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Terminal Velocity of Chopped Corn Silage and Its Separate Fractions as Affected by Moisture Content

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ABSTRACT

Knowledge of the aerodynamic properties of agricultural materials is needed in equipment design for operations such as pneumatic conveying in loading/unloading operations of corn silage into/from silos. While considerable information is available on seed grains, little is known about the aerodynamic behavior of corn (*Zea mays* L.) silage. In this research, the weighed mean terminal velocity of a sample representative of the entire bulk mass was determined using Wolf and Tatepo's method. The terminal velocity of various particle types (leaf, stalk and corncob pieces) of chopped forage corn plants, which were kept in silo for six months, at different moisture contents (40-50, 50-60 and 60-70% w.b.) was also studied. The terminal velocity was determined by measuring the air velocity required to suspend a particle in a vertical air stream using a wind tunnel. A 3×3 factorial treatment arrangement with 30 replications in a completely randomized design was used to study the effect of moisture content and particle type on the terminal velocity. The mass mean terminal velocities of the corn silage at 40-50, 50-60 and 60-70% moisture contents were 7.1, 7.3 and 7.8 m/s, respectively. The results showed that only the effect of particle type on the terminal velocity of corn silage was significant. The mean values of the terminal velocity of corn leaf, stalk and cob pieces were 3.8, 6.8 and 8.8 m/s, respectively. For each particle type at a given moisture content, the terminal velocity was best described by means of the equation of velocity squared in terms of weight.

Keywords: Corn, Corncob, Leaf, Pneumatic conveying, Silage, Stalk, Terminal velocity.

INTRODUCTION

Pneumatic conveying may offer important functional and economic advantages in handling materials such as corn silage and low-moisture grass silage. Potential advantages include flexibility, safety, low initial costs, reliability and capability of handling difficult materials, such as haylage (Wolfe *et al.*, 1970). The utilization of forced-air streams for the transport and drying of agricultural materials is becoming increasingly important in Iran. It is, therefore, necessary that the aerodynamic characteristics of these materials be investigated so that their behavior in an air stream can be estimated with a degree of certainty, and so a fair basis on which to establish blower design can be provided. The most important aerodynamic characteristics to be considered are the suspension velocities of particles. The aerodynamic properties of agricultural products can be determined by recording the rate of acceleration of a particle falling in an enclosed tube or by measuring the air velocity required to suspend a particle in a vertical air stream. For a particle suspended in a vertical air stream, the particle weight acting downwards balances the buoyancy and drag forces acting upwards (Persson, 1991).

Agricultural materials are usually neither symmetrical in shape nor uniform in density. This lack of symmetry causes aerodynamic instability because the centers of gravity, lift

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or drag, and pressure are not co-axial and the particle will attempt to align itself to assume an equilibrium position in the air stream. The unstable behavior of threshed material in a vertical air stream was investigated by Bilanski and Lal (1965) using wheat straw, and by Menzies and Bilanski (1968) for alfalfa stems. They concluded that an end node in a stalk had a significant effect on its aerodynamic properties by causing the stalk to orient itself toward the vertical. Bilanski and Lal (1965) stated that rotation of particles in an air stream caused a higher drag and lower terminal velocity.

Uhl and Lamb (1966) found that suspension velocities of corncob pieces from a combine straw walker ranged from 6.7 to 13.4 m/s, while the suspension velocities of corn stalk pieces ranged from lower to higher velocities than cobs. After a review of previous research, Bilanski (1971) concluded that individual particles behave in an unstable manner and therefore a large number of replications are needed to draw statistical interferences. Extrapolation of single particle research from the behavior of material flow is complicated by increased turbulence caused by particle interaction. Farran and Macmillan (1979) found that higher air velocities were required to separate chaff from grain than to suspend chaff on its own.

Several methods have been used to measure the terminal velocity of particulate materials. Numerous researchers have used vertical wind tunnels to measure the terminal or suspension velocity. Wolf and Tatepo (1972) stated that none of the methods used for grains appeared to be satisfactory for studying chopped forage particles, many of which are extremely irregular in shape and small in size. They suggested an experimental procedure to yield a mean terminal velocity representative of the entire bulk mass as well as a measure of particle aerodynamic variation within the mass. The objectives of this research were:

1) To characterize the mass mean terminal velocity of sample taken from the silo.

2) To determine the terminal velocity of various particle types of corn silage at different moisture content.

MATERIALS AND METHODS

Materials

The samples used in this study were obtained from silage corn (*cv.* 704) kept in silo for six months from Isfahan University of Technology Research Station Farm located at Najafabad, Isfahan, Iran.

Sample Preparation

The moisture content was determined by placing 25 g of the silage sample in an oven at 103 °C for 24 hours, and then cooling the samples before weighing them (ASAE 1992). Silage samples of the desired moisture levels were prepared by drying in an oven or by adding a calculated amount of distilled water and sealing them in separate plastic containers. The samples were kept at 5 °C in a refrigerator for a week to enable the moisture to distribute uniformly throughout the sample. Before starting the test, the samples were taken out of the refrigerator and allowed to warm to room temperature for two hours (Konak *et al.*, 2002).

Test Equipment

The study was conducted in a vertical wind tunnel (Figure 1). The cylindrical wind tunnel was a 100 cm long and 15.2 cm in diameter made of P.V.C. with two longitudinal 3-cm wide slits covered with transparent sheet. Air was supplied by a centrifugal fan driven by a 4 hp motor. A wire-mesh screen was placed 120 cm from the top of the tube (at the bottom of test section) to hold the samples in the air stream. The quantity of air, and hence the air velocity, was controlled by restricting the fan inlet. Standard wind tunnel techniques including a converging nozzle, honeycomb flow straighter and screens were used to reduce irregularities of flow (i.e. swirl, surge and velocity fluctua-

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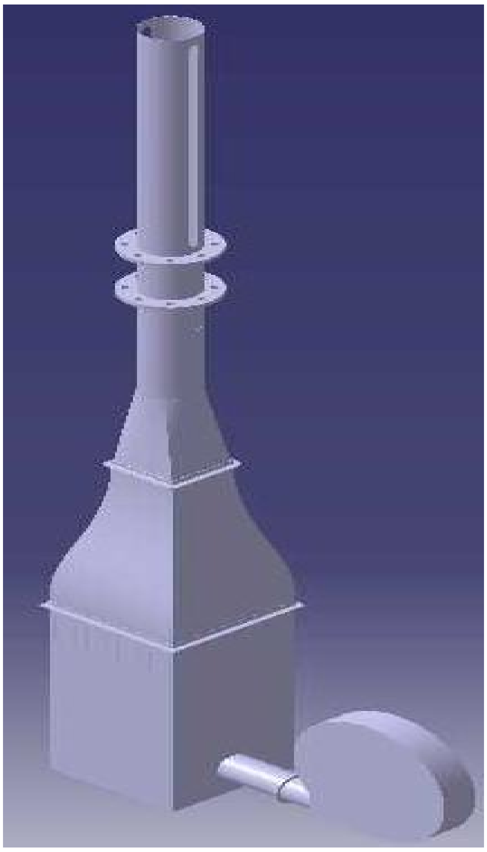

Figure 1. Schematic diagram of wind tunnel for terminal velocity measurement.

tions). The first part of flow straightener section consisted of a sufficient number of 10 cm long, 2 cm diameter tubes laid vertically above the fan so as to cover its entire cross-section. Two wire-mesh screens were laid above the co-axial mesh tubes. The second part of flow straightener section consisted of a sufficient number of 10 cm long, 0.6 cm diameter straws laid vertically below the pitot-tube and a wire-mesh screen was laid above the co-axial mesh straws. This setup provided a uniform velocity profile over the cross-section except near the wind tunnel wall. Figure 1 illustrates the wind tunnel and setup.

The mean air velocity in the test section was determined using 15.2 cm cross pitot-tube. The pitot-tube outlets were connected to a digital differential manometer and the average air velocity was determined using the calibration chart of the pitot-tube (Masoumi and Tabil, 2003).

Methods

Mass Mean Terminal Velocity

The weighed mean terminal velocity of a sample representative of the entire bulk mass was determined using Wolf and Tatepo's method. In this method, the test procedure began by taking a random sample of the material and separating the very small particles. After presetting the airflow, the next step was to randomly select a single particle from the sample and weigh it with the analytical balance and its maximum linear dimension was measured as its particle size. The particle distributions are given in Table 1 on a percentage by length and mass basis. The particle was then taken in a tweezers and released at the center of the wind tunnel cross-section at a distance of 7.5 cm below the top edge. It was immediately observed and recorded whether the particle rose up and out of the wind tunnel or dropped down into the tunnel. The procedure was repeated at the same air velocity until a total of 300 particles had been released. Then the air flow was adjusted to a new setting and another 300 particles were individually weighed and released. For a sample at a given moisture content, the test was conducted after using four appropriate air velocity levels (4.5, 6.7, 8.5 and 9.7 m/s). Then, the mass mean terminal velocity of the sample, V_t, was calculated as follows (Equation 1):

$$V_t = \frac{V_1 y_1 + V_2(y_2 - y_1) + \ldots + V_n(y_n - y_{n-1})}{\sum_{i=1}^{i=n}(y_i - y_{i-1})} \quad (1$$

Where V_i and y_i are the ith selected air velocity and the mass fraction percentage of the particle rise up at the V_i, respectively. A completely randomized design with three replications was used to study the effect of moisture content on the mass mean terminal velocity of corn silage.

Table 1. Particle size distributions for the corn silage samples used for the mass mean terminal velocity measurement.

Length distribution		Mass distribution	
Length group range (mm)	Fraction (% of total)	Mass group range (g)	Fraction (% of total)
0 – 10	4.0	0.0 – 0.01	2.4
10 – 20	26.6	0.01 – 0.1	30.6
20 – 30	22.6	0.1 – 0.2	19.5
30 – 40	16.1	0.2 – 0.3	10.8
40 – 50	9.2	0.3 – 0.4	7.3
50 – 60	5.3	0.4 – 0.5	5.0
60 – 70	4.4	.05 – 0.6	4.6
70 – 80	3.3	0.6 – 0.7	3.6
80 – 90	2.0	0.7 – 0.8	1.9
90 – 100	1.6	0.8 – 0.9	1.7
100 – 130	3.3	0.9 – 1	1.6
> 130	1.6	1 – 10	10.3
		> 10	1.0

Terminal Velocity of Particle Type

A 3×3 factorial treatment arrangement with 30 replications in a completely randomized design was used to study the effect of moisture content and particle type on terminal velocity. Moisture content levels of a 40-50, 50-60 and 60-70% wet basis were used. The particle types were leaf, stalk and corncob pieces. From each sample at a given moisture content, 30 particles for each type (leaf, stalk and corncob pieces) were randomly selected. The maximum linear dimension of each particle was measured as its particle size and then placed in turn in the wind tunnel and the fan discharge was increased until the particle was, as seen through the transparent pane, floated in the air stream. Air velocity was measured by using a cross pitot-tube and reported as terminal velocity.

Statistical Analysis

Analysis of variance (ANOVA) was performed to determine the significance of the treatment and interaction effects (Steel and Torrie, 1980). When analysis of variance was significant at the P=0.05 probability level, treatments were separated by Duncan's new multiple range tests at the 0.05 level of probability. All data were analyzed using Proc ANOVA of SAS. Model coefficients were also determined using the SAS routines, PROC REG for a linear model (SAS 2001).

RESULTS AND DISCUSSION

Mass Mean Terminal Velocity

The percentages of mass fraction of particulate matter rising were computed and are given in Table 2. The mass mean terminal velocity for each moisture content level was calculated using Equation 1 and the data from Table 2 and the results are given in Table 3. These values represent the total bulk material and should be useful, for example, in designing equipment for the pneumatic transport of bulk silage. However, it should be noted that particle interactive effects associated with a particular operation are not accounted for in this procedure.

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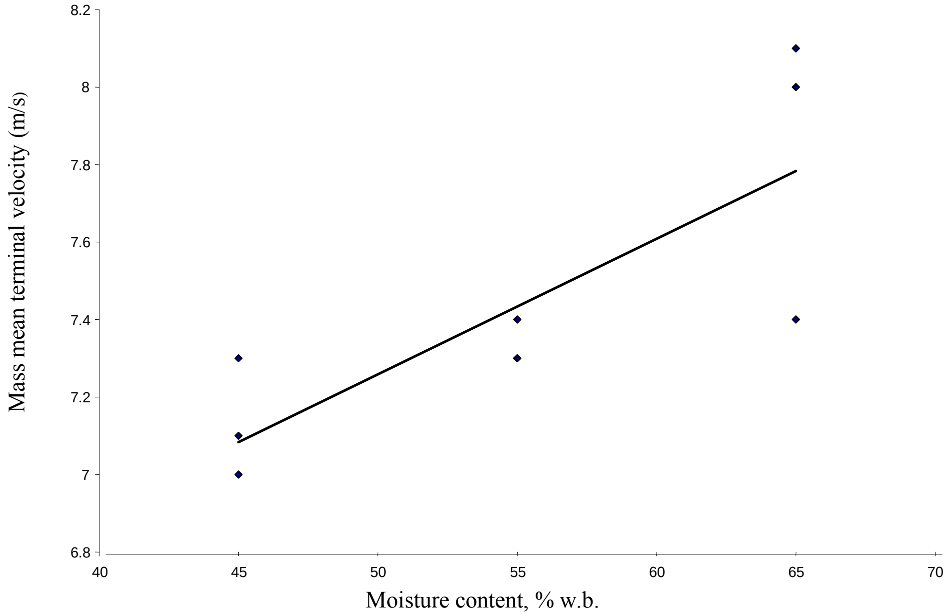

Figure 2. Mass mean terminal velocity of corn silage as a function of moisture content.

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The mass mean terminal velocities are plotted versus moisture contents in Figure 2. The equation of the fitted regression line is as follow:

$$Vt = 0.035MC + 5.508; \quad R^2 = 0.66 \qquad (2$$

where:

V_t = Mass mean terminal velocity, m/s

MC = Moisture content, %w.b.

The values of terminal velocity increased with increasing moisture content. This finding is in keeping with other experiments (Wolfe and Tatepo, 1972).

Table 2. Summary of terminal velocity data.

Moisture content (% w.b.)	Air velocity (m/s)	Particles rising, Mass fraction percentage
40-50		
	4.5	13.7
	6.7	42.9
	8.5	56.6
	9.7	69.5
50-60		
	4.5	14.8
	6.7	34.5
	8.5	47.3
	9.7	63.9
60-70		
	4.5	14.0
	6.7	22.9
	8.5	43.7
	9.7	62.1

Table 3. Mass mean terminal velocity results.

Moisture content (%w.b.)	Mass mean terminal velocity[a] (m/s)	Terminal velocity standard deviation (m/s)
40-50	7.1 b	0.153
50-60	7.3 b	0.058
60-70	7.8 a	0.379

[a] Mean values followed by the same letter are not significantly different according to Duncan's new multiple range test at the 5% level of probability.

Table 4. Analysis of variance for terminal velocity of corn silage as affected by moisture content and particle type.

Source	Degree of freedom	F-value
Moisture content (MC)	2	0.95
Particle type (PT)	2	104.1[****]
MC × PT	4	1.77
Error	81	

[****] Significant effect at a probability level of 0.0001.

Terminal Velocity of Particle Type

Terminal velocity was significantly affected by particle type, but not by moisture content. The effect of moisture content and particle type on terminal velocity was not also significant (Table 4).

The mean terminal velocity of leaf, stalk and corncob pieces at the three moisture levels of 40-50, 50-60 and 60-70% w.b. were 3.8, 6.8 and 8.8 m/s, respectively (Table 5). Leaf and corncob pieces had significantly the lowest and highest terminal velocities, respectively.

The terminal velocity of the different fractions of the corn silage as a function of the particle weight at different moisture content levels are presented in Table 6. The differential equation of motion of a particle in an air stream with the drag force only in the vertical direction may be written as (Menzies and Bilanski, 1968):

$$m\frac{dv}{dt} = mg - F_b = mg - C_r V^2 \qquad (3$$

where:

$$F_d = \frac{C_d \rho A V^2}{2} = C_r V^2 = Drag\ force, N$$

ρ = Density of air, kg/m^3
A = Projected area in direction of flow, m^2
V = Velocity of fluid, m/s
C_d = Drag coefficient, dimensionless
C_r = Resistance coefficient, kg/m.

At the terminal velocity, $\frac{dv}{dt} = 0$

Therefore, $C_r V^2 = mg$

$V^2 = \frac{W}{C_r}$ where W = Weight of body, N.

The constant in the equation for any given particle at each moisture level (Table 6) indicates that the particles did not behave exactly according to the above differential equation of motion. Had they done so, the constant would be zero. Similar results were reported for alfalfa particles by other researchers (Menzies and Bilanski, 1968). The deviation may be attributed to the rotation of particles about their axes, to the horizontal translation of particles, and to the lift force, none of which were accounted for in the above equation (Menzies and Bilanski, 1968). The high correlation coefficients indicate that these equations fit a straight line equally well (Table 6).

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Table 5. Mean and standard deviation of length (mm) and terminal velocity (m/s) of particle type of corn silage.

Particle type	Length		Terminal velocity[a]	
	Mean	Standard deviation	Mean	Standard deviation
Leaf	61.2	41.1	3.8 c	1.01
Stalk	21.1	14.3	6.8 b	1.76
Corncob	18.4	13.0	8.8 a	1.29

[a] Mean values follow ed by the same letter are not significantly different according to Duncan's new multiple range test at the 5% level of probability.

Table 6. Regression analysis of squared terminal velocity (V_t^2) as a function of particle weight (W, N) for the separate fractions of the corn silage.

Particle type	Moisture content (% w.b.)	Squared terminal velocity $(m/s)^2$	R^2
Leaf			
	40-50	$V_t^2 = 9.69 + 1.11$ W	0.68
	50-60	$V_t^2 = 9.64 + 1.52$ W	0.77
	60-70	$V_t^2 = 11.71 + 3.12$ W	0.90
Stalk			
	40-50	$V_t^2 = 17.93 + 4.48$ W	0.98
	50-60	$V_t^2 = 25.35 + 5.28$ W	0.90
	60-70	$V_t^2 = 31.45 + 3.69$ W	0.74
Corncob			
	40-50	$V_t^2 = 67.73 + 0.285$ W	0.97
	50-60	$V_t^2 = 65.79 + 1.60$ W	0.90
	60-70	$V_t^2 = 36.61 + 0.582$ W	0.87

For each particle type, the terminal velocity increased with an increase in moisture content (Table 7). For leaf, the mean terminal velocity increased by 31% (from 3.9 to 5.16 m/s) when the moisture content was increased from 40-50 to 60-70% w.b. However, for stalk the mean terminal velocity increased by 16% (from 6.2 to 7.2 m/s same). For a similar mass group, corn leaf pieces had a lower terminal velocity than corn stalk pieces. The decrease in the terminal velocity might be due to the significant increase in the effective area of the leaf as compared with stalk pieces (Table 5). The corncob pieces were the most variable components and the relation between the moisture content and the terminal velocity was not consistent (Table 7). This was mainly due to the sensitivity of the measurements to particle orientation.

CONCLUSIONS

Based on the results of this study the following conclusions can be drawn:

1. The mass mean terminal velocity of corn silage was significantly increased when moisture content level was changed from 40-50 or 50-60 to 60-70 (%w.b.).
2. The terminal velocity of each particle type (leaf, stalk and corncob) did not change significantly with a moisture content in the range of 40 to 70 (%w.b.).
3. The values of terminal velocity of leaf and corncob pieces were the lowest and highest, respectively.
4. The terminal velocity of silage corn fractions were best described by means of a series of equations of squared velocity in terms of weight at each moisture content level.

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Table 7. Terminal velocity of various size categories of different fractions of corn silage at three moisture levels.

Particle type	Moisture content (% w.b.)	Terminal velocity (m/s)			
		Total	Small [a]	Medium [a]	Large [a]
		$\overline{X} \pm \sigma$ [b]	$\overline{X} \pm \sigma$	$\overline{X} \pm \sigma$	$\overline{X} \pm \sigma$
Leaf					
	40-50	3.93±0.94 (m=0.4) [c]	2.7±0.17 (m<0.2)	4.2±0.81 (0.2≤m<0.8)	4.58±0.17 (m≥0.8)
	50-60	3.87±0.9 (m=0.35)	3.04±1.2 (m<0.17)	4.09±0.54 (0.17≤m<0.38)	4.36±0.29 (m≥0.38)
	60-70	5.16±1.6 (m=0.46)	3.57±1.0 (m<0.19)	5.46±1.3 (0.19≤m<0.6)	5.98±2.2 (m≥0.6)
Stalk					
	40-50	6.24±1.8 (m=0.5)	4.66±0.38 (m<0.2)	6.11±1.7 (0.2≤m<0.7)	8.04±0.97 (m≥0.7)
	50-60	6.67±1.7 (m=0.38)	5.03±0.79 (m<0.15)	6.89±1.58 (0.15≤m<0.5)	8.12±1.19 (m≥0.5)
	60-70	7.23±1.9 (m=0.51)	5.1±0.77 (m<0.15)	7.66±1.8 (0.15≤m<0.7)	8.28±1.26 (m≥0.7)
Corncob					
	40-50	8.75±1.3 (m=3.67)	8.5±0.01 (m<0.22)	8.49±1.6 (0.22≤m<9)	9.86±0.01 (m≥9)
	50-60	8.7±0.8 (m=3.5)	7.9±0.26 (m<0.21)	8.58±0.52 (0.21≤m<9)	9.7±0.43 (m≥9)
	60-70	7.61±2.58 (m=4.62)	6.7±0.01 (m<0.15)	6.88±3.55 (0.15≤m<9)	9.98±0.01 (m≥9)

[a] Size category of each particle type of corn silage.
[b] Mean ± one standard deviation.
[c] m (g) is the mean of particle mass of each type.

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تاثیر محتوی رطوبت بر سرعت حد ذرت سیلویی خرد شده و قطعات مجزای آن

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چکیده

اطلاع از خواص آیرودینامیکی محصولات کشاورزی در طراحی دستگاههایی که در عملیاتی همچون انتقال بادی ذرت علوفه‌ای برای پرکردن سیلو و یا تخلیه نمودن آن به کار برده می‌شود، ضروری است. اگر چه اطلاعات زیادی در خصوص مواد دانه‌ای وجود دارد، ولی دانش کمی در خصوص رفتار آیرودینامیکی ذرت علوفه‌ای سیلو شده وجود دارد. دراین تحقیق، میانگین وزنی سرعت حد نمونه‌ای که نمایشگر توده علوفه بود با روش ولف و تیپو، تعیین شد. سرعت حد قطعات علوفه (شامل برگ، ساقه و بلال) که به مدت شش ماه در سیلو نگه‌داری شده بودند، در سه سطح رطوبت (۵۰–۴۰، ۶۰–۵۰ و ۷۰–۶۰ درصد بر پایه‌تر)، تعیین شد. سرعت حد با اندازه‌گیری سرعت هوای لازم برای معلق نگه‌داشتن یک قطعه علوفه در یک جریان هوای عمودی با استفاده از یک تونل باد بدست آمد. اثر رطوبت و نوع قطعات علوفه بر سرعت حد با آزمایش فاکتوریل در قالب طرح کاملاً تصادفی با ۳۰ تکرار تعیین شد. میانگین جرمی سرعت حد ذرت علوفه‌ای سیلو شده در رطوبت‌های ۵۰–۴۰، ۶۰–۵۰ و ۷۰–۶۰ درصد به ترتیب برابر با ۷/۱، ۷/۳ و ۷/۸ متر بر ثانیه بود. نتایج نشان داد که فقط اثر نوع قطعات علوفه بر سرعت حد معنی‌دار بود. میانگین سرعت حد قطعات برگ، ساقه و بلال به ترتیب ۳/۸، ۶/۸ و ۸/۸ متر بر ثانیه بود. در یک سطح رطوبت معین، برای هر نوع قطعه علوفه، سرعت حد بوسیله یک معادله‌ای که در آن مربع سرعت حد بر حسب وزن بیان شده بود، بدست آمد.

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