# OPTIMIZATION AND EXPERIMENT OF HOT AIR TEA ROASTING MACHINE BASED ON CFD-DEM COUPLING

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# 基于 CFD-DEM 耦合的热风茶叶炒制机优化与试验

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## ABSTRACT

*A drum-type hot air tea roasting machine was designed to improve the quality of the roasted tea. The basic structure and working principle of the machine were studied theoretically and experimentally. The CFD-DEM coupled method and the Box-Behnken experimental design method were introduced to analyse the influence of the shape of the anti-skid bars and working rotating speed on the tea-roasting quality. The optimum combination of the working parameters with the height of the anti-skid bar is 30 cm, the figure of the anti-skid bar is 6, the rotating speed of the roller is 15 r/min, the broken-tea ratio is 2.15%, and the tea's sensory appraisal index is 89.32. The comprehensive performance index was better.*

## 摘要

*为提高焙茶品质，设计了滚筒式热风焙茶机。对整机的基本结构和工作原理进行了理论和实验研究。引入 CFD-DEM 耦合方法和 Box-Behnken 实验设计方法，分析了防滑条形状和工作转速对焙茶品质的影响。工作参数与防滑杆高度的最佳组合为 30cm，防滑杆位数为 6，滚筒转速为 15 r/min，碎茶率为 2.15% ，茶的感官评价指数为 89.32。综合性能指标较好。*

## INTRODUCTION

China is a top-class country of tea production and consumption in the world (*Li et al., 2020; Zhang et al., 2020*). According to the statistics, China's tea production was about 280 thousand tons in 2019, tea cultivated areas being over 4597.87 thousand mu. Nowadays China's tea industry faces these tendencies, the diversification of sales channels, the diversification of consumption, branding development (*Zhao et al., 2020*). But the lower productivity and the high broken-tea ratio of the existing tea processing equipment restricts the development China's industry seriously. The tea roasting process is a key step in the tea processing technique, and it has a very important significance to enhance tea quality further.

Shi *et al., (2015),* set up the numerical simulation of the temperature variation in and the tea-leaf particle movement in the tea roasting machine using CFD-DEM coupled method, the optimized equipment improves the stir-fried green tea's homogeneity and the stirring-fried rate heavily. Lv *et al., (2016),* believed that because there isn't enough heat supplied, the tea leaves receive heat asymmetrically in the tea processing course; they designed the tea roasting machine that could make tea leaves receive heat more equally, improving the heat energy use ratio. Li *et al.,* (2013), developed a tea roasting machine on the basis of the material characteristics of Lu'an Guanpian tea. Although the above machine improves the tea productivity to a certain extent, this technique doesn't give an analysis to the tea leaves movement rule in the roasting course, which affects the design of the tea processing equipment.

On the above analysis, this paper designs a drum-type hot air tea roasting machine in order to deal with the lower productivity and the high broken-tea ratio in the tea processing course. This research is set up based on 6CFG-100 type tea roasting machine.

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By studying the rotating speed of the roller and the anti-skid bars, through CFD-DEM simulation experiment to get the optimum shape of anti-skid bar and the optimum rotating speed of the roller, and then through prototyping and orthogonal tests obtaining the optimum parameters of the tea roasting machine, this research plans to provide methods on the optimizing structural design and working principle of the tea processing equipment.

## MATERIALS AND METHODS

### *The structure and working principle of the tea roasting machine*

### *The structure of the tea roasting machine*

The drum-type hot air tea roasting machine is made up of the outer shell of roller, the roller, hot air control cabinet, the regulator, the rack, the control cabinet, the anti-skid bar, the rear roasting board, the front roasting board and so on, as shown in Fig. 1 and Fig. 2.

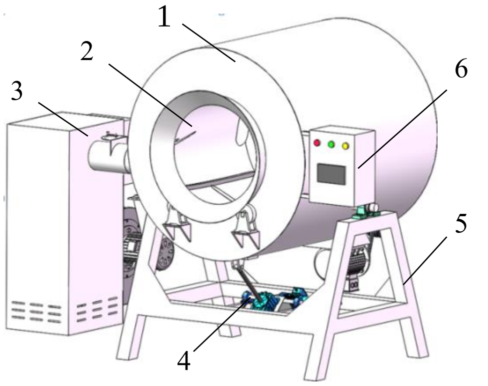



**Fig. 1 - Complete machine**

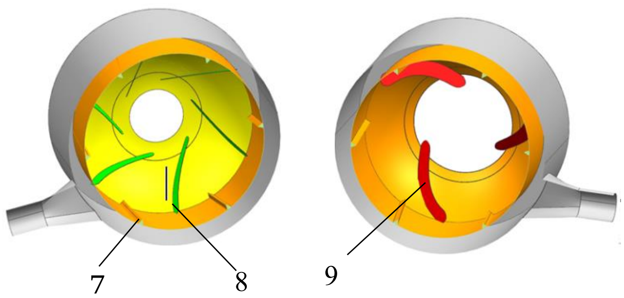



**Fig. 2 - Internal structure**

*1-The outer shell of the roller; 2-the roller; 3- hot air control cabinet; 4- regulator; 5-the rack; 6- the control cabinet; 7-the anti-skid bars; 8-the rear roasting board; 9-the front roasting board*

### *The working principle of the tea roasting machine*

The outer shell of the roller stands on the rack with the two sides of the spindles. During the work, turning on the hot air volume damper, the hot air passes through the square-diameter reducing pipe and then emits into the outer shell of the roller. The hot air heats the inner wall of the roller, the extractor fan makes the hot air distribution be more uniform on the tea leaves. The drive motor makes the roller rotate, the anti-skid bar carries the tea leaves to run around, which makes the tea leaves be heated more homogeneously. The roasting board pushes the tea leaves automatically, which makes the tea leaves shapes more compact. The temperature and humidity sensor in the roasting machine guarantees that the made-up tea fulfil the demand of the moisture content. The motor drives the screw elevator movement, then pulls the in-put and out-put materials mouth up and down, and the made-up tea comes out automatically. During the roasting process, there is an imbalance of temperature and press between the hot air and the tea leaves, their interaction causes the heat transfer and the mass transfer, which makes the temperature of the tea rise and at the same time the inner moisture of the tea go down, and then leads to the made-up tea roasting.

### *The rotating speed of the roller*

When the tea leaves move to the highest point in the roller, this research makes a force analysis of the tea leaves, as shown in Fig. 3. When the tea leaves stay on the highest point K, the research ignores the effect from the anti-skid bar, the own weight of the tea leaves equals the centrifugal force, $F_R$, as:

$$G = mg = F_R = m\omega^2 R = m\left(\frac{\pi n_{lim}}{30}\right)^2 R \tag{1}$$

Where:

$m$ is the total quality of the tea leaves, [kg];

$n_{lim}$ is the ultimate speed of the roller, [r/min];

$R$ is the radius of the roller, [m];

$g$ is the acceleration of gravity;

$\omega$ is the angular speed, [rad/s].

This paper calculates the ultimate speed of the roller, $n_{lim}$=42.28 r/min.

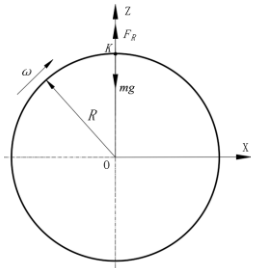



Fig. 3 - Stress analysis of tea grain at K

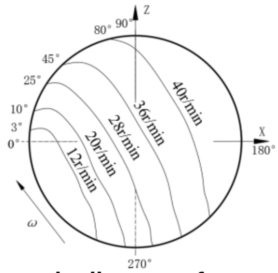
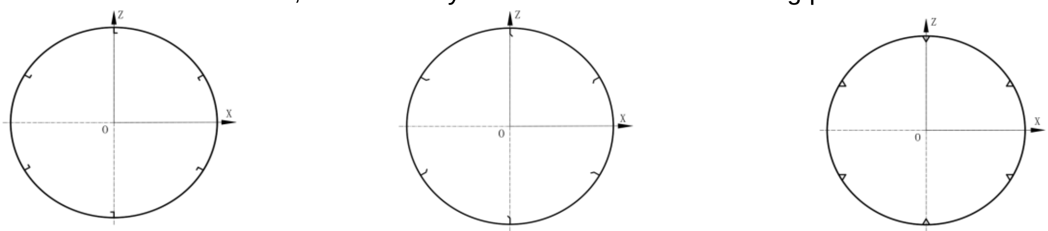



Fig. 4 - Schematic diagram of movement characteristics

This research makes an experiment on the angle of the tea's material-distributed curtain and the tea's movement when the roller speed is 10-40 r/min. The results show that when the deviation angle of the tea leaves in the drum is 10°- 45°, the water content of the tea leaves is reduced, and the appearance of the tea leaves is kept well. Combining the actual experiment and the analysis of the tea's movement characteristics in the roller, when the ultimate rotating speed of the roller is 30%-45%, there is a perfect result.

### *The shape of the anti-skid bar*

Fig. 5 shows three common shapes of the anti-skid bars. The tossing and casting experiments were performed to select the suitable shape of the anti-skid bar. The experiment results show that if the anti-skid bar is the right-angle shape and the obtuse-angle shape, in the rotation of the roller, the anti-skid bar holds a bigger quantity of the tea leaves, generating a bigger rising height of the tea leaves, which makes the tossing and casting speed of the tea leaves bigger, leading to a higher broken- tea ratio. If the anti-skid bar is the triangular shape, in the rotation of the roller, the tea leaves rise at an optimum height and form a better effect of the material-distributed curtain, which is very beneficial to the tea roasting process.




*a) The right-angle* *b) The obtuse-angle* *c) The triangular*

**Fig. 5 - Common shapes of the anti-skid bars**

### *The amount of the anti-skid bars*

Fig. 6 shows the motion state of tea at an instant. The paper assumes the tea particle maintains its position angle $\alpha k$, the casting speed V. The relationship between the particle position angle and time $t$ is:

$$t=\frac{\pi\left(\alpha-\alpha_{k1}\right)}{180\omega}=\frac{2R\omega\cos\alpha_{k1}}{g}+\frac{2\sqrt{\left(R\omega\cos\alpha_{k1}\right)^{2}-\left(R\omega\right)^{2}+Rg\sin\alpha_{k1}}}{g} \quad (2)$$

Where:

$\alpha_k$ is the position angle of K anti-skid bar in a moment;

$\alpha$ is the position angle after time $t$.

In this paper, the concept of the density of the tea material distributed curtain in the roller is proposed to explain the motion characteristics of tea particles with the rotation of the roller, which means that the quantity of the detained tea particles per unit volume when the tea leaves rotate with the roller.

Fig. 7 shows that the change of the position angle of the anti-skid bar follows the time change. Suppose that the anti-skid bar K has the position angle $\alpha$, the amount of the tea leaves is held $P_\alpha$. If the position angle is $\alpha_{k1}$, the amount of the tea leaves is $P_{\alpha k1}$, then the anti-skid bar K casts the amount of the tea particles: $P_{\alpha k1}$-$P_\alpha$. From the above analysis, the density of the tea material distributed curtain has its computational formula：

$$\rho=\frac{\sum_{k=1}^{n}\left(P_{\alpha k1}-P_{\alpha}\right)}{SL} \quad (3)$$

Where: $\rho$ is the density of the tea;

$S$ is the cross sectional area of the tea distributed curtain in the roller;

$L$ is the width of the tea distributed curtain in the roller;

$k$ is the momentary processing amount of the anti-skid bars in the rotation of the roller.

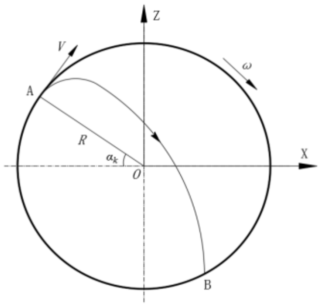


**Fig. 6 - Movement trajectory of tea granules**

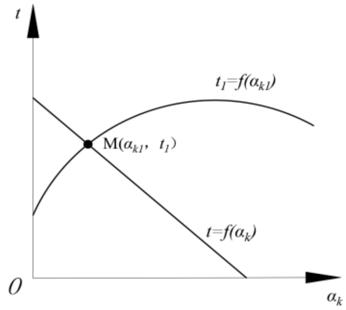


**Fig. 7 - The change law of position angle with time**

From the above analysis of the tea leaves casting test, there is a changing rule between the amount of the anti-skid bars in the roller and the density of the tea material distributed curtain, the results are shown in Table 1.

**Table 1**

**Relationship between the amount of anti-skid bars and the density of the curtain**

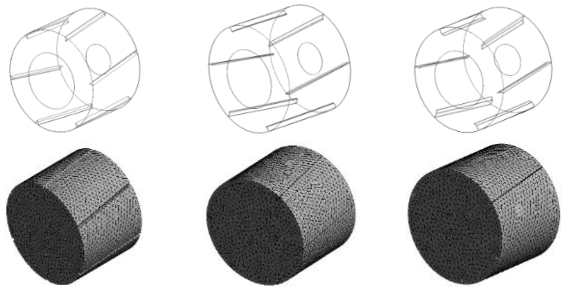
| The amount of the anti-skid bars | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|
| The momentary processing amount of the anti-skid bars in the rotation of the roller | 2 | 2 | 3 | 3 | 4 |
| The density of the tea material distributed curtain kg/m$^3$ | 20.00 | 13.33 | 10.67 | 10.14 | 6.67 |

The results show that: with increase in the amount of the anti-skid bars, the anti-skid bars join the operation in a moment gradually, the density of the tea material distributed curtain decreases gradually.
Considering the influence of the size and shape of tea particles and the uniformity of tea leaves in the process of movement, from the above experiment and reference to the Agricultural Machinery Design Manual, the best solution is determined as follows: 6 triangular anti-skid ribs are evenly arranged on the inner wall of the drum with an interval of 60°.

### *Simulation analysis*

This paper combines Fluent16.0 and EDEM2.7 to make a simulation computation, Fluent software is used to find out the solution of the gas phase, the solid phase finds its solution with the software EDEM, and the Euler-Euler coupling method is introduced for Simulation analysis.

SolidWorks is used to model three kinds of drums with different anti-skid rib shapes. The meshing module under ANASYS16.0 software is used to divide the inner flow channel mesh of the simplified drum, as shown in Fig. 8. To improve the computation speed and enhance the computation accuracy, on the actual shapes of the tea leaves, this research simplifies 4 models in Fig. 9 to make a simulation computation.



*a) the right-angle* *b) the obtuse-angle* *c) the triangular*

**Fig. 8 - Solid model and mesh model of heating roller**

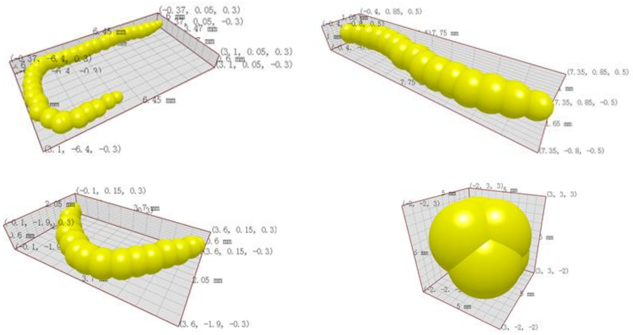
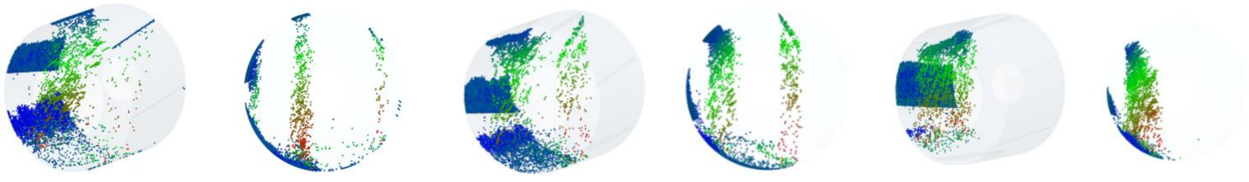


**Fig. 9 - Simplified tea particulate model**

## RESULTS

### *The movement effect of the tea particles from the shape of the anti-skid bar*

Under the same rotating speed (n=15 r/min) and same moment (t=2s), this paper makes three simulations of the different shapes (right-angle, obtuse-angle, triangle) of the anti-skid bar, as shown in Fig. 10.



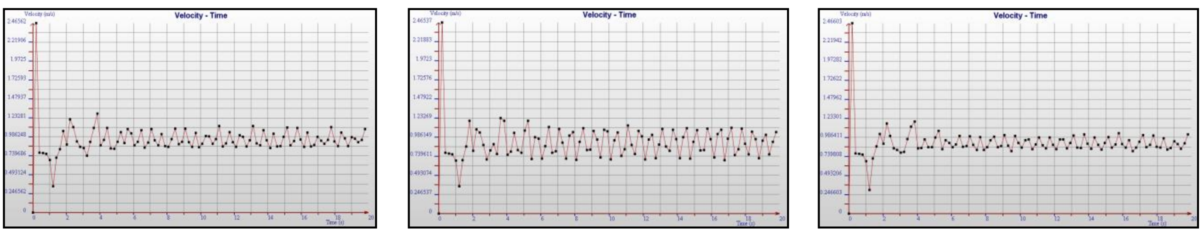
*a) the right-angle* *b) the obtuse-angle* *c) the triangular*

**Fig. 10 - Effects of three non-slip bars on the movement of tea leaves**

From the simulation results, this paper finds that the tea leaves can set up the material distributed curtain with rotation of the roller in right-angle and obtuse-angle situations for contacting the hot air sufficiently, as shown in Fig. 10 a) and b). But under these two situations, the anti-skid bars hold more tea leaves, which makes the tea leaves inhomogeneous distribution, the tea leaves can't get good extrusion shapes, so the appearance of the tea leaves is not good. With the rotation of the roller, the tea particles are taken up so high on the flat XOZ, which makes the angle of the material distributed curtain be too big and makes the broken-tea ratio higher, leading to the lower quality of the tea roasting process. Fig. 10 c) represents the triangle anti-skid bar. Compared with Fig. 10 a) and b), in the roasting process, there is a good extrusion among the tea particles, which is better to make the tea leaves have a good appearance, because the tea leaves are taken up lower in the roller, which decreases the broken-tea ratio heavily, and has the optimum effect in the tea roasting process.

### *The effect of the anti-skid bar shape on the tea particles speed*

Fig. 11 shows that the 3 different shapes of the anti-skid bars have their different effects on the changing rules of the tea movement speed in the roller. Fig. 11 a) is the right-angle shape, the changing speed of the tea particles belongs to the scope of 0.86-1.10 m/s, the fluctuant speed of the tea particles is very high, which makes the position of the tea particles rise higher or lower. In the actual roasting operation, it is very easy to make the tea appearance moulding, which is not good and decreases the tea roasting quality. Fig.11 b) is the obtuse-angle shape, the average speed of the tea particles changes in the scope of 0.73-1.22 m/s, it fluctuates the most and has a harmful effect on the tea roasting process. Fig. 11c) is triangle shape, the changing scope of the tea particles average speed belongs to 0.85-1.09 m/s. Compared with Fig. 11a) and b), the fluctuant scope of the tea particles speed is the minimum one, and there is not the higher peak value or the lower peak value of the speed, which makes the tea particles have a homogeneous speed in the roller, and makes the tea leaves have a perfect appearance moulding, and makes the tea leaves have the best roasting quality in the roasting process.




*a) the right-angle* *b) the right-angle* *c) the triangular*

**Fig. 11 - Effects of three anti-skid bars on tea particles velocity**

### *The effect of the roller's rotating speed on dispersion degree of the tea particles*

This paper uses the separation ratio (q) proposed by Akash Gupta *(2017)* to describe the degree of dispersion of tea particles, q being a smaller number, which shows the tea particles are more sparse, the dispersion effect is better, the tea leaves roasting homogeneity is better; if q is bigger, a bad result is obtained.

This research uses EDEM software to record and resolve the contact number of tea leaves at different times. Through the operation of the statistics data, this paper gets the different segregation ratio curves with 3 different rotating speed of the roller, as shown in Fig. 12.

As can be seen from Fig. 12, the tea leaves segregation ratio rises continuously with 3 different working situations in the beginning stage, and the main reason is that the contact among the tea particles plays the key role in first stage. With the rotation of the roller, in the moment before the tea leaves are cast, the segregation ratios under these 3 different working situations all get their peak values. When the tea leaves are cast, the segregation ratio holds its low ebb. If the rotating speed of the roller is 10 r/min, the tea leaves segregation ratio is max, if the speed is 20 r/min, the segregation ratio is mini. If the rotating speed is very low, the area of the material distributed curtain is small, which makes a bad effect on the roasting process. If the rotating speed is too high, it makes the tea leaves crush, which decreases the tea roasting quality. From the above analysis, when the rotating speed of the roller is 15 r/min, the tea leaves segregation ratio is the perfect one, which gets the best tea roasting quality.

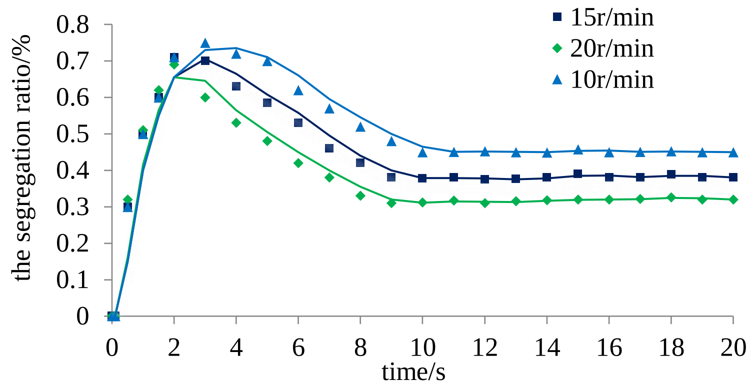



**Fig. 12 - Variation curve of the separation ratio of tea particles**

***The effect of the rotating speed on internal flow field in the roller***

In the ANSYS Fluent processing module, the flow field distribution cloud map under different working situations (n=10 r/min, n=15 r/min, n=20 r/min) is obtained, as shown in Fig. 13.

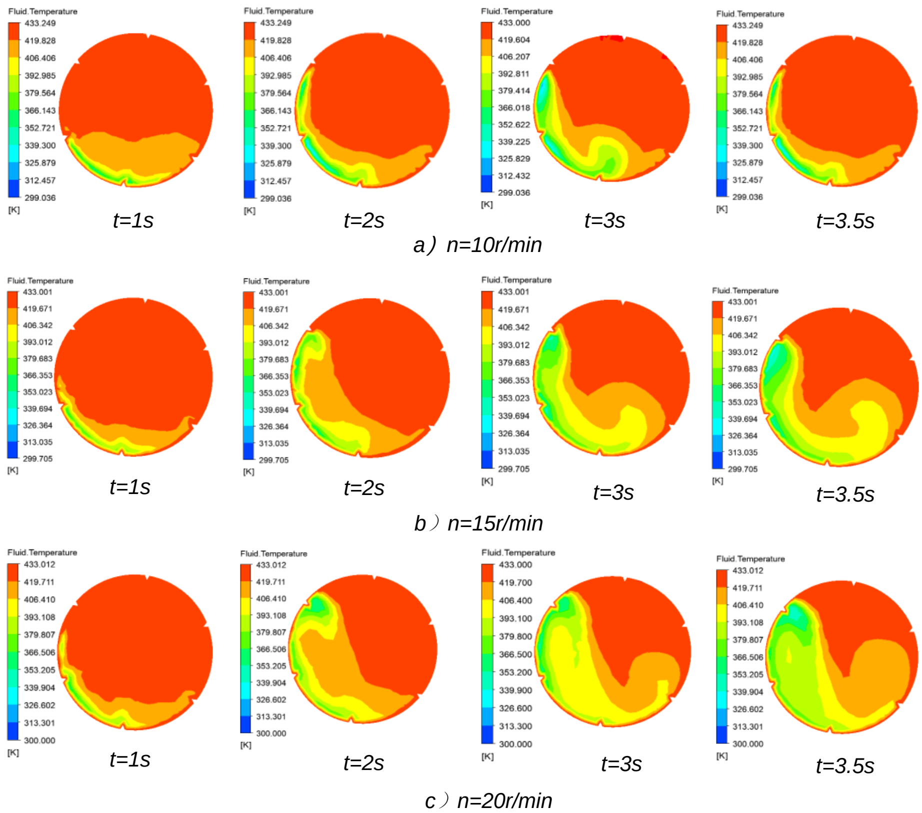



**Fig. 13 - Cloud diagram of flow field distribution in three working conditions at the same time**

As can be seen from Fig. 13, if the rotating speed of the roller is 10 r/min, the temperature change of the solid phase happens mainly in the near inner wall-surface of the barrel, which makes an insufficient contact with the hot air of the continuous phase, gets a smaller regional area of the temperature change, the changing speed is lower, if t=3.5 s, the change regional area of the solid phase temperature is less than 25% of the whole roller sectional area, and the tea roasting effect is obviously lower. In Fig. 13 c), if the rotating speed of the roller is 20 r/min, compared with Fig. 13 a), this paper finds that the temperature changing area of the solid phase increases to a bigger one, which has sufficient contact with the hot air of the continuous phase, and enhances the roasting effect to a certain extent. From the temperature change from t=1 s to t=3.5 s, this research finds that, because of the high rotating speed of the roller, the casting speed of the tea particles is high, if t=3.5 s, the changing regional area of the solid phase temperature is about 70% of the whole roller sectional area, which makes the tea particles of the solid phase crush each other and decreases the tea roasting quality. In Fig. 13 b), this research finds that if the rotating speed of the roller is 15 r/min, the temperature change is sufficient, the near inner wall-surface temperature tends towards the balance with the rotation of the roller gradually, the temperature changing area is about 50% of the whole roller sectional area, the temperature changing area is the best one.

According to the above analysis, if the form of the anti-skid bar is the triangle shape, the rotating speed of the roller keeps 15 r/min, the tea roasting quality is the best one.

***The prototyping experiment***

***The experiment condition***

The prototyping test was carried out to verify the rationality of the working performance and the parameter design of the drum-type tea roasting machine, as shown in Fig. 14.

**Fig. 14 - Experimental prototype of hot air tea roasting machine**

This test chooses 3 degree fresh tea leaves as the row materials, before the tea roasting, the moisture content of the fresh leaves being 15%-20%, the average unit weight being 100.2 kg/m3. The experiment instruments and equipment include the drum-type, hot air tea roasting machine, 1 kg / piece of teapot with a variety of precision, a TCS electronic scale with the precision of 10g-100g, a second chronograph with the resolution precision of 0.01 s, a determining instrument of the crushing tea dust, and an experiment tool bag.

***The experiment method and result***

This paper uses Box-Behnken as a test method, broken-tea ratio and the tea sensory evaluation score as the assessment index. The paper sets out a series of experiments on the height of the anti-skid bar (the level-value $X_1$, the coded value $x_1$ ), the number of the anti-skid bars (the level-value $X_2$, the coded value $x_2$ ), the rotating speed (the level-value $X_3$, the coded value $x_3$). The level-value and the coded value of the experiment elements are shown in Table 2. The experimental scheme and the result are shown in Table 3.

**Table 2**

**Experiment factor level and coded value**

| Coded value | The height of the anti-skid bar | The number of the anti-skid bars | The rotating speed |
|---|---|---|---|
| -1 | 20 | 4 | 10 |
| 0 | 30 | 6 | 15 |
| 1 | 40 | 8 | 20 |

Table 3

**Experiment scheme and results**

| No. | The height of the anti-skid bar, $x_1$ | The number of the anti-skid bars, $x_2$ | The rotating speed, $x_3$ | The broken-tea ratio, $Y_1$ | The tea sensory evaluation score, $Y_2$ |
|---|---|---|---|---|---|
| 1 | 0 | 1 | -1 | 2.3 | 85 |
| 2 | 0 | 0 | 0 | 2 | 90 |
| 3 | 0 | 0 | 0 | 2 | 90 |
| 4 | 0 | 1 | 1 | 2.6 | 83 |
| 5 | 0 | -1 | -1 | 2.2 | 86 |
| 6 | 0 | 0 | 0 | 2.1 | 91 |
| 7 | -1 | 0 | 1 | 2.4 | 84 |
| 8 | 0 | 0 | 0 | 2 | 91 |
| 9 | 1 | 0 | 1 | 2.7 | 82 |
| 10 | 0 | -1 | 1 | 2.4 | 84 |
| 11 | -1 | 1 | 0 | 2.4 | 85 |
| 11 | 1 | 1 | 0 | 2.8 | 84 |
| 13 | -1 | -1 | 0 | 2.2 | 86 |
| 14 | 1 | 0 | -1 | 2.4 | 84 |
| 15 | 1 | -1 | 0 | 2.3 | 85 |
| 16 | -1 | 0 | -1 | 2.2 | 86 |
| 17 | 0 | 0 | 0 | 2 | 90 |

***The regression model***

This research imports the experimental data in Design-Expert 10.0 to make a regression fit, which sets up the regression model of the broken-tea ratio and the assessment index of the sensory evaluation score from different elements, as shown in Eq.(4).

After getting rid of the non-distinctive regression items, the regression model of the broken-tea ratio and the sense assessment index is shown in Eq.(5):

$$\begin{cases} Y_1 = 2.02 + 0.13x_1 + 0.13x_2 + 0.13x^3 0.075x_1x_2 + \\ 0.025x_1x_3 + 0.025x_2x_3 + 0.23x_1{}^2 + 0.18x_2{}^2 + 0.18x_3{}^2 \\ Y_2 = 90.40 - 0.75x_1 - 0.50x_2 - 1.00x^3 + 0.000x_1x_2 + \\ 0.000x_1x_3 + 0.000x_2x_3 - 2.95x_1{}^2 - 2.45x_2{}^2 - 3.45x_3{}^2 \end{cases} \tag{4}$$

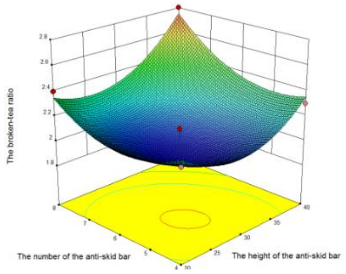
$$\begin{cases} Y_1 = 2.02 + 0.13x_1 + 0.13x_2 + 0.13x^3 0.075x_1x_2 + \\ \quad + 0.23x_1{}^2 + 0.18x_2{}^2 + 0.18x_3{}^2 \\ Y_2 = 90.40 - 0.75x_1 - 0.50x_2 - 1.00x^3 - 2.95x_1{}^2 \\ \quad - 2.45x_2{}^2 - 3.45x_3{}^2 \end{cases} \tag{5}$$

***Analysis of the effect of experimental factors***

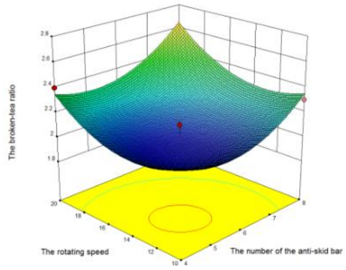
In the regression equation, one element with the factor level *o* is randomly selected, and the remaining two elements are studied to find out their influence on the broken-tea ratio and sensory evaluation indicators. The software Design-Expert 10.0 is used to make an analysis to get the response hook face affected by the interaction factors, as shown in Fig. 15.

In Fig. 15 a), this paper finds that if the same amount of anti-skid bars is maintained, the broken-tea ratio has a changing tendency with the increased height of the anti-skid bar, this tendency decreases at the beginning and then increases at the end. If the anti-skid bar keeps same height, the broken-tea ratio has a changing tendency with the increased amount of the anti-skid bars, this tendency decreases at the beginning and then increases at the end.

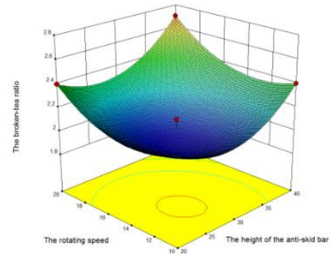
In Fig. 15 b), if the rotating speed of the roller is maintained the same, the broken-tea ratio has a changing tendency with the increased amount of the anti-skid bars, this tendency decreases at the beginning and then increases at the end; if the amount of the anti-skid bar is kept the same, the broken-tea ratio has a changing tendency with the increased rotating speed of the roller, this tendency decreases at the beginning and then increases at the end. In Fig 15. c), if the rotating speed of the roller is maintained the same, the broken-tea ratio has a changing tendency with the increased height of the anti-skid bar, this tendency decreases at the beginning and then increases at the end. If the height of the anti-skid bar is maintained the same, the broken-tea ratio has a changing tendency with the increased rotating speed of the roller, this tendency decreases at the beginning and then increases at the end. In Fig. 15 d), this paper finds that if the amount of the anti-skid bar is kept the same, the sense assessment index has a changing tendency with the increased height of the anti-skid bar, this tendency increases at the beginning and then decreases at the end. If the height of the anti-skid bar is maintained the same, the sense assessment index has a changing tendency with the increased amount of the anti-skid bar, this tendency increases at the beginning and then decreases at the end. In Fig. 15 e), this paper finds that if the rotating speed of the roller is maintained the same, the sense assessment index has a changing tendency with the increased amount of the anti-skid bar, this tendency increases at the beginning and then decreases at the end. If the amount of the anti-skid bar is maintained the same, the sense assessment index has a changing tendency with the increased rotating speed of the roller, this tendency increases at the beginning and then decreases at the end. In Fig. 15 f), this paper finds that if the rotating speed of the roller is maintained the same, the sense assessment index has a changing tendency with the increased height of the anti-skid bar, this tendency increases at the beginning and then decreases at the end. If the height of the anti-skid bar is maintained the same, the sense assessment index has a changing tendency with the increased rotating speed of the roller, this tendency increases at the beginning and then decreases at the end.



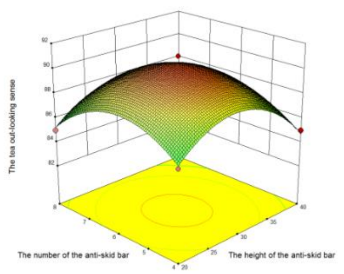

a) $Y_1=f(x_1, x_2, 0)$



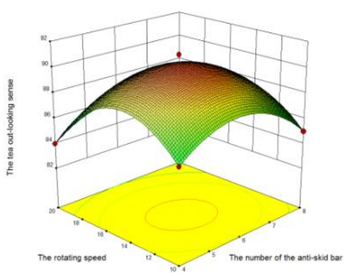

b) $Y_1=f(0, x_2, x_3)$



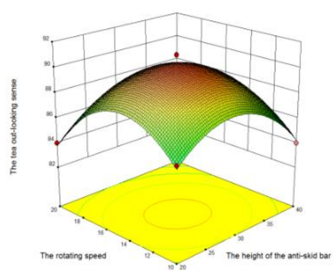

c) $Y_1=f(x_1, 0 ,x_3)$




d) $Y_2=f(x_1, x_2, 0)$




e) $Y_2=f(0, x_2, x_3)$




f) $Y_2=f(x_1, 0, x_3)$

**Fig. 15 - Response surfaces of interactive factors influence on test indexes**

### *The optimization model and the experimental verification*

Based on the working performance demand and the actual working condition of the drum-type hot air tea roasting machine, this work plans to succeed in the lower broken-tea ration, the higher sense assessment index. According to the different elements having different effects, this paper needs to optimize all results. This paper regards the broken-tea ratio and the sense assessment index as an objective function, makes the optimization design to 3 experimental elements, including the rotating speed of the roller, the height of the anti-skid bar and the number of the anti-skid bars.

The optimization constraint conditions can be conducted as follows:

$$\begin{cases} \min Y_1 = f_1(X_1, X_2, X_3) \\ \max Y_2 = f_2(X_1, X_2, X_3) \\ s.t. \begin{cases} X_1 \in (20, 40) \\ X_2 \in (4, 8) \\ X_3 \in (10, 20) \end{cases} \end{cases} \tag{6}$$

The influence laws of three experimental factors affecting the broken tea rate and sensory evaluation indexes are comprehensively considered to get the best parameter combination, using Design-Expert 10.0 software to make an optimization solution. This research gets the optimum working parameter combination, the height of the anti-skid bar being 31.91mm, the amount of the anti-skid bars being 6.4, the rotating speed of the roller 16.52 r/min, the broken-tea ratio 2.15% and the sense assessment index 89.32.

In order to use the optimum parameter combination in the actual production, this paper makes the round number of them, the height of the anti-skid bar is 30 mm, the amount of the anti-skid bars is 6, the rotating speed of the roller is 15 r/min, 3 repetitive tests are made to get the average value, the broken-tea ratio is 2.02 %, the sense assessment index is 90.02, which means the experimental results keep an accord with the theoretical results substantially, thus the regression model is good. The actual roasting effect is shown in Fig. 16 and it fulfils the tea quality demand.

**Fig. 16 - Tea leaves after roasting**

## CONCLUSIONS

(1) According to the present tea processing equipment, there are still many problems, such as low productivity, high broken-tea ratio and so on. To improve the quality of the processed tea, this paper designs a drum-type hot air tea roasting machine. This paper states the elementary working construction and the operation principle, and makes a theoretical analysis of the design parameter, confirms the key parameters, such as the rotating speed of the roller, the form of the anti-skid bar, the number of the anti-skid bars.

(2) The coupling method CFD-DEM was used to analyse the effect from the form of the anti-skid bar in the inner wall of the machine and the rotating speed to the tea roasting quality. The simulation results show, the form of the anti-skid bar is triangle, the rotating speed of the roller is 15 r/min, the tea leaves get an optimum movement rule, an optimum separation ratio and an optimum flow field change.

(3) The Box-Behnken was introduced to design the experimental methods, regarding the height of the anti-skid bar, the amount of the anti-skid bars, the rotating speed of the roller as the experimental elements, and regarding the broken-tea ratio and the sense assessment index as the test indexes, making the series experiments on the operation parameter of the roasting tea machine, finding out that the optimum working parameter combination is the height of the anti-skid bar being 30 mm, the amount of the anti-skid bars 6, the rotating speed 15 r/min, the broken-tea ratio 2.15% and the sense assessment index being 89.32.

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