EFFECT OF FAN'S PARAMETERSON ADHESION MECHANISM OF THRESHED RAPE MIXTURETO CLEANING SIEVE
/
风机参数对油菜脱出物与清选筛的粘附性影响

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ABSTRACT
In order to reduce the adhesion of moist threshed rape mixture and cleaning sieve, a method named "Hot-airflow Cleaning" has been proposed. Firstly, the key factors influencing anti-adhesion property were obtained based on the theoretical analysis. They were temperature, wind speed and fan inclination. Then, based on the single-factor experiments, the proper temperature of the fan was 30-50°C, the proper wind speed and inclination of the fan were 2-4 m/s and 15-45°, respectively. Finally, the fan's parameters were optimized by Box-Behnken design. The results showed that the optimum technological parameters were temperature of 50 °C, a wind speed of 4 m/s and that fan inclination was 45°. This research could provide a reference for the improvement of cleaning system for rape combine harvesters.

摘要
为了降低湿脱粒油菜混合料与清选筛的粘附性，提出了一种"热风清选"的方法。首先，在理论分析的基础上，得出了影响防粘性能的关键因素：温度、风速和风机倾角。通过单因素试验得出风机的适宜温度为 30～50℃，适宜风速为 2～4m/s，倾角为 15～45°。最后，采用 Box-Behnken 设计对风机参数进行了优化。结果表明，最佳工艺参数为温度 50℃，风速 4m/s，风机倾角 45°。本研究可为油菜联合收获机清洗系统的改进提供参考。

INTRODUCTION
Rape has high nutritional value and economic value. It is widely planted in northwest China, north China and the Yangtze River basin, and is one of the major oil crops in China (*Ma Z. et al, 2011; Zhang M., et al, 2019; Chen X. et al, 2018*). Air-and-screen cleaning equipment which were responsible for the separation of unnecessary or even harmful impurities from usable material, have high precision requirements for separation and cleaning and the ability to adjust in a wide range of operating parameters *(Panasiewicz M. et al, 2012; Liu C. et al, 2018; Du H. et al, 2019; Ning X. et al, 2018)*.The purity of the grain determined by the percentage of impurities is the most important target for cleaning. However, when harvesting wet sticky rape, the components of the threshed rape mixture could be bond to each other, unable to disperse and stratify quickly because of the surface tension, grease and other binders on the threshed rape mixture, resulting in high impurity and loss rate of cleaning device. Therefore, it is very helpful to reduce the adhesion on the screen surface to improve the harvest performance.

Numerous scholars mainly study the adhesion mechanism of metal materials with soil, coal and other particles*(Chen S. et al., 2018; Yang X. et al., 2000; Liu Q. et al.,2019; Chen X. et al., 2003; Chen C. et al., 2019*), while few studies have been conducted on the adhesion mechanism of agricultural materials. In order to solve the problem of hole plugging of wet sticky rape materials, some commonly used methods include reducing the moisture content of materials, heating the screen surface, using the screen surface cleaning device had been proposed by *Zuber and Eibs(1995), Chen C. et al. (2019)* have adopted vibrating and heating anti-adhesion test. The results indicated that the increase of temperature effectively decreased the adhesion rate of the shaking plate surface, but this method can only destroy the adhesion interface after two heat exchanges, and the heat transfer efficiency was low. *Li Y. et al(2013)* applied the bionic non-smooth surface to the vibration screen of rape harvester, and the test proved that the bionic non-smooth screen surface has good stability and use effect, but the processing technology of the non-smooth screen is complex and the production cost was pretty high.

Air and screen cleaning device is currently widely used in rape harvesting machinery. Due to different floating speed, the threshed rape mixture can be dispersed and layered under the action of pneumatic force. However, rape is repeatedly impacted and kneaded in the threshing device, which will produce a large number of light impurities such as stem debris and pod diaphragm. These impurities are easy to interact with free water of stem and oil of broken rapeseed and then adhere to the surface of cleaning sieve. Some literature works have pointed out that heating is an important method to control the mechanical properties of adhesion interface, which can reduce the surface tension of water film and the adhesion force (*Ren L., 2011; Liu G. et al, 2008; Peng X. et al, 2020*). *Hiraku et al. (2017)* have studied the law of adhesion by varying the roughness and temperature of the wheel-rail surface. Results showed that the wheel-rail adhesion increases with the increase of water temperature. In this paper, the anti-adhesion mechanism of wet sticky rapeseed under the action of hot airflow and the influence of different fan's parameters on the adhesion characteristics of rapeseed and sieve interface were studied. The optimum operating parameters were revealed to provide references for improving the cleaning efficiency (*Fei Liu et al, 2020*).

MATERIALS AND METHODS

Most of the wet sticky rape materials are the light impurities with large surface area, according to the reference (*Chen C. et al, 2019*), in the high humidity of cleaning chamber, the surface of the particles is uniformly covered with a layer of liquid film. When the particles collide, part of the liquid film will fuse together to form a liquid bridge. Due to the effect of liquid surface tension and pressure difference of gas-liquid interface, the particles and surface of cleaning sieve are affected by the liquid bridge force and would form adhesion-interface. When the particle size exceeds 20 μm, the interaction force of surface water is much greater than van der Waals force and other intermolecular forces (*Chen X. et al., 2002*).

As shown in fig.1, rapeseed was taken as an example and the anti-adhesion model was constructed; the force on stable rapeseed is:

$$F = F_2 + G \tag{1}$$

Where: F represents normal wind force (N); F_2 represents adhesion force (N); G represents gravity of rape. The normal wind force F on rapeseed was based on the following equation:

$$F = F_1 \sin\alpha = m\frac{g}{v_p^2}v^2 \sin\alpha \tag{2}$$

where: m represents the mass of rapeseed (kg), v_p represents the float speed of rapeseed (m/s), v represents wind speed (m/s); α represents the fan inclination. From formula (1) and (2), the change of wind speed and fan inclination will cause the inequality between the left and right sides of the formula. The unbalanced force will make the rapeseed leave the sieve surface or slide along the sieve surface. In addition, the water molecules in the liquid bridge will move violently when heated, expressing phenomenon of vaporization. The water film between the material and the cleaning screen would absorb the heat of the hot airflow and the meniscus radius of the water film (r_1) gradually decreases, resulting in the decrease of the adhesion force between the threshed rapeseed and the screen surface. Therefore, the fan's parameters that affect anti-adhesion properties are wind speed, temperature and fan inclination.

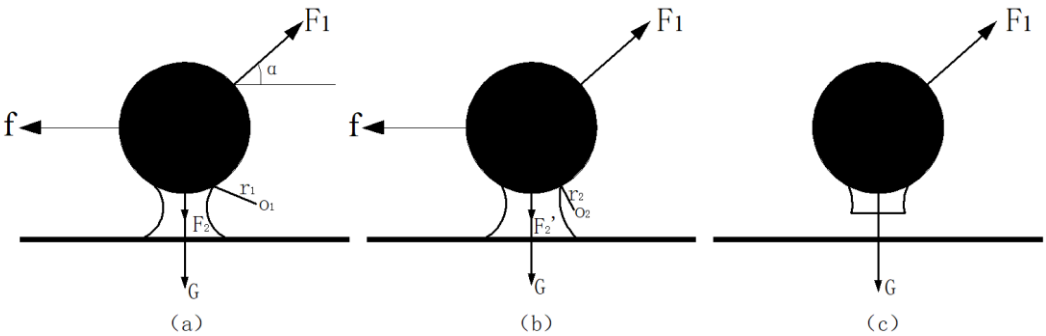


Fig. 1 - Anti-adhesion model

The wet and sticky rape materials were chosen as test subject with strong adhesion, including grains, husks, stems, stalks, horn beaks and other fine particles which were shown in Fig.2. The sealed wet sticky rape mixture was collected from the field, and then taken to the laboratory. The drying method was used to measure the moisture content in time (*Bhupendra M., 2017; Ma Z. et al., 2011*). Screening test was conducted by using 10 standard sieve with 0.1~6 mm aperture to determine size of adhesive materials, screening time was 5 minutes and the size proportion of the adherent of the rape sieve surface was obtained by dividing the mass of the adherent in each size range by the total mass of the sample. The screen test was repeated five times and average value was applied. The measured moisture content of the mixture was 19.4%, and 70% of the wet sticky rape mixture were 0.3~2.6 mm in size, 13% are over 2.6 mm, and the maximum size did not exceed 8 mm.

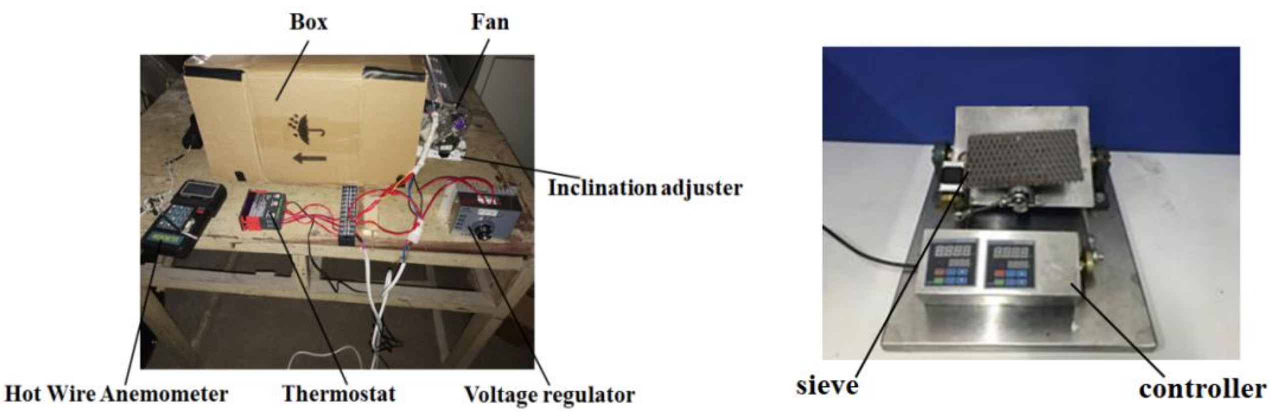
Fig. 2 - Wet sticky rape mixture

A type of PTC (Positive Temperature Coefficient) heating fan was designed to provide hot airflow. The PTC heating fan includes motor, PTC heating, voltage regulator, hot wire anemometer and thermostat, etc. PTC heating is a kind of electric heater with ceramic heating elements, which will not produce redness and avoid fire and scald. The type and parameter of these electronic devices was shown in Table 1. Before the test, the PTC heating fan was fixed on the fan inclination adjuster in front of the sieve. The range of the fan inclination adjuster was 0°to 90°. Temperature can be adjusted by the thermostat and the motor speed can be adjusted by the voltage regulator.

Table 1

Name and parameter of PTC heating fan

Name	Type
Motor	6030
Voltage regulator	BAT100-800B
Thermostat	EK-3010
Hot wire anemometer	AVM-07



a) b)

Fig. 3 - Test equipment

As shown in Fig.3, a square box was chosen as the cleaning room. A hot wire anemometer was used to measure temperature and wind speed of the fan outlet. A circular sieve with 200 mm length and 3 mm height was fixed on the vibration platform in the cleaning room and the vibration frequency and amplitude were 4 Hz and 30 mm, respectively. Round holes with a diameter of 5 mm are evenly distributed on the surface of circular sieve, so the rapeseed can pass through them when vibrating and the impurities were blown out of the box. The wet sticky rape materials were laid on the sieve evenly. Before the test, the mass of wet sticky rape mixture and sieve was weighed by the electronic scale, and it was weighed again when each test finished. Each test in different conditions was repeated three times and the average value was applied. At the end of each test, the surface of sieve was cleaned by towels. In this particle, the test procedure was named "hot-airflow cleaning".

To quantify the effect of parameters of hot airflow on the anti-adhesion mechanism of wet sticky threshed rape mixture to adhesion interface, the escape rate was defined as:

$$\varphi = \frac{m - m_t}{m - m_s} \times 100\% \tag{3}$$

Where: φ represents the escape rate, m represents the mass of wet sticky rape mixture and sieve before each test (g), m_t represents the mass of wet sticky rape mixture and sieve after each test (g), m_s represents the mass of circular sieve (303 g).

RESULTS AND DISCUSSION

The five levels of temperature were selected over a range of 26-60°C, the wind speed and the fan inclination were set at 4 m/s and 30°,respectively and the escape rate on the circular sieve as a function of temperature was shown in Fig.4. It can be seen that with the increase of temperature, the escape rate of threshed rape mixture shows an increasing trend as a whole. When the temperature is below 30°C, the escape rate does not exceed 30%, and the effect of reducing adhesion on the circular sieve is not significant. Because the adhesion force is far greater than wind force when the temperature is low, most of mixture cannot leave the sieve surface. In the range of 30-50°C, with the increase of temperature, the escape rate increases rapidly. When the temperature is 50°C, the escape rate exceeds 60%. The escape rate changes a little when the temperature ranges from 50-60°C, and the anti-adhesion property is gradually stable.

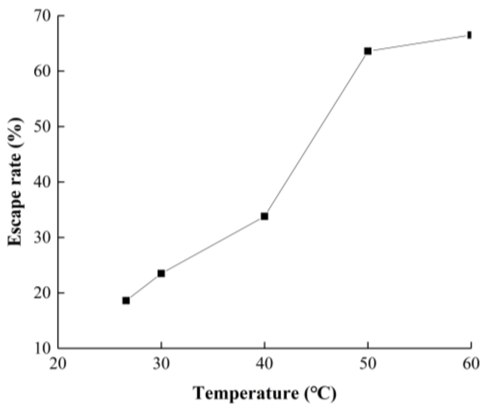


Fig. 4 - Escape rate on the circular sieve as a function of temperature

The five levels are determined over a range of 2-6 m/s, the temperature and the fan inclination are selected at 40°C, 30°C, respectively and the escape rate on the circular sieve with increase of wind speed is shown in Fig.5. It can be seen that when the wind speed is 2 m/s, the escape rate is less than 30% and the escape rate increases rapidly as wind speed increases from 2-4 m/s. In the range of 4-6m/s the escape rate increases slowly, with the increase of wind speed, and the effect of wind speed on the anti-adhesion is not significant. The reason may be that the increase of wind speed may cause turbulence in someplace of the square box, resulting in the local wind speed not reaching the actual measured wind speed, thus affecting the anti-adhesion property. Hence the proper value of wind speed is 2-4 m/s.

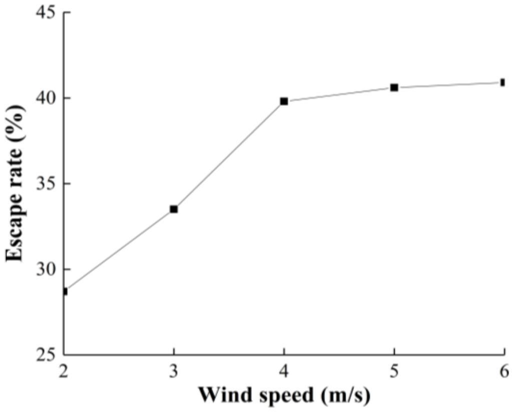


Fig. 5 - Escape rate on the circular sieve as a function of wind speed

Every test was carried out under the condition that the wind speed and temperature were 4 m/s, 30°C respectively. The five levels were selected in the range of 0-60° and the escape rate on the circular sieve with increase of fan inclination is shown in Fig.6. In the range of 0-60°, with the increase of fan inclination, the escape rate increases significantly and then decreases. When the fan inclination is below 15°, the value of the escape rate is less than 30%.There is an inflection point in the escape rate at a fan inclination of 45°, after which the escape rate decreases. The escape rate is more than 60% at the fan inclination of 45°. The reason is that when the fan inclination increases, the normal wind forces subsequently increases, resulting in the anti-adhesion of mixture on the sieve. However, when the fan inclination exceeds the critical value, the tangential wind force will reduce, which is not enough to overcome the friction resistance, resulting in the decrease of the escape rate. Consequently, a better anti-adhesion performance should be achieved from 15-45°.

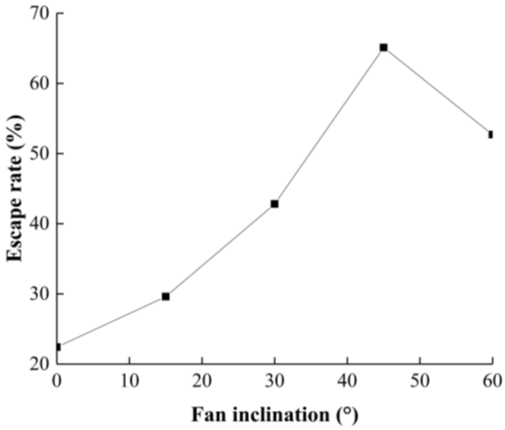


Fig. 6 - Escape rate on the circular sieve as a function of fan inclination

The suitablefan inclination, temperature and the wind speed of the circular sieve outlet were determined to be factors based on the results of the single-factor experiments. Subsequently, orthogonal experiments considering the three factors and three levels were conducted. The escape rate between the threshed rape mixture and sieve were chosen as the evaluation index to the analysis factors that affected the optimal parameter combination. The levels of the factors and results are shown in tables 2 and 3, respectively. Furthermore, ANOVA for response surface analysis was conducted to determine the effect of three factors on the escape rate, as shown in Table 4.

Table 2

Levels of the factors

Level	Factors		
	Temperature A [°C]	Wind speed B [m/s]	Fan inclination [°C]
1	30	2	15
2	40	3	30
3	50	4	45

Table 3

Results of the orthogonal experiments

No.	A	B	C	φ
1	50	4	30	64.2
2	30	3	45	50.7
3	40	3	30	42.2
4	50	3	15	58.6
5	40	4	45	66.1
6	40	3	30	34
7	50	3	45	59.3
8	40	4	30	64.2
9	40	2	45	35.2
10	50	2	30	47.1
11	30	2	30	12.6
12	30	3	15	10.9
13	40	2	15	28.5
14	30	4	30	20.7
15	40	4	15	30.4

Table 4

ANOVA for response surface analysis

Difference source	Sum of squares	Df	Mean of squares	F	P-value
Model	4312.34	9	479.15	23.92	0.0014
A	2254.56	1	2254.56	112.54	0.0001
B	462.07	1	462.07	23.07	0.0049
C	859.05	1	859.05	42.88	0.0012
AB	20.25	1	20.25	1.01	0.3609
AC	382.20	1	382.20	19.08	0.0072
BC	210.25	1	210.25	10.50	0.0230
Lack of fit	66.55	4	16.64	0.49	0.7718
Pure error	33.62	1	33.62		

Values of "P Value" less than 0.0500 indicate model terms are significant. So, the regression model is reliable to optimize the escape rate of threshed rape mixture to cleaning sieve. The key factors affecting the escape rate are as follows: temperature, fan inclination, wind speed. Meanwhile, table 4 demonstrates that the interaction between temperature and fan inclination and between wind speed and fan inclination had significant effects on the anti-adhesion performance of threshed rape mixture. The best combination of parameters for the escape rate was obtained by the optimization of the regression model (software: Design-Expert 8.0.6), which was $A_3B_3C_3$.I.e. The temperature and air speed of the cyclone separator outlet were 50°C, 4 m/s, respectively and the fan inclination was 45°.

The above analysis shows that the hot airflow can effectively reduce the adhesion of the waste on the screen surface, while there was no 220V alternating current in the combine harvester when working in the field, so it is necessary to find a scheme to replace the electric heating. The effective work of output heat equivalent of diesel engine only accounts for 30~40% of the input heat equivalent and the rest of the heat is discharged into the air in the form of hot airflow of the radiator and exhaust, which causes heat loss and even more serious pollution to the environment. The waste heat recovery technology has been widely used in automobile, and its reliability and economy have been confirmed (*Lin G. et al., 1994*). There are two modes of engine waste heat for heating: one is to use the heat of cooling water, the other is to use the heat of exhaust gas. Both of them could run without additional heating on the automobile, and the power consumption of the engine would not increase (*Fen L. et al, 2010*). In order to save costs, the waste heat recovery technology has not been widely used in domestic harvesters. However, with the development of large-scale and intelligent combine harvesters, more and more combine harvesters begin to be equipped with air conditioning to provide a good working environment for farmers. The hot air cleaning system proposed in this paper requires high efficiency and low-cost heat source, so the feasibility analysis is carried out below. Radiator was considered as the heat source for “hot-airflow cleaning” firstly, the temperature and wind speed of radiator were measured when the engine was working in the field test, as shown in Fig.7, Table 5 and Table 6.

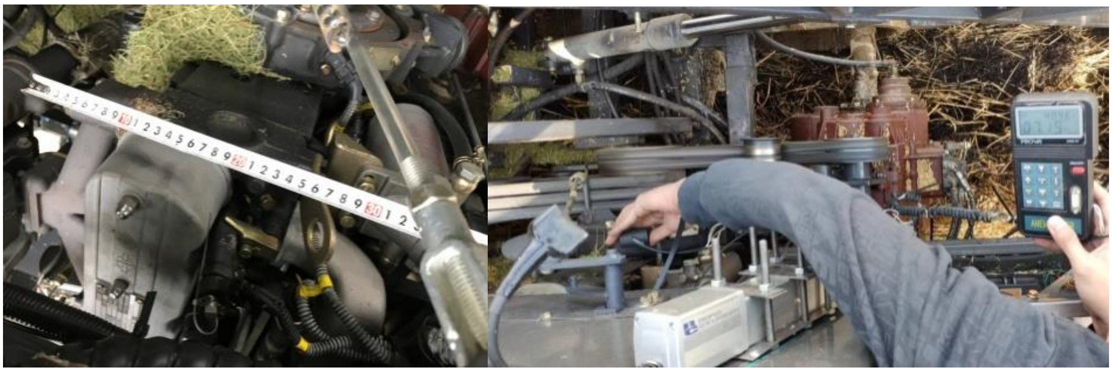


Fig. 7 - Field measuring

It can be seen that the temperature is from 47~51°C and wind speed ranged of 8~10 m/s, which indicate that the radiator can produce enough energy for the anti-adhesion between threshed rape mixture and cleaning sieve. Engine radiator is a good source of hot air, the next challenge is how to collect the hot air of radiator and import it into the cleaning room, which is not discussed here.

Table 5

Wind speed of radiator

Measuring points	Times[m/s]			Average
	1	2	3	
1	10.1	9.6	9.6	9.77
2	10.2	9.9	10.1	10.07
3	7.8	7.8	8.5	8.03
4	9.8	9.6	9.1	9.50
5	9.6	8.8	10.0	9.47

Table 6

Temperature of radiator

Measuring points	Times[°C]			Average
	1	2	3	
1	46.4	47.2	48.3	47.30
2	47.5	47.9	46.4	47.27
3	50.8	52.0	50.2	51.00
4	48.6	49.5	49.9	49.33
5	51.3	51.6	48.8	50.57

CONCLUSIONS

The adhesion interface model of wet sticky rape material and cleaning sieve surface was constructed. The force of wet sticky rape material on the circular screen surface was analysed and the mechanism of hot airflow on the adhesion interface was revealed. The analysis showed that the factors affecting the anti-adhesion performance were wind temperature, wind speed and fan inclination.

The single-factor experiments showed that hot airflow can effectively reduce the adhesion of wet sticky threshed rape mixture on the cleaning sieve. The escape rate is positively correlated with temperature and wind speed. When the fan inclination was 45°, the escape rate reached the peak. In addition, the proper temperature of ventilator was 30-50°C. The proper wind speed and inclination of ventilator were 2-4 m/s and 15-45°, respectively. The interaction between parameters of the fan was studied by orthogonal experiments. The results illustrated that the interaction between temperature and fan inclination had significant effects on the anti-adhesion performance of threshed rape mixture. The optimal working condition of ventilator occurred at a temperature of 50°C, a wind speed of 4 m/s and when fan inclination was 45°. Through the field test, the sufficient temperature and wind force for the anti-adhesion between moist threshed rape mixture and cleaning sieve could be provided by the engine radiator, which is a good source of hot air for “hot-airflow cleaning”.

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