

Dynamic model for sucking process of pneumatic cutting-type safflower harvest device

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Abstract: This study proposed a method using negative pressure sucking the petals adhered around cones. The structural parameters of the sucking device affect the flow-field distribution in the negative-pressure air chamber. In order to improve the harvesting efficiency and quality of the pneumatic cutting-type safflower harvest device, a dynamic model was established and the safflower petals upwind area were measured. According to the test, the size parameters of the thornless Yumin safflower were as follows: the average necking diameter was 6.30 mm, the average capitulum diameter was 20.89 mm and the average petal length was 22.39 mm. The measured maximum frontal area of the safflower petal was 11-40 mm². Secondly, the required negative pressure power that resulted in the rise of safflower petals was calculated. In general, when the suction of the negative pressure reaches 9.8 m/s, the safflower petals can be sucked successfully. The simulation of the flow field in the suction mouth indicated that the streamlined suction mouth was beneficial in reducing resistance and the test results of high-speed photography showed that the aforementioned condition could improve the efficiency of the upright safflower. And the test verified that the rate of the unshaped petals in the cylindrical air tunnel was low and the efficiency of carding and shaping under negative pressure was considerably better in wet petals than in dry ones. Results of the upright safflower petal experiment were consistent with the theoretical analysis and simulation conclusion, and indicated the precision of the dynamic model and suction flower mouth orifice-shaped simulation analysis.

Keywords: safflower petal, pneumatic harvest device, dynamic model, sucking process

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1 Introduction

Safflower is an annual oil and medicine plant with a growth cycle of 120 d. Safflower seeds are primarily

used for oil production, while safflower petals are used for extracting natural pigment and for medicinal purposes^[1-3]. The safflower harvest period is generally from the end of June to the beginning of September. Currently, the safflower is mainly harvested by human hand, which is labor-intensive and inefficient, and even leading to lack of time for picking^[1,4]. Therefore, the low efficiency of safflower petals has restricted the large scale development of safflower, and developing a mechanized harvesting system for safflower is urgently needed.

Safflower is generally harvested on the third day after the flowering period when both the yellow pigment and adenosine contents are high^[5], which will have good medicinal value. However, with the decrease of moisture content, these petals eventually adhered around

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cones, increasing the difficulty of picking. The research and development of safflower harvester mostly are based on pneumatic or cutting harvest principle^[6-9].

The cutting harvester harvests the safflower by using the tool rotary movement^[8]. Accurately positioning the cutting side of the blade is difficult when cutting safflower petals. Consequently, these petals break easily, which decreases the efficiency and quality. The air-blast harvester uses a flower-sucking channel which is aligned with the safflower petals when harvesting. The fan of this equipment produces negative pressure in the airflow field. So the petals are separated from the cones using the flow field effect. However, harvest efficiency decreases and power consumption of the fan increases because the petals pile up.

The aforementioned two existing models are unable to yield a good harvest result; we proposed a method using negative pressure sucking the petals adhered around cones and then cutting them with the rotating tool. The harvesting process of the airflow pressure cutting combined safflower petal harvesters comprises three stages: 1) combing and shaping: safflower petals are combed and shaped to a vertical state by the action of negative airflow field pressure; 2) cutting: safflower petals are separated from the cones by rotary blade action; and 3) collecting and conveying: after separation, safflower petals are collected and conveyed to the storage room through the action of negative airflow field pressure.

This harvesting method can improve both the harvesting efficiency and quality of safflower petals. The structural parameters of the sucking device affect the flow-field distribution in the negative-pressure air room. With the airflow carding and shaping process as the study object, dynamic model of the safflower petals was established to analyze the carding and shaping mechanisms of the airflow field and the airflow change rule.

2 Materials and methods

2.1 Materials

In this study, the thornless Yumin safflowers were used along with varieties of oil-flower. Safflower had a height of 80-100 cm. The minimum length of the

branches of the plant was 35-40 cm. The entire flower ball of safflower reached 10-30 cm. The plant samples used in this study were provided by the Yumin County Technology Bureau Seed Station.

2.2 Parameters measurement methods

Figure 1 shows that safflower clusters are coronal in their natural state. With the decline of water content, the safflower petals wither and adhere around cones.



Figure 1 Forms of safflower after flowering in different days

Referring to the standard NY/T1133-2006^[10], 100 plants were marked. Then we selected three capitulum from the top, middle and lower positions of each plant at full-bloom period. Electronic digital display vernier caliper (precision: 0.02 mm) was used to measure the biggest diameters. The diameters of three sepals nearest to petals cluster were selected as the measurement positions, as shown in Figure 2. At last, the arithmetic mean values were calculated and took as the final result.

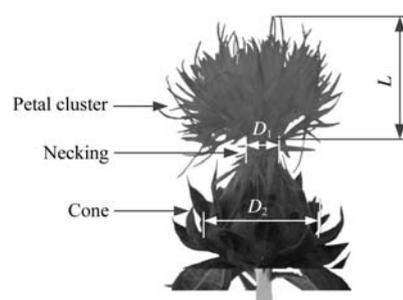


Figure 2 Diameter of the safflower capitulum

Safflowers after anthesis were listed on the tag from the first to the sixth day when these flowers were measured. The safflowers were harvested for five consecutive days at 9:00. The joints of the petals and flower balls are sheared laterally; thereafter, the petals are horizontally placed on white paper with the corresponding length marks. A tripod was used to focus the camera directly on the petals and the segment of length identification under the conditions of the same height and focus. Electronic image software was used to measure and analyze the projection area of the petals perpendicular to the direction of the surface by the calibrated length of the line pixel. The value of the

obtained projected area is the maximum frontal area of the safflower petals. The process of calculating^[11-13] safflower petal length and area with Digimizer is shown in Figure 3.

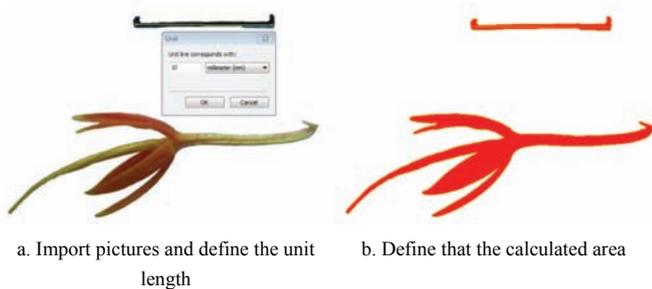
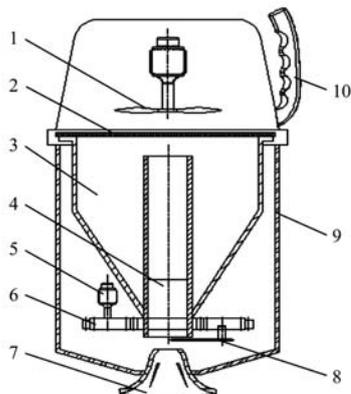


Figure 3 Process of calculating safflower lengths and areas with Digimizer

2.3 Efficiency measurement method

Figure 4 shows the combing and shaping device of safflowers including the positioning mouth of the safflower cones, suction fan, and airflow channel. When the machine works, the negative pressure fan rotates to generate air stream while the harvesting process is in progress. The coronal safflower petals reach the vertical state, carded, and shaped by the negative airflow pressure in the flower-sucking channel. The joints of the petals and cones are both exposed. The planetary gear transmission device drives the tool to cut following the motor rotation so as to separate the petals and cones. The petal cuts are conveyed to the storage room of flowers by means of the negative pressure action. The airflow discharges backward and the petals are left in the storage room of flowers. This process can separate gas and solid, and complete the conveying and collecting of the safflower petals.



Note: 1. Negative pressure fan 2. Filtration system 3. Collection device 4. Air tunnel 5. Motor 6. Planetary gear train 7. Fruit positioner 8. Cutting tool 9. Shell 10. Handle

Figure 4 Working principle diagram of the safflower petal harvest device

In the same working condition, both the structural parameters of the airflow passage and the distribution of the internal airflow field are different^[14-15]. Therefore, the structural parameters of the combing and shaping device and the selection of the suction fan are crucial factors that affect the efficiency and quality of the process^[16-19].

At standard atmospheric pressure, the air density is 1.2 kg/m³^[20]. The calculation of the airflow field Reynolds number is $Re=18665.2 > 2300$ in the flower suction nozzle of the carding and shaping device where the safflower petals are placed. Therefore, the airflow field of the carding and shaping device is identified as the turbulence when the device is working.

The working flow of the pressure source is 310 m³/h, while the airflow inlet diameter of the carding and shaping device is 20 mm. At normal temperature, the specific heat ratio of the gas is $K=1.4$, the gas constant is $R=287$ J/kg·K, the absolute temperature is $T=293$ K. Whether the gas can be compressed is judged through the Mach coefficient Ma , which is calculated as below Equation (1):

$$Ma = \sqrt{\frac{v^2}{KRT}} \quad (1)$$

where, V is the fluid velocity, m/s; K is the gas specific heat ratio; R is the gas constant, J/kg·K; T is the gas constant in K.

Mach number $Ma=0.13 < 0.3$ is obtained by calculating the Mach coefficient; thus, gas can be calculated in an incompressible way.

Figure 5 shows the equipment and systems used in this study, including a Canadian CPL-MS70K-speed camera, fan, clamping device, image display, and processing system.

The high-speed camera was directly focused on the safflower ball^[21-24]. Thereafter, the MS70K-DMG2 system was turned on and the parameters were set. The light source and the focal length were adjusted until the safflower petal was clearly displayed on the image display system. A distance of 5 mm was assigned between the upper part of the safflower petal and the bottom part of the suction channel. The fan was then turned on. The process of the upright safflower petals

being carded and shaped was recorded using the high-speed photography system. Then, the frames from the original to the final state were observed and recorded. Therefore, the time required for carding and shaping the safflower petals can be calculated.

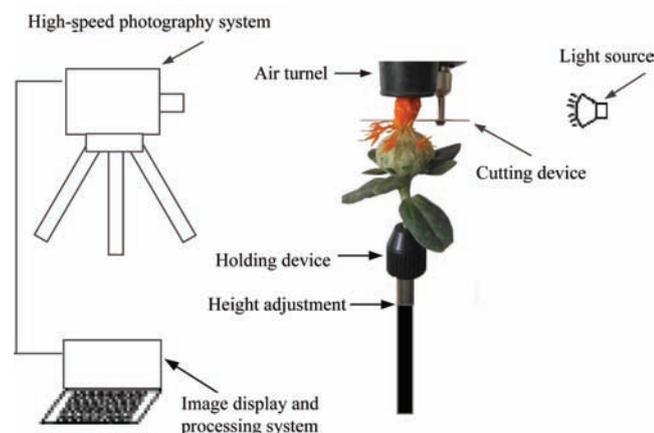


Figure 5 Safflower petals upright test system

3 Results

Table 1 shows the parameter data of the safflower. The average necking diameter is 6.30 mm. The average capitulum diameter is 20.89 mm and the average petal length is 22.39 mm.

Table 1 Measured results of the dimension parameters

Test parameters	Parameter values				
	Max	Min	Ave.	Stand	CV
Necking diameter D_1 /mm	6.98	5.54	6.30	0.41	65%
Fruit ball diameter D_2 /mm	23.66	17.01	20.89	1.94	93%
Petal length L /mm	28.49	15.75	22.39	3.41	152%

Figure 6 shows the filaments change process of surface area and moisture content changes are consistent. The data measured are analyzed by using statistics method. The maximum frontal areas of the safflower petals are between 11-40 mm². In the process of carding and shaping, from the center to the outer edge of the corolla, safflower gradually achieves the vertical state from the natural state, the data of specific test results are listed in Table 2.

Based on the above experiment, the safflower petals gradually transform from the natural state to the upright state. A contrast test shows that the number of unshaped petals is less in the cylindrical air tunnel; the time required for carding and shaping the petals is also considerably shorter in this tunnel than in the cylindrical

pipe. These results are consistent with the previous theoretical analysis and flow field simulations. Therefore, the transverse velocity gradient flow field is obtained by opting for the shrinkage pipe to design the suction channel.

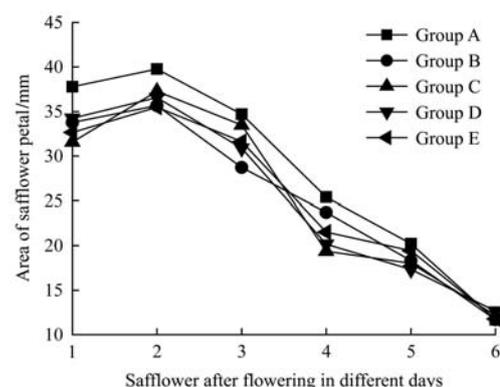
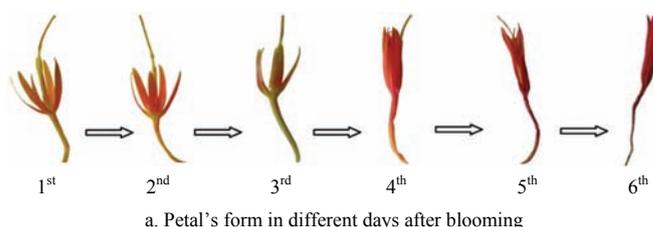


Figure 6 Petals' surface areas and forms in different days after blooming

Table 2 Experimental results of carding and shaping

Test parameters	Cylindrical tube		Contraction tube	
	Fresh flower	Dried flowers	Fresh flower	Dried flowers
Finishing carding and shaping average time/s	0.47	1.24	0.12	0.17
Mass of safflower sorted out/g	0.301	0.221	0.375	0.34
Mass of plastic not combed/g	0.044	0.035	0.005	0.016
Carding and shaping rate/%	87.25	86.33	98.68	95.51

4 Discussion

4.1 Stress analysis of safflower in the airflow

The motion of the safflower petals in the airflow field is a gas-solid two-phase flow^[12,13]. The trajectory and orientation of the safflower petals is described by using the Lagrange method. The length-width ratio of the safflower petals is 5.1:7.3 by calculation. The fluid is a continuous medium and the safflower petals are in a dilute phase; thus, the disturbance of the safflower petals to the flow field can be ignored. Both the interaction and friction generated by the safflower petals can also be ignored. The length of the safflower petals is

significantly shorter than the characteristic scale of the airflow field. Therefore, the motion of every safflower petal can be regarded as a Stokes flow.

With the vertical upward airflow of the negative pressure fan in the carding and shaping process, the safflower petals from the static state in the flow field rotate, rise, and erect around the fulcrum of the necking, as shown in Figure 7a. The trajectories, spatial distribution, and orientation distribution of safflower petals in the flow field depend on the forces and moments acting on these petals, the stress analysis of the safflower petal in airflow is shown in Figure 7b. The flow around resistance forces F'_r , air buoyancy F'_b acting on the petal and gravity F_g . According to reference^[14], they can be calculated as Equations (2)-(4):

$$F'_r = \frac{1}{2} C A_t \rho_f v^2 \quad (2)$$

where, A_t is the frontal area, m^2 ; v is the relative velocity between the air and safflower petals, m/s ; C is the air resistance coefficient; ρ_f is the air density, kg/m^3 ; α is the attitude angle, ($^\circ$), which is the angle between the axis of the safflower petals and the axis vertical to the ground.

$$F'_b = \frac{m}{\rho_s} \rho_f g \quad (3)$$

$$F_g = mg \quad (4)$$

where, ρ_s is the safflower petal density, kg/m^3 ; m is the safflower petal mass, kg ; g is the acceleration caused by gravity, m/s^2 .

4.2 Critical starting speed of the safflower petals during carding and shaping

When the average wind speed has a critical value under the negative pressure flow, the safflower petals break away from the static state by means of the negative pressure to achieve upward acceleration. Figure 7 illustrates that the sum of the upward force of the safflower petals is higher than that of the downward force. Where the vertical direction forces of the safflower petal in airflow is the F_r , F_b and F_g . They are expressed as Equations (5) and (6):

$$F_r = \frac{1}{2} C A_t \rho_f v^2 \sin \alpha \quad (5)$$

$$F_b = \frac{m}{\rho_s} \rho_f g \cos \alpha \quad (6)$$

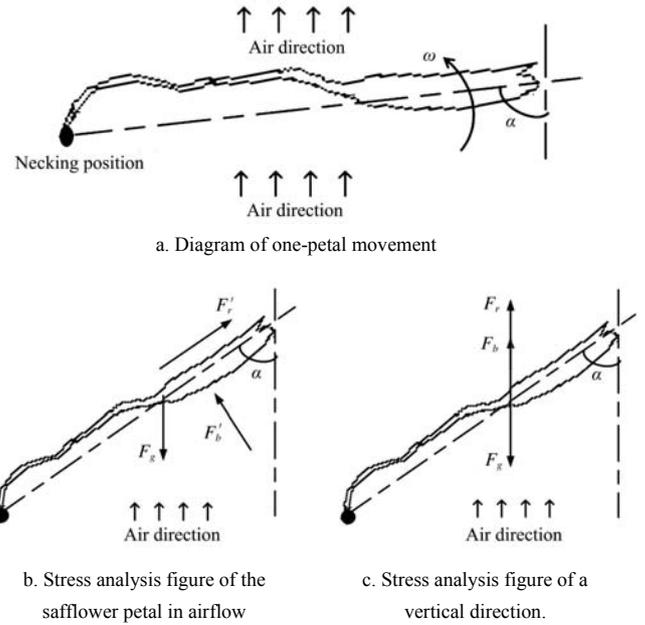


Figure 7 Force analysis diagram of the safflower petal in airflow during upright process

Their relationship is represented as Equation (7):

$$F_r + F_b > F_g \quad (7)$$

When the materials are at a critical speed of suspension or deposition, Equations (4)-(6) are substituted into Equation (7) based on the aerodynamic principle. The boundary conditions are as Equation (8):

$$mg = \frac{m}{\rho_s} \rho_f g \cos \alpha + \frac{1}{2} C A_t \rho_f v^2 \sin \alpha \quad (8)$$

Therefore, the critical speed v_t of the safflower petals is calculated by Equation (9):

$$v_t = \sqrt{\frac{2mg(\rho_s - \rho_f \cos \alpha)}{A_t C \rho_s \rho_f \sin \alpha}} \quad (9)$$

From Equation (9), the critical velocity of the safflower petals is inversely proportional to the air resistance coefficient and frontal area.

The frontal area of the safflower petals is the projection area of these petals in the direction perpendicular to the relative velocity that are directly related to the attitude angle (Figure 7). The relationship between actual frontal area and maximum frontal area is shown in Equation (10):

$$A_t = \frac{A}{\sin \alpha} \quad (10)$$

where, A is the projection area of the safflower petals placed on the horizontal plane, m^2 , it is the maximum frontal area of the safflower petals; A_t is the actual frontal

area of the safflower petals.

The natural attitude angles of the safflower petals related to their maturity are typically between 0° - 160° . Safflower petals are slender and their surface structures are also different depending on maturity levels. The surface structures of these petals are far from the sphere; thus, they cannot be handled by an equivalent sphere.

The maximum frontal area of the safflower petals are between 11 mm^2 and 40 mm^2 . Based on standard atmospheric pressure using hydrodynamics, the split point of the boundary layer is stable when the pressure is $10^3 \leq Re \leq 2 \times 10^5$; the drag coefficient C is substantially constant with a value of approximately 0.44.

The petal quantity of a single safflower is between 0.121-0.456 g, while the density is between 120-196 kg/m^3 . Calculation using Equation (9) shows that the critical speed is between 19.29-19.8 m/s.

4.3 Relationship between gas velocity and cross-section area of the flow channel

The safflower petals can obtain different motion characteristics when the structural parameters of the channel are altered under the same negative pressure power. This study opts for the flow field in the circular tube and contract. The effects of the velocity gradient when the safflowers move in the flow field, as well as the orientation distribution of the petals, were compared.

Negative pressure generated by the fan is sent directly to the safflower petals through the absorption channel. Therefore, the flow-field distribution inside the absorption channel directly affects the efficiency and effectiveness of the safflower petals in the sucking processes. The cross-section of the absorption channel under the same negative pressure is generally different; the distribution of its internal flow field is also different. These differences result in the safflower petals acquiring different moving properties. The commonly used cross-sectional shapes have a cylindrical, shrinking, and intestinal tubular. The relationship between the gas velocity and cross-sectional area of the flow channel can be analyzed using the formula for the fan flow rate.

The fan flow rate, which is the product of wind speed and cross-sectional area of the wind tunnel, is expressed in Equation (11):

$$Q = v \cdot A_j \quad (11)$$

where, Q is the fan flow rate, m^3/s ; v is the gas velocity, m/s ; A_j is the cross-sectional area of flow channel, m^2 .

When the fan flow rate is consistent, the flow obtains an accelerated motion along the streamline and its cross-sectional area of flow must be gradually reduced. The absorption channel should also be a shrinking tube to obtain a gradient flow field of transverse velocity, thereby resulting in the safflower petals turning from static to critical starting. The carding and shaping of safflower petals will be achieved under the action of gas flow.

The flow field of contraction refers to fluid flowing into a wide mouth and flowing out of a narrow one. Table 1 presents the detailed parameters of the structure. The inlet flow size of the flower channel is slightly larger than the maximum value of the safflower diameter $D2$ (25 mm). The outlet size is the maximum value of the necking diameter $D1$ (7 mm). Although the pipeline length is slightly longer than the maximum petal length L , with the value of 30 mm, the conical angle of the shrinkage cast is 34° .

4.4 Simulation for airflow velocity changed result

Airflow velocity is the primary factor that affects the movement efficiency of the safflower petal carding and shaping in the suction mouth. This condition determines the value of airflow force on the safflower petals. Based on the analysis, the suction mouth alters the flow type and airflow velocity. This study simulated and analyzed the relationship between the flow type and the airflow velocity using fluid analysis software.

Table 3 presents the natural characteristics of air, including flow density, viscosity, specific heat, and conductivity when the simulation was conducted using fluid analysis software. According to stability analysis, the flow type is incompressible and the airflow field is turbulent. The initial velocity of the suction mouth reached 19.8 m/s, which was the critical velocity of the safflower petals.

Figure 8 presents the results of the flow-field simulation, showing that no gradient of the velocity is present in the cylindrical tube (Figures 8a, 8b). The outlet velocity of approximately 20 m/s is slightly different from the inlet velocity. To obtain a higher

airflow velocity, fan power should be increased to make the safflower petals proceeding to the airflow direction. However, this process leads to extensive power consumption and prevents a good result in carding and shaping the safflower petals.

Table 3 Parameters of air simulation design

Temperature /°C	Density /kg·m ⁻³	Thermal conductivity /W·m ⁻¹ ·K ⁻¹	Specific heat /J·kg ⁻¹ ·K ⁻¹	Viscosity /Pa·s ⁻¹	Kinematic Viscosity /m ² ·s ⁻¹
30	1.2	259	1.005	18×10 ⁻⁵	1.5×10 ⁻⁵

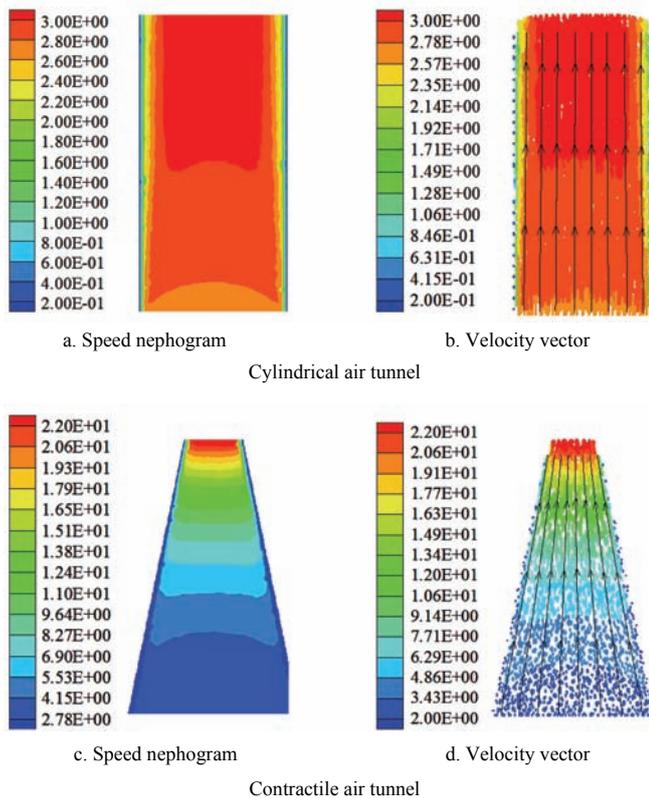


Figure 8 Flow field simulation of the suction tunnel

Combined with the shape of the safflower fruit, the reduction angle of the shrinkage pipe is set as 34° based on fluid dynamics. Figure 8c and 8d illustrate the results of the flow field simulation. A gradient of the velocity was observed with an outlet velocity of approximately 160 m/s. The kinetic energy reached the maximum level because of the velocity coefficient in the pipe. The safflower petals can easily exceed the critical velocity under the action of airflow; thus, the carding and shaping become faster and better.

Based on the preceding analysis, the results of the flow field simulation are consistent with the conclusions of the theoretical analysis. Therefore, with the large opening inflow and structure outflow, the shrinkage pipe

is more suitable for carding and shaping the safflower petals.

5 Conclusions

1) The dynamic model for safflower petals carding and shaping was established in this study. Under normal conditions, this model proved that the air pressure had a direct relationship with the air resistance coefficient, frontal area, and quadratic in velocity. Therefore, the reduction angle opposite the corolla could decrease the frontal area of the safflower petals. In general, when the suction of the negative pressure reached 9.8 m/s, the safflower petals carding and shaping could be successfully completed and it could prepare the best posture for cutting separation.

2) According to the test results, average size parameter values of the thornless Yumin safflower were as follows: the average necking diameter was 6.30 mm, the average capitulum diameter is 20.89 mm and the average petal length was 22.39 mm. The measured maximum frontal area of the safflower petal was 11-40 mm².

3) The finite element model of the airflow field in the suction mouth was established by conducting a simulation of the flow field in the suction mouth. The results indicated that the streamlined suction mouth was beneficial in reducing resistance. The bench test verified that the rate of the unshaped petals in the cylindrical air tunnel was low and the efficiency of carding and shaping under negative pressure was considerably better in wet petals than in dry ones.

Acknowledgements

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