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Color Prediction Model of Gray Hybrid Multifilament Fabric

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Abstract: To facilitate the product design of hybrid multifilament fabric prior to spinning, a color prediction model was proposed. The monofilaments in the multifilament were assumed to have a square cross-section and stacked vertically. The prediction model considered the reflectance, transmittance and arrangement of the monofilaments in the fabric. To test the reflectance and transmittance of the monofilament with the Datacolor spectrophotometer, films with the same material and thickness as the monofilaments were made. Twenty kinds of multifilaments with different blending ratios and fineness were produced and woven into fabrics. The color difference between the fabric color tested by the spectrophotometer and predicted by the new model and classical Kubelka-Munk (K-M) theory was calculated and compared. The result shows that the average color difference obtained by the new model was 1.02 Color Measurement Committee (CMC) (2 : 1) units, which was less than that of 1.78 CMC (2 : 1) units obtained by the K-M theory. Through Spearman correlation analysis, the fabric lightness and the multifilament fineness had a significant influence on calculated color difference, and the color difference decreased with increases of them. Finally, the surface color of a fabric was reproduced, indicating the model can be used to characterize the phenomenon of uneven color mixing on the fabric surface.

Key words: textile multifilament, reflectance, prediction model, color reproduction, multilayer film
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0 Introduction

To produce colored multifilament more easily and reduce the waste in the process of dope dyeing, a novel method for forming color multifilament (named hybrid multifilament) was proposed[1-2]. This method is to directly dye the monofilaments into different colors according to different ratios, and then mix them in different arrangements. Since the monofilament is very fine, it is difficult to distinguish the color difference between monofilaments at normal viewing distance[3-4]. Therefore, using this method, it is possible to produce multifilament with only a few kinds of colored monofilaments. However, this technology still adopts trial-and-error spinning for proofing at present, which is time-consuming and laborious. Therefore, it is desired to propose a model to predict and visualize the surface color of the hybrid multifilament and its blends during product design.

In the field of textile fiber color matching, the most common color prediction models are the Stearns-Noechel (S-N) model[5], Friele (F) model[6] and Kubelka-Munk (K-M) theory[7]. Many scholars have done research on the determination of parameters in S-N model and F model, or the improvement of prediction accuracy of these models. Yang et al.[8] compared different methods of solving unknown parameters in the S-N model. Hemingray and Westland[9], Furferi et al.[10], Shen et al.[11] combined S-N model, F model and K-M theory with artificial neural network to improve calculation accuracy. Wei et al.[12] modified the transfer function of the F model. But the S-N model and the F model are empirical models. To determine the unknown parameters in these models, more samples are generally required. While, the K-M theory is a theoretical model based on the absorption and scattering characteristics of the fibers. In the case of fewer samples, the absorption coefficient and scattering coefficient of the fiber can also be calculated. Besides, the accuracy of the K-M theory is higher than that of S-N model and F model[13]. However, it should be noted that these models above discussed consider that the fibers in the

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blends are uniformly mixed, and do not care the arrangement of internal fibers. For the multifilament, the color of the longitudinal surface at different positions has a strong relationship with the color, number and arrangement of the internal monofilaments. Therefore, these models cannot be used to simulate the uneven color mixing on the mixture surface.

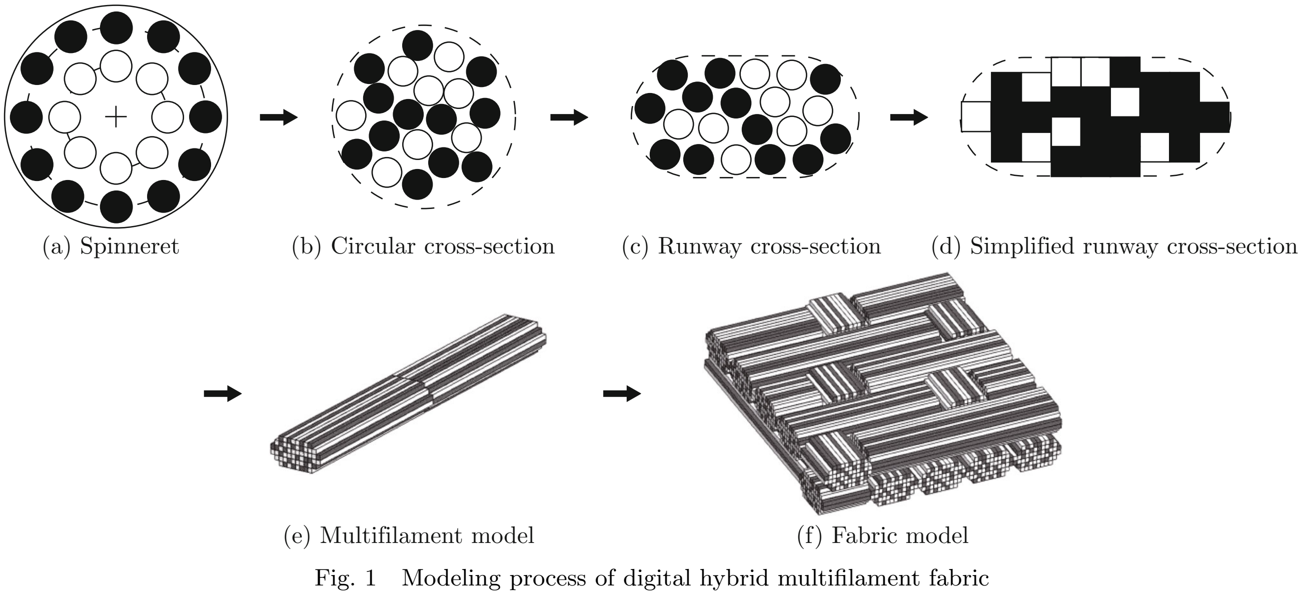
If the fiber arrangement inside their mixture is regarded as similar to the film arrangement in their superposition, the mixed color of the fibers can be obtained through the propagation of light. On the color prediction model of layered films, there are a number of papers. Hirayama et al.[14-15] regarded the multilayer films as a single input-output system. Then the composite reflectance and transmittance of the multilayer film system were calculated from the reflectance and transmittance of each boundary between films. The classical iterative algorithm was used in the calculation process, which is relatively easy to understand. The films are in optical contact with each other, so there are more complicated optical phenomena such as phase difference, interference and diffraction. However, the monofilaments are simply close to each other and in non-optical contact. The light propagation is not the same as that in multilayer films system. In Refs. [16-17], two-flux and four-flux matrix models to calculate the reflectance and transmittance of multilayer specimens were proposed. These models are applicable to all multilayer specimens comprising nonscattering and strongly scattering layers, and can predict the reflectance and transmittance of the layered stack irradiated by collimated and diffuse beams. However, the model consisted of many parameters, which requires a lot of mathematical knowledge to understand.

In the summary, to predict the mixed color and simulate the uneven surface mixing of the hybrid multifilament and its mixture, a new color prediction method still needs to be proposed. Although some research has been done on the color mixing model of the hybrid multifilament[18-19], the effectiveness of the prediction model still needs to be further optimized and verified. The research content of this paper mainly includes: simulating multifilament and its fabric, proposing a color prediction model, verifying and analyzing the effect of the prediction model, and reproducing the color of the fabric surface.

1 Methodology

1.1 Digital Hybrid Multifilament Fabric Model

There are many ways to arrange the monofilaments in the spinneret [20], while the concentric arrangement is the most common one (Fig. 1(a)). The monofilaments spun from the spinneret will randomly transfer internally and externally when they cohere a multifilament. Therefore, the monofilaments arrangement in the multifilament was considered to be random (Fig. 1(b)). The circular cross-section multifilament will be squashed during the weaving process. There are many flattened cross-sectional models of the multifilament. Here, the runway type was selected as the cross-sectional shape of the flattened multifilament (Fig. 1(c)). In some cases, to enhance the yarn spinnability, the multifilament is plied. This does not affect the model use. It is just the total number of monofilaments in the multifilament increases. Considering that the light propagation between monofilaments with circular cross-section is too complex[21], the monofilament cross-section was simplified to be square. Besides, for the calculation convenience, the monofilaments were considered to be vertically distributed in the multifilament (Fig. 1(d)). The monofilament transfer in the multifilament occurs in


(a) Spinneret (b) Circular cross-section (c) Runway cross-section (d) Simplified runway cross-section

(e) Multifilament model (f) Fabric model

Fig. 1 Modeling process of digital hybrid multifilament fabric the whole multifilament, so the monofilaments arrangement in different cross-sections of the multifilament along the length direction is different. To simulate this phenomenon, assume that the monofilaments arrangement in the multifilament remained unchanged within a certain length, and then was rearranged (Fig. 1(e)). The final fabric model (Fig. 1(f)) was based on the simplified flattened multifilament model, but the voids and buckling between the warp and weft yarns were ignored. The digital model of hybrid multifilament fabric was established by using MATLAB software. First, according to the number, fineness and blending ratio of the monofilament in the multifilament, the monofilament distribution in the flattened multifilament (Fig. 1(d)) is calculated. Then, different numbers are used to represent the monofilament with different colors to form the distribution matrix of the monofilament in the cross-section of the multifilament. By stacking multiple cross-sections together, a multifilament can be formed. Then another random distribution matrix of monofilament in the cross-section of multifilament is generated, and another section of multifilament can be obtained by repeating the previous process. After that, different multifilament segments are put together to get a multifilament, and different multifilaments are laid together to form warp and weft layers. Finally, according to the fabric structure to adjust the position of the warp and weft yarns at the weaving point, the final digital model of the original color matching yarn can be obtained.

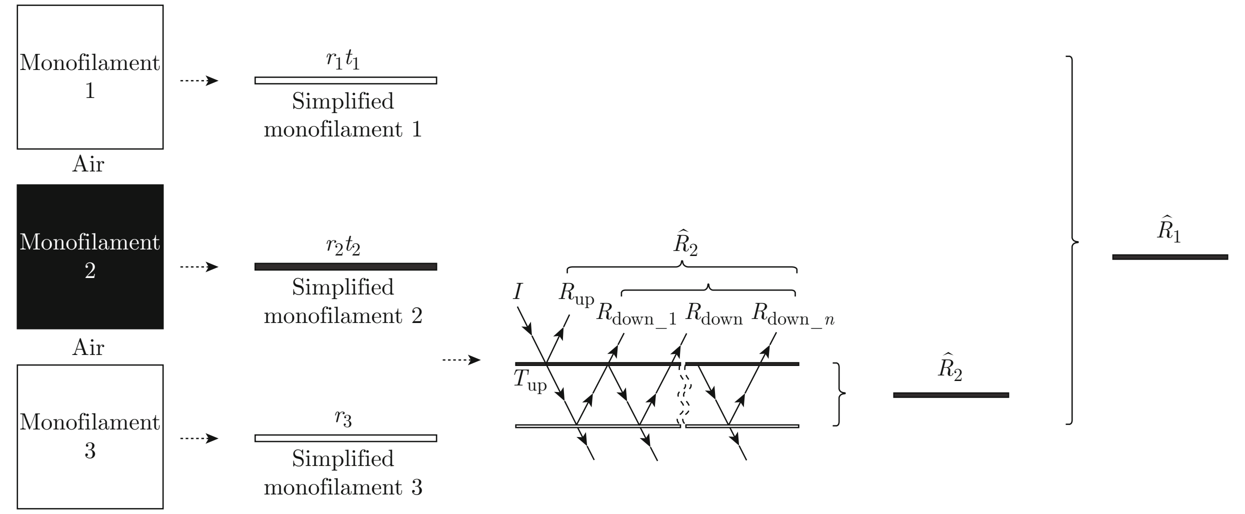
As can be seen from Fig. 1(d), the surface color of the fabric is determined by the color of the inner monofilaments. Therefore, as long as the reflectance, transmittance and arrangement of monofilaments inside a point on the surface of the fabric are known, the point color can be calculated based on the light propagation. After calculating the color of each point on the fabric surface, the mixed color of the entire fabric can be calculated according to the optical color mixing.

1.2 Color Prediction Model

On the basis of the digital fabric model, a color prediction model of the hybrid multifilament fabric was proposed. At the same time, the classical K-M theory was introduced as the reference model of the proposed model.

1.2.1 New Model

Since the monofilaments were simply close to each other, there was an air layer in the middle of the monofilaments (Fig. 2(a)). The light incident into the stack of the monofilaments will be reflected and transmitted multiple times inside the monofilaments and in the air layer between the monofilaments. The former can be directly measured by a spectrophotometer, so only the latter needs to be considered. Therefore, the stack of monofilaments can be equivalent to the stack of films (Fig. 2(b)). The reflectance and transmittance of the films were recorded as r_i and t_i, respectively. The propagation of light in the stack composed of two films and the air layer between them is shown in Fig. 2(c). The incident light I irradiates the film 2. Then, a part of the incident light is reflected by the film 2, recorded as R_{up}, and its another part passes through the film 2 and irradiates the film 3. Next, a part of the light irradiating on the film 3 is reflected by the film 3 back to the film 2. Finally, a part of the light reflected back to the film 2 passes through the film 2, denoted as $R_{\mathrm{down\_1}}$, and its another part is reflected back to the film 3 by the film 2. This process looped n times. The light,



(a) Monofilaments stack (b) Simplified monofilaments stack (c) Light propagation (d) Total reflectance of two monofilaments (e) Total reflectance of three monofilaments

Fig. 2 Calculation method of reflectance of multilayer monofilament stack reflected by film 3 and transmitted through the film 2 for the nth time, was recorded as $R_{\mathrm{down\_}n}$. The light reflected from the inside of the stack of the film 2 and film 3 was the sum of $R_{\mathrm{down\_1}}$ to $R_{\mathrm{down\_}n}$, which was recorded as R_{down}. The total light reflected from the stack of the film 2 and film 3 was the sum of R_{up} to R_{down}, which was recorded as $\hat{R}_2$. The calculation formula of the $\hat{R}_2$ was as follows:

$$\begin{aligned}\hat{R}_2 &= R_2 + R_2 = \\ &R_2 + R_{3_1} + \cdots + R_{3_n} = \\ &r_2 + t_2 r_3 t_2 + \cdots + t_2 r_3 (r_2 r_3)^{n-1} t_2 = \\ &r_2 + t_2^2 r_3 [(r_2 r_3)^0 + (r_2 r_3)^1 + \\ &\quad (r_2 r_3)^2 + \cdots + (r_2 r_3)^{n-1}] = \\ &r_2 + t_2^2 r_3 \frac{1 - (r_2 r_3)^n}{1 - r_2 r_3}.\end{aligned} \tag{1}$$

The film 2, film 3 and air layer between them are regarded as an equivalent film with reflectance $\hat{R}_2$ (Fig. 2(d)), which formed a new stack with the film 1. The propagation process of light in the new stack is similar to that in the stack of film 2 and film 3 above mentioned. The calculation method for the equivalent reflectance of the stack of more monofilaments is also similar to that of the stack of three monofilaments.

When the color of each point on the fabric surface is calculated, the mixed color of the fabric can be obtained through the tristimulus value mixing algorithm, as shown below:

$$X_{\mathrm{m}} = (\sum_i X_i)/N, \tag{2}$$

where, X_{m} and X_i represent the tristimulus values of the blends and the point i, respectively; N is the total number of the points.

1.2.2 Kubelka-Munk Theory

In 1939, Kubelka and Munk derived a relatively simple theory from the complete radiation theory. So far, most color matching software adopts K-M theory as the basis of optical theory, and its simplified form is

$$K/S = (1 - R)^2/(2R), \tag{3}$$

where, R is the reflectance of the blends; K and S are the K-M absorption and scattering coefficient of the primary in the blends at different wavelengths, respectively. For the color matching of pigments, since the pigment exists in the colored medium in the form of particles, the scattering coefficient of each pigment cannot be ignored. When matching colors, K and S must be calculated separately, commonly known as K-M double constant theory. The formula was as follows:

$$(K/S)_{\mathrm{m}} = \sum_i c_i K_i / \sum_i c_i S_i, \tag{4}$$

where, $(K/S)_{\mathrm{m}}$ is the ratio of the absorption and scattering coefficients of the blends; c_i, K_i and S_i are the mixing ratio, absorption coefficient and scattering coefficient of the ith fiber, respectively. When the reflectance of the mixture and the mixing ratio of the monofilaments are known, the K/S value of the mixture can be obtained by Eq. (3), and then the K and S values of monofilaments in the Eq. (4) can be solved by the method of least square[22-23]. For the blends composed of the monofilaments with known K and S values, when the mixing ratio of monofilaments is determined, the K/S value of the blends can be calculated according to Eq. (4). Then, the reflectance of the blends can be calculated according to Eq. (3).

2 Experiment

2.1 Reflectance and Transmittance Measurement

A Datacolor 850 Spectrophotometer (D65, standard observer and specular component included, optical geometry d/8°, and 20 mm medium aperture plates) was used to measure the reflectance and transmittance of samples. The reflectance and transmittance were recorded at 31 points in 10 nm intervals from 400 nm to 700 nm.

Since the fineness of a single monofilament was too small to cover the smallest test hole (6.5 mm) of the spectrophotometer, films with the same material, color and thickness as the monofilament were made to simulate a layer of single monofilaments. To eliminate the influence of the background, the black trap was attached to the back of the film when testing the reflectance of the film. As for the test method of the film transmittance, there was no any change.

2.2 Hybrid Multifilament Fabric

The black polyester masterbatch and polyester chip with matting agent were obtained from Suzhou Baolidi Material Technology Co., Ltd. The black monofilament was formed by adding 3% black masterbatch to the chip, and the white monofilament was directly made from the chip. By adjusting the mixing ratio and draft ratio of black and white monofilaments, 20 kinds of multifilaments were produced and woven into fabrics. The proportion of black monofilaments, fineness of the multifilaments, and colorimetric values of the fabrics are shown in Table 1, where P refers to the proportion of black monofilaments in the multifilament, N_{den} refers to the fineness of the multifilament (in denier, D), and L^*, a^* and b^* are the lightness, red-green value and yellow-blue value in the CIELAB color space.

Each multifilament contained 48 monofilaments, and 3 multifilaments were combined into a ply yarn. Then the ply yarns were woven into a 5/3 weft satin fabric using an SGA598/20″ semi-automatic loom. The average warp density and weft density were 288 pieces/10 cm

Table 1 Proportion of black monofilaments, fineness of multifilaments and colorimetric values of fabrics

No.	P	N_{den}/D	L^*	a^*	b^*
1	0.7	62.2	32.504	−0.056	−0.799
2	0.7	75.9	30.573	0.001	−0.577
3	0.7	85.0	31.585	0.001	−0.809
4	0.7	92.5	31.021	0.004	−0.794
5	0.6	62.4	32.827	0.159	0.003
6	0.6	77.0	29.861	0.103	−0.210
7	0.6	85.5	32.898	0.121	−0.100
8	0.6	91.0	32.817	0.090	−0.081
9	0.5	64.1	37.870	−0.031	−0.795
10	0.5	79.6	36.696	−0.063	−1.111
11	0.5	85.8	33.317	0.089	−0.617
12	0.5	93.0	36.142	−0.014	−1.108
13	0.3	64.1	43.420	0.035	−0.645
14	0.3	78.8	43.071	0.029	−0.874
15	0.3	86.0	41.962	0.023	−0.474
16	0.3	92.3	43.534	−0.017	−0.747
17	0.2	64.8	45.734	0.046	−0.392
18	0.2	77.2	49.307	0.012	−0.702
19	0.2	86.1	49.221	−0.019	−0.958
20	0.2	93.9	49.399	−0.033	−1.087

and 313 pieces/10 cm, respectively.

2.3 Equivalent of Monofilament

To make black film, 3% black masterbatches were added to the chips and dissolved together with the chips in the mixed solution composed of phenol and tetrachloroethane in the ratio of 1 ∶ 1. Then, a little mixed solution was spread on the glass as evenly as possible. After the solvent on the glass was evaporated by heating, the film was peeled off the glass. The method of making white film was similar, except that only chips were added to the mixed solution. The films with a thickness close to the average diameter of the monofilament were selected as the equivalent of the monofilaments. The reflectance and transmittance of the films are shown in Fig. 3.

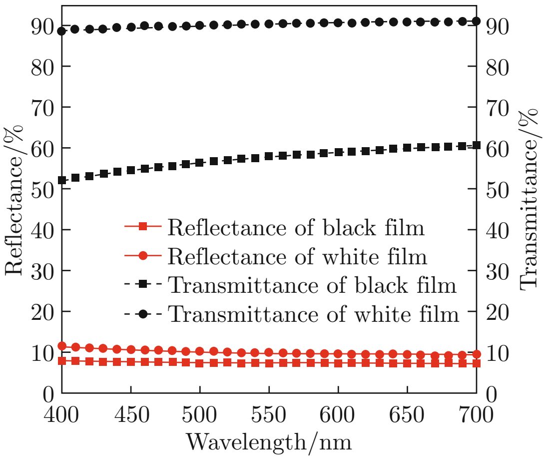


Fig. 3 Reflectance and transmittance of the black film and white film

3 Results and Discussion

The propagation of light in a monofilament with a square cross-section is different from that in a monofilament with a circular cross-section. In addition, the fabric model was also a simplification of the real fabric. Therefore, the tristimulus values of the hybrid multifilaments fabrics calculated by the prediction model need to be modified. To obtain the correction factor, from the samples with the same percentage of black monofilament, a sample with fineness close to the average fineness was selected. Finally, a total of 5 samples numbered 2, 6, 10, 14, 18 were obtained as correction samples. The remaining 15 samples were used to verify the validity of the model. The modified formula of the tristimulus value obtained by the prediction model was as follows:

$$\left.\begin{aligned} X &= 0.556\,0X_{\mathrm{p}} - 0.026\,4 \\ Y &= 0.556\,5Y_{\mathrm{p}} - 0.027\,7 \\ Z &= 0.557\,2Z_{\mathrm{p}} - 0.027\,8 \end{aligned}\right\}, \tag{5}$$

where, X_{p}, Y_{p}, and Z_{p} are the tristimulus values of the samples predicted by the model; X, Y, and Z are the modified tristimulus values of samples.

The Color Measurement Committee (lightness and chroma) (CMC ($l:c$)) formula is used to calculate the color difference between the predicted and tested mixing color of the fabrics. The color difference formula is widely used in textile industry[24-25], and the value of $l:c$ is recommended to be 2 ∶ 1 when used to calculate the color difference of textiles. The results are shown in Fig. 4. It can be seen that the mean and median of the color differences obtained by the new model were 1.02 CMC (2 ∶ 1) units and 0.98 CMC (2 ∶ 1) units,

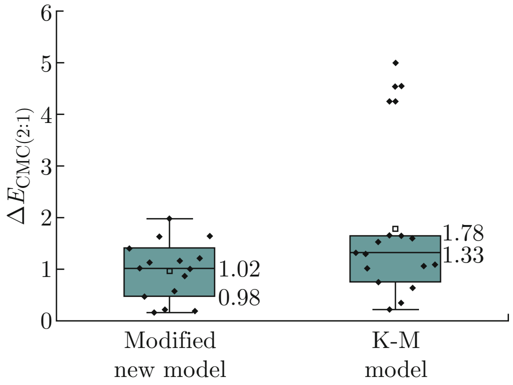
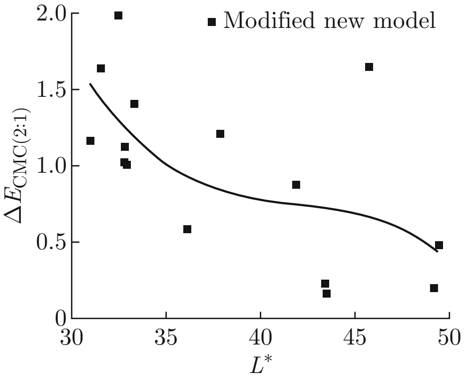


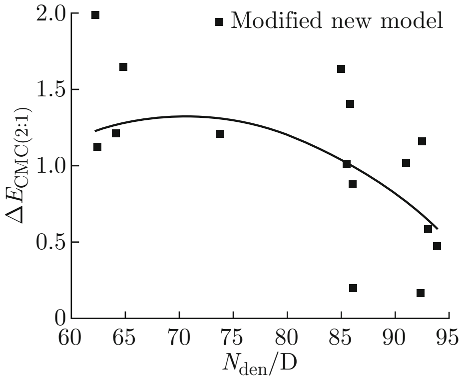
Fig. 4 Color difference of fabrics calculated by modified new model and K-M model

respectively. These results were less than that obtained by the classical K-M model.

To explore the influence factor of color difference, Spearman correlation analysis was carried out on the color difference $\Delta E_{\mathrm{CMC}(2:1)}$ and the tested CIELAB color values of the fabric and the multifilaments fineness N_{den}. The result shows that only the lightness L^* and the fineness N_{den} had a significant effect on color difference $\Delta E_{\mathrm{CMC}(2:1)}$. The relationship between $\Delta E_{\mathrm{CMC}(2:1)}$ and factors that had a significant influence on $\Delta E_{\mathrm{CMC}(2:1)}$ is shown in Fig. 5. It can be seen that in general, the $\Delta E_{\mathrm{CMC}(2:1)}$ decreased with the increase of L^* of the fabric and the fineness of the multifilament. This indicated that the color prediction effect of the prediction model was not as good as that for the fabric with lighter color and thicker multifilament. There were many reasons for this result, such as the lighter color and thicker thickness of the monofilament equivalent film.



(a) Color difference and lightness



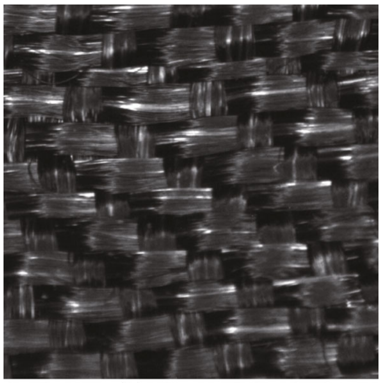
(b) Color difference and fineness

Fig. 5 Color difference obtained by modified new model, lightness of the fabric and the fineness of the multifilament

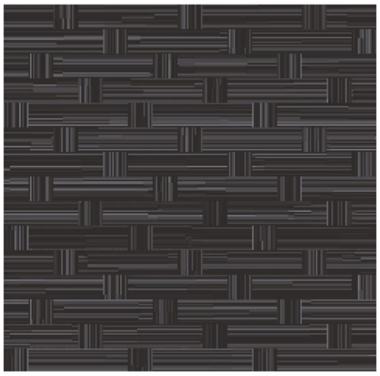
4 Reappear Appearance of Fabric

Another feature of the new model was the ability to calculate the local color of the fabric. Due to the uneven distribution of monofilaments in the fabric, obvious color unevenness appears on the surface of the fabric, as shown in Fig. 6(a). Most color prediction models do not consider the arrangement of the monofilaments in the fabric, so they cannot be used to reproduce the uneven surface color of the fabric. The new model just made up for this defect.

According to the number, fineness and blending ratio of monofilaments in fabric 1, the digital model of fabric 1 was established by using the steps of establishing the digital model of the hybrid multifilament fabric introduced in Subsection 1.1. Then, the color of each point on the surface of the fabric was calculated by using the color prediction model introduced in Subsection 1.2. The final calculated surface color appearance of fabric 1 showed the uneven distribution of the surface color of the fabric (Fig. 6(b)). Of course, due to the simplicity of the fabric model, there was a difference between the simulated and the real fabric surface color appearance.



(a) Real fabric



(b) Simulated fabric

Fig. 6 Surface color of the real fabric and the fabric simulated by the model

5 Conclusion

This paper proposed a color prediction model for the hybrid multifilament fabric composed of black and white monofilaments.

In order to verify the prediction effect of the model, 20 kinds of multifilaments with different mixing ratios and different fineness were woven into fabrics. The mean and median of the color differences obtained by the proposed model were 1.02 CMC (2 : 1) units and 0.98 CMC (2 : 1) units, respectively. This result was less than that obtained by the classical K-M model. To further analyze the effect of the prediction model, Spearman correlation coefficient among the color difference $\Delta E_{\mathrm{CMC}(2:1)}$ and the CIELAB lightness L^*, redness-greenness a^*, yellowness-blueness b^* and fineness of the multifilament N_{den} was carried out. The significant effects found in this study were L^* and N_{den}, and the $\Delta E_{\mathrm{CMC}(2:1)}$ decreased with increases of the L^* and N_{den}. Finally, by reproducing the surface color appearance of the fabric, it shows that the model can represent the phenomenon of uneven color on the surface of the fabric.

It should be noted that the prediction effect of the model needs to be verified with more samples, and the fabric model and the accuracy of the color prediction model still need to be optimized.

References

[1] WANG Q, LI W, GAN X, et al. Hybrid filament and its preparation technology: CN 109112655 [P]. 2019-01-01.

[2] PI F, LI W, LIAO H, et al. The collocation coloured yarns of polypropylene and their key preparation techniques research [J]. *Technical Textiles*, 2019, **37**(3): 24-30(in Chinese).

[3] CHAE Y. The color appearance shifts of woven fabrics induced by the optical blending of colored yarns [J]. *Textile Research Journal*, 2020, **90**(3/4): 395-409.

[4] CHAE Y. The effects of the spatial frequency and size of stripes on the hue appearance of striped woven fabrics [J]. *Textile Research Journal*, 2019, **89**(12): 2423-2432.

[5] STEARNS E I, NOECHEL F. Spectrophotometric prediction of color of wool blends[J]. *American Dyestuff Reporter*, 1944, **33**(9): 177-180.

[6] FRIELE L F C. The application of colour measurement in relation to fibre-blending [J]. *Journal of the Textile Institute Proceedings*, 1952, **43**(8): P604-P611.

[7] KUBELKA P, MUNK F. An article on optics of paint layers[J]. *Zeitschrift Fur Technische Physik*, 1931, **12**: 593-601.

[8] YANG R H, HAN R Y, LU Y Z, et al. Color matching of fiber blends: Stearns-Noechel model of digital rotor spun yarn [J]. *Color Research & Application*, 2018, **43**(3): 415-422.

[9] HEMINGRAY C, WESTLAND S. A novel approach to using neural networks to predict the colour of fibre blends [J]. *Coloration Technology*, 2016, **132**(4): 297-303.

[10] FURFERI R, GOVERNI L, VOLPE Y. Color matching of fabric blends: Hybrid Kubelka-Munk + artificial neural network based method [J]. *Journal of Electronic Imaging*, 2016, **25**(6): 061402.

[11] SHEN J, ZHOU X, MA H, et al. Spectrophotometric prediction of pre-colored fiber blends with a hybrid model based on artificial neural network and Stearns-Noechel model [J]. *Textile Research Journal*, 2017, **87**(3): 296-304.

[12] WEI C, WAN X, LI J. Color prediction model for pre-colored fiber blends based on modified Stearns-Noechel function [J]. *Dyes and Pigments*, 2017, **147**: 544-551.

[13] MA C, WANG Y, LI J, et al. Theoretical and practical analysis of fiber blend model in gray spun yarn [J]. *Journal of Engineered Fibers and Fabrics*, 2017, **12**(2): 28-38.

[14] HIRAYAMA H, KANEDA K, YAMASHITA H, et al. An accurate illumination model for objects coated with multilayer films [J]. *Computers & Graphics*, 2001, **25**(3): 391-400.

[15] HIRAYAMA H, KANEDA K, YAMASHITA H, et al. Visualization of optical phenomena caused by multilayer films based on wave optics [J]. *The Visual Computer*, 2001, **17**(2): 106-120.

[16] SIMONOT L, HERSCH R D, HÉBERT M, et al. Multilayer four-flux matrix model accounting for directional-diffuse light transfers [J]. *Applied Optics*, 2016, **55**(1): 27-37.

[17] HÉBERT M, HERSCH R D, BECKER J M. Compositional reflectance and transmittance model for multilayer specimens [J]. *Journal of the Optical Society of America A*, *Optics*, *Image Science*, *and Vision*, 2007, **24**(9): 2628-2644.

[18] WANG Y, CHEN G, LI W, et al. Reflectance model for filament yarn composed of different color monofilaments [J]. *The Journal of the Textile Institute*, 2020. https://doi.org/10.1080/00405000.2020.1862519.

[19] WANG Y, WANG J. Color prediction model of compound filament[J]. *Journal of Textile Research*, 2021, **42**(2): 156-160 (in Chinese).

[20] WANG Y, SHI C, CUI Z. Design of spinneret [J]. *Polyester Industry*, 2006, **19**(3): 27-30(in Chinese).

[21] ZHAO L, YAO M. A study of light reflectivity and transmission properties of single fiber [J]. *Journal of Northwest Institute of Textile Science and Technology*, 2001, **15**(2): 207-212(in Chinese).

[22] YANG R, XU Y, XIE C, et al. Kubelka-Munk double constant theory of digital rotor spun color blended yarn [J]. *Dyes and Pigments*, 2019, **165**: 151-156.

[23] YANG H, ZHU S, PAN N. On the Kubelka-Munk single-constant/two-constant theories [J]. *Textile Research Journal*, 2010, **80**(3): 263-270.

[24] WANG Y, MA C, LIU J, et al. Matching color technology of color blended yarn based on modified Stearns-Noeche model [J]. *Journal of Textile Research*, 2017, **38**(10): 25-31(in Chinese).

[25] WANG Y. Research on color matching of dyed yarn based on Stearns-Noeche theory [D]. Tianjin, China: Tianjin Polytechnic University, 2017.