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Windmill Power

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ABSTRACT. The results of tests made on a windmill installed near an anemograph at Poona are incorporated in this note. It gives the hourly output of the mill month by month together with the wind velocity at Poona. The characteristic curve for the power output has been prepared and the ratio of the sail-tip velocity to wind velocity indicated. After considering on theoretical basis the maximum amount of air-energy that is likely to be absorbed by the mill-wheel, the author compares with it the actual work done by the mill and indicates its efficiency. The factors that contribute substantially to the power output of a windmill have been discussed at length.

1. Introduction

In some countries windmills are extensively used. They are seen almost anywhere—in the rural districts as well as in the urban areas. But in an agricultural country like India very little use of this machine is being made. The reasons probably are that the information available on windmills is meagre and the price of the machine has not been within the means of average Indian farmers. It is true that the machine runs with the wind, but for its successful application it is essential to give careful consideration as to how much wind the machine is likely to have on its site and what type of load it is expected to carry. The information on wind conditions at different parts of the country is available in publications of the India Meteorological Department. An attempt was, therefore, made to collect data by experimenting on a windmill plant at Poona. The results of the experiments have been included in this paper.

A mill, 8 ft in diameter, having 18 sails was exposed at a height of about 35 ft above ground in the compound of the Meteorological Office, Poona. It operated a pump placed below the millhead through a crank, the ratio of rotation of the mill-wheel to the movement of the crank being 3 : 1. The pump was employed to draw water from a reservoir at the ground against a total head of about 19 ft. The windmill, its tower for installation, and the pump were obtained from Climax Windmill Co. of England and the plant was installed in March 1940. In the delivery pipe of the pump a Flowmeter was placed with a view to obtain a continuous record of the pump output against time. A Veeder mechanical counter was mounted near the connecting rod to the piston of the pump and from its daily registration the total number of strokes executed by the pump in a day was obtained. In the vicinity a Dines' Pressure Tube Anemograph was recording the direction and velocity of winds at a height of about 130 ft. The records of this instrument were used to obtain the information of winds at the windmill level.

The flowmeter was designed to record the rate of pump-discharge as a continuous graph. It was made in April 1940 in our workshop at Poona and carefully calibrated in the laboratory before installation. Its description will be published separately. Its scale was almost linear showing a rate of 160 gal hr $^{-1}$ for one inch pen-travel on the chart. The maximum range was 600 gallons per hour.

Periodically after about one year's use, the flowmeter was cleaned and its calibration checked.

2. Records and their tabulation

The flowmeter was installed in April 1940 on the delivery side of the windmill pump and continued to function satisfactorily with little attendance. One of its daily records is reproduced in Fig. 1 together with the wind record of the same date from the Dines' Pressure Tube Anemograph. Comparison will show that the two records are similar in character. For every gust of wind a corresponding peak can be noticed in the flowmeter record. The rate of flow changes with the change of wind velocity but the change of the former is much faster. It becomes nil or insignificant at very low winds.

From the continuous record of the flowmeter, the hourly value was computed by evaluating the mean ordinate for the complete hour centred at the hour: this value multiplied by one hour would indicate the quantity of water, in gallons, pumped by the windmill during the hour. From the records collected during May 1940 to April 1944, mean hourly values were calculated and grouped under each calendar month in Table 1. For winds prevailing at the windmill level, records of the anemograph which was situated near the windmill but exposed at a height of about 130 ft were used. From anemograms mean hourly value of

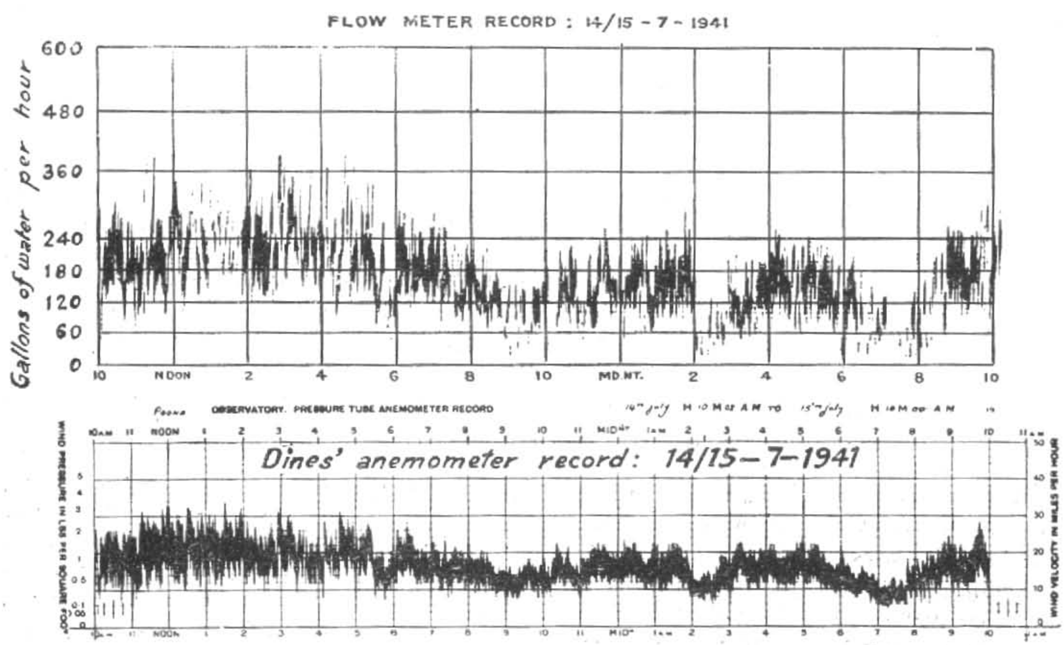

Fig. 1

TABLE 1

Mean hourly output of Windmill Irrigating Plant at Poona. The values represent gallons of water lifted from a depth of 19 ft (Based on data collected during period May 1940 to April 1944)

Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	2	10	34	118	136	192	136	50	4	4	0
2	2	4	8	26	112	130	188	136	40	4	4	0
3	4	6	6	18	114	122	188	120	68	6	4	2
4	6	10	6	16	92	124	202	136	64	4	0	2
5	2	4	4	10	86	122	188	128	38	4	0	0
6	4	4	4	8	110	138	190	112	44	6	0	0
7	4	2	4	8	106	142	184	108	32	8	0	0
8	2	2	2	8	118	152	208	130	52	12	4	0
9	2	2	4	16	160	192	246	210	70	16	6	4
10	4	4	6	22	162	254	294	284	110	38	18	12
11	12	8	20	34	178	286	416	322	132	58	48	28
12	20	32	32	46	196	318	502	384	136	80	68	44
13	24	46	38	62	214	360	500	434	160	94	80	70
14	42	54	56	74	226	354	546	444	186	92	58	72
15	52	58	72	108	252	398	552	536	204	86	50	66
16	66	50	100	130	270	418	498	510	310	82	42	56
17	78	62	128	172	286	418	446	382	318	70	30	46
18	82	82	200	258	346	398	366	334	266	68	24	26
19	78	78	236	268	278	372	296	276	202	42	12	14
20	58	70	224	174	228	328	248	222	126	26	6	6
21	42	30	132	124	184	248	226	180	94	18	2	4
22	18	20	48	102	168	194	206	158	82	8	2	2
23	10	12	22	58	142	148	188	142	62	4	2	0
24	8	4	8	34	136	134	182	140	56	4	2	2
Mean daily output	620	646	1370	1810	4282	5886	7252	5964	2902	834	466	456

TABLE 2

Mean hourly wind velocity in miles per hour at a height of 36 ft above ground (Based on data obtained from Poona anemograph during May 1940 to April 1944)

Hours	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	3·2	3·5	4·1	4·5	5·7	7·5	8·3	7·0	4·5	3·5	3·4	3·0
2	3·3	3·3	4·0	4·3	5·7	6·9	8·3	7·1	4·3	3·4	3·3	3·0
3	3·7	3·6	3·7	4·2	5·3	6·8	8·4	7·0	4·5	3·4	3·0	2·9
4	3·3	3·7	3·5	3·8	4·8	6·3	8·6	6·7	4·1	3·0	2·9	2·7
5	3·3	3·6	3·3	3·7	4·9	6·5	8·6	6·7	4·0	2·9	2·6	2·8
6	3·2	3·5	3·3	3·8	5·1	6·3	8 3	6·4	4·1	2·1	2·6	2·3
7	3·4	3·1	3·1	4·1	4·7	5·9	8·2	6·1	4·0	2·6	2·6	2·2
8	2·7	2·6	2·9	3·6	5·2	7·2	8·7	6·6	3·8	2·5	2·1	1·9
9	2·0	1·8	2·1	3·0	5·6	8·0	9·8	8·2	4·5	2·1	2·3	1·5
10	1·9	2·5	2·0	4·1	6·4	8·6	11·1	9·2	5·8	3·0	3·4	2·3
11	2·7	3·6	3·4	4·5	6·7	9·3	11·8	10·5	6·8	4·6	5·3	4·1
12	4·0	4·8	4·4	5·0	7·5	10·1	12·4	10·9	7·4	5·6	6·3	5·1
13	4·2	5·3	4·7	5·5	7·9	10·7	12·7	12·2	7·8	6·1	6·5	5·9
14	4·9	5·7	5·3	6·0	8·7	11·1	12·5	12·1	8·4	6·2	6·0	5·6
15	5·4	5·7	5·8	7·0	9·3	11·3	12·5	12·3	9·2	6·1	5·3	5·5
16	5·3	5·7	6·6	7·9	9·4	11·7	12·4	12·4	9·9	6·0	5·2	5·2
17	6·2	6·2	7·7	9·5	10·3	11·9	12·2	11·8	10·0	6·0	4·7	5·0
18	6·5	7·4	9·0	11·5	11·2	11·6	11·4	11·0	9·8	5·8	4·0	4·8
19	6·5	7·3	9·5	11·3	11·1	11·4	10·3	9·9	8·6	5·4	4·3	4·7
20	6·2	6·8	8·9	9·7	9·8	10·1	9·4	8·9	7·1	5·0	3·9	4·2
21	4·9	5·3	7·5	8·2	8·6	9·1	8·5	8 0	6·2	4·5	3·7	3·3
22	3·9	4·5	5·3	6·9	7·7	8·3	8·1	7·9	5·7	3·9	3·6	2·9
23	3·7	3·9	4·7	5·2	6·9	7·7	7·8	7·3	5·3	3·5	3·3	3·4
24	3·5	3·5	4·3	4·8	6·5	7·7	8·3	7·3	5·2	3·7	3·2	3·2
Average during a day	4·1	4·5	5·0	5·9	7·3	8·8	9·9	8·9	6·3	4·2	3·9	3·6

wind velocity was obtained by considering the winds during the period of ten minutes previous to each hour. These values were found to be sufficiently representative for the purpose and were used after reduction to windmill level. The reduction was carried out by using logarithmic formula given by Chapman[1]. The mean hourly values shown in Table 2 are based on wind records covering the period May 1940 to April 1944. The hourly value of the data in Tables 1 and 2 which was based on 120 observations can be regarded as sufficiently representative.

3. Discussion of results

Data on Tables 1 and 2 were plotted in Figs. 2, 3, 4, 5 and 6 to show the diurnal variation of wind velocity and windmill output for each calendar month. The values of output are given in gallons of water drawn from a depth of 19 ft. Wind velocity is given in miles per hour. It will be seen that variation of windmill output follows closely that of wind speed: at winds less than 3 mph the windmill plant is unable to produce any work, but as wind speed increases the increase in output becomes very much larger. At Poona winds are generally low at night and in the early morning and the bulk of the output generally occurs during the 10 or 12 hours beginning from the forenoon. The output is maximum in the afternoon. In the four months, May to August, winds are fairly strong during day and night and the mill produces work practically throughout the 24 hours.

As regards the monthly output, the maximum occurs in July and the minimum in December. During the 4 months May to August, the windmill produces a good amount of work drawing daily about 6000 gallons or hourly about 250 gallons of water from a depth of 19 ft. This would indicate that during these four months, the windmill plant on the average was developing about 0·024 horse-power. In the months of March, April and September the windmill lifts only 2000 gallons daily, working on the average 16 hours a day. In the remaining months of the year the output of the windmill plant at Poona is very small amounting to about 600 gallons per day, the mill functioning only about 9 hours a day.

Taking the year as a whole the average daily output of the windmill amounts to about 2700 gallons. The mill, however, remained idle 40 to 50 per cent of the period in a year as can be seen from Table 3 below. Considering, therefore, that the mill worked only 12 to 14 hours a day, the average horse-power developed comes to about 0·022 during the working period.

It will be of interest to know how many hours in a year the mill remained idle due to lack of winds. For this purpose, daily records of the flowmeter were examined and the hours in which output was nil were counted; the result was then averaged for a day of 24 hours. The information is given in the last row of Table 3 from which it will be seen that at Poona the mill is able to function on the average 12 to 14 hours a day.

Table 3 shows periods during which the windmill remained idle due to lack of winds.

TABLE 3

Periods during which the windmill remained idle due to lack of winds

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Total duration in hours per year	515	447	373	338	156	58	40	93	346	409	476	528
Percentage of the month	69·3	66·6	50·1	47·0	21·0	8·1	5·4	12·5	48·1	55·0	66·2	71·0
Average number of hours per day	16·6	16·0	12·1	11·3	5·0	1·9	1·3	3·0	11·5	13·2	15·7	17·1

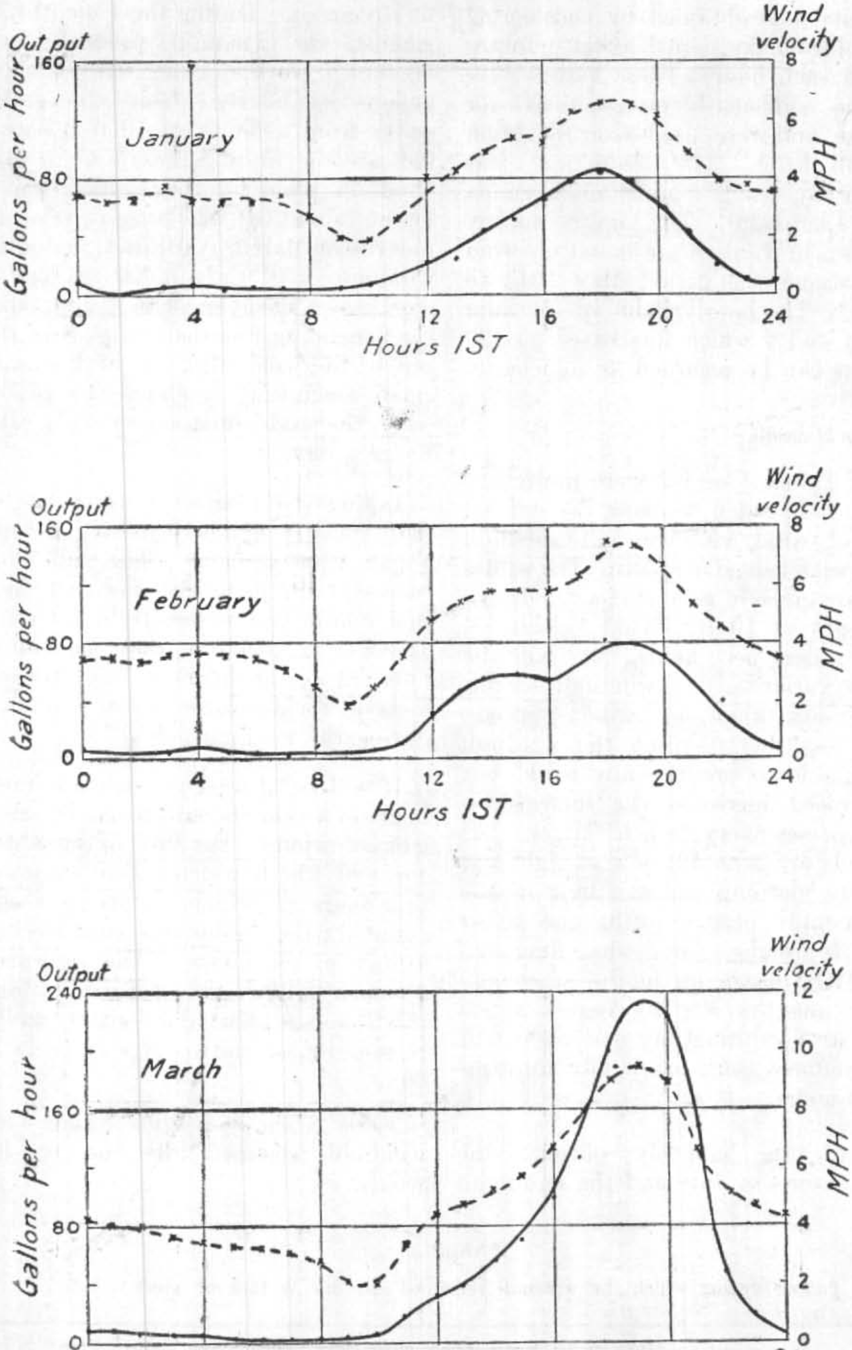

Fig. 2. Curves showing diurnal variation of wind velocity and windmill output for different months

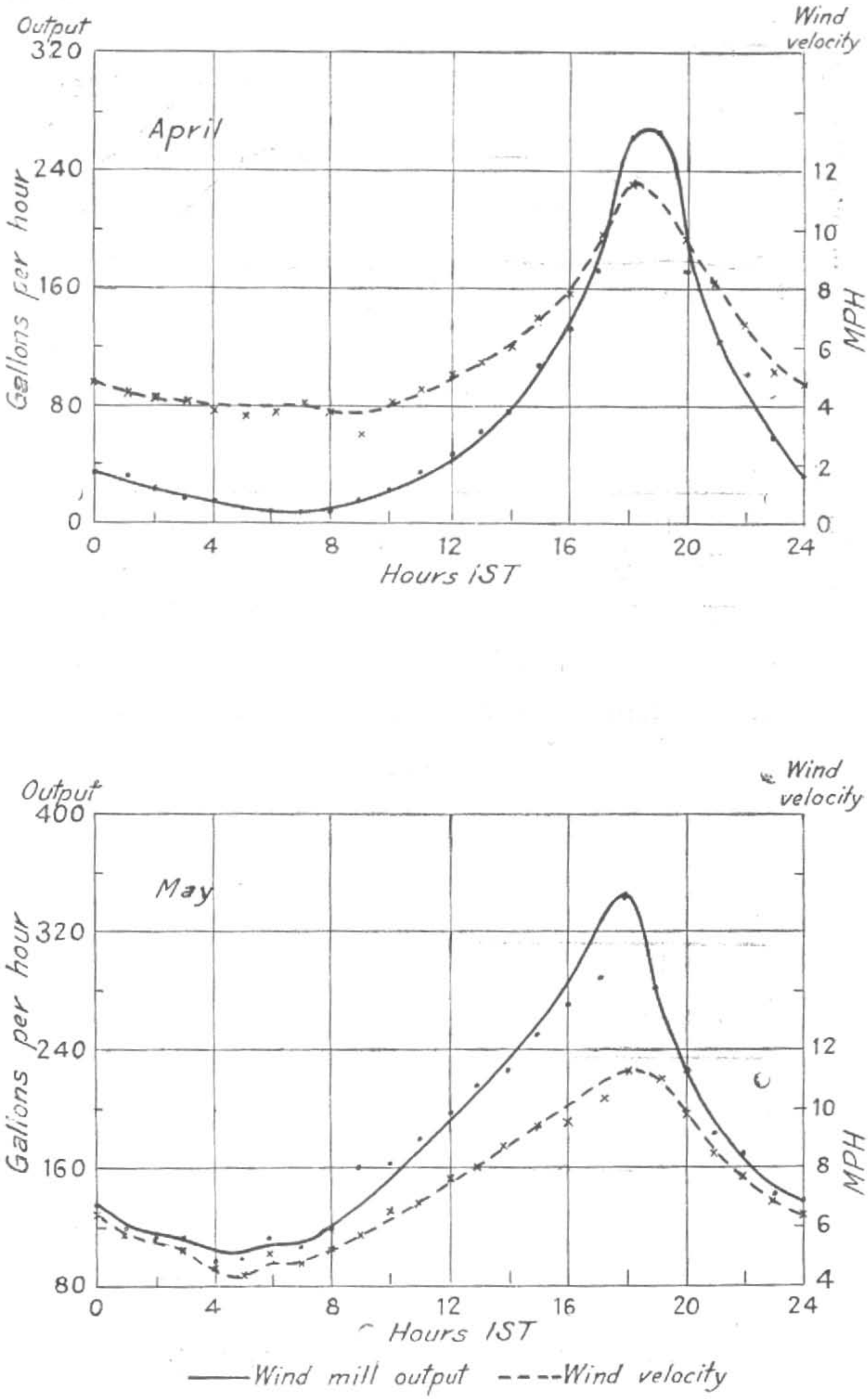

Fig. 3. Curves showing diurnal variation of wind velocity and windmill output for different months

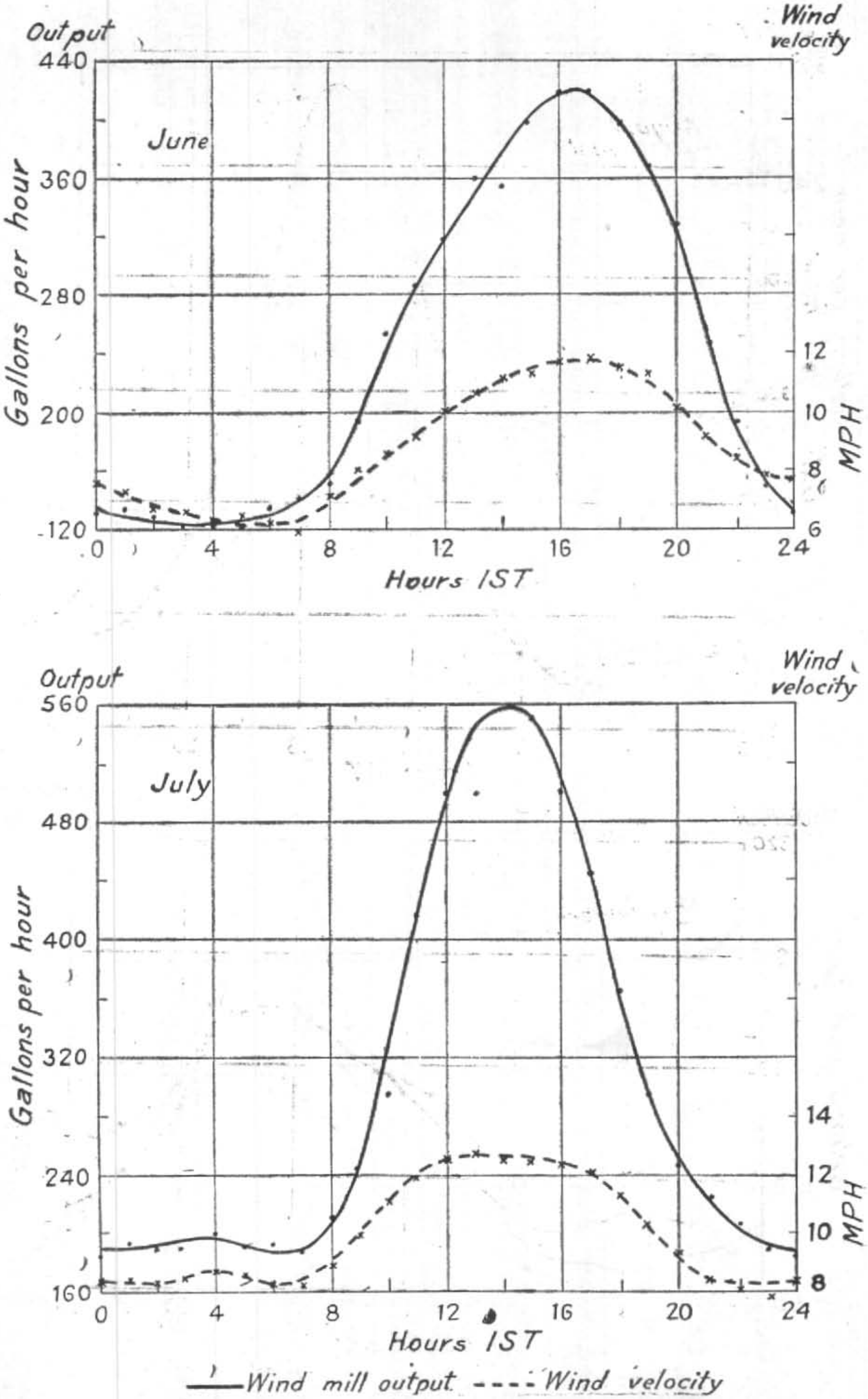

Fig. 4. Curves showing diurnal variation of wind velocity and windmill output for different months

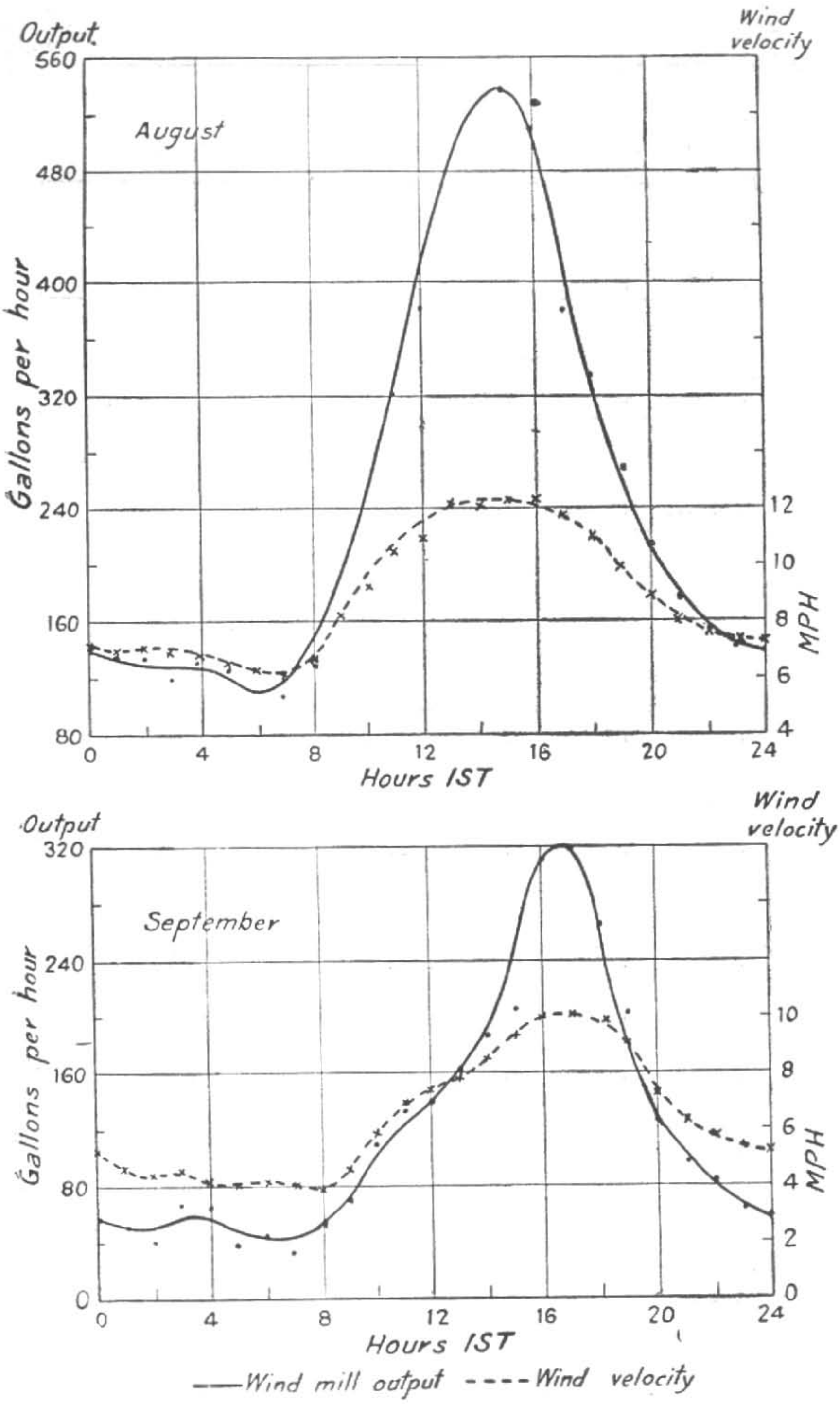

Fig. 5. Curves showing diurnal variation of wind velocity and windmill output for different months

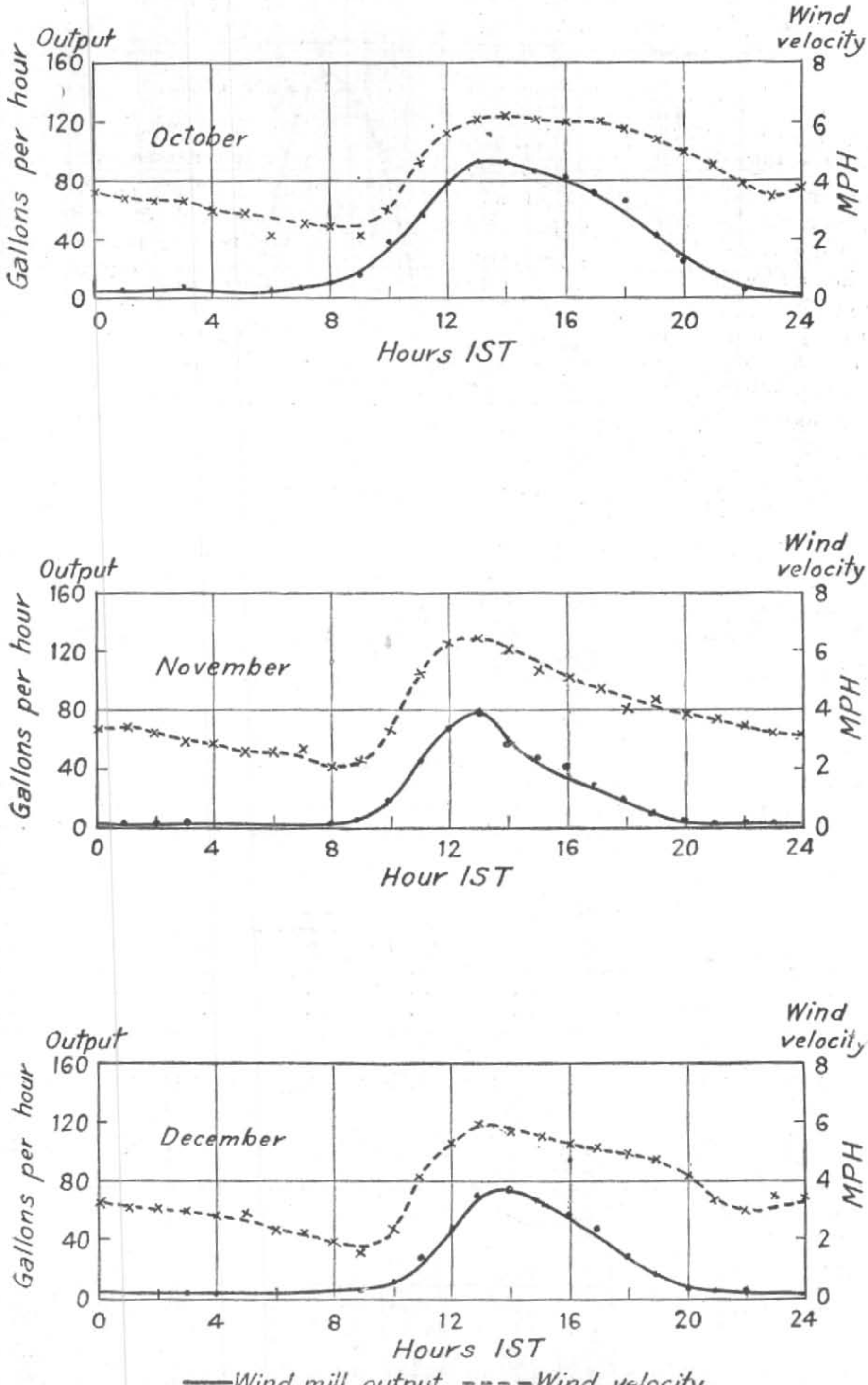

Fig. 6 Curves showing diurnal variation of wind velocity and windmill output for different months

Table 4 below shows how many hours in a day of a month a certain rate of output (gallons of water drawn from a depth of 19 ft) can be expected of the windmill. The information is obtained from analysis of data in Table 2. It will be seen that whereas in the month of July the plant can be expected to give for 24 hours of the day an output at a rate exceeding 150 gal hr^{-1}, the same rate of output can be expected only for 14 hours in a day in May, and 3 hours in a day in March. Similarly, an output rate of 300 gal hr^{-1} can be expected for about 9 hours of a day in June, July or August, but only for 2 hours in a day in the month of May or September. An output rate exceeding 100 gal hr^{-1} cannot be obtained even for an hour of the day in January, February, November or December.

Table 4 shows the average number of hours in a day during which a certain rate of output can be expected of the windmill at Poona.

4. Output Characteristics

To find a curve which will show output of the windmill against wind speed fresh data had to be collected. For this purpose periods of fairly steady winds were first selected from anemograms and corresponding to these periods output values were obtained from the flowmeter records. These data are given in Table 5 and plotted in Fig. 7.

Through the mean positions of the scattered points a smooth curve has been drawn to indicate the average output of the windmill plant at different windspeeds. This may be regarded as the output characteristic curve for this type of windmill.

TABLE 4

Average number of hours in a day during which specified rates of output or more were obtained

	Gals/hour									
	50	100	150	200	250	300	350	400	450	500
Jan ..	8	—	—	—	—	—	—	—	—	—
Feb ..	8	—	—	—	—	—	—	—	—	—
Mar ..	9	6	3	2	—	—	—	—	—	—
Apr ..	12	8	4	2	2	—	—	—	—	—
May ..	24	22	14–15	8	5	1–2	—	—	—	—
Jun ..	24	24	16	12–13	11–12	9	7	3	—	—
Jul ..	24	24	24	16	11	9	8	7	5	4
Aug ..	24	24	14–15	12	10	8	6	4	3	2
Sep ..	20	11	7	5	3	2	—	—	—	—
Oct ..	9	2	—	—	—	—	—	—	—	—
Nov ..	6	—	—	—	—	—	—	—	—	—
Dec ..	6	—	—	—	—	—	—	—	—	—

TABLE 5

Data of windmill output collected during the period when the wind was fairly steady

Wind velocity in mph	Output rate in gallons per hour (based on several observations)										
3·2	12,	4,	6,	6,	14,	4,	12,	16,	6,	4	
4·0	24,	18,	36,	22,	34,	26,	24,	18,	32,	14	
6·5	96,	104,	68,	100,	96,	100,	90,	78,	104,	116	
8·1	162,	148,	208,	192,	178,	204,	152,	182,	198,	144,	158,	174
9·3	292,	248,	280,	258,	242,	264,	274,	296,	272,	258	
10·1	304,	312,	362,	358,	384,	346,	334,	372,	352,	368	
11·5	444,	502,	464,	532,	516,	536,	482,	512,	520,	464	
12·2	532,	616,	624,	560,	628,	594					
13·0	716,	744,	714,	684,	734						
13·2	724,	788,	782,	772							
16·1	1194,	1246,	1268,	1178							

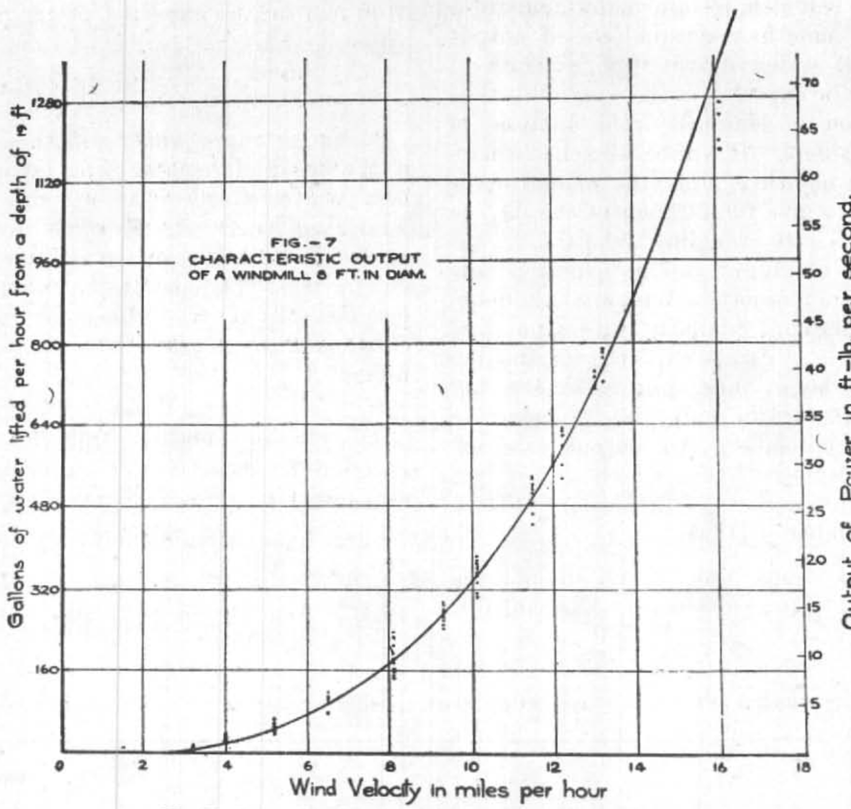

Fig. 7. Curve showing characteristic output of the windmill

From the output curve it is found that at wind velocity of 8, 12 and 16 mph the work done by the plant is 9·3, 29·6 and 69·6 ft lb sec^{-1} respectively; while the wind velocity has increased 1·5 times the power output increased 3·2 times, and with the velocity doubled the output becomes about 7·5 times. This suggests a simple relationship of the form

$$W = K v^3$$

After examining a few other points on the curve an average value of K is taken as ·0172 to fit the curve. Within the usual range of wind velocities (say, up to 20 mph) the power of the windmill plant can be obtained approximately from the formula,

$$W = \cdot 0172\, v^3, \text{ or } W = \cdot 00034\, v^3 \text{ per sq ft of the sail area}$$

where W is the work done in ft lb sec^{-1} and v the velocity of the wind in mph at the windmill level.

The 8 ft windmill plant therefore develops a little more than 1/8 horse-power at wind velocity of 16 mph, and slightly less than 1/16 horse-power at 12 mph.

The horse-power developed per sq ft of the sail area is approximately,

$$P = \tfrac{5}{8}\, v^3 \times 10^{-6}$$

It may be mentioned here that the windmill plant erected at Poona was not at an ideal site from the point of view of its exposure and was not given any special care for its maintenance. The data of output were collected from observations covering a fairly long period and might, therefore, be regarded to have highly averaged values. Whenever the pumping system was cleaned and overhauled a marked improvement in the output was noticeable. The output values shown above may, therefore, be taken to indicate what an ordinary plant is able to do when it is erected in a city area and maintained in the usual way. Undoubtedly the output will be greater if the plant is installed in an open space and more frequent attention is given to the pump.

5. Theoretical considerations

The wind in passing through the area of the rotating sail-plane suffers a loss in velocity. If the velocity of wind upstream is v ft sec^{-1} and that in the downstream where the flow is undisturbed is v'' ft sec^{-1}, the change in kinetic energy of the wind may be taken to represent the work done in rotating the mill-wheel. The mass of air flowing through the area of sail-plane equals

$$A\rho v'$$

where A is the area swept by the sails in sq ft, ρ the density of the air in lb/c ft and v' the velocity of air as it slips through the sail-plane in ft sec^{-1}. Therefore, the change in K.E. $=\frac{1}{2}A\rho v'(v^2-v''^2)$. Applying Bernoulli's Theorem on the flow separately upstream and downstream, it is found that

$$v'=\frac{v+v''}{2}$$

The work spent in rotating the mill-wheel is $\frac{1}{2}A\rho v'(v^2-v''^2)$. Differentiating the expression with respect to v'' and putting the differential to zero, we find the condition

$$v''=\frac{1}{3}v$$

for the expression to become maximum. Physically it means that, when the wind loses 2/3 of its velocity in passing through the sail-plane the maximum amount of power is made available to the mill-wheel. Under this condition the maximum power input to a windmill wheel is $\frac{8}{27}A\rho v^3$.

Incidentally, it may be remarked that the energy of the free air flowing at v ft sec^{-1} through the cross-sectional area A (the mill-wheel not being present) is $\frac{1}{2}(A\rho v)v^2$. Of this amount only $\frac{8}{27}A\rho v^3$ can be absorbed by the mill-wheel when it is present. It shows, therefore, that a common mill-wheel is utmost able to extract only 59 per cent of the air-energy[2], the remaining 41 per cent is retained by the air for maintaining the flow.

For practical purpose we take the power input to the wheel $P_i=\frac{8}{27}A\rho v^3$. A portion of this power is used up due to friction and other losses in the mill-head, connecting rods and pumping system. The rest appears as useful work, P_o. The efficiency of a windmill may be taken as the ratio of P_o to P_i. To find the efficiency of the plant at Poona we first take the value of P_o from the curve in Fig. 7, derive P_i by substituting the values of A, ρ and v in the expression above and then take the ratio. The efficiency of the plant at wind velocity of 10 mph comes to about 17 per cent only.

It will therefore be seen that the efficiency of the windmill plant at Poona is rather poor. In general a windmill plant as a converter of air-energy cannot be regarded as an efficient equipment. The efficiency of the windmill itself—without the pumping system—will, however, be greater and can be found by dividing the efficiency of the plant by the efficiency of the pumping system. Alternatively, by applying Pony Brake Tests directly on the sail-shaft the power developed by the windmill can be found and so the efficiency of the windmill calculated.

It is seen that the windmill power varies directly as the area (or square of the diameter) of the wheel and cube of the wind velocity. In the same installation one may, therefore, get 4 times as much power by having a wheel twice as large; or with the same equipment the power input will be considerably greater if the mill wheel is exposed to a greater height. The wind velocity increases slightly with height at the friction level, and the power varying as the cube of the wind velocity, the gain in power will be quite substantial if the mill-head is raised even only a few feet.

6. Ratio of sail-tip velocity to wind velocity

As already mentioned, a Veeder type mechanical counter was placed near the rod connecting to the piston of the pump. The number of strokes completed by the pump during the 24 hours of a day was obtained from the counter while the pump output was calculated from the flowmeter record. These data are given in Table 6 and plotted in Fig. 8.

TABLE 6

Number of strokes executed by the pump to discharge a certain quantity of water

Gallons of water	No. of strokes	Gallons of water	No. of strokes	Gallons of water	No. of strokes	Gallons of water	No. of strokes
40	340	485	2880	1045	8323	1640	9926
75	612	515	3942	1063	8395	1690	10040
115	890	540	3890	1110	8474	1790	10981
160	1257	570	3767	1160	8511	1990	11713
240	1684	645	5070	1180	7982	2035	13705
275	2100	685	4920	1280	9013	2480	13690
280	1982	745	5100	1310	9421	3020	19874
290	2090	895	6300	1520	9617	3114	20100
400	2722	960	6747	1545	9481		
435	2561	990	6308	1598	9617		

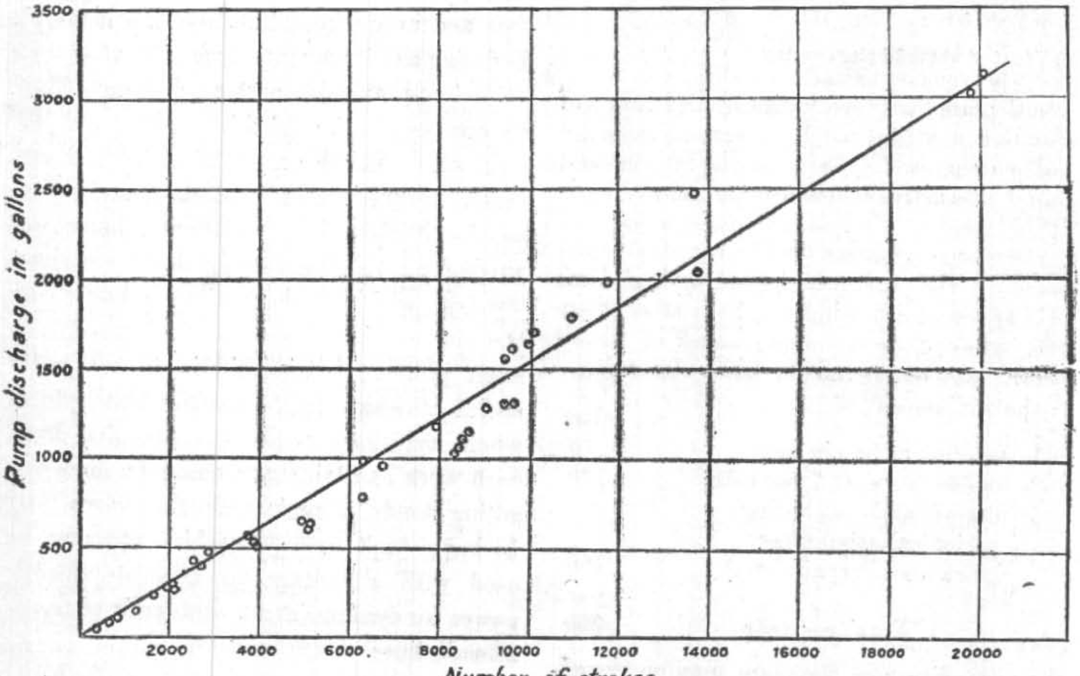

Fig. 8

It is seen that on an average 6 to 7 strokes were required to lift one gallon of water against an effective height of about 19 ft, From these data we proceed as follows to find the ratio of the sail-tip velocity to wind velocity of this type of windmill working under load. We consider wind velocity at 10 mph. With steady wind of this speed the output would be 336 gallons in one hour (*vide* Fig. 7) and the number of strokes executed by the pump would be 2186. As the mill-head gear ratio is 3 : 1, the wheel must have performed 6558 revolutions. In one second the sail-tip has therefore made 1·82 revolutions or travelled 45·8 ft. Meanwhile the wind travelled 14·7 ft. The ratio $\frac{\text{sail-tip velocity}}{\text{wind velocity}}$ is, therefore, 3 : 1 approximately.

This ratio indicates how fast the wheel is likely to rotate at a certain wind velocity and is considered as one of the important factors in the design of mill-wheels. The present tendency of the designers seems to be in favour of smaller ratio.

To a customer this ratio is of interest in as much as it enables him to form a rough idea of the plant output when the specifications of the pump are known. From this ratio, and the gear ratio in the mill-head, one can find the number of strokes, the prime-mover will make at a certain wind speed; multiplying the number of strokes by the volume displaced by the piston per stroke one can get the total discharge.

7 Cost of windmill plant energy

In Section 4 we have indicated the amount of work done by the windmill working about 24 hours a day during the monsoon months and found the average horse-power on the basis of this output. Let us find out now the cost per horse-power-hour of the windmill plant energy. The capital outlay on a plant comprising of an 8 ft windmill, 35 ft steel tower and pump, together with charges of installation may be around Rs 2000. Assuming,

	Rs.
1. Interest at $3\frac{1}{2}$ per cent	70
2. Depreciation at 7 per cent	140
3. Maintenance (including periodical attendance, lubrication, repairs etc.)	150
Total per year	360

the expenditure on the plant may be roughly rupee one per day.

The total energy from the windmill in a day may be $\cdot 024 \times 24$ or about $0 \cdot 58$ horse-power-hour only. The cost per horse-power-hour of the windmill plant energy then amounts to a rupee and a half, approximately, a figure which is much too high compared to the cost of energy from steam-engines or electrical machines. This cost will, however, be very much less in the case of a plant yielding larger output.

8. Conclusion

We have seen that a windmill plant is not a very efficient equipment; for successful operation its use is limited to regions having plenty of winds ; its power cannot be regulated nor is it dependable,—the power may fail at the time when one desired it most ; the depreciation of the plant is usually high—exposed to the inclement weather the machine is liable to quick deterioration and often runs the risks of heavy damage by storms. With all these limitations it has got its uses. The significant fact is that it can work continuously with the wind and the air-supply is free and unlimited. The machine is simple in design and its operation requires very little attendance and its cost is also not high. Careful application of this machine can undoubtedly bring excellent results. For successful operation of this machine one has to see that it is erected in a site having plenty of winds for a good part of the day throughout the year, and that the load to be carried by the machine is not such as to demand constant power. A windmill is an extremely useful machine in out-of-the-way places where electricity is not available for doing such work as draining out marshy land, irrigating fields, illuminating farmyards etc. In larger unit such a machine can also be used with advantage to generate electric power for feeding into a net-work of transmission lines.

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