Development and application of mechanized maize harvesters

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Abstract: Maize harvesting is one of the most important filed operations of maize production. As the accelerating development of maize industry, mechanized maize harvesting is widely accepted and used by farmers in the world. According to the harvesting methods, maize harvesters could be classified into two types, one is maize-for-grain harvesters, including pickers and grain harvesters, the other is whole plant harvesters, including forage harvesters and combined grain-stover harvesters. Structure characteristics, appropriate areas and relative technologies of those harvesters are described in this paper, i.e., pickers are suitable for multi-crop areas, Grain harvesters are mainly for one-crop areas when grain moisture content is lower than 25%, combined grain-stover harvesters are applicable in agro-pastoral ecotone, and forage harvesters are capable in large-scaled animal husbandry farming areas where large amount of silage are required. Meanwhile, the future development trend of the different harvesters is predicted. Big horsepower engines, enhanced working efficiency, automation and intelligence are required by large scaled farms. As maize breeding development, more varieties that are suitable for grain harvesting are put into practice, so grain combine harvesters will be popular in future.

Keywords: maize, harvesting, picker, grain harvester, forage harvester, development trend

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1 Introduction

The purpose of mechanized maize harvesting is to replace manual labor to harvest maize from fields in time with minimum loss while maintaining high quality. The harvesting method and equipment depend upon planting pattern, agronomy and climate conditions. The entire harvesting operation may be divided into gathering, snapping, husking, cutting, threshing, separation and cleaning. Depending on the method employed for harvesting, these functions are performed by different machines, or even be performed by one machine in a single pass over the field. Reducing human drudgery, increasing productivity, improving timeliness of agricultural operations and reducing peak labor demands are among the most advantages of mechanized maize harvesting[1-6].

The development of maize harvesting machinery can be traced back to the successful development of field operation machine of snapping, husking and stalk cutting. In 1908 the United States developed the first field snapping-husking machine. In 1921 Allen designed the world’s first maize combine harvester in Australian. In 1950s Soviet Union developed Kherson-6 type maize

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harvester with snapping and husking device. In the 1960s the United States developed the maize head configured grain combine harvester to harvest maize grain directly. With the development of acceptable maize heads, the popularity of grain combines for harvesting maize increased rapidly during the 1960s. In the middle and later period of 20th century, the developed countries in Europe and America realized the total mechanization of maize harvesting (including grain and forage)[4-9]. At present, maize harvesting in the United States, Germany, Ukraine, Russia and other western countries apply direct threshing way due to their planting pattern of one crop a year and low grain moisture content during harvest period[10-13]. Harvesters from John Deere, CNH, AGCO, Mengle, Deutz, etc. are all possible to mount maize heads on grain combine harvesters to harvest maize grain by adjusting threshing clearance and cylinder rotating speed accordingly.

The development of mechanized maize harvesting has strong correlation with the planting area and cropping system, especially related to maize varieties. For example, maize grain harvesting are suitable in the United States, Canada etc., because of the planting pattern of one crop a year, and low maize grain moisture content during harvest period. In Britain, France and some other European countries, animal husbandry has been highly developed, as a result silage maize is planted widely, and the forage harvesting is the major harvesting method. Maize in Brazil and Argentina is planted in the areas of one crop a year, so the main harvesting method is grain direct harvesting, but there is also partial forage harvesting. In Southeast Asia, the main harvesting method is ear picking and husking because of planting pattern of two crops a year and the high grain moisture content. In interlacing agro-pastoral regions, combined grain-stover harvesters are popular.

This paper summarizes the structure characteristic of various maize harvesters according to the development process and classifies them into maize-for-grain harvesters and whole plant harvesters according to the applicable areas and harvesting methods[4,13].

2 Maize harvesters

The way of maize harvesting depends on the moisture content of kernel which is related to the factors such as variety, planting area and cropping system. When the moisture content exceeds 30%, picker should be adopted. When the moisture content is below 25%, grain harvester should be applied[14,15].

2.1 Maize picker

A maize picker can do all or parts of works including ear picking, husking, collecting and stalk chopping. There are two kinds of pickers in accordance with their power units: tractor-driven and self-propelled type[6]. Tractor-driven picker is inefficient and has high grain loss during field operation, so it is gradually replaced by self-propelled ones. Self-propelled picker is popular in nowadays due to its advantages such as more professional, convenient, desirable effect, high efficient, suitable for scaled farming, etc. The key component for a maize picker is the head.

The primary function of a maize head is gathering, snapping and trash removal. Head row spacing is designed to be in line with planting row spacing. The gathering unit is positioned between maize rows. It assists moving stalks into snapping unit and prevent ear loose from sliding. The key mechanism of the harvest head is the snapping unit[3].

The rolls grab maize stalks and pull them between the snapping bars, meanwhile maize ears cannot pass through the spacing between the snapping bars[3]. Maize ears would be snapped off when they reach the snapping bars and carried into auger by gathering chains. Generally snapping rolls include spiral-lugged rolls and straight-fluted rolls[1].

2.1.1 Spiral-lugged snapping rolls

Spiral-lugged rolls are mostly made of cast iron with spiral ribs or lugs on their surfaces[1]. Maize head with spiral-lugged snapping rolls has a simple structure, high reliability, strong adaptability to variety of stalk conditions and some husks can be pulled downward by the rolls. A higher loss and lower efficiency are due to the direct contact between ear and spiral-lugged snapping rolls. Wang and Jia developed a variable screw pitch rib snapping roll and a spacing-adaptive differential snapping roll to solve the blocking problem between the snapping rolls and improve working efficiency[16,17]. There is a trend that spiral-luger rolls are becoming less used[1,4,6].

2.1.2 Straight-fluted rolls

Straight-fluted rolls are more aggressive than spiral-lugged rolls. Stripper plates located above the rolls prevent maize ears from directly contacting the rolls. Straight-fluted rolls permit larger capacities and higher operation speeds because of their structural advantages[3]. They can be divided into quadrangular, five ribs and six-rowed etc. according to their cross-sectional shape. The maize head of straight-fluted snapping rolls is reliable with high efficient, small losses but leads to a high mixture of stalks and husks in harvested grain. At present straight-fluted snapping rolls are widely used around the world because of its small damage and the stable work performance in the condition of low grain moisture content[1-4].

Snapping techniques are in deep study by many research institutions in order to reduce the loss and the impurity rate as well as to get a better effect of stalk cutting.

The new Oxbo 50 series maize head has been designed with tapered ten-knife snapping rolls for matching with stripper plates. The design feature of stripper plates is the key to cutting the ear off the stalk cleanly for reducing trash and ear damage. The tapered knife snapping rolls slow stalk acceleration into the stripper plates which dramatically reducing ear impact and butt shelling. The gathering belts on the Oxbo 50 series are made of durable rubber which can reduce ear damage, convey more efficiently and operate more quietly[18].

The stripper plates on maize head that can be adjusted automatically and simultaneously according to the diameter of stalks is designed only by Drago in the world, and the automation mechanism of each row can work independently. Furthermore, Drago's stalk rollers are longer than normal ones, which can snap ears from plants gently. To eliminate ear bounce and reduce butt-shelling, Drago's maize head has the longest knife roll with a smaller diameter to reduce tip speed[19].

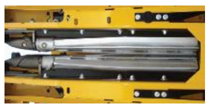
Knife stalk rolls of John Deere's 600C series head are designed with eight opposed full-length blades, and they are self-sharpening types which allow the maize head working at high efficiency in a long time[20].

Geringhoff's maize head is designed to use Rota Disc to pull down stalks through the stalk destruction system. The Rota Disc can make the process effective which will not decrease with increasing ground speed. The Rota Disc system draws an additional horsepower per row to cut stalks into small pieces[21]. Cui et al.[22,23] developed a snapping unit similar to it and experiment results showed that it could reduce power consumption about 60% compared to conventional spiral-lugged snapping rolls and straw choppers.

360 Yield Center designed a new unit named 360 CHAINROLL which can lacerate stalks finely with its double counter-rotating rolls by adequate interaction of the flutes , so residue is more available to be decomposed by microbe for better soil health and nutrient availability. It is a new product to make stalks easily to be resolved[24].

The characteristics of snapping rolls from different companies are shown in Table 1. Different companies developed various pickers and heads, the main types are shown in Figure 1[25,26].

Table 1 Different types of snapping rolls and their features

Manufacturer	Picture	Roll type	Plate type	Plate adjustment method
Lovol		Spiral-lugged snapping rolls	/	/
John Deere		Eight knife snapping rolls	Straight plates with big fillet	Preset, electric adjustment in cab
Drago		Longer four knife snapping rolls	Straight plates with big fillet	Adjust automatically, real-time adjustment
Oxbo		Tapered ten knife snapping rolls	Stripper plates	Preset, electric adjustment in cab
Geringhoff		Two snapping rolls with a disc roll	Straight plates with big fillet	Preset, electric adjustment in cab
360 Yield Center		Ten-rib snapping rolls	/	/

a. Lovol's 4YZ-3H picker

b. John Deere's 600C series head

c. Drago's series II head

d. Oxbo 50 Series maize head

e. Geringhoff's maize head

Figure 1 Maize heads from different companies

With the improvement of maize breeding, maize planting spacing is becoming narrower to increase yield[27]. Some companies think that the traditional row maize head is already close to the maximum capacity because average maize yields are gradually increasing[28]. This is a challenge to the traditional maize head and they are unable to meet the high yield harvest demand. For example, the best way to harvest 15-inch rows is to use a 15-inch row maize head. If a 15-inch maize head is not available, a 30-inch row head can be used, which pulls two 15-inch rows together[29], causing possibilities of increased ear loss sharply. Cutting down the ground speed can avoid this potential ear loss, but it will reduce the operation efficiency at the same time. However, manufacturers and farmers will hardly accept this change. As a result, various research organizations begin to study narrow spacing harvesting techniques and equipment. Among these, there are two available methods, one is to apply a big gathering reel to move the stalks into the snapping rolls with the original spacing, and the other way is to reduce the row spacing of maize head. Geringhoff and Clamer are the typical representatives.

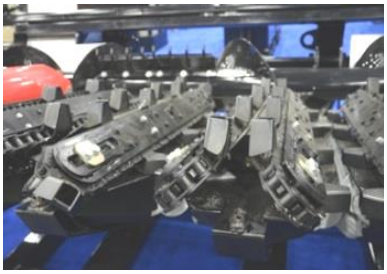
Calmer's maize head is able to cut away one side of the gearbox to build the narrow head. The single gathering chain with bigger paddles guide stalks into the rolls. Also the hydraulic stripper plates are installed for automatic control of head height and row-sensing navigation[27]. Two kinds of independent maize heads have been designed by Geringhoff, one of them is equipped with a big gathering reel and the other is narrow-spaced maize head. The rubber fins are at the top of heads and spin opposite of each other to grab the stalk just above the ear and guide them into the rolls, and the cutting disk is on the bottom of the maize head which can cut the maize stalk off at ground level[30]. Geringhoff's narrow-spaced maize head is designed to enter a maize field at any angle. Also it uses Rota Disc cutting system and unique angled two-chain design to harvest maize in any row spacing. Narrow-spaced maize head has the ability to harvest the lodged maize compared to the reel maize head[31].

Zhang et al.[32] designed a maize stripping monomer mechanism to solve the problem of maize head row spacing could not be adjusted according to maize planting spacing. Field experiment results showed that it could snap ears well with grain loss rate of 0.04% and ear loss rate of 1.96%.

Based on the above techniques, the typical products of row independent are shown in Figure 2[33-35].

a. Calmer's 12-inch head

b. Geringhoff's gathering reel head



c. Geringhoff's narrow-spaced head

Figure 2 Row independent head for maize harvesting

2.2 Maize grain harvester

A maize grain harvester is similar to conventional grain combine, but equipped with an ear picker-head and suitably adjusted to harvest maize grain. It could reduce the procedure and cost compared with the ear picker, so it is widely used in appropriate areas. This kind of grain harvester can be used not only for maize，but also for many different cereals, as a result they are relatively cheaper and easy to operate[36].

A maize grain harvester mainly consists of maize head, conveying, threshing, separation, cleaning units and a grain tank[6]. A maize grain harvester can not only simplifies the harvesting procedure, improve production efficiency, but also reduce grain loss.

As the core unit of a maize grain harvester, the performance of the threshing device influences the harvesting quality directly. Threshing that occurs between cylinder and concave is probably a combination of both kernel wedging effects and bending of kernel attachments[37]. The rotating threshing cylinder and the concave in conventional and rotary combines can accomplish crop threshing process. The crop is compelled across the clearance between the cylinder and the concave, which is subjected to impact and rubbing action that lead to the grain separation[3]. Threshing devices can be classified into tangential, longitudinal axial flow, and tangential-longitudinal combination device according to the forms of ears fed into the threshing device[2].

2.2.1 Tangential threshing device

The main characteristic of the tangential threshing device is that maize ears are fed tangentially into the threshing cylinder[2]. In this kind of device, threshing time is shorter but a high kernel crackage will occur.

Steponavicius et al.[38] found that as the feed rate of maize increased from 4 kg/s to 12 kg/s, the power consumption for threshing process increased. The kernel damage and the kernel moisture have positive correlation[39]. The mathematical relationship between them was $y = ax + b;$ where $y = log_{10}^{kernel\ damage}$ and $x = log_{10}^{moisture\ content}$. Chowdhury's research indicated that kernel moisture content, and cylinder rpm have a highly significant effect on damage rate[40]. The study result showed that the damage was greatly reduced when the maize ears were fed into the threshing cylinder as ears axes parallel to the axis of cylinder. The smallest damage for all orientations from 20% to 22% moisture content[41]. Increasing the distance along the concave resulted in higher damage rate at any moisture content, and the minimum damage occurred under about 20% moisture content at all shelling mechanism zones[42]. The test results showed that for a threshing cylinder with 22 inch diameter and at 28% moisture content, the grain damage increased from about 15% to almost 28% with the cylinder velocity increased from 300 r/min to 700 r/min[43]. Chowdhury et al.[44] indicated that the increase of cylinder speed from 450 r/min to 650 r/min would result in the total damage increased from 26.3% to 42%.

Increasing cylinder speed would contribute to higher threshing capacity of the rotary maize thresher for all kinds of maize cobs[45]. The threshing loss decreased with increase of the cylinder peripheral speed, and the grain damage increased as the cylinder peripheral speed increased[2]. Higher threshing and separation performance will be achieved with smaller concave clearance, on the contrary a higher grain damage rate will occur[46]. Petkevichius et al.[47] found that ears fed into parallel with the cylinder axis contributed to the ears moved speed twice as faster (4-5 m/s) in the concave clearance compared with that ears fed into perpendicular to the cylinder axis. The test results showed that the concave clearance at the front place should be about 10 mm less than the average diameter of maize ears, and that it should be equal to the core diameter at the rear place[48]. Miodragovic et al.[49] reported that the kernel damage reached to upper limit value (6%) and decreased by increasing concave clearance.

2.2.2 Longitudinal axial flow threshing device

The key feature of the longitudinal axial flow threshing device is that the maize ears are fed axially into the threshing cylinder, and the maize ears are moving in axial and tangential direction along the cylinder. It performs the threshing and separation functions and the time of threshing and separating is longer, as well as the device has lower threshing losses and grain damage[2,6].

Gao et al.[50] indicated that increasing feeding rate of maize ears has no significant effect on kernel damage. Damage in the axial device was a half of that in the tangential threshing roller[51]. Grain damage of axial threshing device is lower than that of tangential threshing device, except for the grain moisture content of 12% and the peripheral velocity of 18 m/s[52]. Longitudinal axial flow threshing device includes two kinds of threshing cylinders: twin-cylinder and single-cylinder. Twin-cylinder is made up of two rotors with diameter of 432 mm and length of 2235 mm, and velocity of the two rotors is adjustable at a range of 580-1325 r/min[53,54]. Single-cylinder has just one rotor with diameter range of 610-762 mm and length of 2734 mm, and its velocity can be adjusted from 280 r/min to 1250 r/min[54].

There are researches on mathematical model of materials motion across the axial threshing device, which were used for not only optimal design of threshing devices, but also practical analysis of grain movement effect on threshing performance[55]. Many studies indicated that the best kernel moisture content for threshing maize is about 20%[56].

Test results from Yang et al. showed that the complementary angle of friction angle between grain and helix lamina should be larger than the helix angle of the feeding section, and the friction angle between grain and leading lathing should be larger than the helix angle of threshing and separation section[57]. Wang et al.[58] reported that as the concave clearance decreased from 35 mm to 15 mm, the kernel loss rate and damage rate would decrease. Xu et al.[59] analyzed the grain movement, stress state and regularity of threshing and separating, which laid the foundation for the longitudinal axial flow threshing cylinder to establish the mathematical model. Muammer et al.[60] found that kernel damage rate increased as the threshing cylinder speed increased, and the reduction of kernel moisture content led to the reduction of total kernel damage. Lin et al.[61] conducted a test and results showed that total kernel loss rate was only 2% and kernel damage rate was 1% when threshing cylinder working length, concave clearance and cylinder speed were 2100 mm, 40 mm and 300 r/min, respectively.

2.2.3 Tangential-longitudinal axial flow threshing device

To make full use of the advantages of the tangential and longitudinal axial flow threshing device, tangential-longitudinal combination device was developed by integrating the above two devices together. It is equipped with a tangential threshing cylinder in front of the longitudinal axial flow threshing cylinder, in that way the capacity of the threshing, separation and feeding rate improved significantly[6].

Zhao et al.[62] designed a tangential-longitudinal axial flow threshing and separation device with soft threshing components, which could decrease the kernel loss rate and damage rate effectively. Duan et al.[63] developed a simple tangential-longitudinal axial flow threshing and separation device. The cylinder speed was lower and the threshing and separating period was longer, which contributed to a reduction of kernel damage and loss rate.

Five types of threshing devices widely used at present[64-67] are shown in Table 2.

Through the experimental research on different types of threshing device, the various maize grain harvesters were produced by different manufacturers, and the main representatives are as follows.

New Holland invented the CX8070 elevation maize combine harvester (Figure 3), and threshing device type adopts the tangential threshing device[64].

CASE invented the axial-flow 9240 maize combine harvester (Figure 4), and threshing device type adopts the single in-line axial-flow rotor threshing device[65].

John Deere invented the S690 model maize combine harvester (Figure 5), and threshing device type adopts separator type rotary[66].

New Holland invented the CR8090 maize combine harvester (Figure 6), and threshing device type adopts the twin rotors of axial-flow threshing device[64].

CLAAS invented the Lexion 760 maize combine harvester (Figure 7), and threshing device type adopts the exclusive Accelerated Pre-Separation (APS) threshing system and the ROTO PLUS separation system[67].

Jilin Province Dongfeng Mechanical Equipment Co., Ltd invented the 4YZ-6 E518 maize combine harvester (Figure 8), and threshing device type adopts the twin rotors of axial-flow threshing device[68].

Now threshing technology is well developed and grain harvesters are widely used in developed countries. While in developing countries, especially in China, pickers are still adopted in practice. With the development of maize breeding, varieties suitable for direct threshing will be available, as a result, grain harvesters will become popular in the near future.

Table 2　Different types of threshing devices for maize harvesting

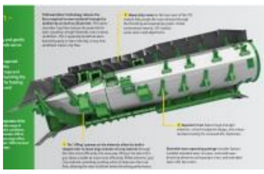
Threshing Device Type	Picture	Length/mm	Width/mm	Diameter/mm	Feature
Tangential threshing device		/	1560	750	Low threshing speed to reduce vibrations and to protect the drive line
Axial-flow threshing device		2623	/	762	High threshing capacity, less horsepower and less fuel consumption
Axial-flow threshing device		3124	/	762	With a slightly tapered front nose, low growling and high productivity
Twin rotors axial-flow threshing device		2638	/	559	Suitable for damp conditions, offer up to a 10% increase in capacity
Tangential and longitudinal axial flow threshing and separation device		4200 (longitudinal axial flow cylinder)	1700 (tangential cylinder)	445 (longitudinal axial flow cylinder)/ 600 (tangential cylinder)	The APS accelerates material and pre-separates up to 30% of the grain, the ROTO PLUS system provide optimizing separation performance

Figure 3　New Holland CX8070 Elevation maize harvester

Figure 4　CASE axial-flow 9240 maize harvester

Figure 5　John Deere S690 maize harvester

Figure 6　New Holland CR8090 maize harvester

Figure 7　CLAAS LEXION 760 maize harvester

Figure 8　Dongfeng 4YZ-6 E518 maize harvester

3 Whole plant harvesters

With the increasing demands for milk, dairy and beef in the world, maize forage becomes a major forage source for beef cattle, providing supplemental energy with high energy. Now harvesting maize for forage is more and more popular. Whole plant harvester is suitable for maize forage harvesting. The advanced forage harvester evolved from its origins which operated with hand powered forage cutters to chop maize into small pieces for storage and feeding[9]. Over the past century, the maize forage harvester has been developed from manual operation, tractor-driven to self-propelled, from single function to multi-function.

Forage harvesters include systems for gathering, chopping and conveying the crop into a wagon or truck[9]. ASAE Standard S472 defines two basic types of forage harvesters: precision and non-precision[69]. Precision cut forage harvesters typically use a cylinder or flywheel cutterhead to chop crop and can be used for harvesting maize silage. The forage harvester may be pull-type or self-propelled. Both types are further classified into either cut-and-blow or cut-and-throw. Cut-and-throw harvesters use energy imparted from cutterhead to convey chopped material. Cut-and-blow harvesters use an auxiliary blower for material conveying. Most current self-propelled and pull-type harvesters are of the cut-and-blow configuration[9].

3.1 Pull type maize forage harvester

In 1891, a patent was issued for a pull-type field implement that combined a pick-up device which took from a hay loader or a direct-cut head, a feed-table and feedrolls, a cylindrical cutterhead, and a conveyor, essentially all the components of modern forage harvesters albeit without the engineering sophistication[9,70]. Although this idea was not commercially successful at the time, work on this concept was rejuvenated in the 1920s in Wisconsin[9]. In mid 1930s, the Fox River Tractor Co. sold the first commercially successful pull-type forage harvester. Pull-type harvester with sensitive whole-plant row-crop units are typically used to harvest whole-plant maize. For pull-type harvesters, row-crop units are available for wide (915-1020 mm) and narrow (710-815 mm) row maize and are able to harvest 2-4 rows at a time. The DION-Ag Inc produced the only rotary non-sensitive whole-plant maize head for pull-type forage harvester[71-74].

Although the pull-type harvester has been invented for more than 100 years, it is still widely used today because of low price and the stable performance. The products of companies such as John Deere and Case are the mainstream models currently.

3.2 Self-propelled maize forage harvester

Self-propelled forage harvesters are suitable for large dairy farms and large-scale cultivation of the crop farms using silage because of its advanced technology, high production efficiency, good mobility, wide adaptability and etc[9]. Currently commercial self-propelled forage harvesters produced by CLAAS, John Deere, New Holland or other companies are usually equipped with non-row-sensitive whole-plant-crop head.

The forage harvesters with non-row-sensitive crop head can harvest independent of either maize row spacing or row direction, thus reducing operator’s fatigue and improving field efficiency. These crop heads consist of a high speed saw tooth stalk cutter, with large diameter, toothed gathering drums and small-diameter, tooth feed drums. The cut stalk is converged toward the feedrolls by the gathering drums in an upright orientation and is tipped forward by the push bar directly in front of the feedrolls. Non-row-sensitive crop units are available in 3.0-9.0 m width. With the higher requirement for the particle size to meet the demand of high forage quality, self-propelled forage harvesters have been equipped with cylinder cutterhead and maize processor[1-3,9,75].

High-protein feed is a key ingredient when fattening and finishing valuable beef cattle, so only the juiciest ears are required[76]. Now, earlage (ear snaplage) has been designed as the demand for high-quality forage. Self-propelled forage harvester with ear snapping head can be used for harvesting the ears at the grain moisture content of 32%-40% to produce succulence. Stover is left in the field or recovered as yellow forage[77].

3.3 Combined grain-stover harvester

This harvester can harvest ear/grain and stover as forage at the same time. There are single-pass, two-pass, even three-pass harvest process according to different forms of harvesting. Single-pass is mostly used since more impurities would be mixed in the feed in multi-pass.

Some researchers add snapping and shelling components on the basis of the pull-type forage harvester to complete the threshing. Hitzhusen designed and built a snapping attachment for a pull-type forage harvester, which was mounted between feedrolls and row-crop gathering head. A cage type sheller was fixed above the snapping attachment, and conveying equipment was added to transport the snapped ears to the sheller and the shelled kernel to a trailing wagon. The cobs discharged from the sheller were dropped into the path of the stalks behind the snapping rolls. The chopped forage was blown into a wagon pulled alongside or behind the machine[78].

Now in United States, these units are usually developed from combine harvester. Modified a grain combine harvester equipping with a whole-plant forage harvester maize head, or modified a grain combine harvester equipping with stalk-gathering head to gather, cut and transport stalk and leaf fractions to get the separated grain and stover flow[79,80]. In China, maize picker is commonly adopted, and stalk cutting, transporting and chopping unit are mounted on the head to cut the snapping stem and finish the convey operation. Grain/ear and stover flows are respectively conveyed into the different tanks, or the stover will be thrown into the wagon rear or beside the harvester[81,82].

In recent years, researches are focused on the operating parameters and energy consumption of forage harvester to obtain the best feeding effect and minimal energy consumption. There are several machine parameters can significantly affect machine performance, such as feedroll contact force and mat length, knife and shear bar clearance and sharpness and crop processing system.

The knife sharpness and the knife-to-shear bar clearance are the most important parameters affecting the final particle length distribution[2]. Maintaining knife sharpness and shear bar clearance are the most important maintenance items on forage harvesters.

Dull knives or excessive knife-to-shear bar clearance made the stalk be pulled and ripped at the shearbar, caused a long final particle size with wide distribution and resulted in wasted power and poor cut quality[9,83,84]. Increased knife-to-shearbar clearance had a negative effect on the difference between actual particle size and TLC (Theoretical Length of Cut)[85-87]. Liljedahl et al.[9,88] indicated an interesting interaction between sharpness and clearance, the negative effect of excess clearance for sharp blades (<0.08 mm edge radius) was less than that for dull blades (>0.08 mm edge radius). Under field conditions, it is common to expect knife-edge radii >0.3 mm and shear bar clearance >0.4 mm. The results of these emphasized the importance of maintaining a sharp blade edge and minimizing shear bar clearance.

Knife sharpening is either semi manual where the operator must move the stone by hand (pull-type harvesters), or automatic (self-propelled harvesters). Shearbars have an adjustment system to move the shearbar toward the cutterhead after knife sharpening[9].

If the feedrolls lose contact with the stalk mat or lack sufficient gripping force, the cutterhead knives tend to tear material free of the feedrolls, resulting in longer and ragged materials. Greater feedroll force and larger mat depth both reduced the deviation between final particle size and TLC[77-79].

Studies on crop processing system showed that the speed differential between the crop processing rolls is not adjustable currently, and which is often from 10% to 30% depending on different manufacturers. Clearance between the rolls is adjustable, with smaller clearance resulting greater reduction in whole-plant final particle size, which can reduce the fraction of kernels left intact after processing. Shinners et al.[75] indicated that speed ratio did not affect the whole-plant final particle size with small roll clearances.

Pull-type and self-propelled models are both in use, and some mounted models are still used in the developing countries. The main models in use are shown in Table 3.

To produce adequate fermentation for preservation in the silo, forages must be harvested at the right moisture content and with the proper particle size distribution. Rapid harvest with properly configured forage harvester is crucial to meet these two requirements.

Table 3 Comparison among various models of maize forage harvesters

Model	Picture	Type	Harvesting Approach	Crop Unit	Chop Length/mm	Engine Output	Cutter Head
John Deere 3955		Pull type	Whole plant silage	Row sensitive crop unit	6-25.4	110 kW	cylinder
Case FHX300		Pull type	Whole plant silage	Row sensitive crop unit	5-11	132-220 kW	cylinder
New Holland FP240		Pull type	Whole plant silage	Row sensitive crop unit	7.1-33.3 (4 knives), 7.1-22.2 (6 knives), 7.1-16.7 (8 knives), 4.8-11.1 (12 knives)	132-220 kW	cylinder
Mushen 4QSD-180		Mounted	Whole plant silage	Non Row sensitive crop unit	7-50	Minimum 66 kW	cylinder
CLAAS 870		Self-propelled	Whole plant silage	Non Row sensitive crop unit	3.5-15 (28 knives), 4-17 (24 knives), 5-21 (20 knives)	440 kW	cylinder
John Deere 8600		Self-propelled	Whole plant silage	Non Row sensitive crop unit	7-26 (40 knives) 6-22 (48 knives)	453 kW	cylinder
NewHollandFR850		Self-propelled	Whole plant silage	Non Row sensitive crop unit	6–33 (16 knives), 5-27 (20 knives), 4-22 (24 knives)	570 kW	cylinder
CLAAS		Self-propelled	Ear snaplage	Row sensitive crop unit	3.5-15 (28 knives), 4-17 (24 knives), 5-21 (20 knives)	/	cylinder
Guofeng 4YZB-2620		Self-propelled	Combined ear-stover harvester	Row sensitive crop unit	50-100 (12 knives)	160 kW	Flywheel

4 Development trend of maize harvester

Although basic functions of maize harvesters have not changed much for decades, more and more innovations and high-techs on mechanical harvesting have been developed. The new trends of maize harvesters are as follows.

1) More versatility and adaptability. A harvester can be equipped with a variety of special cutting heads to fit for harvesting different kinds of crops. Moreover, a harvester can also be equipped with different width cutting heads to satisfy the requirements of different working efficiencies. Tires with different width and even crawler-type walking mechanism are used for improving the adaptability of harvesters in different field conditions.

2) Greater capacity and productivity. At present, high speed, large cutting width and high feeding rate are

the main features of the advanced maize harvesters. The biggest maize harvester, with cutting head width of 18 m and engine power of 600 kW, can harvest 24 rows in one pass. The new forage harvester, with the cutting head of 9 m width, has the high production efficiency and is suitable for large scale lands and big farms.

3) Automation and intelligentization. Mechanical and electrical technologies are widely used in harvesters to reduce harvesting loss, improve working efficiency and reduce labor intensity. For example, sensors for detecting rows and heights of cutting heads are developed and installed on harvesters, which can help to adjust the driving direction and the heights of cutting heads. And as a result, drivers do not need to pay close attention to drive. Furthermore, sensors and control systems are applied to measure grain mass-flow, moisture content and yield. Then parameters of harvester can be adjusted in real time according to the detecting information to obtain optimal effect. Combining with information technologies such as GPS and GIS, the control system of modern maize harvester can also provide technical services and whole pack solutions for producers to make the next step plan.

5 Conclusions and recommendations

1) The development of modern agriculture promotes the progress of maize harvesting mechanization, but the development of maize harvesting mechanization is extremely unbalanced. The maize harvesters which are suitable for the local geographic and economic conditions should be promoted in different areas, e.g. large harvesters should be used on large-scale farms; medium and small size harvesters with better flexibility should be selected on small individual farms; and crawler-type harvesters should be applied in hilly areas for the its stability and safety.

2) Some large-scale farmers can accomplished maize harvest by importing advanced large maize harvesters abroad, but other producers are restricted by the conditions such as economy, business scale etc., and they have specific demands for the harvesting technology and machine, so the imported foreign harvesters are not feasible. Such situation is more common in developing countries, so it calls for a funding from the relevant national government departments to support the local R&D entities to research and develop the suitable harvesters, and pay more attention to the reliability of the harvesters.

3) The cost of maize grain harvest is lower and it is becoming a developing trend, however the maize picker would exist in some areas for a long time because of the maize varieties and the regional conditions. As a result enhancing the deep research and development on efficient and low damage maize picker is in need.

4) As the emerging of new maize varieties with the ability of dense planting and high yield, it will cause the change of cultivation modes, especially plant row spacing. It is required to study new harvesting technologies and harvesters with more adaptability; and at the same time, maize dense planting puts forward a higher request for picking ears and threshing technology. The research and development of new efficient picking ears, threshing and separation device will become the emphasis for improving the production efficiency and reducing the yield loss.

5) With the improvement of living standard and change of dietary structure, the consumptions of meat, eggs and milk are increasing rapidly. It will promote the development of animal husbandry, and cause further adjustment of agricultural structure. And as a result the planting area of the silage maize will expand. There is a bright market prospect for the forage harvesters with high efficiency, intelligentization and strong adaptability.

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