Development of an Improved Cereal Stripping Harvester

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ABSTRACT

Theoretical analysis and experiment validation were conducted to optimize development of improved stripping harvesters. The header loss of the stripping harvesters was greatly influenced by parameters such as the height and rotational speed of the stripping rotor, the forward velocity of the machine, and the airflow field, etc. Mathematical models for the optimal design and the use of stripping harvesters were developed. During the operation, the center axis of the stripping rotor must be at the height below the ears of crops. When the cylinder was running, the linear velocity of the stripping teeth should be up to14 – 17m/s (the keyhole center of slotted teeth). Also, the airflow velocity at the entrance should be higher than that at the exit and should not be lower than 5 m/s.

Keywords: Cereal harvesting, threshing prior to cutting, stripping, models, China

1. INTRODUCTION

Many researchers have devoted their interest in development of the stripping harvest technology since 1984. Stripper harvesting is an approach of the threshing prior to cutting, which "differs from conventional cereal harvesting methods by removing only grain, leaf and a proportion of straw, leaving most straw in place" (J. S. Price, 1993). The advantage of this innovative technology is it can increase production capacity, reduce power consumption, and possibly reduce header loss. "Compared with a conventional cutting table, straw intake by the stripper header ranged from a few percent of the straw yield in early standing crops to ≈50% in over-mature crops which were laid and tangled. In consequence, under normal conditions the grain output of the combine harvester was increased by over 50% to more than 100% at identical loss levels" (Klinner et al., 1987). Also "the proportion of crop threshed in this way varies in different crop conditions but typically in wheat it is around 80%." "Removal of material other than grain (MOG) ranged from less than 1% to 25% representing chaff only." "Stripping offers considerably increased work rates due primarily to the reduction in material other than grain (MOG) harvested and the consequent increase in grain separation efficiency." (Price, 1993). Moreover, the stripping technology may be able to resolve problems confronted by traditional combine harvesters. In fact, "in performance terms the design of present-day combine harvesters has two major shortcomings. One is that header losses increase with crop maturity from the time combine ripeness is reached. In particular, the loss can be correlated with the progressively decreasing height above ground of the seed-bearing heads. In difficult, late-season crop conditions, front-end losses can amount to several percent of the grain yield, and over the whole of the harvest period they can total more than the drum, shaker and sieve losses combined. The second shortcoming is that combine harvester performance depends critically on the straw throughput; reduction in the straw intake leads automatically to higher potential work rates. For these reasons, headers which can strip the seed from the crop can materially influence harvester design and performance, and possibly even harvesting technique.” (Klinner et al., 1987).

“A horizontal stripping rotor carrying eight banks of comb-like stripping elements rotates at appropriately 650 rev/min, speed being adjusted to suit different crop conditions” (Price, 1993). It works as follows: “Flexible comb-like elements on the stripping rotor pass upward through the crop” (Price, 1993). Crops standing in the fields are channeled into the working area of the rotor by the device called "guide nose" – the leading edge – on the stripping header. Then the heads of cereal plants are immediately stripped. As a result, the heads and pedicels are pulled apart by the stripping elements. Being stripped off and obtaining an initial velocity, the mixture of grains moves backward along the inside of the upper hood and finally drops into the conveying auger because of the inertial force and the airflow field force, which are produced by the rotating cylinder, as seen in Figure 1. Thus the primary characteristic of the harvester is that most of the straw does not enter the machine, which essentially distinguishes the stripping from traditional full-feed combines.

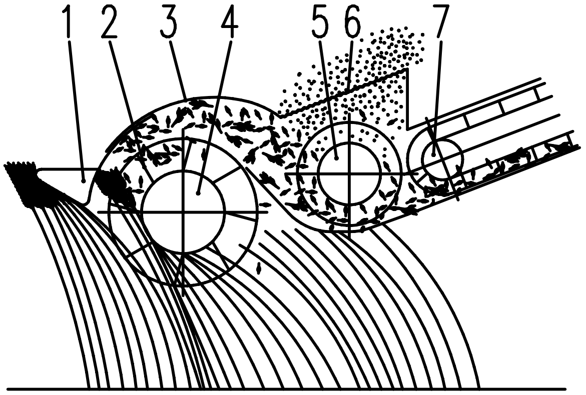

Figure 1 Working principle of stripping harvest

1—Leading edge 2—Stripping teeth 3—Upper hood

4—Stripping rotor 5—Conveying auger

6—Airflow exit with mesh 7—Conveyor

In general, the amount of loss in the harvester depends on the splashing at the entrance of the leading edge, turning back of the stripping cylinder, and un-threshed heads etc. The factors produced can be attributed to the height of the rotor axis from the ground, rotating speed of the roller, forward speed of the machine, oblique angle of the stripping teeth, the hood’s leading direction, horizontal clearance at the entrance, the vertical clearance of the leading edge of the rotor hood relative to the bottom-dead-centre level of the stripping rotor (Klinner et al., 1987), kinematical parameters and structure of the auger, formation and its effect of the airflow field, and so on. Some investigations revealed that either over 75% (Glancey, 1997) or around 70% (Li et al., 1998) of the total field loss occur at the stripping header. Furthermore, “the results of single and multi-factorial experiments showed that the effect of the horizontal to the teeth tip at the entrance and the vertical clearance of the hood nose relative to the rotor center are the most important to grain losses, rotational speed and forward velocity are less important. The developed regression models revealed the interaction between the parameters and threshing performance.” (Jiang et al., 2000).

2. MATERIALS AND METHODS

This article concerns the kinematical and aerodynamical analysis of stripping harvest process to the rice and wheat. A trial 1.5 m wide stripping combine harvester fitted with rubber-track driving device was used for the whole research, as shown in Figure 2. Two different stripping rotors of 500 mm and 560 mm diameter were arranged in circumferential spacing of eight rows comb-like stripping elements with keyholes (shaped as Figure 3).

The working process of the stripping header is the primary issue that needs to be realized and analyzed.

Figure 2 A trial prototype of 1.5 m wide stripping combine harvester with rubber-track driving device

3. RESULTS AND DISCUSSION

Kinematic Analysis of the Stripping Header — Flying Direction of Grain Stripped

When a stripping combine works with forward velocity v_m and the stripping rotor turns with rotary speed n as well, the combs have correlative circumference velocity v_s, and the tracks of points on the teeth show trochoids, as seen in Figure 4. It is evident that the tracks critically depend on the ratio λ between v_s and v_m:

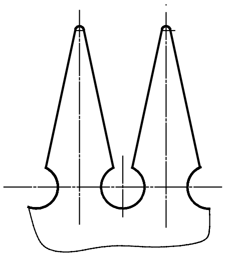

Figure 3 Comb-shaped stripping elements with keyhole-slotted teeth

$$\lambda = \frac{v_s}{v_m}$$

It can be found that *EE*' is the longest horizontal chord on the trochoid, and there is an absolute velocity in vertical direction at the *E* and *E*' points. At points above *EE*', the velocities of teeth have the horizontal backward components that throw threshed grains to the back; while below *EE*', only horizontal forward components are produced and grains cannot be thrown to the back. As a result, E should be the start point from which the heads of corps arestripped by the combs.

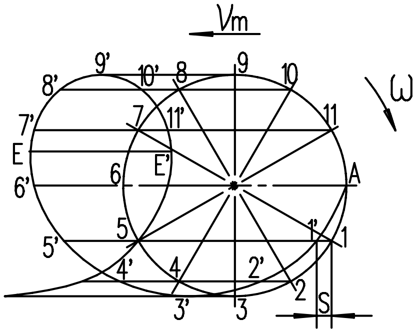

Figure 4 Moving track of the stripping teeth

Figure 5 shows three types of trochoidal paths – long trochoid, trochoid, and short trochoid – that can be separately formed by the different characteristics λ, that is, $\lambda<1$, $\lambda=1$, and $\lambda>1$. It is obvious that there are no horizontal backward components of velocities at any point of curves when the relationships of $\lambda=1$ and $\lambda>1$ exist. So the prerequisite of the normal working for the cylinder is the stripping ratio of velocity $\lambda>1$, or the tooth's tracing path should be a short

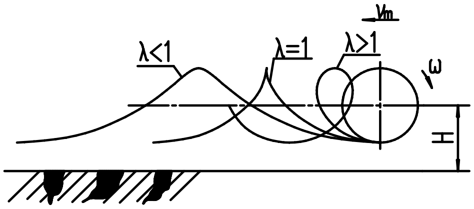

Figure 5 Tooth's tracing paths in three varieties of λ

trochoid. It is known that the roller's rotating speed is one of the significant kinematical parameters. At present, the value of λ all of the designed machines are much more than 1 in; the circling velocity v_s – at the keyhole of a tooth – is usually from 14 to 17m/s. In order to decrease the loss of the stripping cylinder in working, not only is the relation $\lambda>1$ required, but also the corresponding structure and other kinematical parameters should be ensured in the design and performance.

3.1 Start Stripping from Vertical-Upward Velocity Point

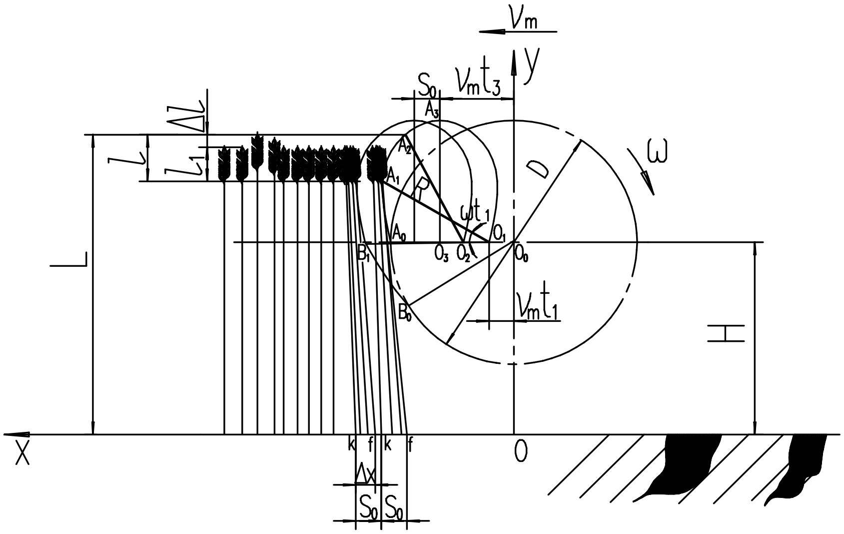

Figure 6 Schematic diagram of the working process of a rotor without leading edge and upper hood

The rotor's working process without the guide nose and upper hood is shown with a simple diagram in Figure 6. In the first instance, it is supposed that crops are on a perpendicular state. It will not be analyzed in this article when crops are on the lodged or even laid states, because it is rather complex and lacks trials.

While teeth begin stripping spikes at the point of the vertical-upward velocity, crops are tangent to the trochoid at the front end point of the maximum vertical chord, and the tangential point A_1 coincides completely with the bottom of the heads. For kinematical analysis, an imaginary coordinate is established: a) the origin of the coordinates is at the point O, the spot that is projected onto the ground from the stripping cylinder center O_0; b) the horizontal axis X along the ground and towards the working direction; c) the vertical axis Y upwards; and d) the initial phase of the stripping tooth at the horizontal position A_0 (Figure 6), then the tooth's displacement equations at any moment t can be shown as.

$$\begin{cases} x = v_m t + R\cos\omega t \\ y = H + \sin\omega t \end{cases} \tag{1}$$

Where: R – the radius of the cylinder; ω – the angular velocity of the cylinder; H – the working height of the cylinder.

As the combs start stripping heads at the vertical-upward point of velocity, its speed component in horizontal direction (v_{1x}) should be zero, as shown in the following expressions:

$$v_x = \frac{dx}{dt}$$

$$v_{1x} = v_m - R\omega\sin\omega t_1 = 0$$

$$\sin \omega t_1 = \frac{v_m}{R\omega} = \frac{1}{\lambda} \tag{2}$$

Where: t_1 – the time parameter when the tooth is at the point A_1.

At the time t_1, as shown in Figure 6, the tooth tip reaches the point A_1, that is, $y = L - l_1 - \Delta l$. Let Eq. (2) is substituted into Eq. (1), and then the following can be derived:

$$H = L - l_1 - \Delta l - \frac{R}{\lambda} \tag{3a}$$

Where: L – the height of crop; l_1 – the head length of crops; Δl – the difference between the highest and lowest plants.

This is the relationship between different parameters, under which crops are stripped below heads and the teeth's velocity is vertically upward. In other words, because A_1 is the entering point of stripping, the equation (3a) also becomes the highest position between the roller shaft and the ground:

$$H_{\max} \le L - l_1 - \Delta l - \frac{R}{\lambda} \tag{3}$$

3.2 Finish Stripping

The stripping action of the tooth A is completed at the point A_2 (Figure 6). The equations (1) can be written in the following form by replacing y with L:

$$L = H + R\sin \omega t_2 \tag{4a}$$

When the table drops until the highest point of tooth tip reaches the point A_3, the tooth's speed component in the vertical orientation, v_{3y}, becomes zero. At this moment, the point A_3 becomes the end-point at which stripping operation finishes. Theoretically, combs still have the horizontal backward component of velocity after it gets over the point A_3. However, this kind of working status is not thought in a normal range due to the limitation of the table structure, which may lead to the straw snapping.) It is shown below:

$$v_{3y} = \frac{dy}{dt} = R\omega \cos \omega t_3 = 0$$

$$\omega t_3 = \frac{\pi}{2}$$

Put the above into Eq. (1) and then make a comparison with Eq. (4a) to obtain the lowest height of the cylinder's axis from the ground:

$$\mathrm{H}_{\min} > \mathrm{L} - \mathrm{R} \tag{4}$$

So the range of the working height can be obtained according to (3) and (4):

$$L - l - \frac{R}{\lambda} \ge H > L - R \tag{5}$$

Where: l – the generalized length of heads, $l = l_1 + \Delta l$.

It is clear that when the kinematical parameter λ and structural parameter R are constant, the height of the stripping cylinder should be adjusted according to the different crop characters, such as the plant's height, the head's length and the length difference (between the highest and lowest crops).

3.3 Relationship between the Cylinder Height and the Stripping Loss

Table 1 shows the stripping loss ratios measured as harvesting keng rice (a kind of rice that is grown in eastern and southeastern Asia) at the different axis heights, H. Testing conditions: rice, the average height of crops – 800 mm, the average length of heads – 90 mm, the average difference of heads' length – 105 mm, the yield of crops – 9750 kg/ha, the diameter of the cylinder – 560 mm, the rotating speed of the cylinder – 546 r/min, the forward velocity of machine – 1.2 m/s (Figure 7).

Figure 7 Stripping combine prototype in the experiment of harvesting rice

Table 1. The loss ratios of the stripping head at different harvesting heights

Cylinder axis heights	Stripping head's loss ratios		Remarks
H (mm)	Kg/ha	%	
510	92.6	0.95	Height calculated to < (4)
535	60.5	0.62	Height calculated to > (4)
584	72.2	0.74	Height calculated to = (3)
650	99.5	1.02	Height calculated to > (3)
674	181.4	1.86	Only $\triangle l$ considered in (3)
690	225.2	2.31	Only l_1 considered in (3)
710	975	3.97	

As seen from this table, there is a smaller loss value of stripping when H is calculated in accordance with the equation (5); while the head is gradually lifted, the loss appears to increase along with the lifting, which is mainly caused by splashing from the guide nose. Furthermore, the loss has a slight rise when H is lower than that value calculated by (4), which is produced by the over-low position of the header. In fact, the table loss mainly comes from two aspects in this state: one is that the nose seriously bends crops and pushes grains down; and other occurs behind the cylinder (reverse of the guide nose) and is caused by the inertia of rotation of the rotor.

3.4 Stripping Capacity of an Individual Tooth

When a tooth moves from A_1 to A_2 (the top of heads), the crops that grow in the range from point f to point k will be collected into a bundle to be stripped, as shown in the Figure 6. This shows that the stripping capacity of a single tooth can be indicated by the line segment $\overline{fk}=\Delta x$. The point f is those crops which are adjacent to the last tooth's working area. The maximum of Δx is $\Delta x=S_0$ That is called the "Effective Action Area" and its value represents the stripping capacity of a single tooth. Suppose that there are Z rows of combs on the cylinder, then:

$$S_0 = v_m \frac{2\pi}{Z\omega} = \frac{2\pi R}{Z\lambda} = \frac{\pi D}{Z\lambda} \tag{6}$$

The equation (6) shows that the stripping capacity S_0 is influenced by the cylinder's structural parameters. That is, it is directly proportional to the roller's diameter D, and is inversely proportional to the teeth's row numbers Z. Therefore, if it is necessary to increase the single tooth's capacity, one way of achieving is to enlarge the diameter D of the cylinder. But it should be noticed that too big a diameter makes the structure larger and also increases its weight. Trials indicate that it will have little influence on the stripping quality if the roller's diameter is in a range of 450 – 600 mm. In addition, the capacity can be increased by decreasing the number of teeth rows. Having a similar opposite effect, excessive reduction of the row numbers will cause more stripping crops to be slanted. In this way, if it is required that crops start to be stripped at the point of vertical-upward velocity, the working height H of the stripping cylinder must decrease. Otherwise, it will certainly lead to increased loss.

The equation (6) further indicates that the stripping capacity S_0 is in inverse proportion to the stripping velocity ratio λ. In other words, the decline of λ, or the increase of the forward speed v_m, can obtain the result of the mono-tooth capacity S_0 enhancement. But even so, too high forward speed will increase the amount of the sloping crops. Hence, if a higher productivity is expected by speeding a harvester forward, the tooth's row number Z should properly be increased in the structural design. As a result, this will tend to decrease the amount of slanted stripping crops, but at the same time, produce the repeated stripping on the next comb, which accordingly raises the ratio of the straw vs. grain after stripping. In contrast, under a low speed state, the mono-tooth capacity S_0 is relatively small. Decreasing the row numbers Z can also have the mono-tooth capacity S_0 that is close to that high speed. A comparison of stripping capacity between two different working speeds is shown in Figure 8. Here, $v_{m1}=3v_{m2}$. It can be seen that the S_0 in Figure 9 (b) is much smaller than that in (a).

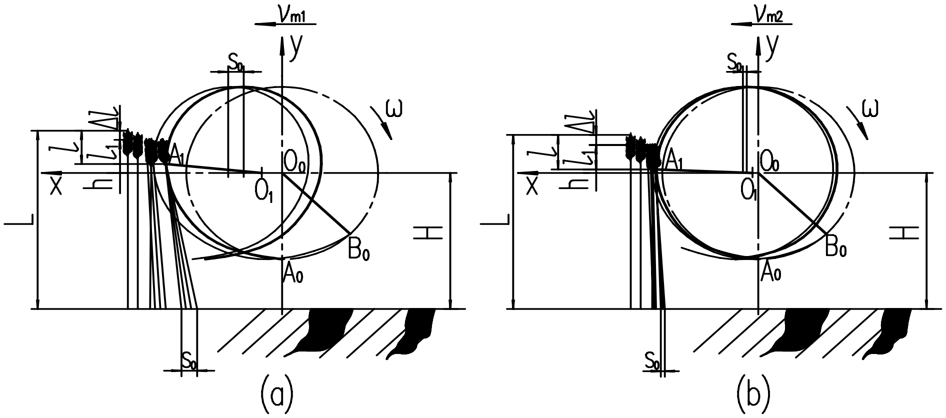

Figure 8 The mono-tooth capacity comparison between two different forward speeds

（a）Forward speed $v_{m1} = 3v_{m2}$ （b）Forward speed v_{m2}

3.5 The Working Speed's Influence on the Stripping Performance

The following is also gained from the Eq. (2):

$$h = R\sin\omega t_1 = \frac{R}{\lambda} = \frac{v_m}{v_s}R \qquad (7)$$

It is obvious that the higher the working speed, the higher the position of the vertical-upward velocity point and the smaller the stripping velocity ratio λ under the same crop conditions. In this case, therefore, in accordance with Eq. (5), the rotor needs to remain a lower working height *H* comparing with the state of slow forward speed.

Figure 9 showed the relationship between the forward speed and the stripping loss rate (testing conditions are same as above except the forward speed). From the graph it can be distinctly seen that both parameters are approximately in a logarithmic function with a negative exponent.

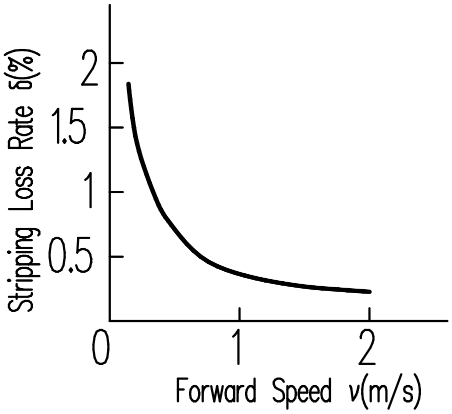

Figure 9 Relationships between the forward speed and the stripping loss

When the forward velocity v_m is between 0.3 to 1.2 m/s, the loss decreases considerably with the increase of v_m. That is mainly because the forward force is not large enough to support harvested crops when v_m is small (0.3 m/s or a bit bigger than 0.3 m/s). Plants have less compression under such a force, and the teeth's action on crops is rather "soft" so that it is not easy to gather crops into bundles for stripping. Because low speed v_m makes small mono-tooth stripping capacity S_0 [Eq. (6)], crops easily produce an effect of "give-up", which leads to parts of grains struck down in an abnormal stripping state. Besides, because the combs have a rather weak capability of controlling the motion orientation of stripped mixtures under low speed, the flying tracks of grains are in disorder. This situation is difficult to develop a steady moving layer of mixtures; hence stripping loss greatly rises. As the forward speed v_m increases, the teeth's action on crops gradually becomes "harder". It helps gathering in the bundles effectively, and the teeth's directional control remains stronger. Therefore, the loss decreases correspondingly. When the v_m is over 1.5 m/s, the extent of reduction of the stripping loss ratio gets quite slow. Comparing this result with that of a previous investigation (Klinner et al., 1987a), an evident discrepancy could be found on the tendency curve in the relationship between the header losses and the forward speed. For instance, their previous research indicated that there was a peak – the loss rising – on the curve when the forward speed was at about 5.9 km/h (1.64 m/s), or the losses on the both sides of this speed point tended to decrease. However, they also said that on several occasions stripping header losses decreased with increasing forward speed. A speed of 7.5 km/h (2.08 m/s) was possible with the stripping header at a slightly lower front end loss of whole or part heads (Klinner et al., 1987b).

With respect to the influence of three factors – forward speed of machine, horizontal front end hood-to-rotor clearance, and vertical relative clearance of leading edge – on header losses, a research based on geometrical analysis and orthogonal experiment was developed by Jiangsu University of Science and Technology of China (Zhang et al., 2000). The trials indicated that the effect of the forward speed, among these three factors, was the most remarkable; there was scarcely difference in header loss-brought between the vertical relative clearance of leading edge and the horizontal hood-to-rotor clearance (Li et al., 1998).

3.6 Aerodynamical Analysis of the Stripping Header

Two issues, both the distribution of airflow field around the stripping rotor and the influence of the field on the stripping performance, are not only paid great attention to, but also have been theoretically analyzed based on the measurement to the field (Jiang et al., 2000).

While the stripping cylinder turns at a high speed, the surrounding air is fanned by the turning teeth and forms an air field with no-spin circumfluence motion under no impediment (E. Jiang et al., 2000), as shown in Figure 10. Suppose that the curvature radius at somewhere in the flowing line is *r* and the velocity *v*. The arc differential *dn* can be assumed to be equal to *dr*. Thus, we can have:

$$\frac{dv}{dr}+\frac{v}{r}=0, or\frac{dv}{v}=-\frac{dr}{r} \qquad (15)$$

By integrating:

$$\ln v = -\ln r + \ln C \qquad (16)$$

i.e.

$$v=\frac{C}{r} \qquad (17)$$

Where, C is an integral constant.

From this result, it can be realized that the closer the distance to the center, the higher the air velocity. According to the Bernoulli's Law, the pressure:

$$p=K-\frac{1}{2}\rho v^2=K-\rho\frac{C^2}{2r^2} \qquad (18)$$

Where, ρ – air density, K – constant.

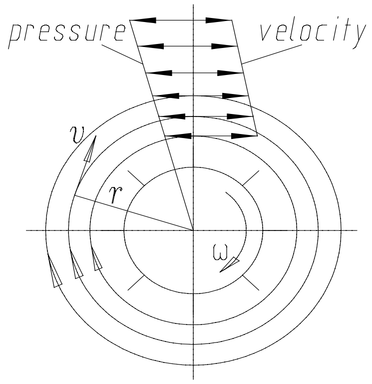

Figure 10 The turning aero-circumfluence without header hood

The Eq. (18) indicates that when far away from the center, the dynamic pressure $\frac{1}{2}\rho v^2$ decreases rapidly, while the (static) pressure increases quickly (Prandtl, 1974). This flowing field's effect produces a centripetal attraction force on the objects around the cylinder.

After the cylinder is covered with the upper hood over it, the air-flowing field has a great change owing to the hood's asymmetry-ability relative to the roller. As the stripping roller runs and the machine is driven on the open ground, the airflow has no alternative but to enter from the intake A_1 and go to the outtake A_2 because the cylinder is constructed in an entirely closed column. The air-streamlined field during that period is shown in Figure 11. Pressure differences are formed by the meeting of airflows from the circumfluence underside of the roller and head-on air, which produces air vortexes at the outside of the entrance A_1.

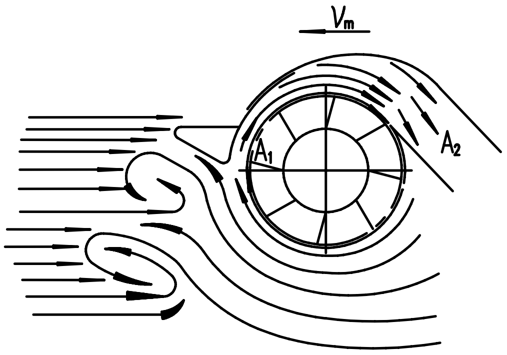

Figure 11 The movement of the airflow when the machine walks on the open ground

During operation, the airflow is blocked by a crop 'wall' in the foreside of the nose, which is schematically shown in the Figure 12 The movement of gas should keep its continuity in accordance with the principle of conservation of mass. Therefore, the following expression can be obtained:

$$A_1 v_1 \approx A_2 v_2 = \text{Constant} \tag{19}$$

Where: A_1, v_1 – the area and the average air velocity at the entrance section;

A_2, v_2 – the area and the average air velocity at the exit section.

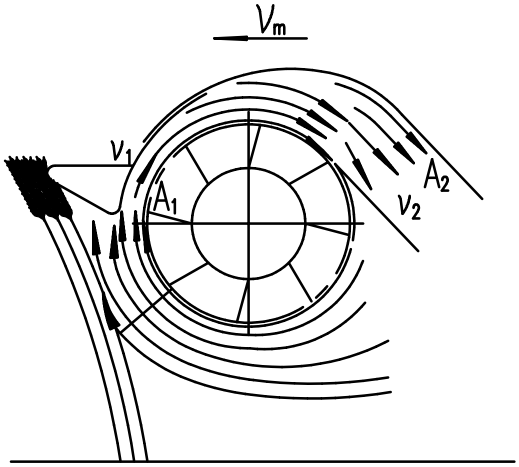

Figure 12 Schematic diagram of the aero-flowing field during work

In order to reduce the grain splash loss from head during stripping, there should be a slightly higher air velocity v_1, in other words, $v_1 > v_2$, or $A_1 < A_2$. In this way, $p_1 < p_2$ is obvious in accordance with Bernoulli's Law. The augmentation of the air velocity and decompression of the pressure produce a pumping effect on mixed materials at the entrance so that the grains stripped under the vertical-upward velocity point can be inhaled into the cover chamber. A series of trials represent that a minimum velocity of 5 m/s or over should be retained at the entrance. On the other hand, high v_1 brings v_2 rise [Eq. (19)]. And the growing of v_2 may have to suffer grains' loss from the air-exit of the hood, which leads to increasing whole header losses. Hence, in order to decrease the loss, a feasible measure is to reduce the value of v_2, or to enlarge the size of exit. However, both the raise of header loss and the expansion of air-exit are not expected. As a result, the too high speed of the flow is not advisable. In general, 6-9 m/s is desirable. In other words, an appropriately higher air velocity at the entrance will be one of the key measures to reduce the stripping loss. Therefore, it is important to control the size of feeding access. Some researches have shown that, at the entrance, the horizontal hood-to-rotor clearance was of secondary importance, but it should be at least 90 mm in most of crops and conditions (Klinner et al., 1987). The value of 90 mm should be a minimum. And at the same time, our design and trials brought other suggestions that the space (Figure 1 and 13) – the minimum place at the feeding entrance A_1 – should not be bigger than 110 mm.

5. CONCLUSIONS

(1) Theoretical analysis and experimental validation concluded that factors such as forward velocity of the stripping harvester, working height and rotational speed of the stripping rotor, air-flowing field effect, and others greatly affected the stripping loss.

(2) To keep the cylinder under a normal working condition, the prerequisite is that the speed ratio of stripping should be: $\lambda = \frac{v_s}{v_m} > 1$; that is, the movement track should be retained to form a short trochoid.

(3) The height of the roller shaft above the ground should be within the range: $L - l - \frac{R}{\lambda} \geq H > L - R$; otherwise, the loss would be greatly increased. Also, the amount of straw handled by the machine would considerably increase if the shaft was very close to the ground, causing an overload and certainly a slight increase in loss.

(4) A negative logarithmic exponent function was found between the stripping loss and the forward velocity of the machine; that is, a higher velocity could result in the lower loss. Controversially, the loss usually rises when the machine is operated at low speeds under the real field conditions.

(5) Proper formation of the air-flowing field could greatly reduce the loss of feed grains. A higher air velocity at the entrance than the air outlet should be applied to the stripping harvester development.

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