AN ANALYSIS OF THE POWER CONSUMPTION OF BALERS

by

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1. Among agricultural products, the fibrous plants have always caused the greatest problem in transport and handling. The transportation of loose fibrous plants having a small bulk density over considerable distances is also cumbersome and wrought with the risk of accidents. Over and above the difficulties of transport, manual handling (fork) is laborious and a lengthy procedure.

To solve these problems straw and hay compacting machines were developed and constructed already as early as towards the end of the 19th century. These were available with manual, mechanical and team drive. Although the problem of the mechanisation of harvesting grain crops has been satisfactorily solved with the development of harvester threshers, these machines take care of grains in the first place and for the economical harvesting of the more important by-products, for instance straw, separate balers must be used. Another indispensable task is to increase the bulk density of fodders.

To see to the above jobs diverse machines and machine systems are available to the producers. Nevertheless, it seems rational to examine the economy of this operation, i.e. the ways to increase bulk density, on a given machine. To this end let us measure the power uptake of the machine and study each factor which might have a role in the basic process one by one, so as to get a clear picture of their power consumption, in different variations.

The compactness of forage is characterised by its bulk density. There being no completely reliable and generally accepted method to define this parameter, its value must be determined for different conditions and within them, between certain limits.

The factors having an influence on bulk density are as follows:

1. the species of the plant,
2. the length of the stalk,
3. the thickness of the stalk,
4. moisture content,
5. the method of arrangement and loading,
6. the degree of compression.

The effect of the above factors is only partly and approximately known. The factor having the strongest bearing on mechanics is the surface pressure caused by compression, which can be calculated and measured. In the course of measurements the conditions with regard to the rest of the factors should also be recorded, as far as this is possible.

20. Compacting experiments

21. Compacting by compression

Mewes [1] performed his experiments with various materials and along various principles of compacting, in a modell duct of 225 by 225 mm cross section and 177 mm height. Compression took place in a hydraulic rig.

21.1. Tests with straw

The compression versus power consumption chart for threshed barley straw having a 23 per cent moisture content is shown in Fig. 1.

The same curves can be plotted also for wheat straw. Fig. 2 shows the pressure versus bulk density curve for unthreshed wheat straw, in the logarithmic scale.

21.2. Tests on whole green fodder

The test findings with high-moisture whole green fodder are shown in Fig. 3.

In the figure the dry bulk density is marked with *a* and the value of wet bulk density with *b*. The relationship between the two is indicated by δ_s for dry and with δ_n for moist bulk density.

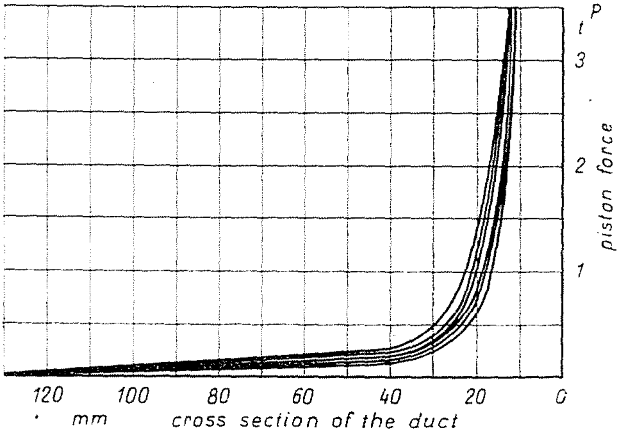


Fig. 1

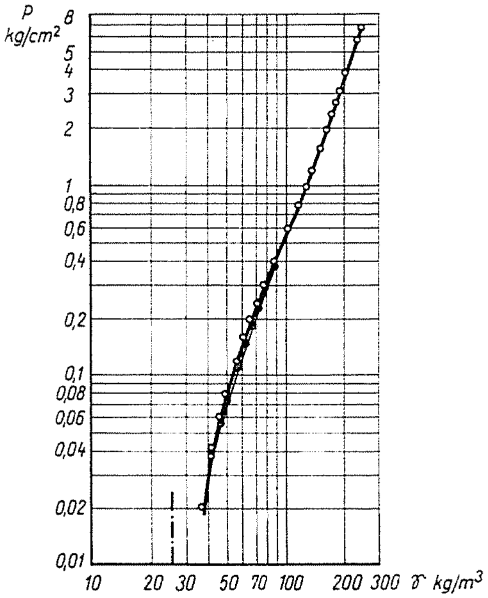
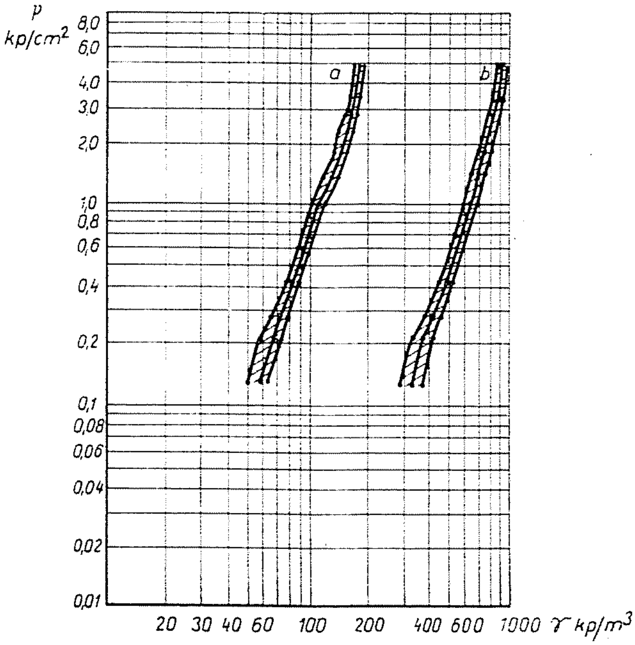

p
kg/cm²
8
5
4
3
2
1
0,8
0,6
0,4
0,2
0,1
0,08
0,06
0,04
0,02
0,01
10
20
30
50
70
100
200
300
γ kg/m³

Fig. 2


p
kp/cm²
8,0
6,0
4,0
3,0
2,0
1,0
0,8
0,6
0,4
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0,1
0,08
0,06
0,04
0,02
0,01
a
b
20
30
40
60
100
200
400
600
1000
γ kp/m³

Fig. 3

$$\delta_s = [1 - w]\delta_n \ \mathrm{kp/m^3}$$

where

w designates the moisture content. In this case the relationship between the two curves (w being equal to 82.5 per cent) is

$$\delta_n = 0.175 \cdot \delta_n \ \mathrm{kp/m^3}$$

Fig. 4 shows the dry and mean values for grass with 75 per cent moisture. It may claim interest that water escapes at a pressure of $p = 5$ kp/cm^2 (indicated by the arrow).

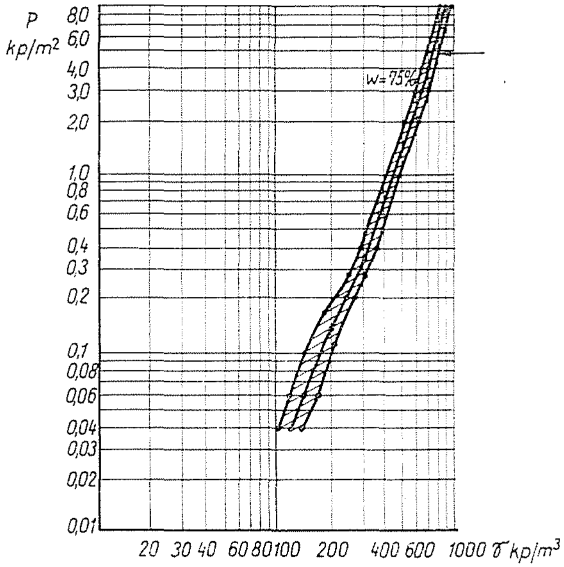

Fig. 4

A comparison of Fig. 3 and 4 proves that to compact grass with 75 per cent moisture, a greater pressure is required than for the compacting of alfalfa with the same percentage ratio of moisture.

22. Compacting tests by rolling

The tests performed with rolling are regarded as basic tests along the so-called Roll-type of baling. The equipment used in the process is shown in Fig. 5. It consists of a straw bundle with a spring-fitted torquemeter at one of its ends and a manually operated level for rolling, at the other.

Fig. 6 illustrates the variation of torque in function of the angular displacement per unit of length.

Fig. 7 shows the reduction in the diameter of the straw bundle and the increase of bulk density as a function of the specific angular displacement.

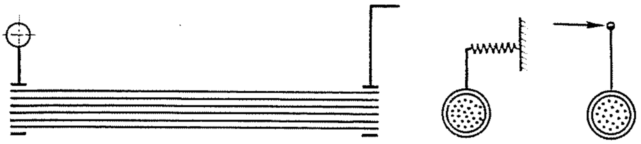

Fig. 5

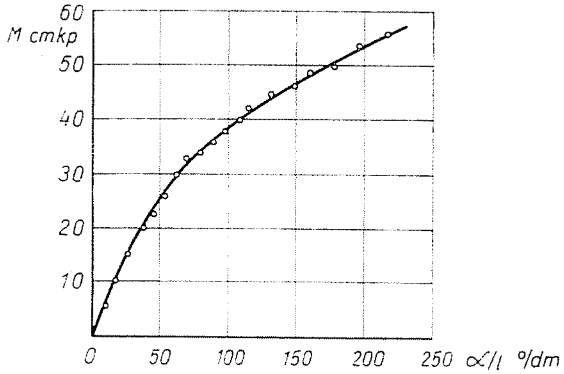

Fig. 6

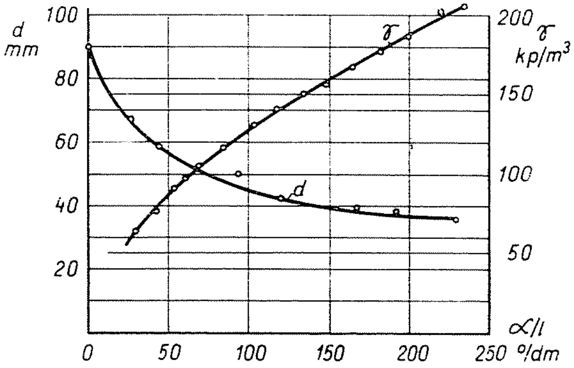

Fig. 7

Fig. 8, by way of comparison, shows the relationship between the specific input of work,

$$\frac{L}{G}\ \frac{mkp}{kp}$$

and bulk density, achieved in the piston-type baler (a) and the above outlined roller-compacter (b). The substantially lower specific power requirement of the latter as compared with the piston baler is conspicuous.

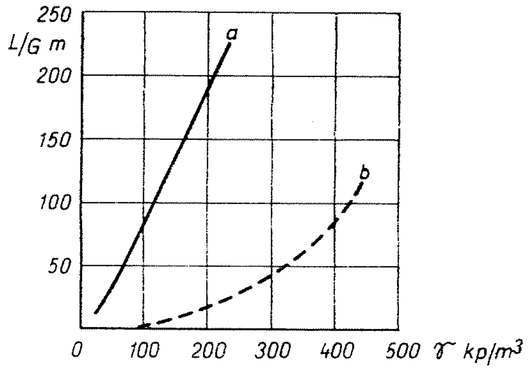

Fig. 8

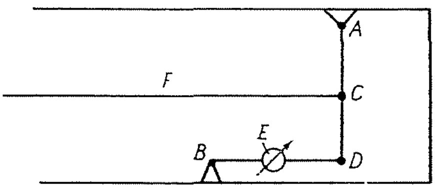

Fig. 9

3. Measurement of the power uptake

31. The Nation measurement method [3]

The essence of the Nation method lies in measuring the forces under actual conditions by a tensometric dynamometer incorporated in the piston.

The block schematic of the apparatus can be seen in Fig. 9.

The shackle AD and the dynamometer (E) are inserted between the points marked A and B of the piston head. The connecting rod (F) is coupled to the shackle AD in point C. The electric lead from the dynamometer may be arranged along the connecting rod. The diagrammes plotted on the measurement results indicate the maximum piston forces.

Fig. 10 shows the relationship for piston force versus bulk density for straw.

Fig. 11 indicates the same for dried alfalfa.

The same apparatus can be used also to measure the variations of the forces in time. The curves are shown in Fig. 12.

The power versus time curves shown in Fig. 12a refer to straw with 10 per cent moisture content, 6.6. tons/h baler output and 93 kp/m^3 bulk density, while Fig. 12b refers to alfalfa hay with 39 per cent moisture, 15.4 tons/h of baler output and 152 kp/m^3 bulk density.

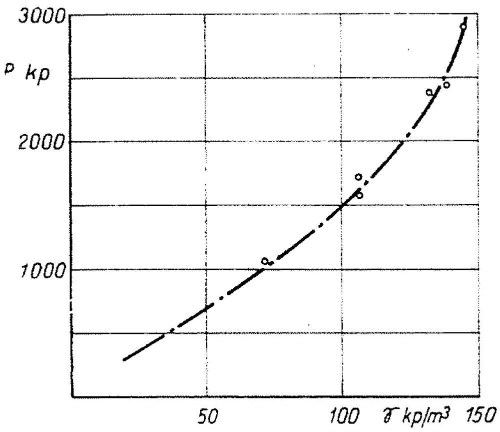

Fig. 10

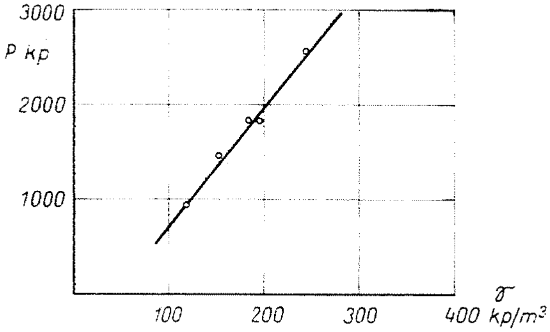

Fig. 11

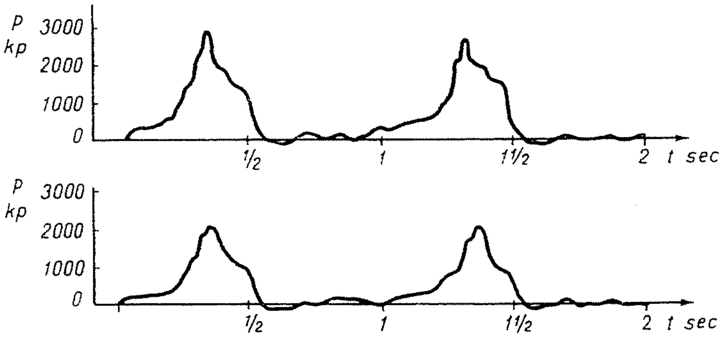

Fig. 12

The charts show clearly that the piston forces, shortly before the completion of compression, diminishes. Its possible explanation is as follows: near to maximum pressure the baled mass tends to slip in the duct, whereupon the static friction diminishes to friction through motion.

32. Complex measurements

Burrough and Graham [2] carried on thoroughgoing examinations on a pick-up baler and, through complex tests, determined not only the baler's power consumption but also that of the auxiliaries (control device, feeding, binding, etc.). While it is the measurement method which might claim special attention, the trend of the measured and calculated forces, the output and the generalisations which can be deducted from them, are also important, and may come in good stead for research workers and machine constructors.

The painstaking experiments performed in many repetitions were called upon to elucidate the following problems:

1. to determine the values and characteristics of the power uptake of the baler;
2. to analyse the characteristics of the compacting force in consideration of the factors which might have an influence upon the variation of the forces;
3. to determine the complete power consumption of the auxiliaries.

For the measurements a high-pressure baler fitted with a pick-up was selected and suitable adjusted for the purpose. The baler had a piston moving along a straight path, a feeder and a binder. Measurements were carried out with alfalfa and wheat straw of varying moisture content and varying bulk density.

The time allotted for the tests was equivalent to the time required for the completion of one bale. Bale weight divided by time yields the specific baling output in terms of kp/sec. In possession of the bale weight and the bale dimensions we may obtain the bulk density in terms of kp/m^3. The moisture content of the bale was determined by drying.

32.1. Examination of the force arising in the connecting rod

Essentially the measurements series is based on the following realization:

Under working conditions the forces arising in the connecting rod can be measured by relatively simple means.

In possession of the findings, the friction and acceleration of the piston can be measured and/or calculated.

Accordingly, subtracting from the measured force of the driving rod the friction forces and the resistance of acceleration, we obtain the force, respectively the power, required for compacting.

From the total energy uptake of the baler the auxiliaries' power consumption can be measured or calculated in the same way.

Fig. 13 is a typical chart showing the variations of power versus time for each complete revolution of the crank handle. The first dead centre position of the piston can be identified by drawing several strokes side by side; it falls between the two peak forces. At this point, namely, only the friction, respectively the mass resistivity caused by acceleration, act upon the piston. Friction can be measured by simple means. Causing the piston to move forward and back in the sleeve, friction can be measured by a dynamometer. It is a known fact that in the front dead centre position friction resists to acceleration. With the piston beginning its path in the other direction (in the direction of the rear dead centre), friction will be added to the resistance of acceleration.

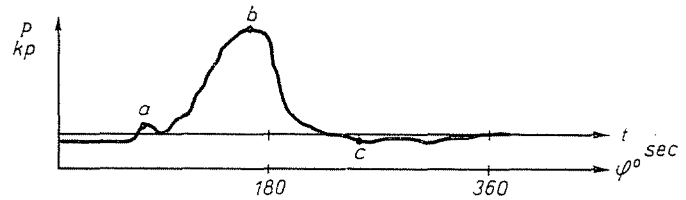

Fig. 13

In Fig. 13 there is a local maximum at the point indicated by approximately 115°. It is known from experience that it is at this very point that the mass of straw in the baling space is cut across by the blade mounted on the baler head. In relation to the maximum force this shear force is rather small, since in the instant of the cut, practically no compressive force is present. The baling space is namely closed when the cutting is complete and basically compacting begins only afterwards.

Fig. 13 shows also that the cut completed, the force arising in the connecting rod increases at a very rapid rate. This rise continues until the point just ahead of the dead centre (b) is reached, then drops. This is the point at which, as outlined above, the compacted material slips in the chute. The compacted mass exerts a certain force upon the piston starting forward on its path from the rear dead centre up to the point *c* and throughout the rest of the cycle only the frictional and acceleration forces are present in the connecting rod.

From the force versus time curve the force taken up by the drive can be determined in each 10° position of the crank handle. Multiplying the forces with their pertinent handles we obtain also the torque values.

It is useful to perform the same experiments also for wheat straw and alfalfa since these materials cause the greatest problems in baling and also because the experiments on these two widely different plants permit the drawing of more general conclusions.

32.2. Baling of wheat straw

With a view to generalisation, the experiments with the baling of wheat straw were performed under different conditions and with different characteristics.

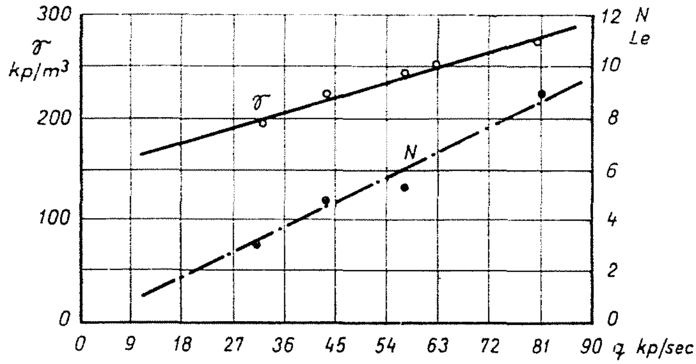

Fig. 14

As Fig. 14 shows, bulk density and power uptake increase proportionally with increasing specific power consumption.

The power uptake yielded a steeper curve in these tests than did bulk density, due to the following reasons: with increasing bulk density the friction resistance of straw passing along the baling chute also increases with motion and causes power to increase at a faster rate than the rate at which the bulk density is growing.

The machine was operated at three speeds, 38, 48 and 55 rpm. After a considerable number of repetitive tests at all three speeds, a relationship was obtained between the revolution speed of the crank handle and the maximum of the forces.

Fig. 15 shows the curves for the forces arising at P = 160° as a parameter of the revolution speed of the crank handle, in function of the different specific baling powers. It clearly indicated that, due to the fast increasing power uptake and similarly fast decreasing kinetic energy of the flywheel, no higher specific baling power can be achieved at low speed. The power rise

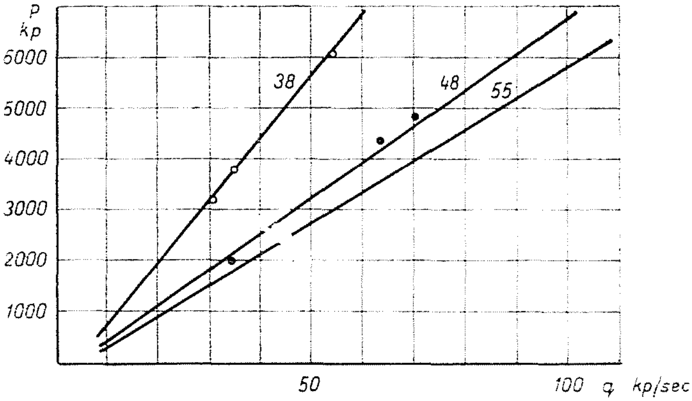

Fig. 15

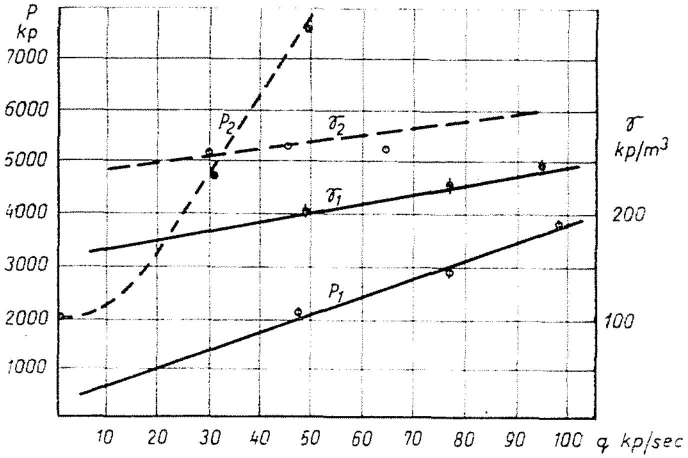

Fig. 16

at low speeds of revolution may be attributed to the piston speed or to the quantity of material increasing from one stroke to the next.

Fig. 16 yields a correlation between the speed of revolution and the piston forces, for a nearly constant amount of baled mass per piston stroke.

As apparent, up to $n = 50$ rpm force tends first to diminish then to stay approximately constant even with further increasing speed. This proves that there is very little advantage in increasing the speed of revolution to above 50 rpm in relation to the quantity of material compacted per piston stroke.

Fig. 15 can be used to advantage also for other cases. It enables, for instance, the reading off of power uptake and rpm at a constant specific baling output.

The other variable which has an influence on the P max. force is the specific baling performance.

Fig. 16 shows the relationship between bulk density and force in function of the specific baling power at two different degrees of compacting.

A lower bulk densities force increases approximately linearly with the bulk density values; at higher bulk densities, however, force increases faster than that rate. From this it follows that at a given compactness (bulk density) the specific baling output has its constraints. If also follows that at lower bulk densities a higher specific baling output can be achieved without the risk of overloading the connecting rod.

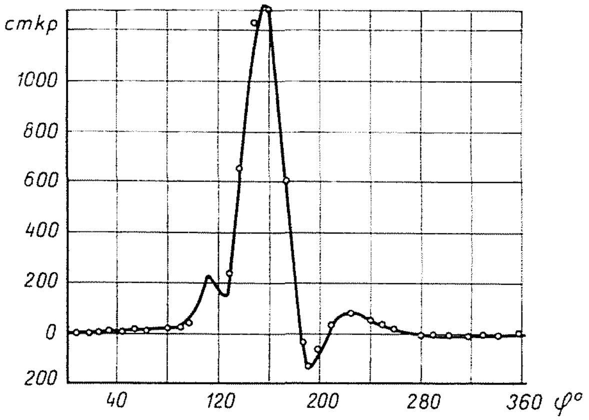

Fig. 17

From the above data the torque curve of the crank handle can also be plotted. This curve can be usefully applied in the calculation of the flywheel, to prevent that the differences in rpm should exceed the usual values.

Fig. 17 indicates that the rise of torque between 0 an 80° may be attributed to acceleration and friction. The local rise and the local maximum ahead of 120° are due to the shearing away of straw, after which the baling space is closed and the piston begins the compacting of the mass. The torque arising on the crank handle is rapidly increasing. The curve has a maximum around 150 to 160° then drops steeply due to the fact that the baled matter shifting, the force acting on the piston and on the rotating arm will be smaller. Not only does torque become zero but, due to the rebound of straw, the baled mass enhances piston movement. This is a cyclically repeated loss since the straightened-out straw must be compressed once more, during the next revolution. The rebound, viz. energy feedback of the compacted matter grows linearly with both the specific baling output and the bulk density. In the further rotation of the crank arm, the curve will again show a negative value near the front dead centre which means that the piston dissipates energy also at this point, to drive other parts of the baler.

Fig. 17 shows also the power uptake. The area enclosed by the curve and the abscissa gives the power uptake from which the average torque and average HP can be readily determined. The integral of the area below the curve gives the output, the maximum torque provides information to be used in the design of the flywheel. Namely, the motor which drives the baler does not yield the maximum torque continuously because this would make the operation of the set rather uneconomical. The difference between the output required to produce the average torque as per the Figure, and maximum output, can be stored in the flywheel. As a general rule, with a deceleration of the flywheel below 20 per cent, operation is still regarded as being stable.

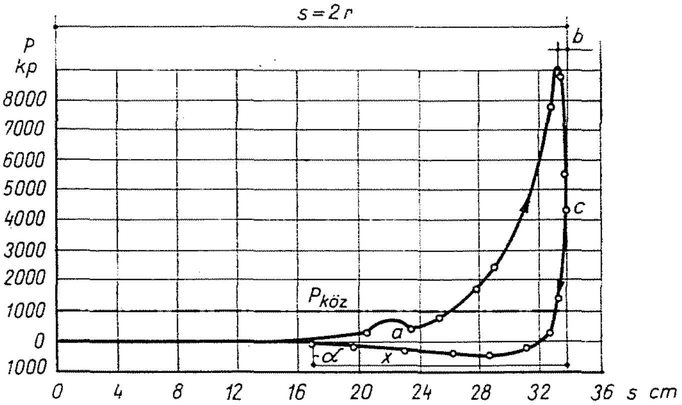

Fig. 18

Determining the force versus displacement chart for the face of the piston a still more general conclusion can be drawn for the actual process of baling.

The force versus displacement chart can be assumed in the usual way or may be constructed from the diagrammes already known. Detracting the values of friction and acceleration from the force values in Fig. 13, we obtain the force arising on the front face.

Fig. 18 illustrates the force versus displacement chart. The local maximum in point "a" is due to the cut. As the Figure proves, force on the front wall of the piston on its path to the internal dead centre increases up to the point *b* then diminishes, although the piston continues to proceed to reach point *c*. The slip is characterised by the distance *y*. Upon the piston starting on its return path from point *c* the compacted straw exerts a force up to the point *d* whereafter the cycle terminates at a value around 0. The baled matter rebounds over the section *x* which means that over this stretch energy is fed to the piston. This energy, however, cannot be recovered and in the next fun the sprung straw must again be compacted, with the input of additional energy.

In theory, in the knowledge of the area enclosed by the curve and the stroke, $P_{\text{köz}}$ can be determined. This $P_{\text{köz}}$ is one eighth to one ninth of the maximum force. Accordingly — only in theory — it is possible to build balers in which, at the necessary power consumption and without rebound, only the $P_{\text{köz}}$ energy is required. The balers known and in use at present cannot satisfy this requirement.

Although the above described examinations were performed on wheat straw, the findings are similar if alfalfa is used. They permit some general conclusions to be drawn, all the more so as the two most important materials baled in agriculture are straw and alfalfa.

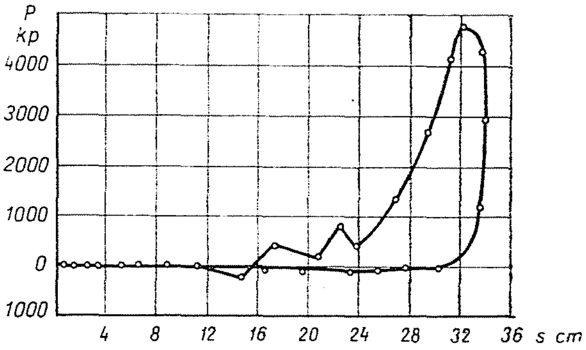

Fig. 19

Fig. 19 shows the chart plotted on the tests performed with alfalfa. A comparison with Fig. 18 proves that the baling process is very nearly the same.

From the diagramme the $P - \gamma$ function pertaining to different angular displacements may also be constructed. These curves bear the character of $y = a \cdot x^b$ viz. they are exponential. The $y = 1 \cdot x^b$ curves can be plotted also in the parameters of moisture content, specific baling efficiency and the speed of revolution. However, whereas this examination extending as it does to every detail, involves a considerable amount of painstaking work, for the practice it is sufficient to know the moisture content, the specific baling efficiency, the bulk density and the speed values for the general case, together with the maximum forces. Along the usual design procedures, from these force effect the mass of the flywheel, the dimensions of the crank handle, the connecting rod, etc. can be readily determined.

It may be worthwhile also to establish the influence of bulk density upon the power required to bale one ton of material.

Fig. 20 shows the variations in output as the function of the bulk density. With greater bulk densities—as will be apparent—the curve will increase

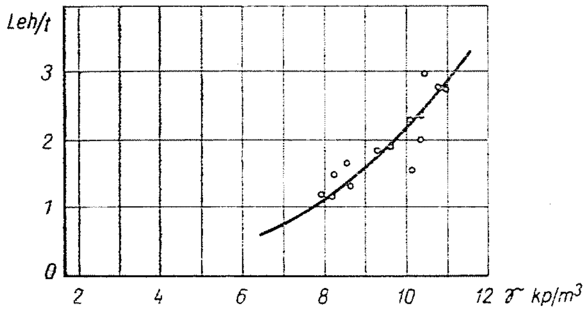

Fig. 20

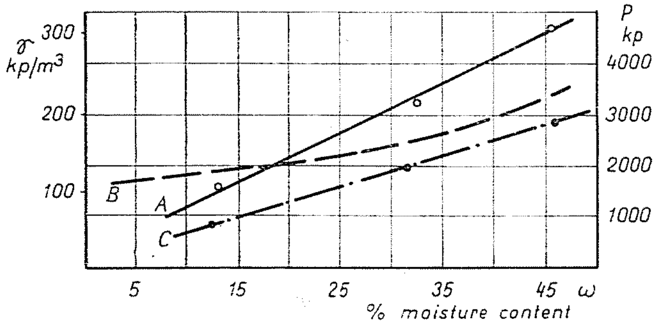

Fig. 21

exponentially. From this it would follow that for best economy, baling should be carried out at low bulk densities. However, sometimes high bulk densities may also be required, mainly for easier transport.

To solve this problem—as is usual in agriculture—complex methods must be used, viz. due consideration must be taken of all essential moments. It may be of interest that most balers used in agriculture operate at low or medium pressures. High-pressure balers are used almost exclusively in the Army.

32.3. Baling of alfalfa

In most balers the bulk density of the bales varies with the moisture content of the straw. Moisture content, however, varies even within one and the same plot and as great as plus or minus 100% variations are not unusual. With higher moisture content bale weight increases parallel and it might be appropriate to examine whether this increase is attributable to higher moisture content alone, or whether the dry matter content, too, has a share in it.

Fig. 21 shows three curves plotted during our tests related to this problem.

Curve A illustrates the variation of the bulk density of the bale; it shows a direct relationship.

Also curve B denotes the variations in bulk density but this time in connection with a dry matter content with a ratio of 20 per cent moisture (these two curves will assume identical form after drying).

Curve C shows the variations in the forces at 160°. This, too, is approximately directly proportional to the moisture content.

Fig. 22 illustrates the variations of force as a function of the bulk density at different moisture content values.

As will be clear, with increasing moisture content the bulk density attainable by the baler will also rise. This means that dry alfalfa gives bales with low bulk density, whereas materials with a higher moisture content yield bales with higher bulk densities.

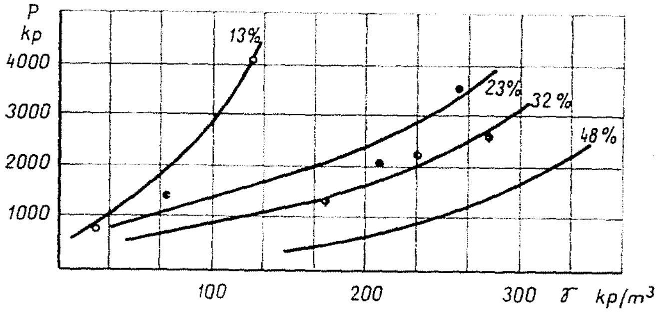

Fig. 22

33. *The power uptake of the auxiliaries*

The auxiliaries of the baling process are as follows: the mechanism actuating the feeder head and the needle, and the mechanism driving the binder.

In general the feeding head emerges fast from baling space. This high degree of acceleration increases the power uptake. Having emerged, the feeding head comes to a sudden halt. The two structural parts being positively coupled, the force of inertia arising here can be utilised in the piston work.

The power consumption of binding is also noteworthy. Binding is performed in the following way: the needle carrying the cord begins working when the piston reaches its external dead centre position. At this point power uptake is considerable also in the piston. The power needed to return the needle is very slight; the cutting of the knot or the cord, however, may cause slight local peaks.

Our experiments have proved that the power uptake of the auxiliary drives represents 10 to 15 per cent of the total power consumption of the baler.

Summary

The most important characteristics of the power uptake of balers with reciprocating piston are as follows:

The most important variables in the operation of these types are the moisture content, the specific baling efficiency and the rpm of the crank mechanism driving the piston.

1. The compactness, bulk density of the bale varies proportionally with the variation of the moisture content.

2. Increasing bulk densities need more power. The extra power demand is not in linear proportion but very much higher. Raising the bulk density from 135 to 167 kp/m^3 for instance, will cause the maximum force jump from 2000 to 4500 kp, increasing the baling power from 1.2 to 2.2 HPh/ton.

3. To raise the bulk density value beyond a certain limit, among other things, piston inertia sets limits. Although the flywheel may have a sufficiently large mass to overcome temporary peaks, the very considerable forces arising reduce the machine's service life.

4. It is an important characteristic that with high specific baling output the best suited bulk density cannot be achieved.

5. From the above it follows also that although a higher rpm of the crank handle may increase the specific baling output and the bulk density, it increases also the imbalance of the machine, enhancing wear and tear.

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