TWO-STAGE MOTION OF PARTICLES IN THE DISCHARGE SPOUT OF FORAGE HARVESTER

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Abstract. The purpose of the work was to characterise chaff movement and to determine particles velocity in any location in the discharge spout, depending on the knife disc rotational speed and quantity of maize plant material stream fed into a forage harvester with flywheel cutting unit. Conducted experiments allow to prove that the particle movement in the discharge spout proceeds in two stages. In the first stage the particles move in a dispersed way and in the second stage, after colliding with upper spout wall, the chaff stream acts as a dense stream. An abrupt change of chaff velocity occurs at the boundary of these stages, which then decreases degressively in farther spout sections.

Key words: forage harvester, discharge spout, chaff velocity

Introduction

The shape of the discharge spout in forage harvesters is diversified and depends on the harvester type (self-propelled, towed, suspended), cutting unit type (drum, flywheel) and shredded material type (grass, maize, wood). In order to ensure proper machine work in various service conditions it is recommended not to exceed spout inclination angle of 15-20°, while curvature radius should be as large as possible, limited only by design purposes. However, spout inclination at its base causes problems with spout rotary motion, especially in self-propelled forage harvesters, where shredded plant material may be received either on the machine's right or left side.

To date, researchers have completed many studies on forage harvester discharge spouts characterised by various shapes and inclinations [Roszkowski 1974; O'Dogerthy 1982; Baranov 1998; Osobov et al. 2002], however without any detailed analysis of chaff motion inside the spout. The motion of plant material particles inside cutting unit housing is generated by kinetic energy received by the particles from flywheel unit working components, or results from using an auxiliary blower or directly working drum unit accelerating the chaff. Reznik [1967] observed that pneumatic conveying efficiency for particles was higher when air stream velocity at spout curvature and at its end was higher, which was ensured by proper shape of spout part combining the drum unit housing with spout extension characterised by gradually decreasing cross-section. 40% of total demand for unit energy used for forage harvester operation reaching 3.5 $kWh \cdot t^{-1}$ [Shinners et al. 1994] is consumed by pneumatic conveying [Shinners et al. 1991], which shows the significance of the problem and potential as regards improvement in forage harvester operation efficiency. Energy for chaff pneumatic conveying was characterised as energy needed to accelerate, discharge, and overcome the resistance of friction between the particles and spout surface [Totten and Millier 1966]. The first studies in this field included the research carried out by Chancellor [1960], and Chancellor and Laduke [1960], who employed a stationary blower connected to a vertical spout ended with guide plate to convey the shredded plant material. At guide plate setting angle of 90°, more than 50% of kinetic energy was consumed to overcome the frictional resistance. Moreover, it was observed that at a specific guide plate inclination angle, more energy was wasted during collision of particles with the plate than used to overcome the particles motion along curvature of spout set at comparable inclination angle. For example, as a result of change in the direction of particles motion at 45°, there was less energy loss for particles which were colliding with curved plate at an angle of 15° and then ran along surface curved at 30°, than for straight collision with flat guide plate inclined at an angle of 45°.

Research results obtained to date allow to conclude that the characteristic of chaff motion in the discharge spout depends on the proper selection of spout design parameters, physical properties of harvested material, and machine throughput. The following parameters affect chaff motion characteristics for the discharge spout: spout width, discharge phase angle, spout convergence as determined by ratio of cross-sections at outlet and inlet (optimal ratio values are deemed to range from 0.4 to 0.6 [Roszkowski 1974]). Another important parameter is the area of holes in the drum housing side walls, determining the volume of air drawn into the discharge spout, which for drums with diameters 500-700 mm was estimated to range within 0.07-0.09 m^2.

The analysis of state concerning chaff motion characteristics and assessment of particles velocity in forage harvester discharge spout allows to observe that the researchers completed theoretical analyses for simplified motion conditions [Chancellor 1960; Chancellor and Laduke 1960; Reznik 1967; Baranov 1998; Osobov et al. 2002; Lammers 2005], most often determining the particles velocity at spout end or their throw range. There are no reliable verification tests confirming the approved assumptions. This is the result of using insufficiently accurate measurement methods. Available literature contains results of chaff velocity measurements carried out using radar sensors [Missoten et al. 1997], or a digital camera with high recording speed [Lammers 2005], however they concern the area of chaff discharge from the cutting unit. Due to irregular shredded material flow, radar sensor readings were burdened with significant errors, image obtained from the camera had poor quality, and the chaff particles were hard to distinguish. Camera recording speed allowed to make only three pictures of a given particle before it would leave the frame [Lammers 2005]. Our preliminary experiments [Lisowski and Świątek 2009], carried out using an ultra-fast digital camera Photron Fastcam SA 1.1 with maximum available rate of up to 600,000 frames per second allowed to carry out precise determination of particles velocity at spout end. Results of these studies were an inspiration to examine chaff motion and to determine the particles velocity at any point of the discharge spout, depending on the knife disk rotational speed and the stream volume of maize plant material fed into a forage harvester with flywheel cutting unit. At the same time, it was the purpose of this work.

Material and methods

The tests were carried out using a setup which was partially described in the article published by Lisowski and Świątek [2009]. According to the suggestions contained in it, the researchers designed their own harvester discharge spout made of transparent material – polycarbonate, characterised by high resistance to abrasion. This allowed them to extend research methodology and carry out chaff velocity measurements in four points of the discharge spout (Fig. 1). The measurements were carried out while feeding cutting unit equipped with 10 knives with maize plants material stream of 1.25, 2.5 and 3.75 $kg \cdot s^{-1}$, for the disk rotational speeds of 52.4, 83.8 and 104.7 $rad \cdot s^{-1}$. The researchers used an ultra-fast digital camera Photron Fastcam SA 1.1 recording the motion of particles at the rate of 2,000 frames per second. When viewing successive frames of the recorded film, the researchers were tracing the particles motion along marked 0.1m-long sections, which allowed them to determine the particles velocity taking into account the known time of their travel.

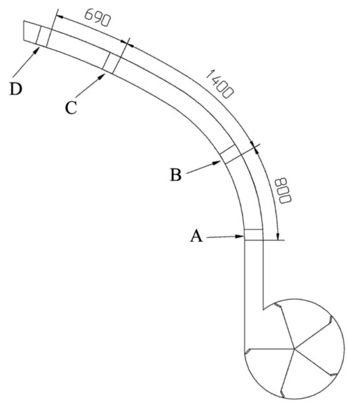

Fig. 1. Measurement points for chaff particles velocity in the discharge spout

Results and discussion

Recording the particles motion in a transparent discharge spout allowed them to observe that within its first section, directly after leaving the cutting unit's chamber, the chaff particles are dispersed and move in a rectilinear way vertically upwards. This motion lasts until particles hit the wall of curved discharge spout. For a plant stream of 3.75 $kg \cdot s^{-1}$ and cutting unit rotational speed of 52.4, 83.8 and 104.7 $rad \cdot s^{-1}$, average chaff velocity in section A (Fig. 1) was 13.72, 19.30 and 22.64 $m \cdot s^{-1}$ respectively. For the knife disk rotational speed of 104.7 $rad \cdot s^{-1}$ and harvester feeding with plant stream of 2.5 and 1.25 $kg \cdot s^{-1}$, the chaff velocity was 23.23 and 23.81 $m \cdot s^{-1}$, respectively. These velocities were approximately 2 times lower than peripheral speed of feeder beater vanes, which for rotational speeds of 52.4, 83.8 and 104.7 $rad \cdot s^{-1}$ reached 23.8, 38.1 and 47.6 $m \cdot s^{-1}$ respectively. The main reason for this phenomenon is that at the joint between cutting unit and discharge spout, cross-section shape turns from square into circular. In this place, chaff particles hit the cutting unit's housing, thus partially loosing their velocity. Chaff and air mix fills the whole discharge spout cross-section (Fig. 2), but the velocity and concentration of particles in a diphase air-chaff medium are not compensated there. On the right side (closer to feeder beater axis), velocity of chaff particles is approximately 30% higher than in case of particles moving in the other cross-section part, however their concentration is lower.

After hitting a curved spout wall, the particles characterised by medium humidity (67%)considered as elastoplastic material, continue their movement along the wall's surface not bouncing from it. As a result of the collision, kinetic energy is partially lost and the chaff velocity decreases. When feeding harvester with material stream of 3.75 $kg{\cdot}s^{-1}$ and for a cutting unit equipped with 10 knives, which disk with vanes was moving at a rotational speed of 52.4, 83.8 and 104.7 $rad{\cdot}s^{-1}$, directly after collision mean chaff velocity (section B, Fig. 1) dropped by 22.1, 36.9 and 35.6%, to the values of 10.69, 12.18 and 14.59 $m{\cdot}s^{-1}$ respectively. For a rotational speed of 104.7 $rad{\cdot}s^{-1}$ and feed stream of 2.5 and 1.25 $kg{\cdot}s^{-1}$, the decrease in velocity reached 38.6 and 37.4%, down to the values of 14.27 and 14.91 $m{\cdot}s^{-1}$respectively.

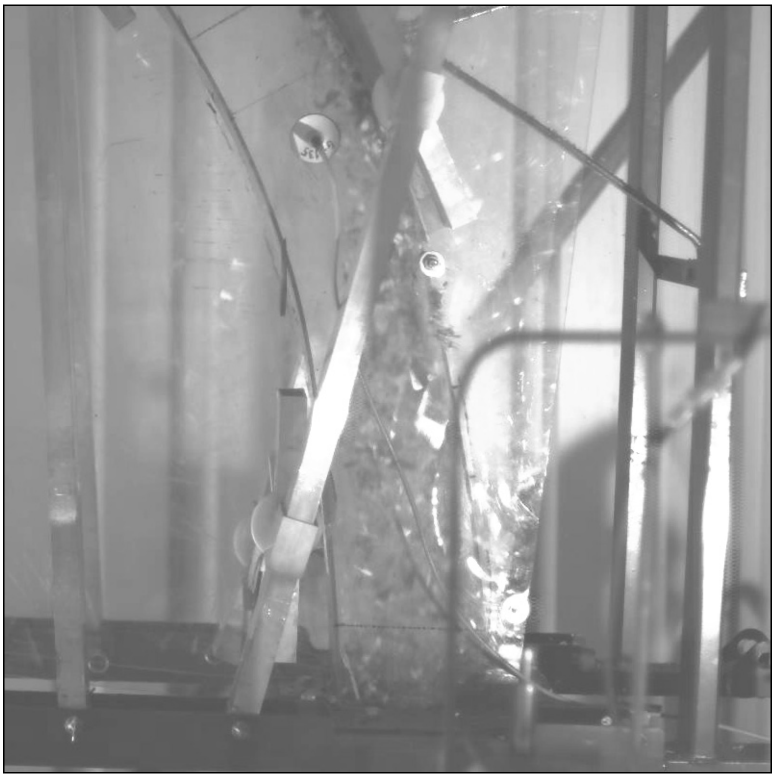

Fig. 2. Motion of chaff particles in the first spout section

Completed experiments give grounds to state that the material runs through the remaining spout section in a form of a dense stream. Frame-by-frame analysis of the film enables to observe that due to the occurrence of centrifugal force, the chaff particles drove air out of the space between them, which considerably reduced air resistance impact. However, the same centrifugal force that is responsible for particles pressing against the surface of upper spout wall, causes resistance resulting from the friction force between particles and spout wall, which leads to reduction of chaff velocity in the spout. In the analysed spout, its curvature radius beyond measurement area B (Fig. 1) increases 2.6 times, which changes relations between the centrifugal force and friction. The sum of diversified factors with feedback decides about the decrease in particles motion velocity. For input plant material stream of 3.75 $kg \cdot s^{-1}$ and knife disk rotational speeds of 52.4, 83.8 and 104.7 $rad \cdot s^{-1}$, in spout section C (Fig. 1), at the distance of 1400 mm from the previous measurement point, the chaff particles reached velocities 6.00, 8.63 and 9.49 $m \cdot s^{-1}$ respectively, and at spout end (section D, Fig. 1) - 5.87, 8.58 and 8.96 $m \cdot s^{-1}$ respectively. For a disk rotational speed of 104.7 $rad \cdot s^{-1}$ and chaff stream 2.5 and 1.25 $kg \cdot s^{-1}$, chaff velocity in spout section C was 9.88 and 10.6 $m \cdot s^{-1}$ respectively, and at its end (section D, Fig. 1) - 8.72 and 9.82 $m \cdot s^{-1}$ respectively. Dynamics of the chaff velocity decrease, converted into one metre of distance covered in the spout, was changing degressively. In the spout's middle section it was few times higher than at its end. This is a result of the change in frictional resistance between the chaff particles and discharge spout inside surface, which decreases in geometrical progression with dropping material velocity. This confirms the previous explanations concerning the feedback of physical phenomena.

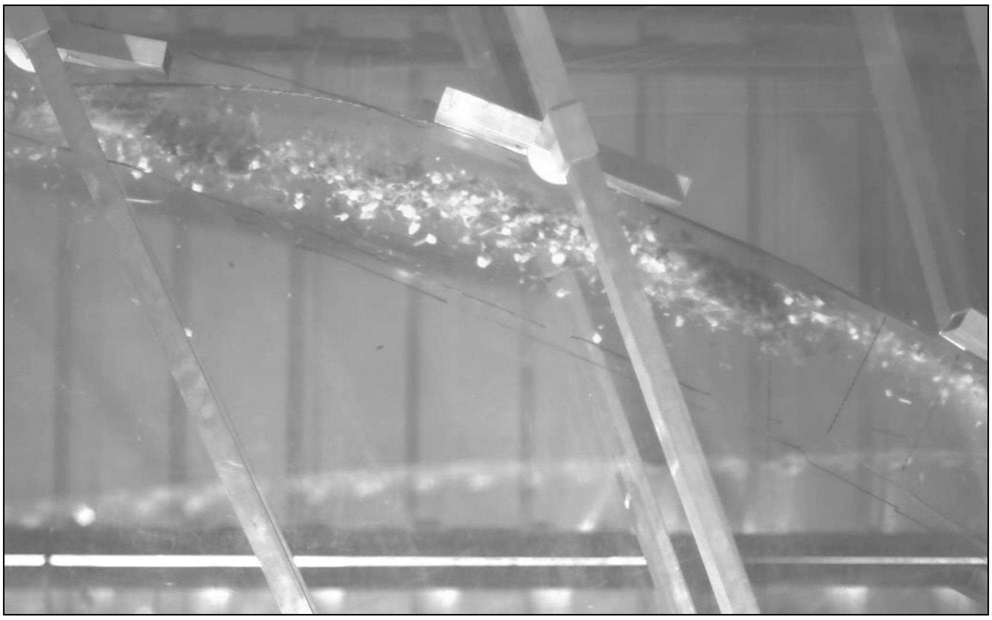

Fig. 3. Dispersed chaff stream in the discharge spout

For a knife disk rotational speed of 104.7 rad·s^{-1}, from the moment of hitting the upper spout wall until it leaves the spout, the chaff is moving in a uniform, 20–30mm-thick stream, and initial differences in the particles velocity at the cross-section compensate. The chaff motion analysis allows to observe that, in general, the particles in the stream do not tend to rotate or move across stream movement direction. Particles rubbing directly against the spout wall move at the same speed as other particles in the stream. Only some single lighter fraction particles sometimes separate from the main chaff stream, and while rotating about their own axes (spin motion) they assume a random flight path, most often moving at a different speed compared to the other particles. This is probably caused by the forces generated by turbulent air flow under chaff stream. This effect slightly intensifies in the end spout section, but due to scarce amount of these particles their impact on parameters of chaff motion in the discharge spout may be omitted.

For lower knife disk rotational speeds, chaff velocity in the rear spout section decreases so much that the effect of particles pressing against upper spout wall due to the centrifugal force ceases, and chaff stream continues to move in a dispersed way (Fig. 3). This effect occurs at the spout's end for a knife disk rotational speed of 83.8 rad·s^{-1}, while for 52.4 rad·s^{-1} it is observed already in the middle of its length.

Conclusions

1. It has been proven experimentally that the chaff particles ejected by vanes of cutting unit feeder beater are dispersed and fill the whole discharge spout cross-section until they collide with upper spout wall.
2. From the moment of collision between particles of maize plant elastoplastic material (humidity: 67%) and upper spout wall, chaff stream continues to move in the form of a dense stream.
3. For a knife disk rotational speed of 83.8 rad·s^{-1}, the chaff particles in the spout's end section cease to press against the surface of the upper spout wall, and at 52.4 rad·s^{-1} this effect occurs already in the middle of spout length.

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Scientific work financed by the Ministry of Science and Higher Education in years 2009-2011, as a promoter research project no. N N 313 003936.

DWUETAPOWY RUCH CZĄSTEK W KANALE WYRZUTOWYM SIECZKARNI POLOWEJ

Streszczenie. Celem pracy było scharakteryzowanie ruchu sieczki i wyznaczenie prędkości cząstek w dowolnym miejscu kanału wyrzutowego w zależności od prędkości kątowej tarczy nożowej i ilości strumienia materiału roślinnego kukurydzy wprowadzanego do sieczkarni polowej z toporowym zespołem rozdrabniającym. Na podstawie przeprowadzonych eksperymentów uzasadniono, że ruch cząstek w kanale odbywa się w dwóch etapach. W pierwszym etapie cząstki poruszają się w sposób rozproszony, a w drugim etapie, po zderzeniu z górną ścianą kanału, strumień sieczki zachowuje się jak zwarta struga. Na granicy tych etapów następuje skokowa zmiana prędkości sieczki, która następnie zmniejsza się degresywnie w dalszych odcinkach kanału.

Słowa kluczowe: sieczkarnia polowa, kanał wyrzutowy, prędkość sieczki

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