Use of Density Probability Distribution for Creating the Detection Model of Cigarettes' Dense-end Position

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Abstract*—The density distribution of cigarettes was analyzed to improve the detection precision of cigarettes' dense-end position. The density distribution pattern under the ideal production condition was combined, and a dense-end position detection model was constructed. The model parameters were determined based on data optimization. MW-T and cigarettes validated the model. We got the conclusions below. 1) For the measurement of dense-end with the Dense-end Position Standard Parts, the average error of the measurement was 0.1646 mm, and the maximum error was -0.2735 mm. 2) The average error between the measured value of the dense-end position with ordinary cigarettes and that of the MW4420 was 0.79 mm, which meets the actual production demand (≤1 mm). The model has high accuracy and reliability and can provide favorable technical support for the dense-end position detection of cigarettes. It is helpful to improve the level of quality control in cigarette production and inject new vigour for the sustainable development of the cigarette industry.

Keywords—Cigarette, Density probability distribution, Detection model, Dense-end position detection

I. INTRODUCTION

As a key technology in the production process of cigarettes, the detection of cigarettes' dense-end position is one of the important indicators to measure the quality of cigarettes. The distribution and difference of cigarette weight and density are directly determined by the accuracy of the dense-end position, which also has a certain influence on the loose-end ratio of cigarettes; then, it influences the index of absorption resistance, hardness, combustion rate and user's smoking experience. Therefore, the accuracy of cigarettes' dense-end position has immeasurable value for improving the quality of cigarette production, meeting market demand and establishing brand image.

To ensure the quality and appearance of the cigarette, the filling density of the tobacco at the burning end of the cigarette will be increased to form the "dense end of ignition"; the middle portion corresponds to the "normal dense part". Ideally, the dense-end position is located at the centre of the burning end of the double-length strips, as shown in Fig. 1. The corresponding A, B, C, and D strips are of an equal density weight. Due to the machine's zero deviation and cigarette jitter in the online production process, cigarettes' dense-end position will shift during production, resulting in defective products.

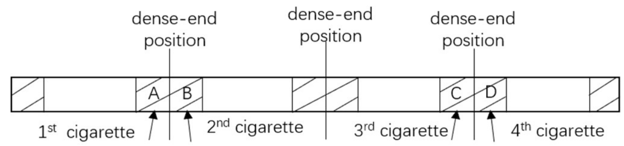

Fig. 1 Ideal dense-end position of cigarettes

At present, most research on the detection of cigarettes' dense-end position is limited to the interaction between the dense-end density value and cigarette quality indicators (such as loose-end rate, suction resistance, end drop tobacco, hardness, etc.). There are few specific analytical algorithms and correction methods for detecting cigarettes' dense-end position. In addition, the research on detecting the dense-end position in the process of cigarette production at home and abroad mainly focuses on the cigarette weight, that is, studying the weight distribution of the cigarette. It was proposed to find the center position of the dense-end of the double-length cigarette in the way of "dense-end tracking" (that is, the zero point of the dense-end position). This method is mostly used for real-time monitoring in the production process. Due to the lack of calibrated standard parts, it is easy to cause position offsets in the actual production process, which cannot be corrected in time. Therefore, it is necessary to carry out empirical accumulation correction for various specifications of cigarettes, which cannot expand the applicability of the results and realize the universality between different machines[1-6]. Based on the probability distribution characteristics of cigarette density, this study established a dense-end position detection algorithm model to improve the detection accuracy. It can improve the quality of cigarette production, optimize the production process, reduce costs, increase efficiency, and bring significant economic benefits to cigarette production enterprises.

II. MATERIALS AND METHODS

A. Materials, instruments and devices

Materials

A cigarette factory provided the samples used in the experiment, including six cigarette brands. The specific brand information is shown in Table 1.

TABLE 1. INFORMATION OF SIX CIGARETTE BRANDS

No.	Filter tip length /mm	Cigarette length /mm	Circumference /mm
A	30	54	24.2
B	30	54	24.2
C	25	59	24.2
D	30	54	24.2
E	34	50	24.2
F	30	54	17.0

Instruments** and **Devices

MW-T Microwave Moisture and Density Profile Measuring System, Dense-end Position Standard Parts (Wuxi Nanmu Measurement and Control Technology Co., Ltd.); MW4420 Microwave Moisture and Density Profile Measuring System (TEWS Elektronik, Germany); BSM-120.4 Electronic balance (Shanghai Zhuojing Electronic Technology Co., Ltd.; ±0.0001g); DHG-101 Drying oven (Shaoxing Supo Instrument Co., Ltd.).

B. Methods

Model and Theory

It can be seen from Fig.1 that the zero point of the ideal cigarette's dense-end position is the centre point of the medium-density distribution of the double-length cigarette. Based on the above arguments, this paper has designed an algorithm flow for cigarettes' dense-end position detection, as shown in Fig. 2. 1. According to the cigarette specifications and process parameters, the dense-end and normal dense parts of cigarettes are divided manually. 2) Cigarette density data are used to calculate the dense-end part weight *wt*, the normal dense part weight *wl*, and the relative density values d_t and d_l of the dense-end and the normal dense part, respectively. 3) The relative density probability distribution is calculated from their relative density values. 4) The weighted probability distribution value is calculated with the weight of the dense end and the normal dense part. 5) The density resolution is determined, and subsequently, the ratio of the weighted density probability distribution difference and the density resolution of the inner arrangement and outer arrangement of cigarettes' dense-end are calculated, which is the detection value of the cigarettes' dense-end position. The specific equation is shown in Equation (1).

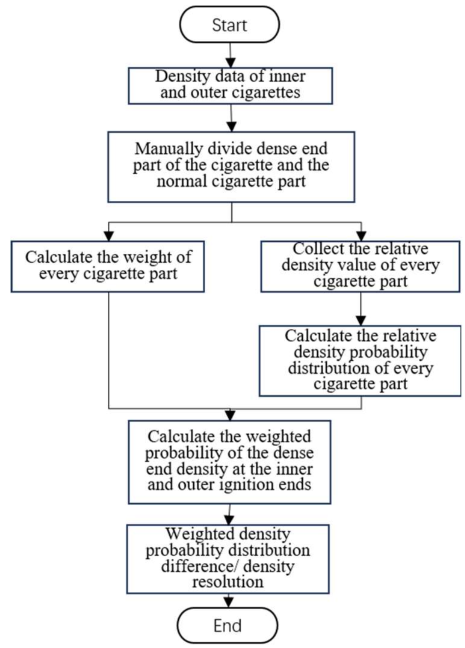

Fig. 2 Algorithm model for cigarettes' dense-end position detection

$$c = \left(P_{inside}(w_{ti} \cdot d_{ti} | w_{li} \cdot d_{li}) - P_{outside}(w_{to} \cdot d_{to} | w_{lo} \cdot d_{lo})\right)/r \quad (1)$$

Where, *c* is the detection value of cigarettes' dense-end position, in mm; P_{inside} and $P_{outside}$ are the weighted relative density probability distribution of the inner arrangement and outer arrangement cigarettes, in %; w_t and w_l are the weight of the dense-end and the normal dense part (Equation 2), in %; d_t and d_l are the relative density of dense-end and normal dense part (Equation 3), in %; *r* is the relative density resolution, in %/mm.

$$w_t = \frac{l_{dense-end}}{l_{cigarette}} \quad (2)$$

$$d_t = \frac{\bar{d}_{dense-end}}{\bar{d}_{cigarette}} \quad (3)$$

Where, respectively, $l_{dense-end}$ and $l_{cigarette}$ *are* the length of the dense-end part and the cigarette, in mm; $\bar{d}_{dense-end}$ and $\bar{d}_{cigatette}$ are the average density values of dense-end parts and cigarettes in mg/cm^3.

Determination of the model parameters

Determination of the relative density resolution r

The relative density resolution *r* is defined as the minimum distinguishable value of the relative density of the cigarette within 1 mm, and the unit is percentage per millimeter (%/ mm). Generally, the density resolution is used to characterize the measurement results of cigarette density in the process of cigarette production. For example, the density resolution of MW-T and MW4420 is 0.01 mg/cm^3, which meets the needs of cigarette density detection in the industry. However, this resolution is absolute. In statistical analysis, if the number of samples selected is insufficient or there are abnormal samples, random errors may occur in detecting cigarettes' dense-end position, affecting the accuracy and repeatability of the calculation results. Therefore, the relative density resolution was introduced to improve the accuracy of cigarettes' dense-end position detection. Since the relative density resolution *r* is affected by factors such as sensor sensitivity, electrical signal noise, and algorithm sensitivity of the detection device, the relative density resolution between different devices is different. Therefore, it is necessary to use the Dense-end Position Standard Parts to optimize the calculation of *r* parameter.

Under the environmental conditions of temperature at 25±2 ℃ and relative humidity at 40% to 70% RH, relative density resolution data were acquired using the Dense-end Position Standard Parts with the device MW-T. The relative density resolution was optimized using the algorithm shown in Fig.3.

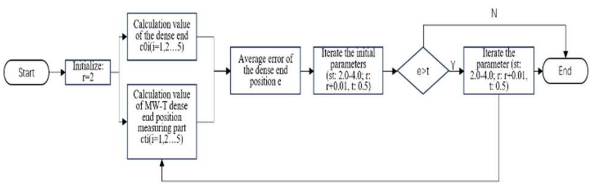

Fig. 3 Optimization algorithm flow of the relative density resolution

Determination of the density weight w

The density weight *w* is defined as the proportion of the length of the dense-end part or length of the normal dense part to the entire length of the cigarette. This parameter is used to weigh different density parts, highlighting the importance of the dense-end part and reducing the influence of the normal dense part, thereby increasing the density weight of the dense-end part. Take brand A in Table 1 as an example; the cigarette length is 54 mm. According to the process specifications, the dense-end part at the ignition end is located at 1 to 11 mm, the dense-end part at the filter end is located at 44 to 54 mm, and the normal dense part at 12 to 43 mm. Since the measurement window width of MW-T is 3 mm, and the cigarette sample was injected horizontally and uniformly, there was a transition step of filling the measurement window in the initial sampling process, which may bring an error of 4 mm in front of the dense end at the ignition end. Therefore, the first 4 mm data was not included in the weight calculation when calculating the weight of the dense end at the ignition end. Because of the influence of the rubbing of the filter tip, the density measurement may produce a larger error, so it is not included in the calculation and statistical analysis.

Model verification

Two methods carried out the model verification. First, the algorithm model is validated based on the Dense-end Position Standard Parts matched with the MW-T. The Dense-end Position Standard Parts are put into MW-T for 10 times repeated measurements in both positive and negative directions (simulating the inner arrangement and outer arrangement cigarette discharge conditions), and the average error and standard deviation between the model test results and the metering results. The other one was based on the six kinds of cigarette samples shown in Table 1; the algorithm model was verified by using the MW4420, widely recognised in the industry as the reference instrument, and then the error between the model detection value and the reference instrument measurement value was calculated.

III. Results and Analysis

A. Optimization results of the model parameters

Optimization result of the relative density resolution r

Table 2 shows the standard value of the Dense-end Position Standard Parts for MW-T, which have been accurately measured by the Wuxi Institute of Inspection, Testing and Certification and the Wuxi Institute of Metrology and Testing. The density data of the Dense-end Position Standard Parts was calculated according to the method described in section 2.2.2.1, and the optimization algorithm optimized the relative density resolution was optimized by the optimization algorithm.

TABLE II. STANDARD VALUES OF THE DENSE-END POSITION STANDARDS PARTS

No.	*0*	*1*	*2*	*3*	*4*
Standard values of the Dense-end Position Standard Parts /mm	*0.0025*	*0.9965*	*1.9985*	*2 .9765*	*3.9730*

In the optimization algorithm, the initial value of the relative density resolution is 2.0 mm, the range is 2.0 to 4.0 mm, the iteration step is 0.01 mm, and the optimization threshold is 0.5 mm. After 201 iterations, the results shown in Fig. 4 were obtained. The red dotted line in Fig.4 is the optimized threshold line, and the black solid line is the optimized solution value curve. According to the graph, when the iteration reached the forty-seventh time, the optimized solution value reached the minimum (0.0113 mm), far less than the optimized threshold of 0.5 mm, and the corresponding relative density resolution *r* was 2.47 % / mm. In this paper, this optimized value is used to establish and analyze the algorithm model.

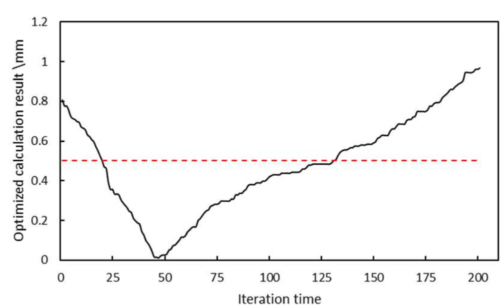

Fig. 4 Optimized calculation result of the relative density resolution *r*

Calculation result of the density weight w

According to the formula (2), combined with the production process used in a cigarette factory, the 1~11 mm part of the cigarette was manually divided as the dense-end part at the ignition end, the 11 mm part at the cigarette tail was the dense-end part at the filter end, and the middle part was the normal dense part. Fig. 5 and Fig. 6 are the density distribution maps of B-brand cigarettes after manual division. The orange dot line in the map is the density distribution map, which was manually divided, with the part from 10 to 11 mm as the division interval, and the average density value in this interval was used as the current interval density distribution statistics. The blue solid line is the density distribution curve obtained by MW-T. The graph shows that the manual division of the density interval distribution agreed with the actual measured density distribution in the middle section. There were differences in the "dense-end" part at both ends of cigarettes, mainly concentrated in the part of 1 ~ 4 mm and the part of 50 ~ 54 mm. Based on the previous analysis, without statistical analysis on the first 4 mm part of the cigarette and the filter end, the weight of the dense end of the ignition end was 14.81%, and the weight of the normal dense part was 51.85%. Table 3 shows the density distribution weights for the above six cigarette brands.

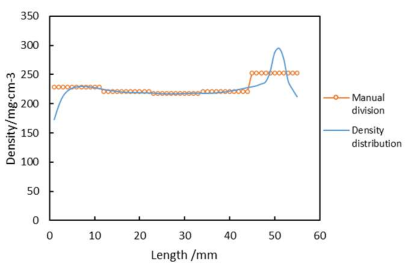

Fig. 5. Density distribution of inner cigarette

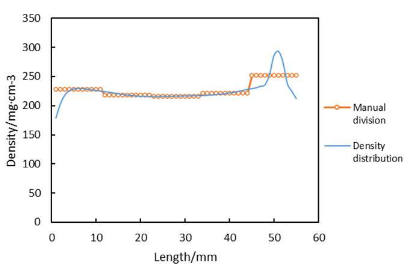

Fig. 6 Density distribution of outer cigarette

TABLE III. DENSITY DISTRIBUTION WEIGHTS OF SIX CIGARETTE BRANDS

Brand	Cigarette length /mm	Dense-end at the ignition end		Normal dense part	
		Location /mm	Weight /%	Location /mm	Weight /%
A	54	4~11	14.81	12-39	51.85
B	54	4~11	14.81	12-39	51.85
C	59	4~11	13.56	12-44	55.93
D	54	4~11	14.81	12-39	51.85
E	50	4~11	16.00	12-35	48.00
F	54	4~11	14.81	12-39	51.85

Note: Because the data of 4mm in the front of the ignition end is affected by the width of the sensor's measurement window, it is not included in statistics and calculations.

B. Model verification results

1) 3.2.1 Verification results with the standard parts

Table 4 shows the results of detecting the Desne-end Position Standard Parts in the dense-end position based on the above model. Among them, a single Dense-end Position Standard Part was calculated by measuring 10 times in both positive and negative directions, and the "Model measurement value" in the table is the mean value of 10 measurements. According to the table, the average error of the Dense-end Position Standard Parts detected by the above model is 0.1646 mm, and the maximum error is -0.2735 mm, much less than the requirements (⩽ 1 mm) in the production process. It indicates that the algorithm model can meet the actual production demand.

TABLE IV. VERIFICATION RESULTS OF THE DENSE-END POSITION STANDARD PARTS

No	Metering value/mm	Model measurement value /mm	Error/mm
1	0.0025	0.18	0.1775
2	-0.0025	-0.09	-0.0875
3	0.9965	1.06	0.0635
4	-0.9965	-1.15	-0.1535
5	1.9985	2.22	0.2215
6	-1.9985	-2.19	-0.1915
7	2.9765	3.13	0.1535
8	-2.9765	-3.25	-0.2735
9	3.9730	4.16	0.1870
10	-3.9730	-4.11	-0.1370
Average	——	——	0.1646

Verification results with the cigarettes

To verify whether the detection model is suitable for the dense-end position detection of cigarettes, verification experiments were carried out based on the B cigarette brand shown in Table 1. In addition, due to the lack of recognized verification methods and uniform standards in the industry for detecting the dense-end position of cigarettes, most enterprises still rely on MW4420 to detect the dense-end position of cigarettes. Therefore, this paper referred to the test results of MW4420 as a benchmark for the detection of cigarette verification.

Sample division

Taking brand B cigarettes as an example, the SPXY method was used to divide the correction set and the prediction set according to the ratio of 7:3. Table 5 shows the results of sample division. From the table, it can be seen that the dense-end density range of B brand cigarette's correction set is 164.13 ~ 251.57 mg/cm3, which includes the dense-end density range of prediction set sample (213.63 ~ 243.29 mg/cm3). It indicates that the sample division is reasonable.

TABLE V. RESULTS OF SAMPLE DIVISION

Brand	Item	Qty.	Max density /mg·cm^{-3}	Min density /mg·cm^{-3}	Average density /mg·cm^{-3}	Standard deviation /mg·cm^{-3}
B	Correction set	196	251.57	164.13	227.18	10.80
	Prediction set	84	243.29	213.63	227.86	6.61
	Total	280	251.57	164.13	227.38	9.73

Calculation and verification of dense-end position detection of cigarettes

For the cigarette samples divided in Table 5, the position of the cigarettes' dense end of the correction set was calculated based on Equation (1), and the comparison and verification results were obtained, as shown in Figure 7. The orange sample points in the figure are the calculation results of the detection model designed in this paper, and the blue sample points are MW4420 verification results. Figure 8 shows the error distribution of the corresponding data points in Figure 7. According to the calculation, the maximum error of the detection value of the dense-end position of the correction set of brand B cigarettes is 2.05 mm, the average error is 0.79 mm, and the standard deviation is 0.58 mm. The maximum error of the detection value of the dense-end position of the prediction set is 2.07 mm, the average error is 0.91 mm, and the standard deviation is 0.61 mm.

The above results show that the model based on the probability distribution of cigarette density is reliable in this study, but there is still some error between the model and MW4420. Due to the difference in sensor structure and algorithm between the two devices, the results of the two devices cannot be completely consistent.

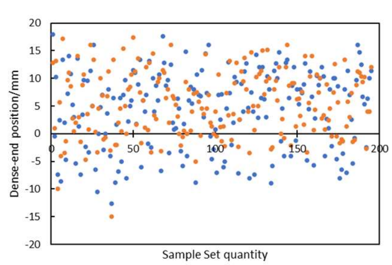

Fig. 7 Results of brand B cigarette dense-end position

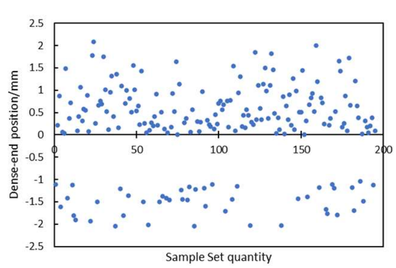

Fig. 8 Measurement error of two equipment

Correction of the results of the comparison and verification by MW4420

Based on the comparison and verification results in the previous section, the measurement results need to be corrected to avoid the measurement error of MW-T and MW4420 caused by the different sensor structures, density detection resolution, data algorithm, cutting offset analysis principle of dense-end position, etc. According to the relevant literature [7], the linear transformation matrix method was used to correct it. The specific correction principle is as follows: the MW4420 was used as the target reference instrument, and the detection value of the dense-end position is Ci (i = 1,2,3, corresponding to cigarette brands B, C and H); the MW-T was a corrected instrument, and its dense-end position detection value is $C'i$ (i = 1,2,3, corresponding to the cigarette brands, B, C and H). By using the linear transformation matrix, the relevant calculation was converted, and the conversion was carried out according to the following matrix.

$$\begin{bmatrix} D_{Lt1} & D_{Lt2} & D_{Lt} \\ D_{Rt1} & D_{Rt2} & D_{Rt} \\ D_{Pt1} & D_{Pt2} & D_{Pt} \end{bmatrix} \begin{bmatrix} C_1' \\ C_2' \\ C_3' \end{bmatrix} = \begin{bmatrix} C_1 \\ C_2 \\ C_3 \end{bmatrix} \tag{4}$$

Where, D_{Lti}, D_{Rti} and D_{Pti} (i=1,2,3) is the coefficient matrix, that is, the correction coefficient of the correction instrument. The same group of cigarette samples of the same brand were used for correction and coefficient solution. Three groups of B, C and H brand cigarettes (20 inner arrangement and 20 outer arrangement cigarettes) were selected respectively, and the conversion matrix was calculated as follows.

$$\begin{bmatrix} D_{Lt1} & D_{Lt2} & D_{Lt3} \\ D_{Rt1} & D_{Rt2} & D_{Rt3} \\ D_{Pt1} & D_{Pt2} & D_{Pt3} \end{bmatrix} = \begin{bmatrix} 16.4190 & -3.0866 & 35.9390 \\ -2.6408 & 0.8432 & -8.2836 \\ 2.8116 & -1.4968 & 3.9041 \end{bmatrix}$$

Several more sets of cigarette samples were taken, and the correction results and errors calculated by the linear transformation matrix based on the measured values of the calibration instruments are shown in Table 6. Table 6 shows that after linear transformation, the average error of the dense-end position detection values of MW-T and MW4420 reduced from 1.11 mm to 0.60 mm. This indicates that the linear transformation method can effectively correct measurement errors between devices.

Table 6 Comparison of the corrected detection value of the dense-end position of the cigarettes

Brand	MW-4420/mm	MW-T not-corrected/mm	Not-corrected error/mm	MW-T corrected/mm	Corrected error/mm
B	1.74	1.38	0.36	2.4	-0.66
B	0.87	-0.19	1.06	1.0	-0.13
B	0.98	-0.58	1.56	1.9	-0.92
F	-0.20	0.94	-1.14	-0.6	0.40
G	0.67	-0.86	1.53	1.1	-0.43
C	0.92	-0.52	1.44	1.9	-0.98
C	0.23	1.51	-1.28	-0.1	0.33
E	1.20	0.38	0.82	1.8	-0.60
E	0.14	-0.66	0.80	1.1	-0.96
Average	——	——	1.11	——	0.60

IV. CONCLUSIONS

In the study, we carried out the analysis of the cigarette density distribution, combined with the cigarette density distribution pattern of the cigarette in the ideal production state. A dense-end position detection model based on the density probability distribution of cigarettes was established, and the relevant parameters in the algorithm model were determined by data optimization. The model was validated with the Dense-end Position Standard Parts of MW-T and cigarettes. From the results, we got multiple conclusions. 1) The average error of the dense-end position detection of the Dense-end Position Standard Parts is 0.1646 mm, and the maximum error is -0.2735 mm. The accuracy is far less than the actual production demand (≤ 1 mm). 2) The average error between the detection value of the dense-end position of cigarettes and the measured value of MW4420 is 0.79 mm. It indicates that the model has high detection accuracy in detecting the dense-end position of cigarettes and can meet the actual production needs. In addition, to further improve the applicability and universality of the algorithm, this study creatively introduced a linear transformation matrix, which can effectively correct the measurement error between different devices and provide strong technical support and solutions for the accurate measurement of the dense-end position of cigarettes. It reflects the leading position of this research in technological innovation and provides valuable ideas and references for further development of the cigarette production industry.

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