PNEUMATIC CONVEYING OF FORAGE WHEN LOADING TOWER SILOS

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INTRODUCTION

Tower silos may be loaded with forage mechanically or pneumatically. Pneumatic conveying is the most common system, because the equipment is simpler, requiring little repair and maintenance, and having a lower prime cost.
The disadvantages, high power requirement and low efficiency i.e. of energy utilization, have to be accepted. Also the blower is always regarded to be the bottleneck in the sequence of operations involved in silage making (8) There is a lack of knowledge on pneumatic conveying, especially that of prewilted grass and silage. Therefore, an extensive study was initiated to analyse the blower performance and to indicate possible improvements.

EQUIPMENT FOR PNEUMATIC CONVEYING

The equipment for pneumatic conveying comprises blowers, pipes and bends. The blowers can be divided into impeller,suction and cutter blowers. The pipes and bends normally used for pneumatic conveying of forage have a diameter of 0.23, 0.31, 0.38 or 0.45 m. Table 1 gives some characteristic values for the different pipe diameters (13). The power for air displacement is calculated for an efficiency of 30%.

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Table 1 Characteristic values for different pipe diameters.

Pipe diameter	Cross-sectional area		Air throughput required for a velocity of 30 m/s)*		Static pressure	Power requirement
m	m^2	%	m^3/s	m^3/h	Pa	kW
0.23	0.042	100	1.3	4,500	171	7.1
0.31	0.075	182	2.3	8,200	127	9.3
0.38	0.113	273	3.4	12.300	104	11.5
0.45	0.159	379	4.8	17,200	88	18.7

)* Recommended air velocity for conveying forage to a height of 30 m.

EXPERIMENTS

A scaffolding to which the blower pipes were attached was built at the experimental farm of the institute for the experiments (Fig. 1 and 2). The diameter of the pipes was 0.23, 0.31 or 0.38 m. The lifting height ranged from 20 to 30 m.
Experiments were run with impeller and suction type, and cutter blowers with flywheel of different designs, settings and speeds. The machines were driven by a diesel engine of 145 kW. The p.t.o. speed could be adjusted up to 1200 rev/min. Maize and grass were handled. The maize was chopped very short (6 mm) and harvested at two stages of ripeness (75 and 80% m.c.). The grass of the first, second or third cut was handled as chopped as well as unchopped material with a moisture content of 30 to 80% (wet basis). The chopped grass was harvested by a cylinder type field chopper at a theoretical chop length of 12 mm. The average actual particle length was 27 mm (66% < 25 mm, 13% 25-40 mm, 15% 40-80 mm and 6% >80 mm).
The torque and speed of the driving shaft, the capacity and the evenness of metering were measured, the latter two by using a continuous weigher. The data were registered by a recorder and analysed by hand. In most experiments the forage was metered from dumpboxes. The capacity of each of these metering units could be regulated and it was possible to use 1 or 2 at the same time. In addition, a self-loading trailer with an unloading (metering) unit was used with grass in some cases. Each experiment involved at least 1 tonne of forage. The throughput was gradually increased from a low initial value to the maximum possible. A total of about 400 experiments was carried out.

RESULTS AND DISCUSSION

The criteria for the evaluation of the results are throughput, delivery height and power requirement. Since the evenness of metering determines the throughput limit, attention is paid also to this aspect.

Evenness of metering

The evenness of the forage flow was analysed by establishing the values per 10 s. The results are summarised in Table 2.

Table 2 Summary of the results of evenness of metering using different equipment.

Equipment	Type of forage	Number of exp.	Standard deviation (%)
Self-loading trailers with unloading unit	Unchopped prewilted grass	16	66,8
One dumpbox	Unchopped prewilted grass	40	43,5
One dumpbox	Chopped prewilted grass	47	51,7*)
One dumpbox	Chopped prewilted grass	5	20,1**)
Two dumpboxes	Unchopped prewilted grass	14	25,8
Two dumpboxes	Chopped prewilted grass	18	31,9*)

*) Automatic control of the dumpbox(es) was not optimal for chopped forage.

**) Automatic control of the dumpbox was eliminated. The dumpbox was then controlled manually.

This table shows that in most cases the evenness of the forage flow was poor when using one metering unit. When handling chopped material and controlling the metering unit manually, the result was acceptable. Fairly good results were obtained with the combination of two units,but this is not a practical solution.

Impeller blowers (Fig. 5)

Three impeller blowers (A1, 2, 3) were used. The specifications are given in Appendix 1. Pipe diameter was 0.23 m. Fig. 5 is an example of a characteristic curve for air displacement. With a 30 m pipe and at 540 rev/min the air displacement is about 3600 m^3/h; at 750 rev/min 5000 m^3/h. The static pressure is then 55 and 110 Pa respectively, the air displacement corresponds to an air velocity of 24 and 33 m/s respectively. The three machines have only small differences in air volume, that of A3 being about 5% greater and that of A2 about 5% less than for A1. By opening a supplemental adjustable air inlet valve, the air displacement increases by 3%.

To prevent blockages when conveying grass to a height of 20 or 30 m the rotational speed must be at least 500 and 600 rev/min respectively, corresponding to a nominal air velocity of 20 and 25 m/s. When conveying a heavier product like maize, the fan speed is important apart from the air velocity.

The max. throughput limit when conveying grass with an impeller blower is 75 kg/10 s at 750 rev/min and 54 kg/10 s at 540 rev/min; it is directly proportional to the rotational speed, and hence to the air displacement. With grass the moisture content has an influence on the max. throughput.

For wet grass (> 75% m.c.) the limit was 85 kg/10 s and for fairly dry material (< 40% m.c.) 70 kg/10 s at 750 rev/min. This difference is due to the bulk density of the forage.

When conveying maize, the max. throughput was not attained. At 750 rev/min this limit is over a 400 kg/10 s. The differences compared with grass are very great. This is because of the higher bulk density of maize. Moreover, the heavier product is impelled more strongly by the paddles so that the velocity of the material is higher than with grass.

The attainable throughput depends on the max. throughput, the evenness of metering of the forage and the performance of the blower. Machine A3 has an auger and A1 and A2 have one or two impeller(s) to feed the blower. The auger is also metering the forage to the blower, corrects errors of the metering unit and is therefore less sensitive for an uneven flow of material. To exceed the throughput is permissible with machine A3 to the extent of 2½% and for machines A1 and A2, 1¼%. The attainable throughput for wilted grass is given in Table 3 for the different machines, for some max. throughputs and for 3 levels of evenness of metering. This table clearly shows that the attainable throughput is much lower than the max. throughput, usually about 50%.

Table 3 Attainable throughput of impeller blowers.

Max. throughput	Permissible extent to exceed the limit	Attainable throughput (kg/10 s) at an evenness of metering with a stand. deviation of		
kg/10 s	%	20%	40%	60%
75	1¼	47	34	27
	2½	54	42	34
65	1¼	41	30	23
	2½	46	36	30
55	1¼	34	25	20
	2½	39	31	25

Power is used for accelerating and conveying the forage, and for driving the idle machine (10). The power requirement for air displacement by the machines tested at 750 rev/min was:

Blower A1 4.9 kW
Blower A2 6.5 kW
Blower A3 6.7 kW

For grass the power requirement was as follows:

Blower A1 : 4.9 kW + 1.5 kW/t.h (r^2 = 0.80)
Blower A2 : 6.3 kW + 1.1 kW/t.h (r^2 = 0.74)
Blower A3 : 13.2 kW + 1.8 kW/t.h (r^2 = 0.64)

For machines A1 and A2, the power for air displacement agrees fairly well with the intercept of the power requirement curve. With machine A3 there is a big difference; this indicates a frictional resistance in the machine, caused by insufficient unloading of the blades.

The part of the power requirement for conveying grass (the so called specific power requirement) presented by the slope of the curve is large. Gluth (2) mentioned 0.8 kW/t.h for conveying maize. We found that the higher values are due to the greater friction resistance of grass.
For machine A1 the higher number of blades may also be important. In the case of machine A3,the forage passes through 180^{o} before it reaches the outlet, with A1 and A2 90^{o}. This means that it has a longer way to travel in the machine. Therefore the power requirement for conveying material is higher with A3.
Expressing the power requirement for conveying maize by means of a linear regression line was not reliable. The tendency was, that apart from power requirement for air displacement, the conveying of maize required 0.7 to 0.8 kW/t.h. This agrees with the power requirement mentioned by Gluth.

Suction blowers *(Fig. 6)*

Appendix 2 shows the specifications and Fig. 6 an example of the characteristic curve for air displacement for the three suction blowers (B1, 2, 3). The pipe diameter of 0.38 m was generally used, machine B1 was also connected to a pipe of 0.31 m. For maize not only the standard blowers but also some special accessories were used;these were an extra vane for B1 and extension pieces to the blades of B2.
The max. vertical displacement of grass was determined by the air velocity. It was 20 m at an air velocity of 20 m/s and up to 30 m at 25 m/s.
The max. throughput of the suction blowers is associated with the air displacement rate. At 12 x 10^3 m^3/h it is 45 kg kg/10 s and at 18 x 10^3 m^3/h, 70 kg/10 s, varying linearly with air displacement.
Apart from the max. throughput, the attainable throughput depends on the evenness of metering and the performance of the blower. There was no difference between the 3 suction blowers in conveying an unevenly metered flow of forage. One could reckon with a probability of 15% that the max. throughput would be exceeded. The relation between max. attainable throughput,air

displacement and evenness of metering is shown in Table 4. The difference between the max. throughput and the maximum attainable throughput is smaller than with the impeller blowers, but with the suction blowers the throughput is also reduced by the unevenness of metering.

Table 4 Attainable and max. throughput of suction blowers with respect to air displacement and evenness of metering.

Air displacement	Max. throughput	Attainable throughput (kg/10 s) when metering with a stand. dev. of		
x 10^3 m^3/h	kg/10 s	20%	40%	60%
9	35	29	25	22
12	47	39	34	29
15	58	48	41	36
18	70	58	50	44

Suction blowers have a high power requirement for air displacement (10 - 30 kW). Moreover, accelerating and conveying grass through the machine only requires 0.2 - 0.4 kW/t.h for chopped and 0.3 - 0.6 kW/t.h for unchopped forage at speeds from 1000 to 1500 rev/min. The lowest values are for a low speed. There was no significant difference between the 3 machines. The higher values for unchopped grass are due to the lower bulk density, which increases friction. Compared with the impeller type blower the power consumption for conveying forage is low. This is because of the relatively small proportion of forage in relation to the high air displacement. The air is accelerating the forage, which is transported through the blower by means of an air cushion, so that it hardly touches the blades and walls. This is also reflected in the wear and tear of the blower.
Normally suction type blowers cannot be used for conveying maize. The relatively heavy product drops through the large clearance between blades and housing. This applies particulary when the maize is heavier (higher moisture

content) and the eccentricity of the impeller of the blower is greater. Dry, well ripened maize (< 70% m.c.) can just be conveyed. A max. throughput of 80 - 200 kg/10 s was reached, depending on the machine and the rotational speed.
Machine B2, which has the smallest eccentricity, gives the highest capacity.

Special accessories for conveying maize

Accessories for conveying maize are necessary to minimise the clearance between wall and blades. In this case, suction blowers are converted to impeller blowers with a high air displacement, as shown by throughput and power requirement. The max. throughput was not reached in the experiments. It was more than 400 kg/10 s. The power requirement tended to be 0.7 - 0.8 kW/t.h higher than for driving the machine at no-load.

Pipe diameter

Machine B1 was also used for experiments with a pipe of 0.31 m diameter. As showed in Table 1, the cross-sectional area of the pipe is then just 67% of that of a 0.38 m pipe. This means that for the same air velocity in the pipe, the air displacement and hence the rotational speed could be reduced, whereby the power requirement is reduced (Table 5). On the other hand, this also reduces the max. throughput.

Table 5 Air displacement, power requirement and max. throughput when using a suction blower combined with a pipe of 30 m length and 0.31 or 0.38 m diameter at various air velocities.

Air-velocity m/s	Air displacement m^3/h		Power consumption: Driving blower conveying kWh		Power consumption: Conveying grass kWh/t		Max. throughput kg/10 s	
	Ø 0.31m	Ø 0.38m	Ø 0.31m	Ø 0.38m	Ø 0.31m	Ø 0.38m	Ø 0.31m	Ø 0.38m
20	5.400	8.200	2,8	3,4	0,20	0,30	21	32
25	6.800	10.200	5,4	6,7	0,22	0,32	26	40
30	8.200	12.300	9,3	11,5	0,24	0,34	32	48
35	9.500	14.300	14,8	18,3	0,26	0,36	37	56
40	10.900	16.300	22,0	27,3	0,28	0,38	42	63
45	12.300	18.500	31,4	38,8	0,30	0,40	48	72

Cutter blowers (*Fig. 7*)

In experiments, 2 cutter blowers with flywheel were used. Appendix 3 shows the specifications and Fig. 7 a characteristic curve for air displacement. The machines were used with a pipe of 0.31 diameter and a rotor speed of 540 rev/min. The results for chopping (Table 6) did not differ significantly from those for field choppers. The average particle length was 2 to 2½ times the theoretical chop length set.

Table 6 Comparison between actual en desired particle length.

Set theoretical chop length	Actual fractional size distribution (%)			
mm	< 25 mm	25-40 mm	40-80 mm	> 80 mm
3½	80.4	7.5	7.7	4.5
5½	83.8	7.6	7.7	1.0
8½	68.4	13.4	12.2	6.0
14	57.8	15.2	17.9	9.2
24	31.4	20.8	28.8	19.1

At a rotor speed of 540 rev/min the delivery height was greater than 30 m. The throughput was limited by the speed of the input conveyor or by the blower part of the machine. The relation between throughput A and chop length C is

$$A = \begin{cases} 8.5 \text{ kg/10 s} * C & (C \leqslant 10 \text{ mm}) \\ 85 \text{ kg/10 s} & (C \geqslant 10 \text{ mm}) \end{cases}$$

The attainable throughput depends on the max. throughput, the evenness of metering and the performance of the machine. No difference was found between the 2 machines.

When determining the attainable throughput one may reckon with an extent of

$2\frac{1}{2}$% for exceeding the max. throughput. The ultimate throughput for some selected chop lengths and evennesses of metering is given in Table 7.

Table 7 Relation of ultimate throughput of flywheel type cutter blowers, to chop length and evenness of metering.

Selected chop length	Max. throughput	Attainable throughput (kg/10 s) at an evenness of metering with a rel. stand. deviation of		
mm	kg/10 s	20%	40%	60%
$3\frac{1}{2}$	30	21	17	14
$5\frac{1}{2}$	47	34	26	21
8	68	49	38	31
10	85	61	47	39

The no-load power requirement was 19.9 kW for machine C1 and 12.4 kW for machine C2, this being due to differences in design. Conveying and chopping grass required 1.6 kW/t.h extra at a set chop length of 8.5 mm.
The equation: power (kW/t.h) = 1.9 - 0.037 x selected chop length (mm) may be used for determining the influence of the chop length.

Appendix 1 Specifications of the 3 impeller blowers tested.

Machine	A1	A2	A3
Impeller diameter (m)	1.37	1.43	1.38
Pipe diameter (m)	0.23	0.23	0.23
Number of blades	2x6	6	6
Feed system	2 impellers	1 impeller	auger
Rotor speed when n = 540 rev/min (m/s)	39	40	39
Air velocity with a pipe of 30 m length when n = 540 rev/min (m/s)	23	22	25

Appendix 2 Specifications for suction blowers.

Machine		B1	B2	B3
Impeller diameter (m)		1.08	1.11	0.97
Pipe diameter (m)		0.38	0.38	0.38
Number of blades		4	6	5
Eccentricity of the impeller	horizontally	50	90	85
	vertically	50	25	50
Rotor speed when n = 1100 rev/min (m/s)		62	64	56
Air velocity with a pipe of 30 m length when n = 1100 rev/min (m/s)		36	45	31

Appendix 3 Specifications for cutter blowers.

Machine	C1	C2
Impeller diameter (m)	1.54	1.48
Pipe diameter (m)	0.31	0.31
Number of blades	8	6
Rotor speed when n = 540 rev/min (m/s)	44	42
Air velocity with a pipe of 30 m length when n = 540 rev/min (m/s)	32	33

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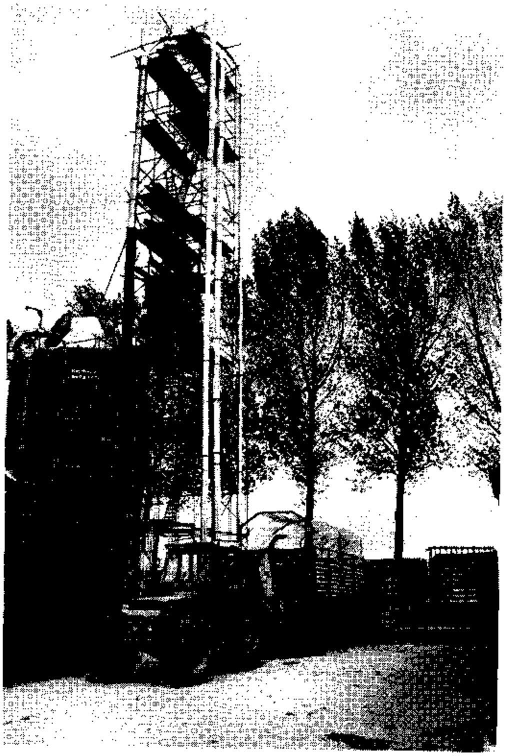


Fig. 1 Test rig with pipes of different diameters.

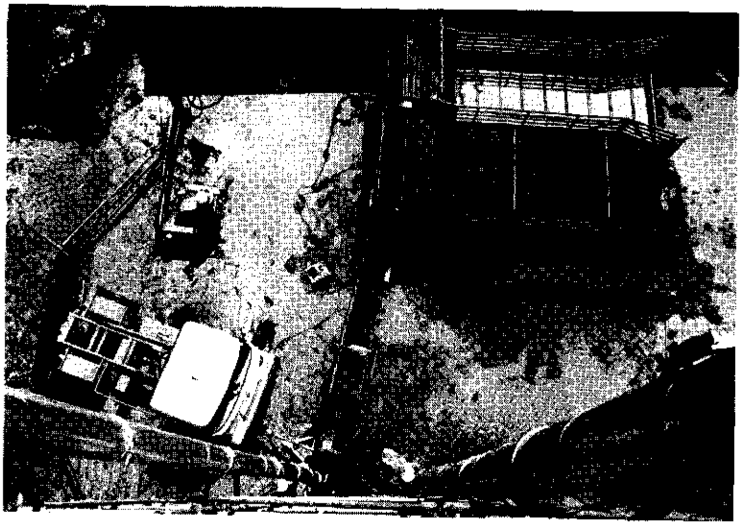


Fig. 2 Test rig as seen from above.

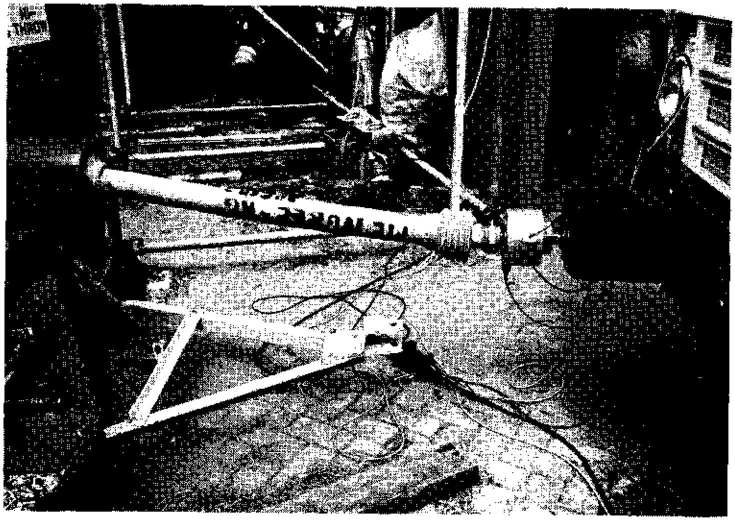


Fig. 3 Torquemeter for measuring torque and rotational speed of the p.t.o.

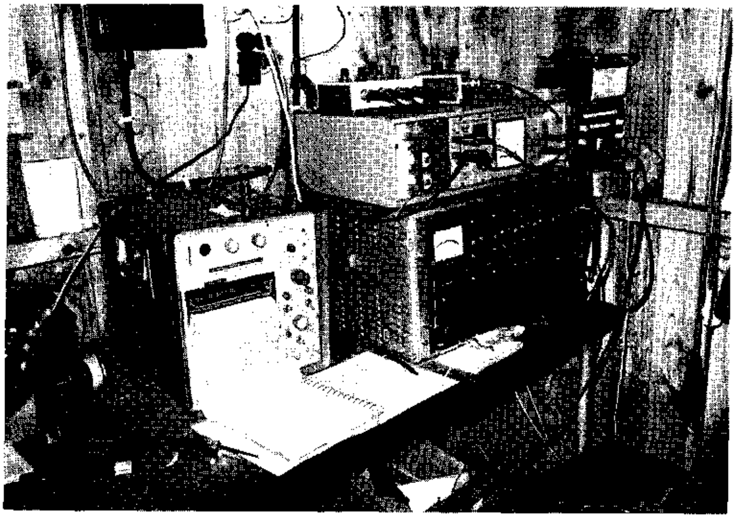
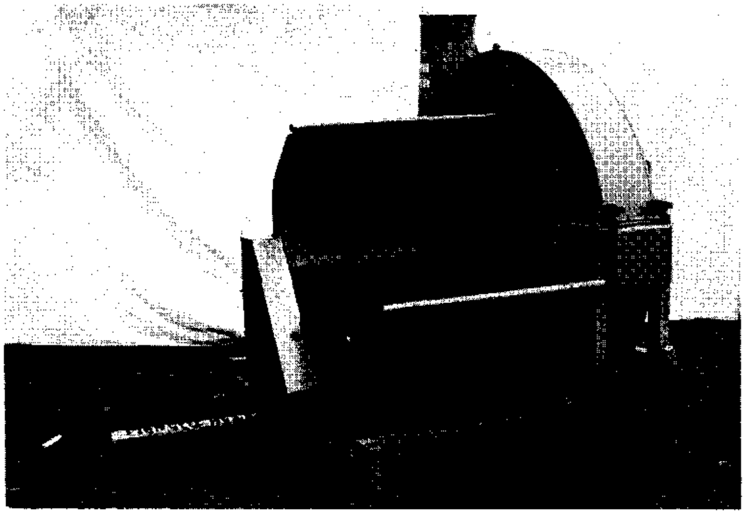


Fig. 4 Recorder.



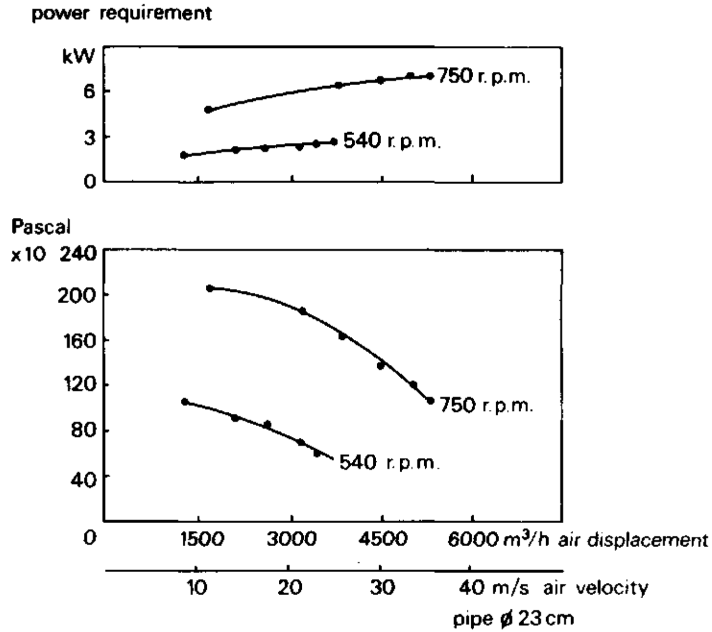
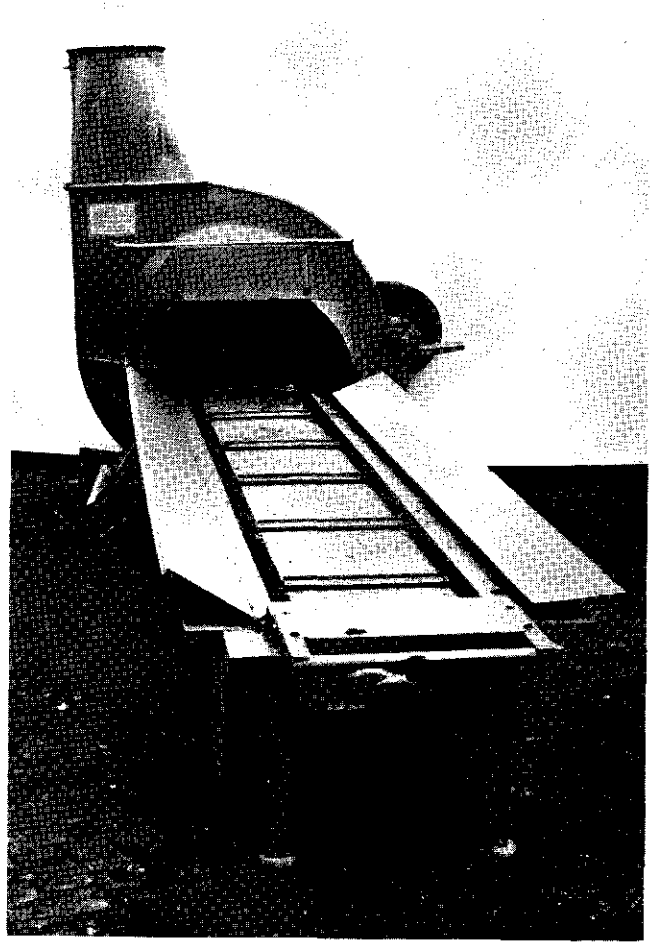


Fig. 5 Impeller blower and a characteristic curve.



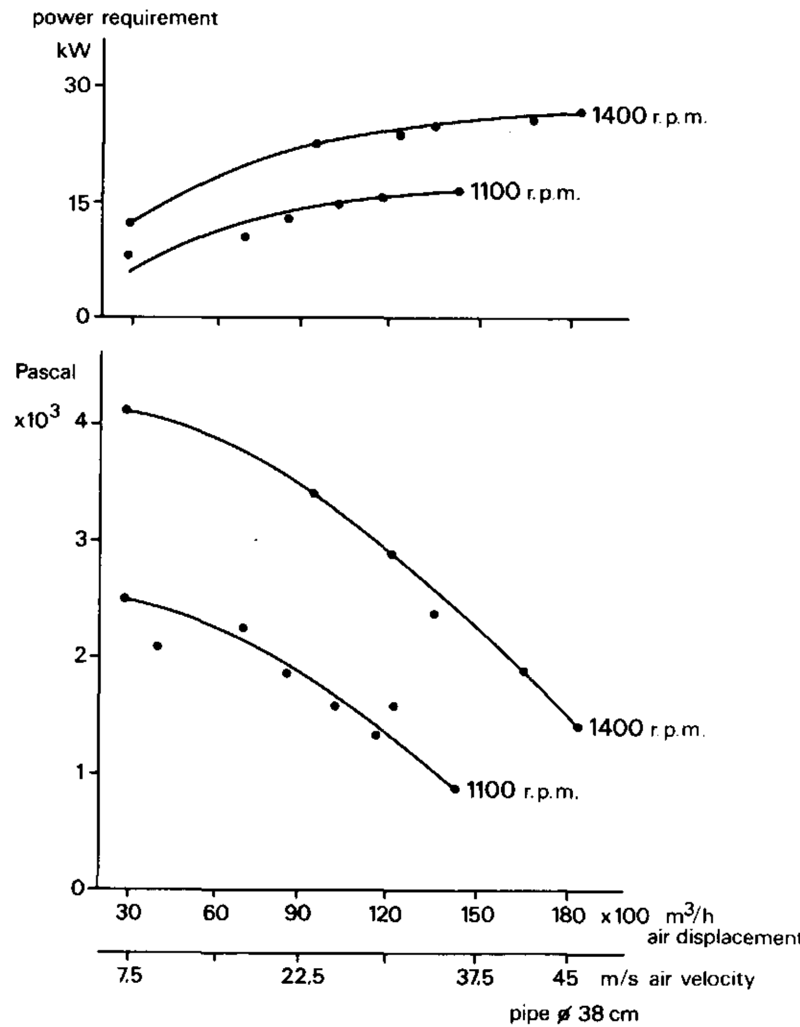
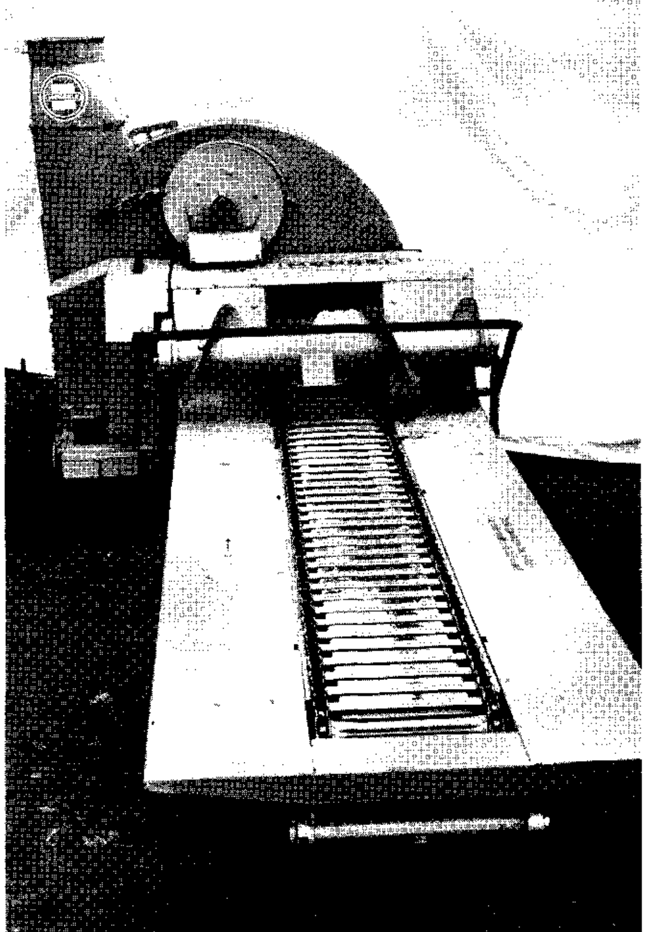


Fig. 6 Suction blower and a characteristic curve.



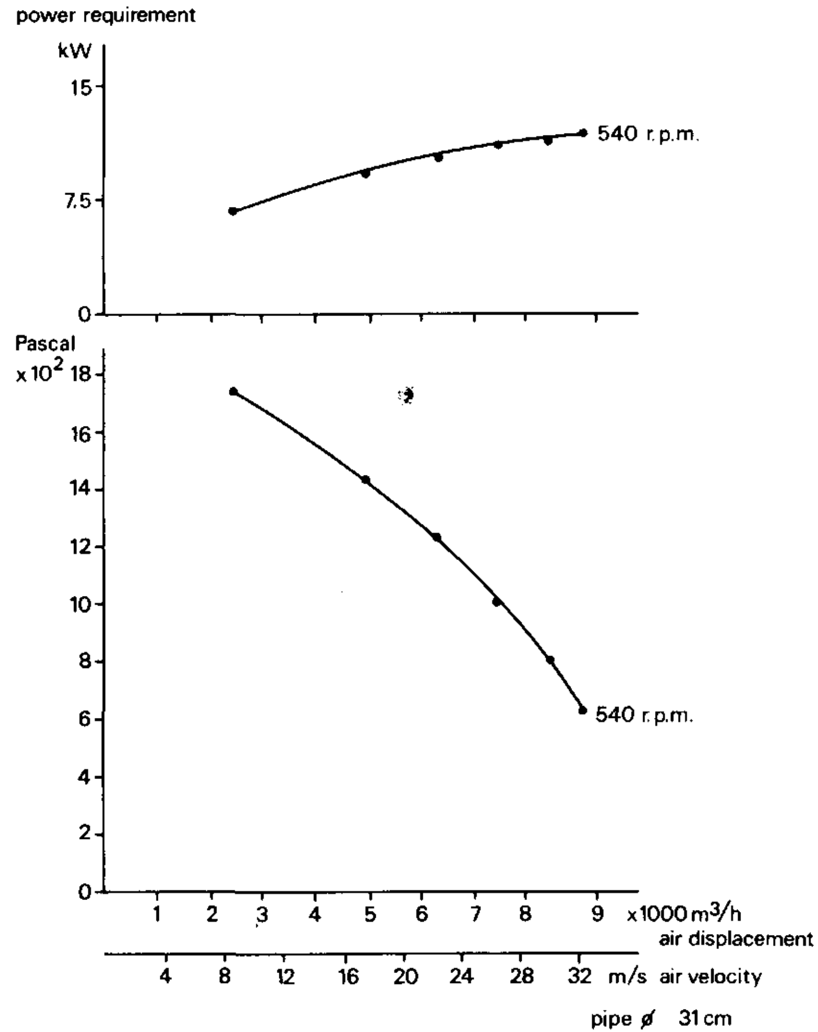


Fig. 7 Cutter blower and a characteristic curve.