily built with mature technology and applied to the industry faster.

II. DESIGN OF THE YARN DYEING MACHINE

A typical dyeing machine with high liquor ratio usually involves in immersing yarn in the water, which brings many environmental problems such as high water, energy consumption, low efficiency, etc. The proposed dyeing machine, however, directly sprays the dye on yarn without soaking it in dyeing liquor. As shown in Fig.1, the dyeing machine consists of poriferous creels, creel base and an increased level 3 impeller pump (highlighted in red dashed rectangle). The creels are hollow and poriferous, mounted in a creel base which contains liquid circulation channels connected with the dye vat. The level 3 impeller pump driven by inverter motor is fixed under the dye vat likewise connected with the creel base through an oviduct (highlighted in green dashed rectangle). As a connecting channel of pump and vat, properly designed oviduct can decrease the liquor ratio for less liquor staying in circulation channel. The creels are hollow and poriferous, mounted in a creel base which contains liquid circulation channels connected with the dye vat. The level 3 impeller pump driven by inverter motor is fixed under the dye vat likewise connected with the creel base through an oviduct (highlighted in green dashed rectangle). As a connecting channel of pump and vat, properly designed oviduct can decrease the liquor ratio for less liquor staying in circulation channel. The 3D model of oviduct is shown in Fig. 2. There are dual independent cavities in the oviduct serving as inflow channel and outflow channel. An insolation board is utilized to insulate the two channels. The inflow channel is connected with the exit of pump directly and outflow channel is connected with the entrance of pump. To ensure the continue working of pump, a storage is designed to store the liquor flowing back to the pump. For the compact structure of oviduct, an ultra-low liquor ratio of dyeing machine can be achieved. Besides, these simple structure can be easily manufactured at low cost.
When the dyeing machine is working, the flow of dyeing liquor is divided into two processes: the flow from pump to vat and flow from vat to pump, which is indicated both in Fig.1 and Fig.2, respectively with solid arrow and dashed arrow. In the first process, the inverter motor drives the impellers of the pump to rotate at a high speed and dye liquor is then forced to flow into inflow channel of the oviduct from pump. After flowing through the channels of the creel base and creels, dye liquor sprays on yarn twined around the creels and penetrates it rapidly. During the jet, dyeing compound is absorbed by yarn and then dye liquor flow into the vat. In the second process, the dye liquor freely flows to the storage through outflow channel, and then pumped into the level 3 impeller pump. Different from the fact that traditional dyeing machine usually soaks the yarn in water, the dye liquor of this novel one doesn’t stay in vat and soon flow into pump through the channels in creel base and outflow channel of the oviduct. Thus, a lower liquor ratio can be attained by this dyeing circulation.

To increase the dyeing machine’s performance, some special designs have been adopted. A water-filled drum is ebbed in the hollow of creel, decreasing the dye liquor occupied space so as to lower the liquor ratio. Generally speaking, the pressure of dye liquor decreases as height increases. Uniform distribution of holes in creels may leads to uneven dye because pressure has significant influence on dyeing. Therefore, more holes lies on higher position of the creels. Additionally, the creels is made of smooth-faced plastic, which reduces fluid resistance loss and eventually improves the energy efficiency.

The pump of ultra-low liquor ratio dyeing machine should possesses high head and high capacity. If the head is too low, dye liquor is not able to penetrate the yarn. On the contrary, excessively high head goes against energy-saving performance. So an appropriate head of pump is required. However, when the liquor ratio is rated to be 1:3, a traditional pump is hardly satisfied the requirements. A single axial pump has high capacity and low head while the centrifugal pump is opposite. Nevertheless, neither axial pump nor centrifugal pump is capable of ultra-low liquor ratio dyeing machine. Hence, a special level 3 impeller pump has been developed. The pump is composed of axial level, centrifugal lever and fixed flow deflectors and the impellers of the first two levels are coaxially mounted in the same shaft (Fig. 3). This level 3 pump can be considered as the combination of axial pump and centrifugal pump so that it owns all the advantages (high head and high capacity) of both pumps. When the inverter motor drives the pump, dye liquor flow into the axial level through the entrance of pump and directly flow into the centrifugal lever after flowing out of the former level. Meanwhile the axial level serves as inhaling amount of liquor and primarily raising the head. The centrifugal impellers continue to raise the head to a rated level. The flowing direction of liquor in axial level is parallel to the axis of shaft, and then converted to tangent direction by centrifugal impellers. The pressure distribution of the dye
liquor flowing out of centrifugal level is non-uniform and the flow is rotational. In order to change the pressure distribution and flow direction, the flow deflectors are fixed in the entrance of centrifugal level, serving as the third level of pump. For the 45° installation angle between deflectors and flow direction, the dye liquor is turned into directional current and flow into the inflow channel of oviduct. Comparing with a traditional pump, this level 3 impeller pump has higher head and capacity due to its combination of dual kinds of pumps.

![Fig. 3. Details of level 3 impeller pump.](image)

### III. THEORETICAL ANALYSIS OF DYEING CIRCLE

The minimum dyeing time and levelness play important roles in dyeing performance. Thus, the optimization of minimum dyeing time and levelness will be obtained. For an inverter motor, the output rotational speed $n$ is proportional to its frequency $f$, which can be expressed as the following equation.

$$n = k_1 f$$  \hspace{1cm} (1)$$

Where $k_1$ is constant factor for a certain motor. Similarly, the capacity $Q$ and head $h$ of the pump are also proportional to the rotational speed $n$ and its square $n^2$, respectively, i.e.:

$$Q = k_2 n = K_1 f$$  \hspace{1cm} (2)$$

$$h = k_3 n^2 = K_2 f^2$$  \hspace{1cm} (3)$$

Where $k_2$, $k_3$ is constant factor and $K_1 = k_1 k_2$, $K_2 = k_1 k_3$. Eq.(1) and (2) reveal a fact that the capacity and head can be adjusted by tuning the frequency of motor. Furthermore, the liquor ratio $\eta$ is defined by the ratio of the whole weight of dyeing liquor $M$ and yarn $m$, which can be written as:

$$\eta = \frac{M}{m}$$  \hspace{1cm} (4)$$

To estimate the dyeing time, the circulation frequency $k$ and dyeing rate per minute $D$ are necessarily acquired. The circulation frequency $k$ can be defined as:

$$k = \frac{\rho Q}{M}$$  \hspace{1cm} (5)$$

Where $\rho$ is the density of dyeing liquor and considered to be approximately equal to the density of water. According to the definition of rate flow $q$ (the ratio of capacity $Q$ and weight of yarn $m$) and liquor ratio, Eq. 5 can be rewritten as:

$$k = \frac{\rho q}{\eta}$$  \hspace{1cm} (5a)$$

The dye exhaustion rate per minute $D$ is proportional to circulation frequency, and it can be determined by the following expression.

$$D = \mu k \times 100\% = \frac{\mu \rho q}{\eta} \times 100\%$$  \hspace{1cm} (6)$$

Where $\mu$ is constant. If the circulation frequency $k$, as well as dye exhaustion rate per minute $D$, have been given, the dyeing time $t$ can be estimated by the following expression:

$$t = \frac{100}{D} \cdot \frac{1}{k} = 100 \left( \frac{\eta q}{\rho} \right)^2$$  \hspace{1cm} (7)$$

Eq. 7 provides two possible ways to minimize the dyeing time. On one hand, a lower liquor can lead to a shorter dyeing time. On the other hand, to hasten the dyeing process, a larger rate flow is required. However, considering that the liquor ratio is usually fixed according to the dyeing process, the only method left to reduce the dyeing time is maximizing the rate flow $q$. Substitute Eq.(2) to the expression of dyeing time, Eq.7 can be rewritten as:

$$t = \frac{\beta}{f^2}$$  \hspace{1cm} (7a)$$

Where $\beta = \frac{100 \rho^2 m^2}{\rho h_k^2}$. Assume that $\beta = 19000 \ h/Hz$, Fig.4 shows the relationship between dyeing time and frequency. From Fig.4, by increasing the motor frequency, a minimum dyeing time can be achieved.
Levelness is the other parameter that can be optimized by tuning the rate flow. To evaluate the levelness of dyeing, volume exchange rate is adopted. According to volume exchanging law, volume exchange rate $NL$ is defined as the multiply of circulation frequency and ratio of effective volume and whole volume, which is expressed as:

$$NL = k \frac{V_e}{V} \times 100\% = \frac{V_e}{V} \frac{\rho q}{\eta} \times 100\% \quad (8)$$

Where $V_e$ is the effective volume occupied by yarn and $V$ is the whole volume of dyeing liquor. From Eq. (8), the volume exchange rate is also related to the rate flow. That is, the larger volume exchange rate, the better levelness for other variables are usually constant. Therefore, it is better to increase the rate flow in order to improve the levelness performance. Substitute Eq.(2) to the expression of volume exchange rate, Equ.8 can be rewritten as:

$$NL = \gamma f \quad (8a)$$

Where $\gamma = \frac{K_1 \rho V_e}{V \eta}$. Fig.5 shows that the volume exchange rate goes up with frequency linearly.

Seemly, it is an effective way to obtain a higher performance of dyeing time and levelness through maximizing the rate flow, i.e., maximizing the motor frequency. It should be kept in mind that, however, a higher frequency would result in extremely high head of the pump from Eq.(3). Though high head is beneficial to dyeing levelness, excessive head may fractures the yarn and increase the energy consumption. So an appropriate head is chosen by experiments on the basis of different kinds of yarn. For given head $h'$ based on a certain kind of yarn, a maximum motor frequency can be solved by Eq.(3):

$$f = \sqrt{\frac{h'}{K_2}} \quad (9)$$

Thus, the optimized dyeing time and levelness can be achieved by substituting Eq.(9) to Eq.(7a) and Eq.(8a), respectively.

IV. CONTROL SYSTEM OF PULSATING CURRENT DYEING

Section 3 suggests that better levelness benefits from larger rate flow. Unfortunately, since the output power of motor is proportional to the cubic frequency, more energy consumption would occur if the dyeing current is steady and motor keeps working under the condition of maximum frequency. Additionally, working under full load may shorten the life of motor. Therefore, a pulsating current dyeing control system has been proposed. As shown in Fig.6, the signal generator sends pulse signal to comparator and the error signal is later sent to the PLC after the pulse signal compares with the feedback signal in comparator. After processing the error signal, the PLC sends data to the inverter. And then the inverter change the frequency of motor, which finally changes the rate flow and head of the impeller pump. In this close loop system, the controlled objective is the head of pump. Thus, a sensor is mounted in the exit of the pump for detecting the output head of the
pump. The output electrical signal of sensor will be sent to the comparator as feedback signal after A/D conversion.

As shown in Fig. 7, a circle of pulsating current includes four periods: 1) ascending period (0 to t1); 2) steady period (t1 to t2); 3) descending period (t2 to t3); 4) resting period (t3 to t4). During the first period, the rate flow increases rapidly along with the motor’s frequency goes up. When the head of pump is raised to a rated value which can be detected by the sensor, the frequency begins to keep constant and last for a certain time, i.e., the steady period. After the second period, the frequency turns into a low value linearly so that the impellers of the pump decelerates. In the last period, the frequency remains to be low so that the dyeing liquor is pumped back from the vat. In this circle, it is only the steady period that plays an effective role in dyeing. Thus, it is better to shorten and extend However, the last period is still essential because the liquor ratio is ultra-low and it takes some time for the liquor flowing back to the pump from vat.

Assume that the dyeing time of a substitutional dyeing method adopting steady current is \( t' \), while it takes the pulsating current dyeing \( t \) to complete the dyeing. If equivalent levelness of dyeing is required, the integrals of these two methods’ volume exchange rate in a circle are also equal. Considering the dyeing liquor only flows through the yarn during steady period, the rate flow of pump in ascending and descending period will not be figured in. So the following equation is obtained.

\[
\int_0^T N_{\text{steady}} \, dt = \int_0^T N_{\text{pulsate}} \, dt \tag{10}
\]

i.e.:

\[
\frac{f_{\text{steady}} \, \alpha \, \frac{t-\alpha}{T}}{f_{\text{pulsate}} \, \alpha} \tag{10a}
\]

\[
\frac{f_{\text{steady}}}{f_{\text{pulsate}}} \tag{10b}
\]

Where \( \alpha = \frac{t_2 - t_1}{T} \). Substituting Eq.(10b) to Eq. (8a), the dyeing time of these two methods can be solved.

\[
t' = \frac{\beta}{\frac{f_{\text{steady}}^2}{f_{\text{pulsate}}^2}} > t = \frac{\beta}{\frac{f_{\text{pulsate}}^2}{f_{\text{pulsate}}^2}} \tag{11}
\]

From Eq.(11), pulsating current dyeing performs better than steady current dyeing in time-saving under the condition of equivalent levelness. In fact, the head of pump can only achieve the rated value when it stays in the steady period. Since \( f_{\text{steady}} < f_{\text{pulsate}} \), the pump may not reaches enough head to penetrate the yarn, which brings the problem of uneven dyeing. Thus, pulsating current dyeing also performs better than steady current dyeing in even dyeing.

V. EXPERIMENTS

A prototype of the above-discussed dyeing machine was made to validate the dyeing performance including dyeing time, dyeing levelness, energy consumption, etc. The prototype has ultra-low liquor ratio of 1:3 and minimum dyeing time of 2 hours. Comparing to traditional machine, this novel machine has an improved efficiency of 33.3% in time.

During the experiments, the dyeing time and levelness of a same kind of yarn are tested under the conditions of different motor frequency. The dyeing time and levelness are measured by timer and spectrophotometer [10], respectively. The smaller the reflectivity variation coefficient (RVC) shown by spectrophotometer, the better levelness. Tab. shows the testing data and shows the dyeing time and levelness with respect to motor frequency. From the data, the
dyeing time and the value of reflectivity variation coefficient both decrease when the frequency increases.

Table 1. Testing data

<table>
<thead>
<tr>
<th>Frequency(Hz)</th>
<th>Dyeing time (h)</th>
<th>RVC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>5.6</td>
<td>3.41</td>
</tr>
<tr>
<td>70</td>
<td>4.1</td>
<td>2.05</td>
</tr>
<tr>
<td>80</td>
<td>3.3</td>
<td>1.67</td>
</tr>
<tr>
<td>90</td>
<td>2.6</td>
<td>1.13</td>
</tr>
<tr>
<td>100</td>
<td>2.0</td>
<td>0.73</td>
</tr>
</tbody>
</table>

Fig. 7. Dyeing time and RVC with respect to frequency

VI. CONCLUSIONS

Base on the above discussions, the following conclusions can be made.

(1) A novel yarn dyeing machine with ultra-low liquor ratio is developed to improve the performances by using a non-immersed dyeing mechanism that involves a special pump and pulsating current control system.

(2) The dyeing circle and pulsating current control system was analyzed and optimized, which gives the optimized parameters for enhancing the time-saving and dyeing levelness performances.

(3) A prototype was built to test. Experiments show that the minimum dyeing time is 2 hours under a liquor ratio of 1:3 and the machine saves 33.3% dyeing time.

REFERENCES


