Study on optimum temperature value setting for the heat-setting process based on PSO

Minnig Gu
Institute of Automation, Faculty of Mechanical Engineering and Automation, Zhejiang Sci-Tech University, No.928, Second Avenue, Xiasha Higher Education Zone, Hangzhou 310019, China

Corresponding email: Guminming@163.com

Abstract. Based on a mechanism model of the temperature of fabric, this paper discussed the optimum temperature value setting in a heat-setting process using Particle Swarm Optimization (PSO) algorithm. First, a mathematical modeling method was developed from energy balances, then, a PSO algorithm was employed to optimize the temperature setting value of each chamber. The experimental results have shown a good agreement with the proposed model. The obtained load parameters lead to a lower energy consumption strategy of the heat-setting according to the technological requirements.

1 Introduction
Heat-setting is a thermal and mechanical process to guarantee size accuracy and dimensional stability for textile materials. Textile construction causes constraints on the textile. Constraints occur due to the arrangement of dipole links and hydrogen bonds, as well as crystallisation and chain stiffness. During the heat-setting process, these inner constraints are rearranged. Thus the shape of the textile is changed, resilience and elasticity are improved. It also brings changes in strength, stretch ability, softness, dye ability and sometimes on the color of the material [1]. The important process parameters are temperature, dwell time, width and overfeed. These values have a great influence on the performance of fabric. Many studies on the relationship among them have been undertaken by numerous of experiments [2-5]. But they all focused on the qualitative analysis and lacks of precise mathematical model. A more detailed investigation of the fabric of such processes is still required.

Mathematical modeling of the heat-setting behavior of textile materials is vital because it can reduce costs due to quality constraints [6]. It can also be used to control process and optimize the operating conditions [7]. Many studies are available in the literature concerning the investigation of heat-setting or heat and mass transfer mechanisms in textile fibers [8-11], but only a few of them are concerned with heat-setting process occurred in stenter. In addition, Zhang et al. [12] proposed a model from energy balances, analyzed the dynamic relationship among hot air temperature, flux and temperature of heat transfer oil, flux of air. By using the finite element method, the model of drying of cotton fabric in a stenter has been presented in [13], and the influence of ambient conditions on the performance of the stenter was also investigated. Then, moisture and temperature profiles were calculated and it was observed that the model represented the real process adequately. Ren and Zhou [14] established energy consumption model of heat-setting process, and proposed an improved Multi-Constrained Condition Adaptive Genetic Algorithm (MCC_AGA). The simulation results of real
industrial data showed the suggested MCC AGA algorithm has faster and better optimization performances. But the temperature model of fabric is still not mentioned.

In this context, the application of a mathematical model, which can contribute knowledge of the stenter, is a very useful strategy. The aim of this paper was to model and mathematically simulate the temperature of fabric in the heat-setting process, and to validate the model by comparing with experimental data. Furthermore, optimization of the chambers’ setting temperature value is established by PSO algorithm based on this model.

2 Problem Statement

The heat-setting process taken place in the stenter was shown schematically in Figure 1, which basically consists of several chambers, progressive structure, falling cloth structure.

![Figure 1. Schematic view of the stenter](image)

The heat Exchange Process is mainly concentrated in the chambers. First, the air in the chamber is directed to the heat-exchanger by a centrifugal fan. Then, the hot air jets onto the fabric through the nozzles. It can be represented in Figure 2.

![Figure 2. Schematic of air flow in stenter](image)

As seen in the figure2, the fabric is heated in the chamber, the process is complicated. Heat-conduction, convective heat transfer, radiative heat transfer, these three kinds of heat transfer forms coexist. However, the temperature of the fabric is mainly affected by the impact of jet convective heat transfer. Because the fabric itself is thin, so it can be considered that there is no temperature difference in the longitudinal. When the surface temperature changes, in the thickness of the direction, they have the same changes happened.

In order to obtain the model, this paper makes the following assumptions:

• Assumption 1. Suppose the air in the stenter is dry.
• Assumption 2. Suppose the fabric is dry without water evaporation.
• Assumption 3. Suppose the fabric is uniformly heated.
• Assumption 4. Suppose the flow and speed of air stays the same.

Here we now can write the energy balance equations for the above system. So the increment of internal enthalpy of fabric is equal to that of hot air carry on the heat transfer to the fabric.

\[
\Phi(\tau) = h(\tau)\Delta S[T_w(\tau) - T(\tau)] = \rho c_p \Delta V \frac{dT}{d\tau}
\]  \hspace{1cm} (1)

Here, \(\Delta S\) is the unit fabric heat exchange area, \(\Phi(\tau)\) is heat transfer through a certain area in a unit time, \(h(\tau)\) is coefficient of heat transmission, \(T_w(\tau)\) is the temperature of fabric after time \(\tau\). \(\rho\) is density.
of the fabric, \( c_p \) is specific heat capacity, \( \Delta V \) is the unit fabric heat exchange volume, let \( \Delta V / \Delta S = \delta \), here \( \delta \) is the thickness of fabric.

By mathematical transformation, the temperature of the fabric can be shown as follows:

\[
T(\tau) = T_w(\tau) - \exp(-\frac{h(\tau)}{\rho c_p \delta} \tau)(T_w - T_{w0}) \tag{2}
\]

Where boundary temperature \( T_w(\tau) \) can be written as:

\[
T_w(\tau) \approx \frac{T_{aw}(\tau) + T(\tau)}{2} \tag{3}
\]

The temperature of the fabric can also be written as follows:

\[
T(\tau) = T_{aw}(\tau) - \exp[-\frac{h(\tau)}{\rho c_p \delta} \tau](T_{aw0} - T_0) \tag{4}
\]

3 Optimization of setting value

3.1 Basic PSO algorithm

The PSO algorithm is a heuristic optimization method that searches an entire solution space by starting from randomly distributed particles such as swarm, it is widely used in real optimizing problems.

It uses a number of agents (particles) that constitute a swarm moving around in the search space looking for the best solution. Each particle in search space adjusts its “flying” according to its own flying experience as well as the flying experience of other particles. Each particle has two attributes: its current position and velocity. Each particle moves towards a promising area to get the personal optimum called \( P_{best} \), and will share with its colleagues, the best value of any particle called global best: \( G_{best} \). Each particle adjusts its travelling speed and modifies its position dynamically according to its current position, current velocity, \( P_{best}, G_{best} \). The algorithm is terminated after a given number of iterations, or once the fitness values of the particles are close enough in some sense.

3.2 Optimization problem of heat setting

During the heat-setting process, the largest energy consumption occurs in air heating. When the process time is fixed, the energy consumption can be significantly reduced by Reducing chamber setting temperature according to follow formula.

\[
Q_{air} = c_{air} m_{air} \times (\Delta T_{air}) \tag{5}
\]

Where \( Q_{air} \) is the heat of heating of fresh air. \( c_{air} \) is the heat capacity of hot air, \( m_{air} \) is the mass of hot air, \( \Delta T_{air} \) is the thermal increment of hot air in the stenter chamber.

Form 100°C to 140°C, \( c_{air} \) changes little, and the density of the hot air has no obvious changes. When stenter works, the flow of the hot air and the speed of fabric also keep steady, so mass of air change very little at different times.

The the optimization problem in heat setting process discussed in this paper is to minimize sum of each chamber setting value\(^{13}\).

3.3 A case study

The fabric discussed in this paper called Super Cotton-Like PET fabric, which has good wearable and in some respects even better than cotton fabrics. Its recommended setting temperature is 140°C, the time of heat setting is about 40 second\(^{10}\). The stenter used is called Glotech Platinum, which has 10 chambers, the length of each chamber is 3m. The speed was set to 20 m/min.

In order to meet the requirement of heat setting, the final 5 chambers temperature can be set to 140°C. And the temperature should be close to 140°C at the end of the 5th chamber.

When the fabric do the heat-setting in the stenter, its temperature can be represented as:
\[ y_i = X_i - \exp\left(-\frac{h(\tau)}{\rho c_p \delta} \tau\right)(X_i - y_{i+1}) \]  

(6)

Where \( X_i \) is the temperature of each chamber, \( y_i \) is the fabric temperature at the end of chamber \( i \) (\( i=1,2,3,4,5 \)). Here \( -\frac{h(\tau)}{\rho c_p \delta} = -1.25 \) , it can be obtained by experiments, when the fabric go through one chamber at speed 2.5 min/min, \( \tau = 9 \) s.

So, the optimization problem can be described as following:

Minimize \[ \sum_{i=1}^{5} X_i \]  

(7)

Here number 5 represent 5 chambers setting value in the stenter could be Optimized.

The following constraints are used:

\[ 30 < X_i < 160 \quad (i=1,2,..5) \]  

(8)

\[ 140 - y_5 < 3 \]  

(9)

The PSO algorithm is adopted. It Create a population of agents (particles) uniformly distributed over \( X \) within a certain range from 30 to 160 which Initial population numbers were 800. The Maximum Iterations were limited to 1000.

Optimal results can be obtained by MATLAB as follow:

| Item | \( X_1 \) | \( X_2 \) | \( X_3 \) | \( X_4 \) | \( X_5 \) |
|------|------|------|------|------|------|
| Optimized Result | 34  | 59  | 78  | 131  | 149  |

Comparative results of fabric temperature was shown in Figure 5. The solid line in the figure represents the fabric temperature simulate value using mathematical model using PSO, and the dashed line is representative of the fabric temperature where all chambers setting value were 140°C. It can be seen that both of the value can reach heat-setting process requirements from Figure 3.

**Figure 3.** The fabric temperature comparison between optimized and original

Comparison between fabric simulation value and actual value was shown in Figure 4. The dot represents the actual sample value obtained by equipment \(^{[14]}\), obtained the same conclusion with simulation results.
Figure 4. The fabric temperature comparison between simulation and sample data

Comparative results of chamber setting temperature was shown in Figure 5. It is also come out that optimized the sum of temperature set value by PSO is much lower than that of Original setting value, which means less energy is required.

Figure 5. The curves using PSO and original

4 Conclusions.
This paper has presented a model for estimation temperature of the fabric in heat-setting process. An Optimization has been made using PSO for the model, new optimal set value of each chamber can reduce the energy consumption significantly. It can be concluded that the present model and PSO algorithm appears to be a significant tool for optimization of heat-setting processes.

In the coming research, multivariate variables, such as fabric speed, fan speed and environment temperature will be considered and the optimum value will be more reasonable.

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