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Research Article

Design Optimization of Rotary Tiller Blade using Specific Energy Requirement

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Abstract

Design optimization in terms of total specific energy requirements has been carried out for an ''L" shaped Rotary tiller blade through the development of a mathematical model. This model mainly includes the forward speed of the machine, the rotational speed, the depth of soil cut, the width of soil cut, the rotor radius, the angle of periphery, the angle of rotation, the specific soil resistance, the dry soil bulk density and volume of soil tilled. At the same working conditions the total specific energy requirement was predicted for the twenty five newly designed ''L" shaped Rotary tiller blades used in this study. The higher total specific energy requirement the lower volume of soil tilled and the most effective and optimum soil tillage operational cost is achieved. Based on the results optimized blades has been selected.

Keywords: *Power, Specific Energy, Rotary Tiller, Blade, Tillage*

1. Introduction

A rotary tiller or rotavator is a specialized mechanical tool used to plough the land by a series of blades which are used to swirl up the earth. Rotary tillers have become world famous for preparation of seedbed Rotary tillers have become world famous for preparation of seedbed in fields. These equipments are often used for breaking or working the soil in lawns, gardens, etc (Hendrick & Gill, 1971c). Nowadays, utilization of rotary tillers has been increased in agricultural applications because of simple structure and high efficiency for this type of tillage implements. By taking advantage of rotary tillers, the primary and secondary tillage applications could be conjugated in one stage (Topakci *et al*., 2008). Despite of their high energy consumption, since rotary tillers have the ability of making several types of tillage applications in one stage, the total power needed for these equipments is low (Culpin, 1981). Energy requirement is the issue of concern in agricultural machinery management in crop production systems. The design characteristics of rotary blades are the biggest determinants of power consumption.

Many researchers studies and reported regarding the power and specific work requirements of rotary tillers in different soil conditions. Dalin and Pavlov (1950) have developed a theoretical equation to predict power requirement for the determination of cutting, and loosening, throwing soil, power losses in power train, power for overcoming resistance to forward motion and pushing power requirement. Zhuk (1952), Sohne and Eggenmuller (1959) have developed a mathematical model to predict the specific work of rotary cultivators. Sakai (1969) and, Hendrick and Gill (1971c) developed a mathematical model to predict power requirement. Sakai (1969) reported per meter working width in both sand and clay soil conditions. Bernacki *et al*. (1972), Perdok and Burema (1977) and Sineokov (1977) developed a mathematical model to predict the specific work for the efficiency of rotary cultivators in heavy and pure clay. Sineokov (1977) formulated the total power requirements of a rotary tiller model to determine for the operation of rotary cultivators. Gupta and Visvanathan (1993) formulated and developed the total power requirements of a rotary tiller model under saturated soil condition.

Based on the available literature survey, this study was aimed to fulfill the application of optimization theory for the design parameters in terms of the total specific energy requirements for rotary tiller blade under sandy loam soil condition. The total power requirements which is the summation of the pushing power, the cutting and loosing of the soil slice, the overcoming of soil-metal friction between the soil and the knife of the rotary blades and the throwing of the cut soil slice by the centrifugal action of the rotary blade are expressed in terms of total specific energy required has been expressed.

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Based on the market survey and available literature, it was found that generally three types of blades are used in a rotary tiller or rotavator. These are L' shape, 'C' shape, & 'J' shape, to suit various operating conditions as shown in Fig.1. L-shaped blades are better than C or J type blades in trashy conditions as they are more effective in killing and they do not pulverize the soil as much (Adams, 1959). The detail of an L-shaped blade is shown in Fig.2. Again in India, L-shaped blades are mostly used in rotavator which are normally mounted with three right handed and three left handed blades per flange as shown in Fig.3.

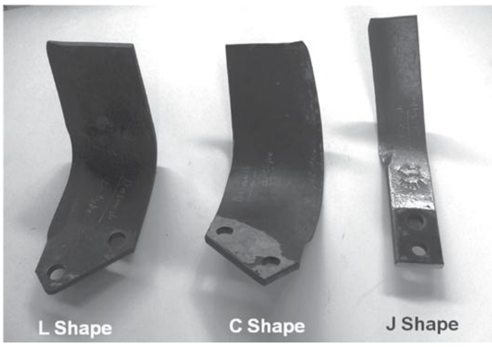

Fig.1 Different types of rotavator blade (Mahal *et al*., 2012)

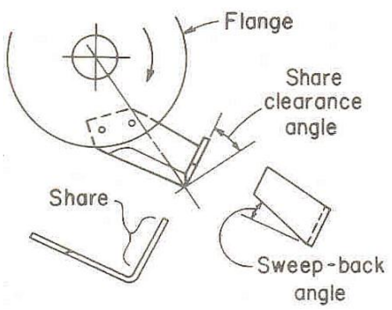

Fig.2 Three views of an L-shaped blade for rotary tiller (Kepner *et al*.,1977)

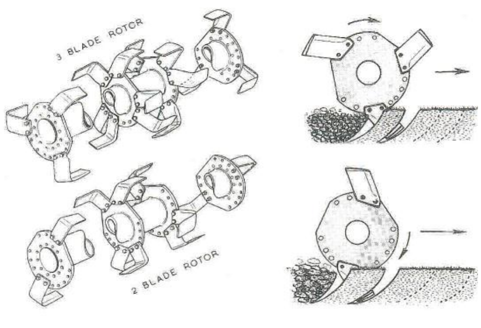

Fig.3 Rotary tiller rotors with L-type blades showing methods of mounting and cutting action (Culpin, 1981)

The rotor usually rotates in the same direction as the tractor wheels. Each blade cuts a segment of soil as it moves downward and toward the rear as shown in Fig.4. Most rotary tillers make either 2 or 3 cuts per revolution. The work quality by using a rotavator not only depends on design parameters but rotor blade layout, speed of rotors, forward speed significantly affects the machine performance. When a tillage operation is performed in the field, the soil texture will be a function of soil conditions, blade geometry and soil flow dynamics (Mandal *et al*., 2015).

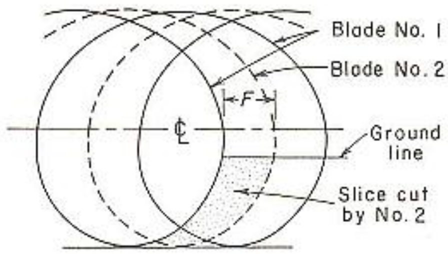

Fig.4 Paths of cutting edges or tips for 2 blades 1800 apart, in relation to forward travel (Kepner et. al., 1977)

2. Materials and Methods

To fulfill the objectives of the present study, initially a commercially available blade which used mostly in the specific region of West Bengal was selected. This blade is readily available and is being used in tractor mounted rotavator. Based on the available data and feedback from the users, it has been found that the blade is worn out after 25-60 hrs field usages depending on the soil conditions. This may be due to excessive load or stresses coming on the surface which exposed most part in the soil while in the field usage of rotavator. This excessive loads and stresses caused wear of the blade tip or cutting plane. Although the material used in the blade is having sufficient wear resistance properties, but the wear is taking place because of geometry and profile of the blade. Based on the geometrical configuration of the selected blade 24 more different blades were designed. Table 1 depicts the design parameters considered in this study. Designed values of geometrical parameters of these blades are given in Table 2. All these twenty five blades were analyzed to find out the maximum torque coming on to the working surface soil bin experiments. Based on the results, best design of the blade was chosen. The geometry and 3D model of the original blades has shown in Fig.5 whereas Fig.6 describes the important design parameters of a typical rotary tiller's blade (Mandal *et al*., 2015).

Fig.5 The geometry and 3D model of the original blades

Table 1: Geometrical Parameters of different blades designed for the study

Parameters	Notations
b	Blade span, mm
L_d	Effective vertical length, mm
B_w	Blade cutting width, mm
R	Curvature between L_v and L_h mm
θ	Blade angle, degree
β	Clearance angle, degree
t	Blade thickness, mm

Table 2: Designed values of geometrical parameters (Statistical method)

Blade Number	β degree	θ , degree	*b*, mm	L_v , mm	L_h , mm	*R*, mm	*t*, mm
1	18°	97.2	40	212	88.5	45	8
2	18	102.6	40	212	88.5	45	8
3	18	108	40	212	88.5	45	8
4	18	113.4	40	212	88.5	45	8
5	18	118.8	40	212	88.5	45	8
6	19	97.2	40	212	88.5	45	8
7	19	102.6	40	212	88.5	45	8
8	19	108	40	212	88.5	45	8
9	19	113.4	40	212	88.5	45	8
10	19	118.8	40	212	88.5	45	8
11	20	97.2	40	212	88.5	45	8
12	20	102.6	40	212	88.5	45	8
13	20	108	40	212	88.5	45	8
14	20	113.4	40	212	88.5	45	8
15	20	118.8	40	212	88.5	45	8
16	21	97.2	40	212	88.5	45	8
17	21	102.6	40	212	88.5	45	8
18	21	108	40	212	88.5	45	8
19	21	113.4	40	212	88.5	45	8
20	21	118.8	40	212	88.5	45	8
21	22	97.2	40	212	88.5	45	8
22	22	102.6	40	212	88.5	45	8
23	22	108	40	212	88.5	45	8
24	22	113.4	40	212	88.5	45	8
25	22	118.8	40	212	88.5	45	8

3. Calculation of Energy

Energy requirement in agricultural operation is an important in present day management scenario for crop production system. The design characteristics of any rotary tiller blades are the biggest determinants of power consumption. The total power requirements which is the summation of the pushing power, the cutting and loosing of the soil slice, the overcoming of soil-metal friction between the soil and the knife of the rotary blades and the throwing of the cut soil slice by the centrifugal action of the rotary blade are expressed in terms of total specific energy required has been expressed in this present study. The measurement of the total power required has been expressed in terms of total specific energy required per unit volume of soil tilled. Optimizing the total specific energy requirement is one the performance efficiency and the selection of criteria for land preparation implements. An optimization technique using the total specific energy requirement of various blades of rotary tiller is presented in this research work.

Dalin and Pavlov (1950) presented a general theoretical equation of rotary tiller to predict total power requirement as:

$$P_{Total} = P_{Cut} + P_{Throw} + P_{Loss} + P_{mf} + P_{Push} \quad (1)$$

Where
PTotal = Total power requirement, kW,
PCut = cutting power requirement,kW,
PThrow = throwing power the cut soil slice power requirement, kW,
PLoss = Power loss in the power train, kW,
Pmf = overcoming soil-metal friction power requirement, kW,
PPush = pushing power requirement, kW.

The total specific energy requirement (power per unit volume of soil tilled) modification model is defined as a function of pushing (PPush), cutting and loosening the soil slice (Pcut), overcoming soil- metal-friction (Pmf) and throwing the cut soil slice (PThrow) power requirement and volume of soil tilled (VST). The modified total specific energy requirement for the various rotary blades is exhibited as

$$E_{TSP} = \frac{P_{Push} + P_{Cut} + P_{mf} + P_{Throw}}{V_{ST}} \quad (2)$$

Hence, P_{push} is pushing power requirement, kW ((Saraswat, 1987)

$$P_{push} = \frac{716196(V_f P_e)\eta_C \eta_Z}{RN\cos(\varphi_1)}[\sin(\alpha)\cos(\varphi_1) + \cos(\alpha)\sin(\varphi_1)] \quad (3)$$

Where

V_f = machine forward velocity, m/s

P_e = engine power, hp

η_C = prime mover's efficiency [0.9 for power tiller]

η_Z = coefficient (η_Z =0.75; Bernacki *et al*., 1972);

R = rotor radius, m

N = rotational speed, rpm

α = the angle of direction (α = 420, Sineokov, 1977) and

φ_1 = the angle of periphery, (Sineokov, 1977).

$P_{Cut} = K_{SP} B_W L_d V_f$ (Dalin and Pavlov, 1950)

K_{SP} = specific soil resistance (K_{SP} =7000 kgm-2 for firm soil; Bernacki *et al*.,1972)

B_W = width of soil cut, m

L_d = depth of soil cut, m

$P_{mf} = L_d R V_f B_W S_{PW} \mu_K$ (Gupta and Visvanathan, 1993)

P_{mf} is the overcoming soil-metal friction torque requirement (kw),

S_{PW} is the dry soil bulk density (S_{PW} =1700 kgm-3) and

μ_K is the kinetic coefficient of soil–metal friction.

The kinetic coefficient of soil–metal friction occurs between the uncut soil and the metal surface under any soil condition by soil amendment implements. Besides, the value of the kinetic coefficient of soil –metal friction was calculated using the following equation as: (Gupta and Visvanathan, 1993)

$$\mu_k = \frac{1.09}{\sqrt{0.105RN}} \quad (4)$$

$$P_{Throw} = \frac{0.219RNL_d V_f B_W S_{PW}(3R - L_d)}{GZ} \quad (5)$$

P_{Throw} is the throwing the cut soil slice torque requirement (kW), Z is the number of blades on the drum, and G is the acceleration due to gravity. The total specific energy requirement (E_{TSP}) used for the various rotary blades was modified from Eqn (1) and it's derivation, Eqn (2) to Eqn (5), is written as the following:

$$E_{TST} = \{(\frac{4834.323(V_f P_e)\sin(\alpha + \varphi_1)}{RN\cos(\varphi_1)}) + B_W L_d S_{PW}(\frac{K_{SP}}{S_{PW}} + \frac{1.09R}{\sqrt{0.0105RN}} + \frac{0.219RN(3R - L_d)}{G})\}/V_{ST} \quad (6)$$

Where V_{ST} is the volume of soil tiled per second, 10^{-6} m^3. V_{ST} was calculated using the equation cited by Bernacki *et al*. (1972);

$$V_{ST} = B_W L_d V_f \quad (7)$$

The design parameters used to calculate the total specific energy has been shown in Fig. 7. The parameters and their values has been calculated and shown in Table 3. Therefore, a smaller effective specific energy requirement would indicate a highly efficient blade producing high amount of backfill (useful soil tilth) with the expenditure of a low amount of energy.

4. Calculation of Total Specific Energy

Design parameters and operational parameters required for calculation of total specific energy of the selected twenty five numbers of L type rotary tiller blade is presented in Fig. 7 and data were shown in Table 3. Table 4 provides the average minimum bulk densities of soil textures. Based on the selected design parameters, total specific energy has been calculated and the results are shown in Table 5. Fig.8 represents the comparison of total specific energy for twenty five blades.

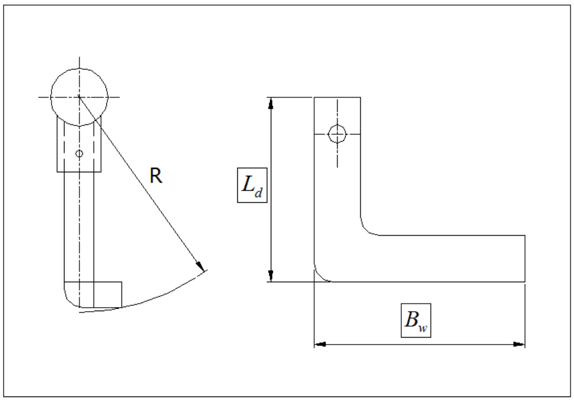

Fig.7: Design parameters of L type rotary tiller blade

Table 3: Design parameters and operational parameters of individual blade

Design Parameters						Operational Parameters		
Blade No.	α degree	φ degree	B_W mm	R Mm	L_d mm	V_f m/s	N rpm	P_e hp
1	42	11	88.5	260	75	0.5	150	18
2	42	14	88.5	260	93.75	0.94	180	18
3	42	19	88.5	260	112.5	1.35	210	18
4	42	25	88.5	260	131.2	1.78	240	18
5	42	30	88.5	260	150	2.20	270	18
6	42	9	88.5	260	93.75	1.35	240	18
7	42	15	88.5	260	112.5	1.78	270	18
8	42	20	88.5	260	131.2	2.20	150	18
9	42	23	88.5	260	150	0.50	180	18
10	42	28	88.5	260	75	0.94	210	18
11	42	12	88.5	260	112.5	2.20	180	18
12	42	13	88.5	260	131.2	0.50	210	18
13	42	21	88.5	260	150	0.94	240	18
14	42	26	88.5	260	75	1.35	270	18
15	42	32	88.5	260	93.75	1.78	150	18
16	42	10	88.5	260	131.2	0.94	270	18
17	42	17	88.5	260	150	1.35	150	18
18	42	22	88.5	260	75	1.78	180	18
19	42	27	88.5	260	93.75	2.20	210	18
20	42	31	88.5	260	112.5	0.50	240	18
21	42	8	88.5	260	150	1.78	210	18
22	42	16	88.5	260	75	2.20	240	18
23	42	18	88.5	260	93.75	0.50	270	18
24	42	24	88.5	260	112.5	0.94	150	18
25	42	29	88.5	260	131.2	1.35	180	18

Table 4: Average minimum bulk densities of various soil textures (James, 1972)

Soil texture	Bulk density (g/cc)
Coarse, medium and fine sand	1.80
Loamy and sandy clay loam	1.75
Loam and sandy clay loam	1.70
Clay loam	1.65
Sandy clay	1.60
Silt and silt loam	1.55
Silty clay loam	1.50
Clay	1.40

Table 5: Calculated value of total specific energy requirement of individual blade

Design Parameters						Operational Parameters			Output	
Blade No.	α degree	φ degree	B_W mm	R mm	L_d mm	V_f m/s	N rpm	P_e hp	V_{ST} $10^5 m^3$	E_{TST} kJm^{-3}
1	42	11	88.5	260	75	0.5	150	18	6637.50	145.24
2	42	14	88.5	260	93.75	0.94	180	18	1489.46	1044.70
3	42	19	88.5	260	112.5	1.35	210	18	2508.98	827.32
4	42	25	88.5	260	131.2	1.78	240	18	3770.10	693.54
5	42	30	88.5	260	150	2.20	270	18	5256.90	591.79
6	42	9	88.5	260	93.75	1.35	240	18	2867.40	542.10
7	42	15	88.5	260	112.5	1.78	270	18	4241.36	471.35
8	42	20	88.5	260	131.2	2.20	150	18	2920.50	1610.53
9	42	23	88.5	260	150	0.50	180	18	796.50	1293.53
10	42	28	88.5	260	75	0.94	210	18	1737.70	945.44
11	42	12	88.5	260	112.5	2.20	180	18	3504.60	988.44
12	42	13	88.5	260	131.2	0.50	210	18	929.25	831.57
13	42	21	88.5	260	150	0.94	240	18	1985.94	686.02
14	42	26	88.5	260	75	1.35	270	18	3225.83	553.42
15	42	32	88.5	260	93.75	1.78	150	18	2356.31	1931.84
16	42	10	88.5	260	131.2	0.94	270	18	2234.18	462.44
17	42	17	88.5	260	150	1.35	150	18	1792.13	1567.61
18	42	22	88.5	260	75	1.78	180	18	2827.58	1150.03
19	42	27	88.5	260	93.75	2.20	210	18	4088.70	914.97
20	42	31	88.5	260	112.5	0.50	240	18	1062.00	816.93
21	42	8	88.5	260	150	1.78	210	18	3298.84	697.83
22	42	16	88.5	260	75	2.20	240	18	4672.80	591.13
23	42	18	88.5	260	93.75	0.50	270	18	1194.75	536.57
24	42	24	88.5	260	112.5	0.94	150	18	1241.21	1684.31
25	42	29	88.5	260	131.2	1.35	180	18	2150.55	1306.82

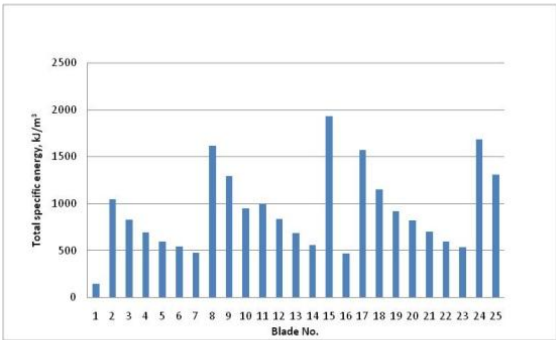

Fig. 8: Comparison of total specific energy for twenty five different blades

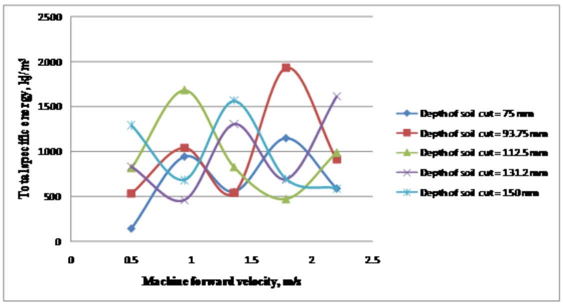

Fig.9: Effect of total specific energy to machine forward velocity for various depth of soil cut

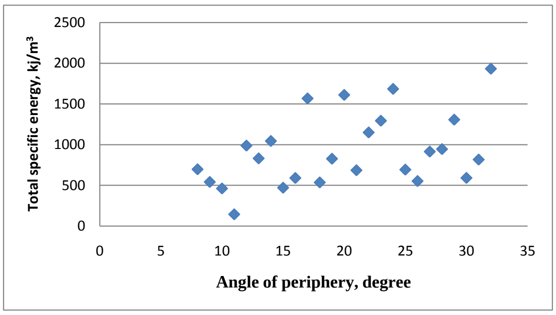

Fig.10: Relation of total specific energy with angle of periphery of blade

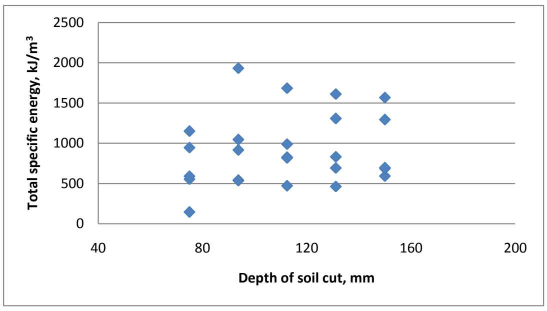

Fig.11: Relation of total specific energy with depth of soil cut

Fig.9 shows the effect of total specific energy to machine forward velocity for various depth of soil cut. The characteristics obtained is similar to a sinusoidal curve where it appears that highest specific energy obtained at a depth of 93.75mm soil cut where machine forward velocity is almost 2 m/s. Fig.10 depicts the relation of total specific energy with angle of periphery of blade. It has been observed from the figure that highest energy obtained at 32 degree angle of periphery. Relation of total specific energy with depth of soil cut has been shown in Fig.11. Here highest specific energy is obtained at a soil cut depth of 93.75 mm. The specific energy decreases with increase in depth of soil cut. This may due to the fact that as depth increases more losses occurred which reduces the energy.

Conclusion

Optimal design parameters of rotary tiller's blade were determined total specific energy requirements. The highest specific energy requirement was exhibited by 15th blade. The higher specific energy requirement the lower volume of soil tilled and the most effective and optimum soil tillage operational cost is achieved. This research focuses on the design optimization of L-type rotary tillers blade . From the results, it has been observed that angle of periphery and machine forward velocity leads to better control on specific energy requirement. The results of this study should be verified by further tests on rotary tillers according to the results offered in this paper.

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