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DESIGN OF A POWERLESS PUMP FOR RAINFED REGION BASED ON INVERSION OF A DOUBLE SLIDER CRANK MECHANISM

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ABSTRACT

The development for this working model is prompted due to the need for pumping systems that does not use electricity or any fossil fuel as its power source and no geographical limitations, especially in underdeveloped remote areas.

In this paper, the oscillatory motion of a weighted pendulum which conserves momentum, obtained with the application of human effort, is converted into rotational motion of two shafts of 2.5 cm diameter and three rear sprockets via a 4.5 mm module bevel gear mechanism and gear ratio 6 which rotate the crank disc working on an inversion of double slider crank chain, known as Scotch Yoke Mechanism. The scotch yoke mechanism converts its rotary motion obtained from the sprockets into reciprocating motion of the two plungers used to suck water in one stroke into the cylinder and to deliver the same out from it in the next stroke. Efficiency of the system is found up to 48%- and 2.7-liters discharge per minute. The virtual model is created with software.

KEYWORDS: Bevel gear, Freewheel Sprockets, Pendulum & Scotch Yoke Mechanism.

INTRODUCTION

A pump is device that moves a fluid or sometimes slurries, by mechanical action. Pumps are generally operated by rotary and reciprocating mechanism, and they perform mechanical work by fluid movement with consumption of energy. They may operate via many energy resources, and also by manual operation other than electricity or wind power. A reciprocating pump uses to and fro motion of the plunger to displace the fluid.

People of ancient Greece and Rome used device like Archimedean screw that was shaped like a giant screw and worked by lifting water through inside of a pump for irrigation purpose. Turning of screw was done by hand with usually two workers. Piston pumps were also contemporary to the Archimedean screw. Gear pump was invented shortly after the sliding vane pump in 1580[1]. A sort of hand-powered water pump that was once common worldwide, also known as 'pitcher pump' was installed commonly over community water wells before piped water supplies come into picture[2].Today's low-cost hand-operated community pumps are considered as most sustainable and an option for safe water supply in rural areas of developing countries. A hand pump explores pollution free deeper groundwater and also protects the water source from contamination. Pumps like 'Afridev' are designed to be cheap to build and for ease of installation with simple parts. But, scarcity of spare parts for these types of pumps has diminished their utility [3].C. A. Okoronkwo et al. [4] gave a modification to existing lift pump by designing a hand water pump with a gear train drive and quick return mechanism which results in, 15.2 litres per minute discharge at an effort of 102.7N.N.Tulasi Radha et al. [5] developed a mechanism which uses pedal power for dual action of generating electricity and water pumping. A dual pump with scotch yoke mechanism, where reciprocating action is done by cam plate; was designed and developed by R. Praveen Kumar et al. [6]. Mogaji P. B. [7]developed an improved version of water pump machine powered by pedal action, which resulted a discharge of 0.0016 cubic meter per second at 20m head with a driving torque of 29.5 Nm and an estimated efficiency of 90%.Yathisha.N et al. [8] also designed scotch yoke mechanism actuated and pedal powered reciprocating water pump. Mragank Sharma et al. [9] designed and fabricated a water pumping machine where physical energy was utilized and converted to mechanical energy during cycling in gym to lift the water with no electricity. Biswas K. W. [10] have examined the pumping water from geologically safe deep tube wells with possible applications of renewable energy to overcome limitations in existing technologies of arsenic-contaminated water in the villages in Bangladesh. According to J.T. Winpenny [11], both water and energy sectors need to be promoted and work in conjunction for required changes in planning philosophy of developing countries. Scotch yoke mechanism may be a replacement for other mechanism to improve dynamic behaviour by balancing the input torque to a satisfactory level [12]. Scotch yoke mechanism also finds its application in microfluidics like syringe pump with precise flow rate [13]. Again, to improve the discharge of a reciprocating pump, two extra pistons may be incorporated in a double acting cylinder [14]. With solar energy and motor as alternate source of power, modification can be done in dual reciprocating pump using scotch yoke mechanism [15].

This paper presents a prototype of a powerless reciprocating pump working on scotch yoke mechanism with little human effort.

METHODOLOGY

Two sprockets are mounted on Shaft 1A and 1B between the two bevel gears connected by a third gear meshed with them perpendicularly. The third acts as tumbler gear that serves the purpose of reversing the direction of motion. The two sprockets are chained to two free wheel sprockets sitting on Shaft 2. Between them is mounted a third sprocket. Because of the system enabled due to the two freewheel; the shaft rotates in unidirectional motion. The middle sprocket is chained to another sprocket mounted on Shaft 3. This shaft receives constant unidirectional rotation because of the movement fed to it by the chain that wraps the sprockets on Shaft 2 and Shaft 3. Attached to the ends of the Shaft 3 are two circular crank discs.

When the pendulum is oscillated by human effort, it gives rotation motion to the shaft. The rear sprocket connected with it gives rotational motion to the crank disc through the Scotch yoke mechanism and the plunger gets reciprocated. Fig. 1 shows the assembly of the pump set.

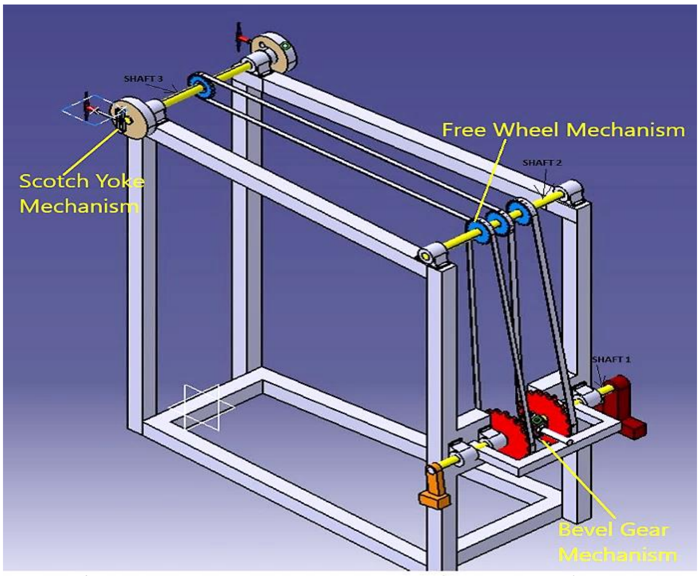


Figure 1: Assembly of Pump Set.

BEVEL GEAR MECHANISM

When the pendulum gets oscillated, it gives rotational motion to the shaft connected with it and the bevel gear connected with that shaft give rotational motion to the pinion mashed with it, which in turn give rotational motion to another bevel gear meshed with it which in turn gives the oscillating motion to the pedal. The Fig. 2 shows the bevel gear mechanism with CATIA drafting.

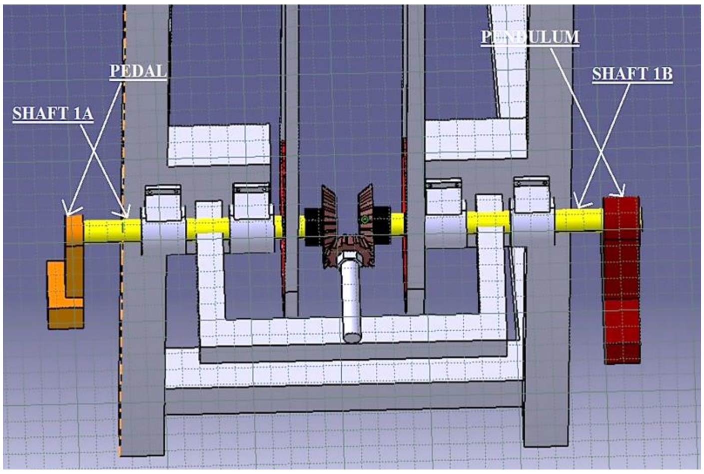


Figure 2: Bevel Gear Mechanism

For bevel gear, material is Mild steel having yield strength, s_t = 268MN/m^2 and Young's modulus of elasticity, E= 200MN/m^2.Standardgear ratio is 6, Number of teeth on pinion, Z_1 = 10, ratio of width B_1 to pitch diameter D_1 for pinion = 0.5 and Pressure angle, a = $14\left(\frac{1}{2}\right)$ degree. So, the calculated module, m=4.5mm and pitch diameter for pinion as well as gear are D_1=4.5cm and D_2=7.2cm as obtained below:

Calculation of Pitch Diameter of pinion and gear:

Theoretical Power [16], (in this case, human power) required:

$P_{th} = \frac{\rho gAlsNh}{60000} kW(1)$

$= \frac{1000\times9.8\times\pi\times4.3^2\times9.5\times30\times4}{60000\times1000000}$

=2.704W

For pinion, N= 48RPM

M_t[17] $= \frac{60P_{th}}{2\pi N}$ (2)

$= \frac{60\times2.704\times60}{2\times\pi\times48}$

= 0.538 N-m

Beam strength[17],

$S_b = \frac{M_t}{R_m} = [1 - b/Ao]$

or, $S_b = mb\sigma Y[1 - b/Ao]$ (3)

For pinion,

R_m[17]= $(D_1\text{-}bSin\gamma 1)\times 0.5$ (4)

Here, $Sin\gamma_1 = \sin\{\tan^{-1}\left(\frac{10}{16}\right)\} = 0.53$ (5)

$b=0.5D_1$ (6)

So, $R_m = D_1\times 0.5\times \{1-(0.5\times 0.53)\} = D_1(0.3675)$

A_o[17]= $D_1\times 0.5 \times \sqrt{\frac{16^2}{10^2}+1}$

$=0.94D_1$ (7)

Y= 0.113

From equation

$\frac{0.538}{D_1\times0.3675} = m\times 0.113 \times D_1\times 0.5\times \frac{268\times10^6}{4} \times 0.137[1-\frac{0.5D_1}{0.94D_1}]$

Or, $D^2 \times m = 1.3\times 10^{-6}$

Or, m = 2.4mm

Standard Module,

m =4.50mm

Pitch Diameter,

$D_1=10\times 4.50 = 45mm$

Pitch Diameter,

$D_2 = 16 \times 4.50 = 72mm$

FREE WHEEL MECHANISM AND ITS INCORPORATION

Shaft-2 has mounted on it three freewheel sprockets which is a hub that incorporates a ratchet mechanism, that allows continuous linear or rotary motion in only one direction while preventing motion in the opposite direction.

When the teeth are moving in the unrestricted (i.e., forward) direction, the pawl easily slides up and over the gently sloped edges of the teeth, with a spring forcing it (often with an audible 'click') into the depression between the teeth as it passes the tip of each tooth. When the teeth move in the opposite (backward) direction, however, the pawl will catch against the steeply sloped edge of the first tooth it encounters, thereby locking it against the tooth and preventing any further motion in that direction. Based on this principle, the two sprockets work together to provide a unidirectional rotation to the shaft. The Fig. 3shows the CATIA drafted model of free wheel sprocket.

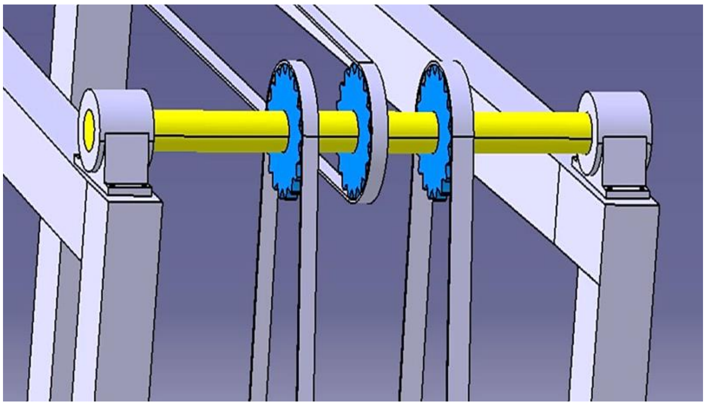


Figure 3: Free Wheel Sprocket

For chain, Centre distance between two rear sprocket, a_1 = 86.5cm; rear and front sprocket,a_2 = 63.8cm and theoretical power to be transmitted, P_{th}= 27.05W.So,on the basis of power to be transmitted; we have selected '08B' chain drive. It has Pitch, P =12.70mm, roller diameter, D = 8.5mm, Rated power, P_r= 0.34KW at 50 rpm. So calculated number of links are LN_1=168 &LN_2=132. As follows:

Calculation of number of Chain Links[17]**:**

$$LN_1 = 2\times\frac{a_1}{P} + \frac{(Z_1+Z_2)}{2} + \left(\frac{Z_1-Z_2}{2\pi}\right)^2 \times \frac{P}{a} \quad (8)$$

$$= 2 \times \frac{865}{12.7} + \frac{(44+18)}{2} + \left(\frac{44-18}{2\pi}\right)^2 \times \frac{12.7}{865}$$

$$= 168$$

$$LN_2 = 2\times\frac{a_1}{P} + \frac{(Z_1+Z_2)}{2} \quad (9)$$

$$= 2 \times \frac{638}{12.7} + \frac{(44+18)}{2}$$

$$= 132$$

For sprocket, Pitch of chain, P =12.7mm; Number of teeth on rear sprocket, Z_1 = 18,Speed ratio,$\frac{n2}{n1}$ = 2.5; so calculated value of Pitch diameter of rear sprocket, D_1 = 7.5cm&Pitch diameter of front sprocket, D_2=17.8cm obtained as follows:

Calculation of Sprocket Pitch Diameter[17, 18]:

$$D_1 = \frac{p}{\sin\frac{180}{z1}} \quad (10)$$

$$= \frac{12.7}{\sin\frac{180}{18}} = 7.32\text{cm}$$

Standard diameter, D_1= 7.5cm

$$D_2 = \frac{p}{\sin\frac{180}{z2}} \quad (11)$$

$$= \frac{12.7}{\sin\frac{180}{2.5\times18}} = 17.8\text{cm}$$

Yield strength for shaft material is 268MN/m^2. For a speed of 30 rpm, inside diameter of collar, d =2.5cm; theoretical power, P_{th} = 27.05W; τmax = 0.3 of s_t=80.4MN/m^2. So, predicted value of standard diameter, D= d= 2.5cm.Bearing ISI No. 25BC02 deep grove ball bearing is used with an axial load on the bearing, F_a = 190N and no radial load. Dynamic load on bearing, p = 374.11 < 10690N obtained from following calculation:

Calculation of Shaft Diameter:

$$Mt = \frac{60P_{th}}{2\pi N} \quad (12)$$

$$= \frac{60\times2.704\times60}{2\times\pi\times30}$$

=1.305Nm

$$\tau_{max}[18] = \frac{16M_t}{\pi D^3} \quad (13)$$

$$268\times 10^6 \times 0.30 = \frac{16\times1.305}{\pi\times D^3}$$

or D = 0.14cm

Standard diameter of the shaft, D=2.5cm

Calculation of dynamic loads on bearing:

Bearing Selection:

- Assumption:

  Axial load on the bearing, F_a = 190N

  Radial load on the bearing, F_r = 0

- **Selection of Bearing:**

Bearing ISI No. 25BC02 deep grove ball bearing is used

The 'Table 1' is for the parameter of the selected bearing:

Table 1: Bearing Parameters [18] (Table 16.9, series 62. Page 387)

ISI No.	*SKF*	*d(mm)*	*D(mm)*	*B(mm)*	*r(mm)*	*Basic*	*Capacity*	*Maximum permissible speed(rpm)*
						Static	Dynamic	
25BC02	6205	25	52	15	1.5	6965	10690	13000

$$\frac{F_a}{c_o}[17]=\frac{190}{6965}= 0.03 \quad (14)$$

Again, for value of e,

$$\frac{0.056-.028}{0.26-0.22} = \frac{0.03-0.028}{e-0.22} \quad (15)$$

or e = 0.223

For the value of thrust factor Y,

$$\frac{0.26-0.22}{0.223-0.22} = \frac{1.17-1.99}{Y-1.99} \quad (16)$$

or, Y=1.969

Dynamic load on the selected bearing[17],

$$P = YF_a \quad (17)$$

or, P = 1.969×190

or, P=374N < 10690N

SCOTCH YOKE MECHANISM

This mechanism is used for converting rotary motion into a reciprocating motion through a slider which is connected with crank disc by a pin. The Fig. 4shows the scotch yoke mechanism developed in CATIA.

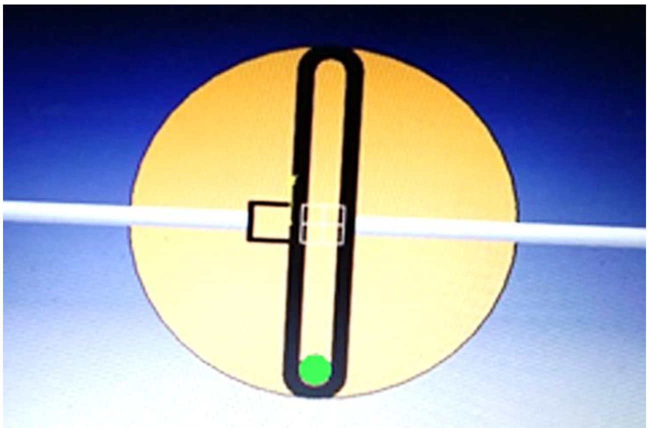


Figure 4: Scotch Yoke Mechanism

RESULTS, DISCUSSION AND VERIFICATION

Calculation of Inside Diameter of cylinder:

Discharge [16],$Q = ANl_s$ (18)

or$\frac{100}{1000\times3600}$= $\frac{\pi D^2\times30\times D\times2}{60}$

or, D=3.14cm

Considering, D= 4.3cm

Calculated length of Stroke, *ls*= 2×4.3, or *ls*=8.6cm

Considering, *ls* = 9.5cm

Calculation of theoretical Discharge**:**

Q= $\frac{ALN}{60}$ (19)

=$\frac{\pi\times4.3^2\times9.5\times10^{-6}\times N}{4\times60}$

= 2.3× 10^{-6} ×*N*(20)

Using Equation (20), theoretical discharge can be determined at different RPM.

Calculation of Slip[19]**:**

Slip =$Q_{th} - Q_{exp}$ (21)

Calculation of mechanical Efficiency**:**

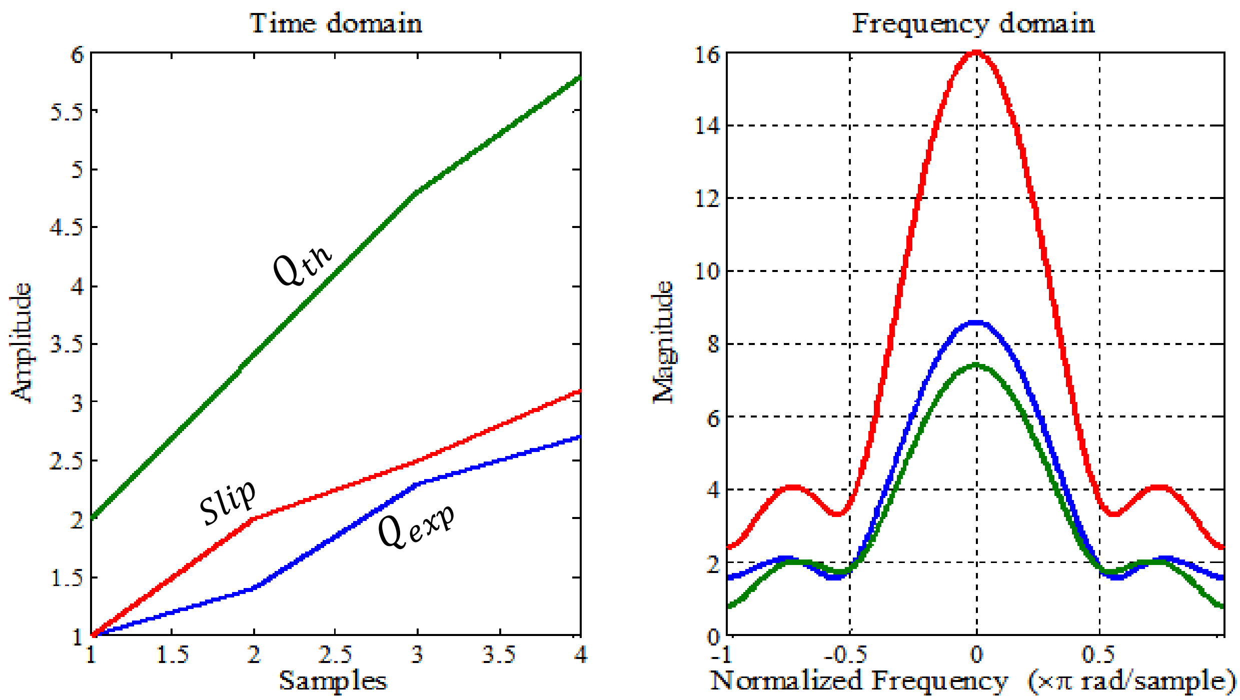
η =$\frac{P_{act}}{P_{th}}$ × 100 % (22)

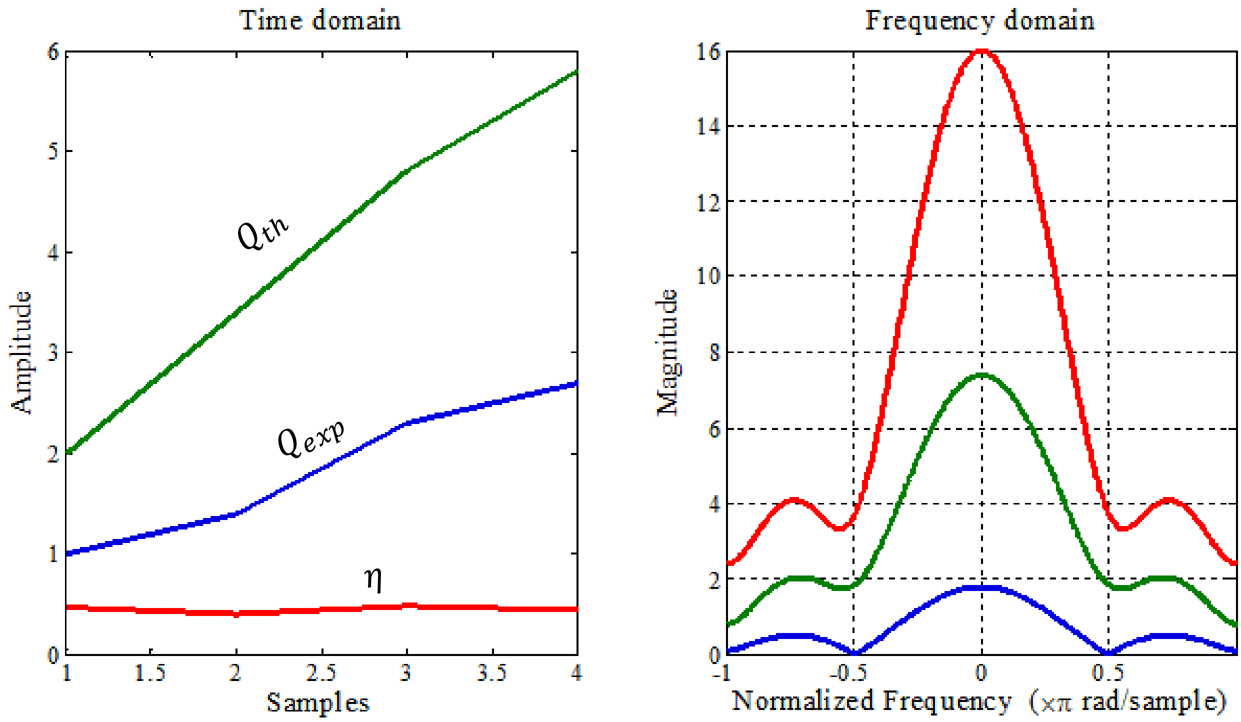
The following observations have been listed in Table 2 during the experiment at four different RPMs.

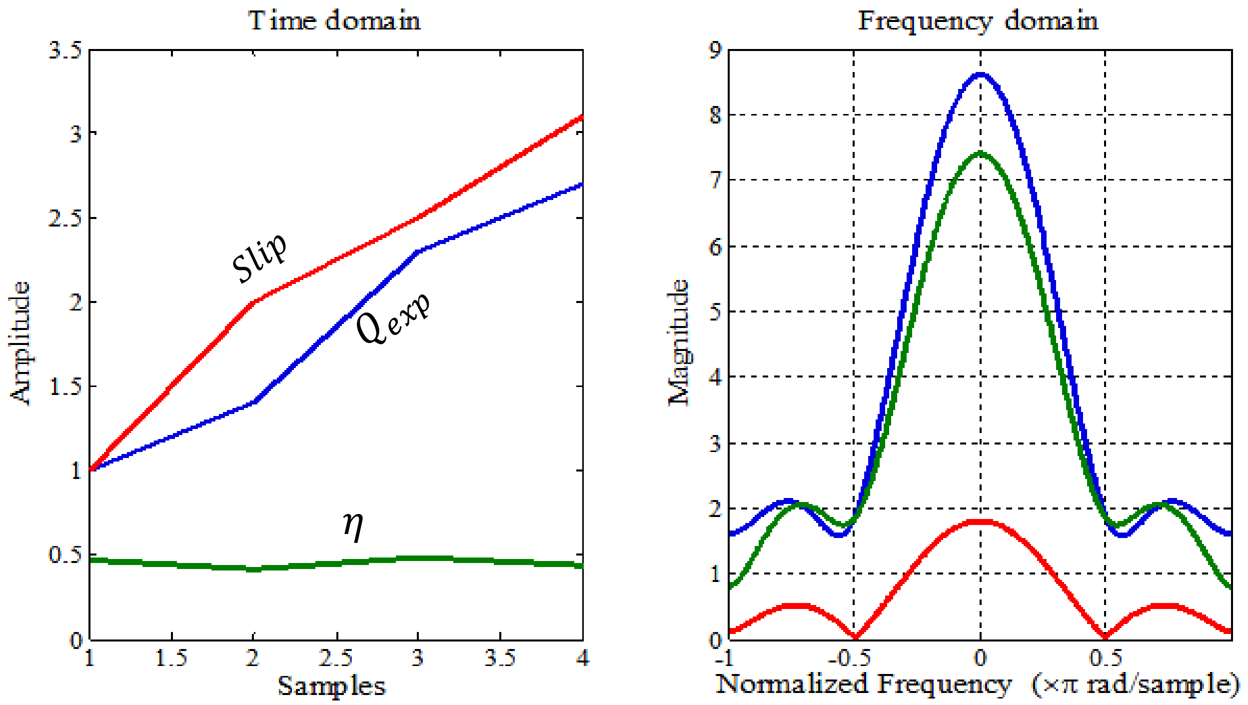
Table 2: Results Showing Discharge, power, slip and efficiency against RPM of Disc

RPM of The Crank Disc (*N*)	Discharge (Q) in litre/min		Power (P) in Watt		Slip in lit/min	Efficiency (η)
	Theoretical (Q_{th})	Experimental (Q_{exp})	Theoretical (P_{th})	Operating (P_{exp})		
***N*$_1$=15**	2	1	0.34	0.16	1	0.47
***N*$_2$=25**	3.4	1.4	0.56	0.23	2	0.41
***N*$_3$=35**	4.8	2.3	0.79	0.38	2.5	0.48
***N*$_4$=45**	5.8	2.7	1.01	0.44	3.1	0.44

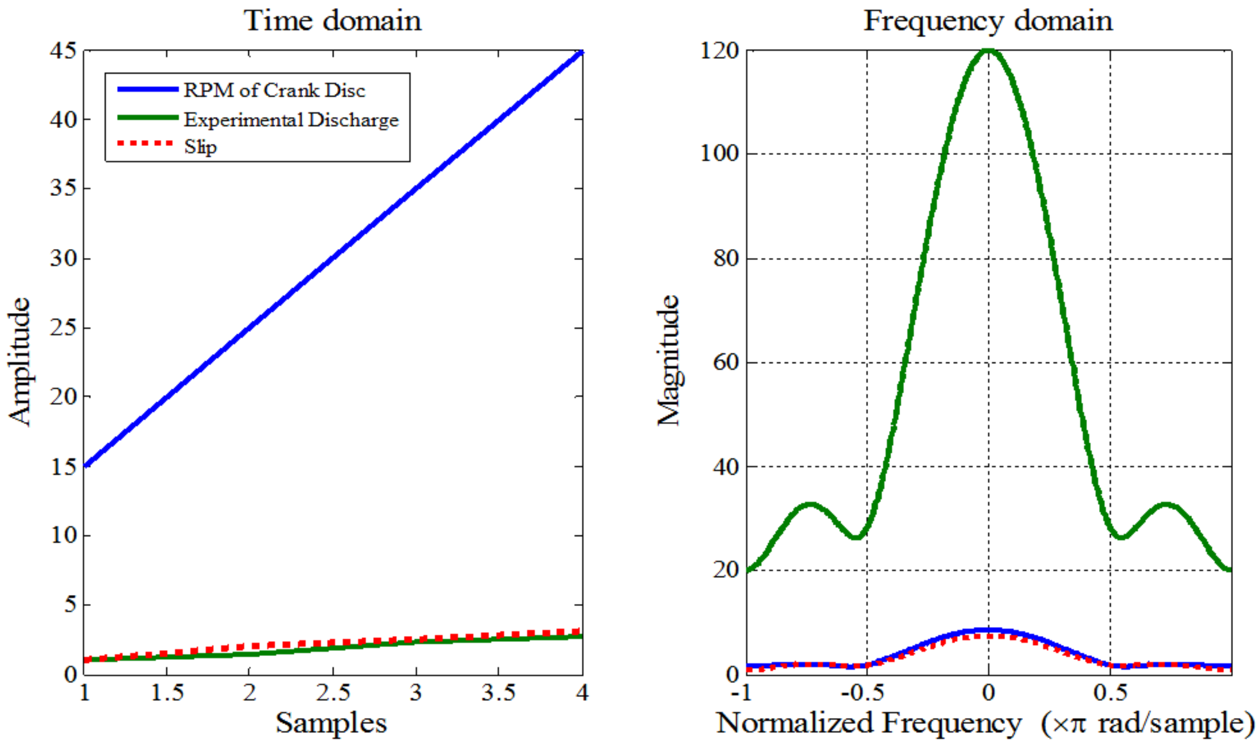
The results have been analysed graphically in time domain and frequency domain as shown in Fig. 5.


Time domain
Amplitude
Samples
Qth
Slip
Qexp
Frequency domain
Magnitude
Normalized Frequency (×π rad/sample)


Time domain
Amplitude
Samples
Qth
Qexp
η
Frequency domain
Magnitude
Normalized Frequency (×π rad/sample)



Time domain
Amplitude
Samples
Slip
Q_{exp}
η
Frequency domain
Magnitude
Normalized Frequency (×π rad/sample)



Time domain
RPM of Crank Disc
Experimental Discharge
Slip
Amplitude
Samples
Frequency domain
Magnitude
Normalized Frequency (×π rad/sample)

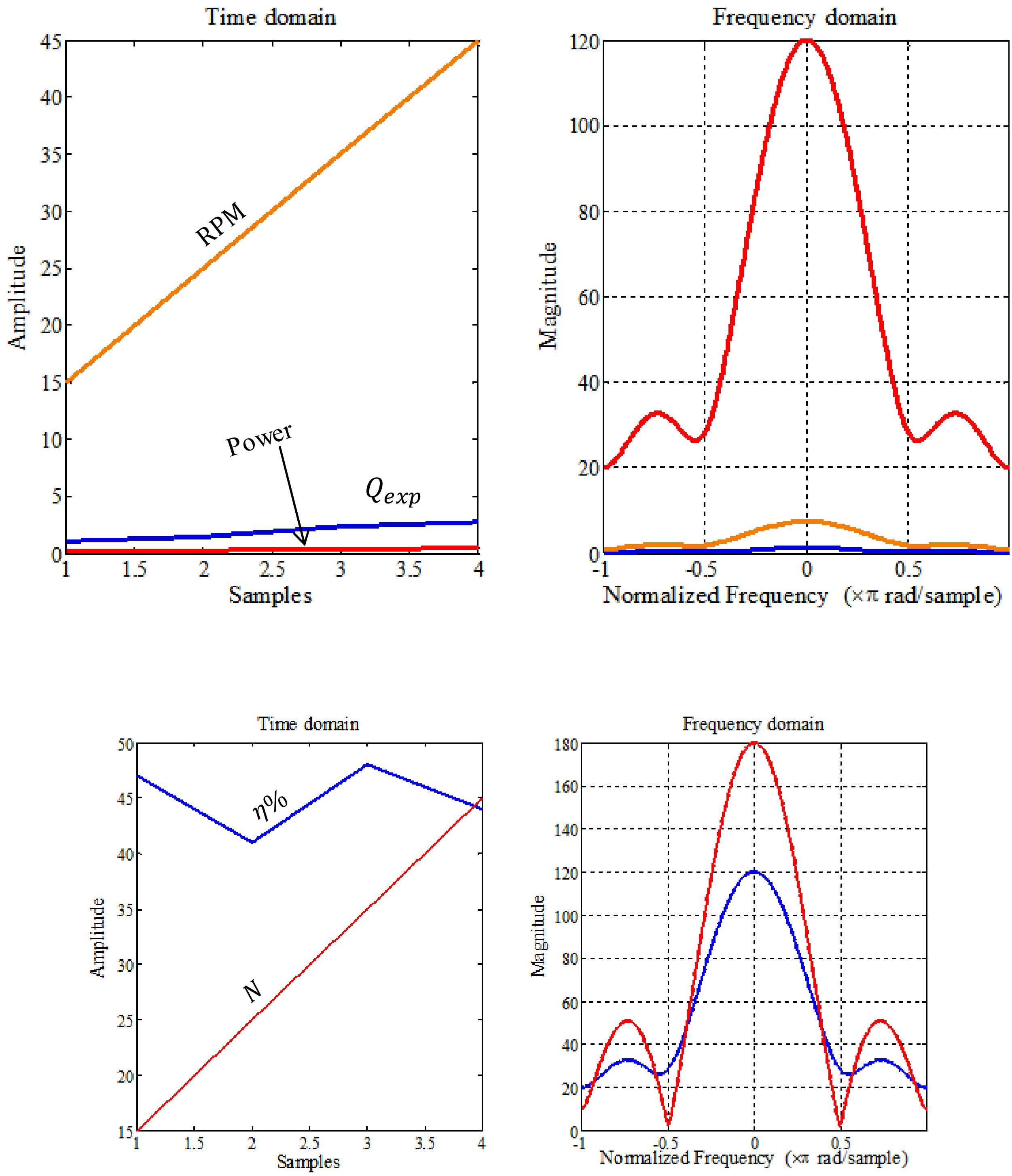
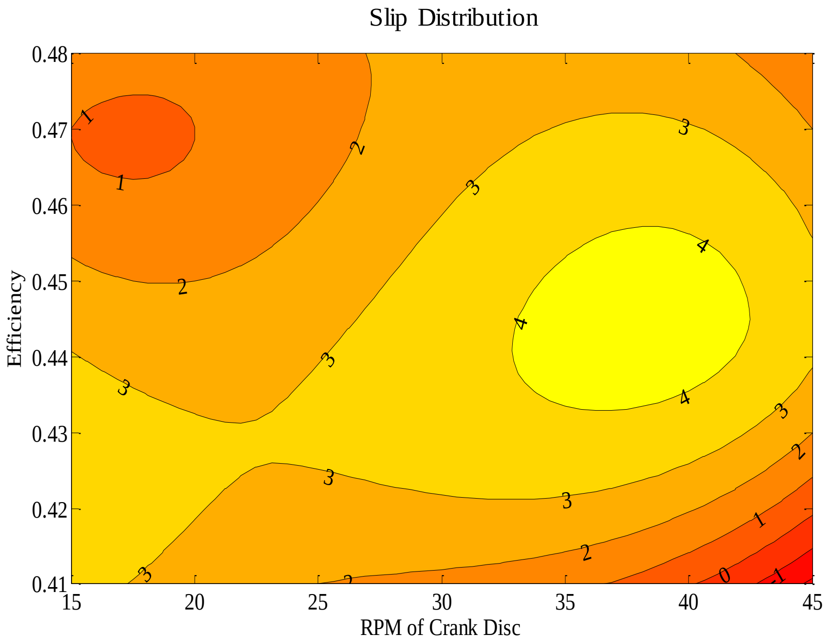
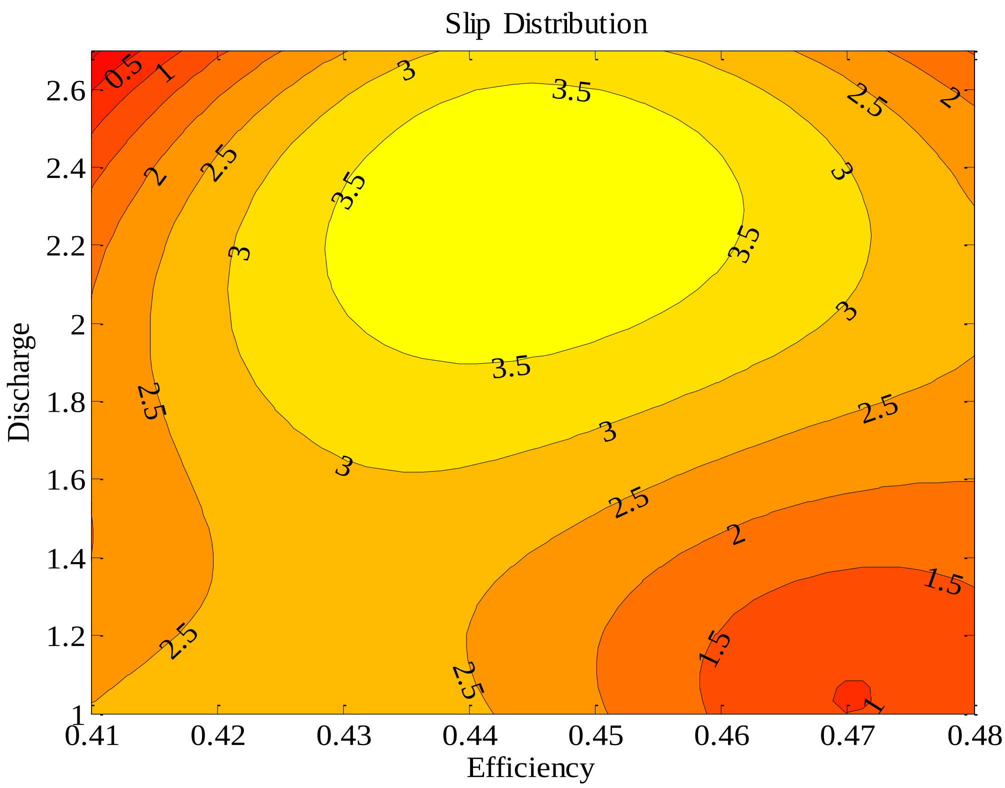


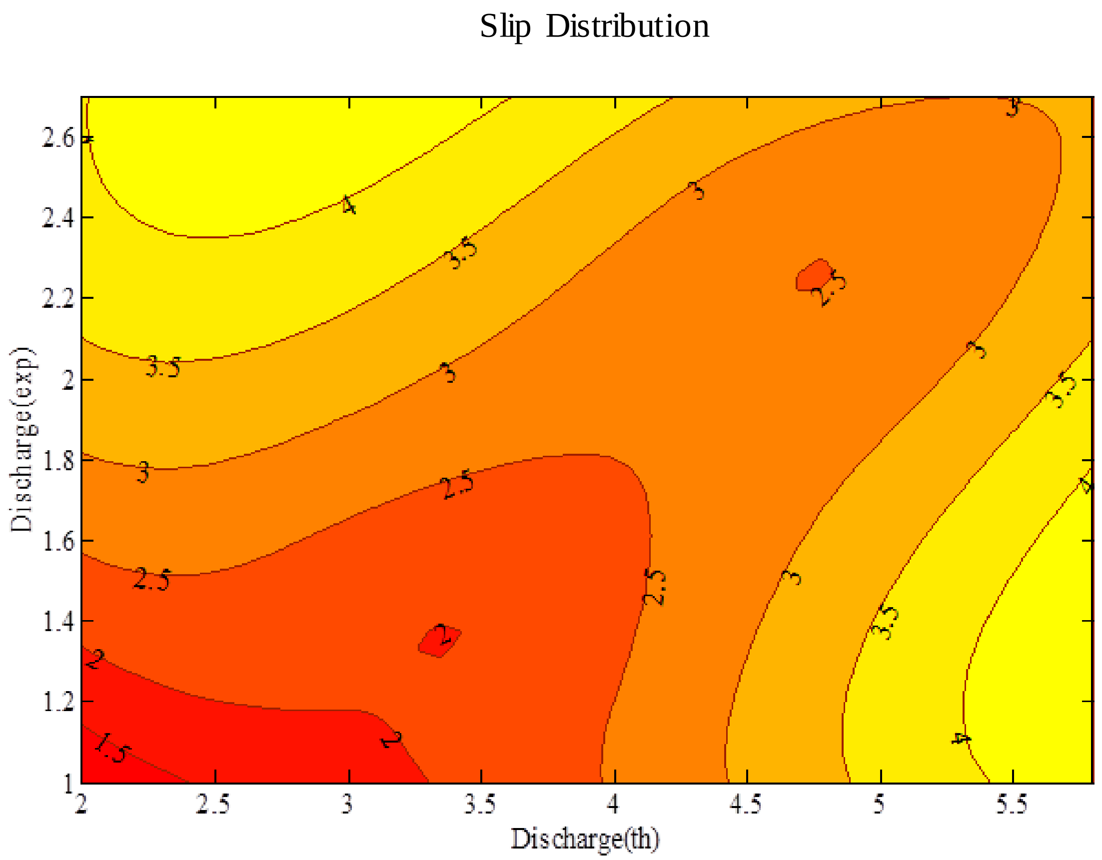
Figure 5: Graphical representation of results obtained in Time and Frequency Domain Analysis.

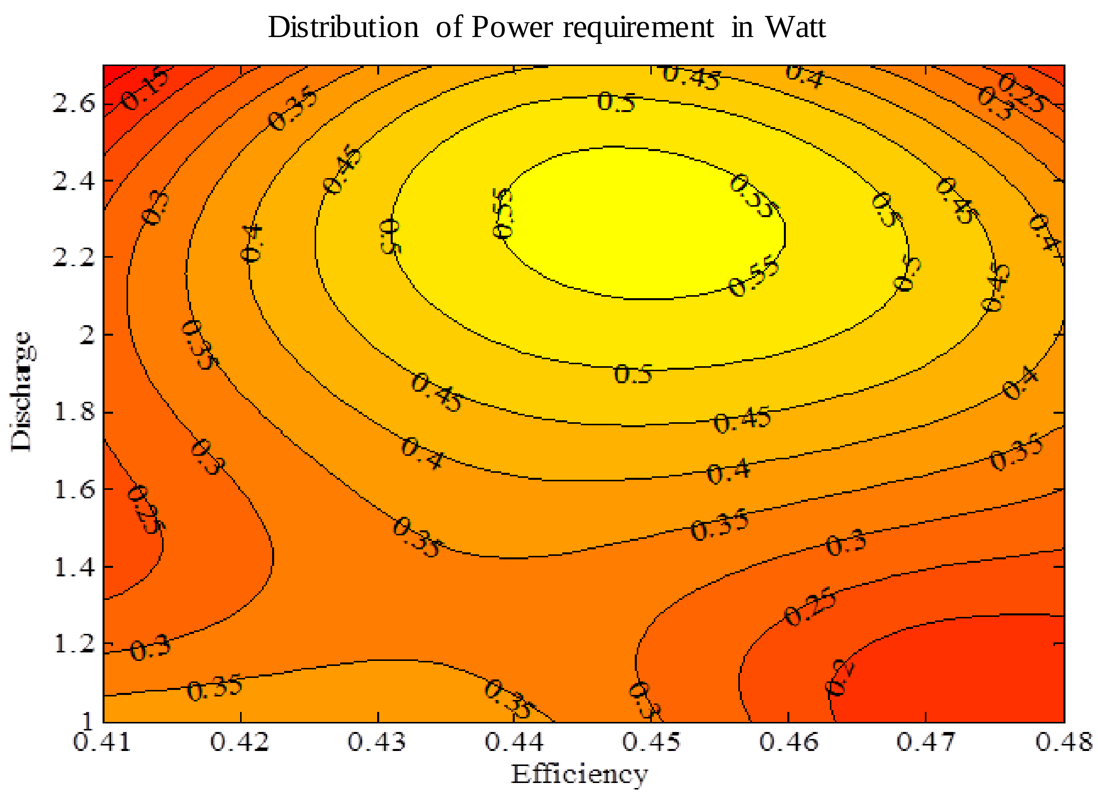
As seen from the graph, with increase in speed, slip factor also increases. Smooth running of the crank disc is desirable and may be achieved by maintaining continuous reciprocating motion. The 'slip' factor on account of which difference between the theoretical and practical discharge value increases, may be reduced by maintaining continuous reciprocating motion which in turn depends on manual effort. On the other hand, with sufficient lubrication of the rotating surfaces, difference of power required in theoretical and practical values can be diminished. Though discharge is increasing with respect to increasing rpm, operating human power is also increasingly desirable. Around fifteen hundred RPM of the crank disc, result is showing satisfactory value.

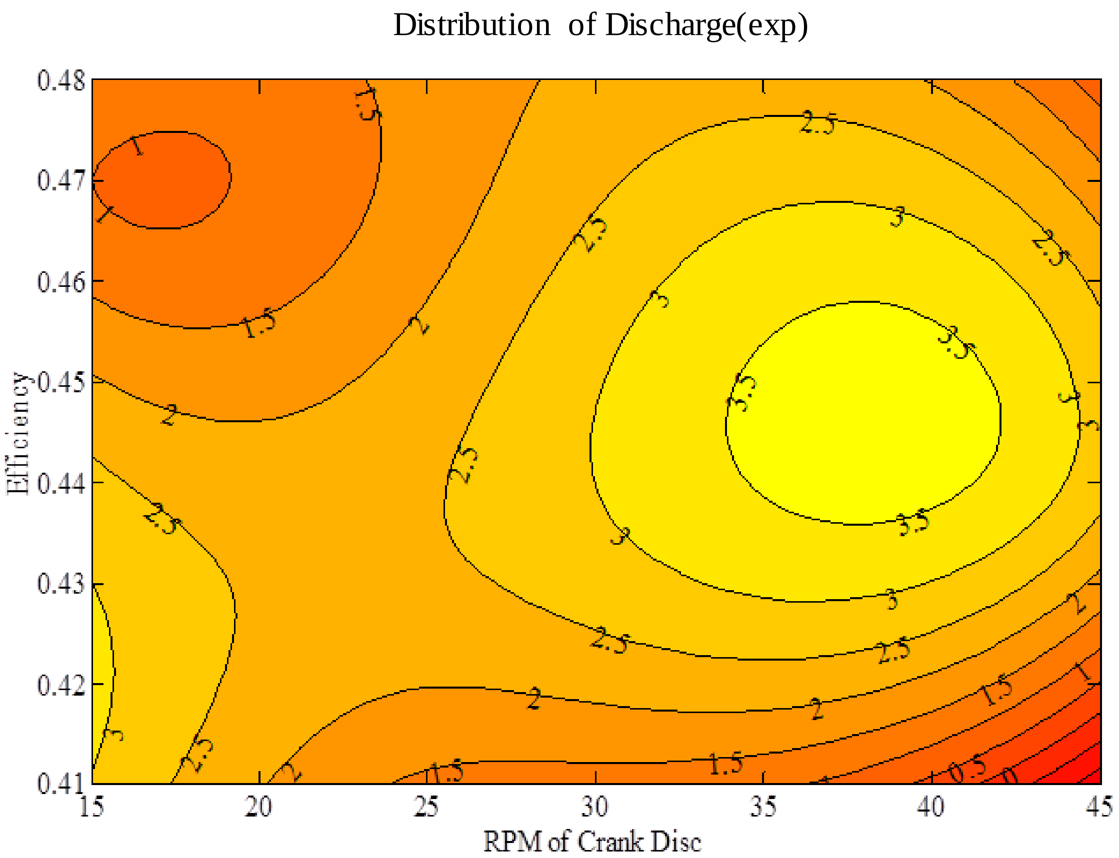
The results have been verified by curve fitting tool in MATLAB and distribution of slip, discharge, efficiency (in fraction), and power required (in watt) as a function of ordinate and abscissa value in contour plot are shown in Fig. 6.






Slip Distribution
Discharge(exp)
Discharge(th)
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
2
2.5
3
3.5
4
4.5
5
5.5


Distribution of Power requirement in Watt
Discharge
Efficiency
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.41
0.42
0.43
0.44
0.45
0.46
0.47
0.48



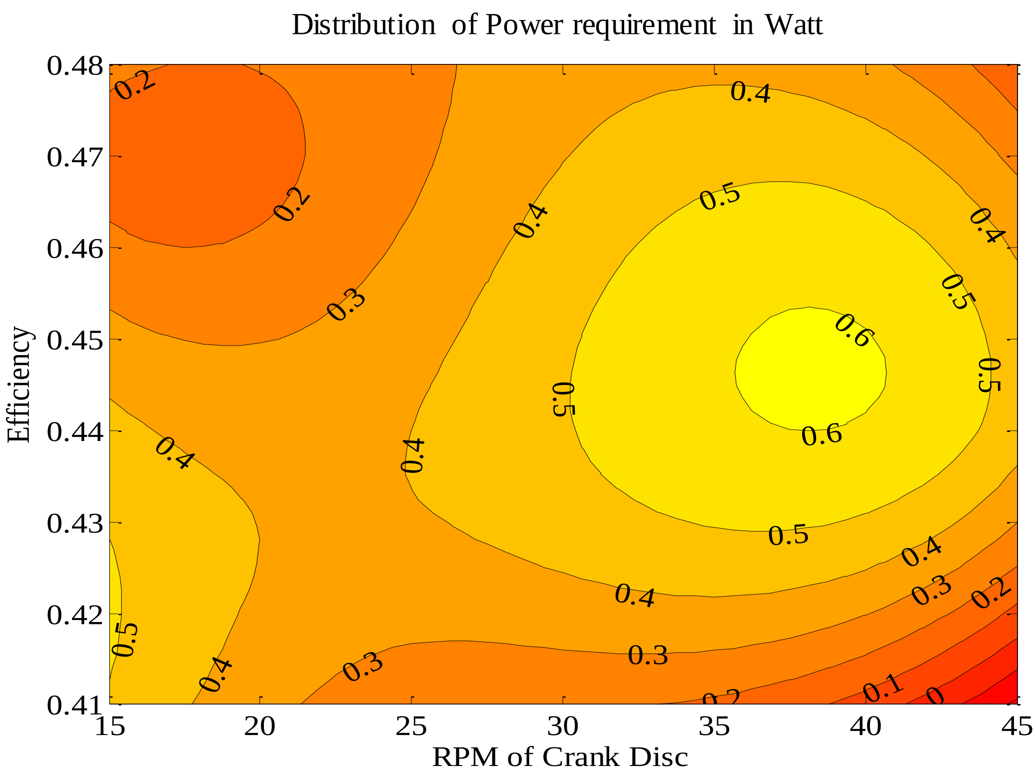


Figure 6: Contour Plot showing Distribution of Slip, Discharge, Efficiency, and Power

Materials of components used in the pump set and their specifications are listed in 'Table 3'

Table 3: Materials of components used and their specifications, no. of requirements and cost per unit.[20]

Sl. No.	*Components*	*Material*	*Specifications*	*Requirements*	*Cost per unit (Rs)*
1	Bearing blocks	Mild Steel	Inside diameter=25 mm	8	480
2	Bevel gears	Mild Steel	Pitch diameter=72 mm	2	150
3	Pinion	Mild Steel	Pitch diameter= 45 mm	1	100
4	Rare sprockets	Cast Iron	-	4	260
5	Collar for rare sprocket	Cast Iron	Inside diameter=25mm	4	60
6	Front sprocket with pedal	Cast Iron	Pitch diameter=mm	2	320
7	Nut and bolt	Cast Iron	Length =70mm, Pitch diameter=15mm	16	30
8	Metal square plates	Mild Steel	Length(breadth)=17mm	2	50/plate
10	Shafts	Mild Steel	Diameter=25mm	3	360/unit length
11	Chains	Cast Iron	Pitch=12.7mm	3	180
12	Square metal bar	Mild Steel	Breadth(height)=40mm	12	55/kg
13	Pendulum	Mild Steel	Length=2540mm, heigth100mm	1	55/kg
14	Pedal	Steel	Length=15mm, Diameter=20mm	1	(Included with 6.)
15	Cylinder	UPVC	Inside diameter=43mm Stroke length=95mm	2	50/feet
16	Valves	Brass	Diameter=10mm	4	600
17	Tee joints	Cast Iron	Diameter=10mm	2	50
18	Pipes	Plastic	Diameter=10mm	4	40/feet
19	Scotch Yoke apparatus	Mild Steel	Length=14.7mm	2	50/kg
20	Crank discs	Mild Steel	Diameter=165mm	2	50/kg
21	Cylinder cap	Mild Steel	Inside diameter=8mm, Outside diameter=53mm	2	(Included with 15)
22	Small ball bearings	Mild Steel	Diameter=32mm	2	70

CONCLUSIONS

Rainfed and dry regions wherein fields need to be irrigated regularly, this prototype will aid in pumping out water from dug out canals or other water sources. It can be operated manually with least effort in a swinging motion and does not need any alternate source of electricity for its action. So, this project is extremely suitable for such type of environment. It has been established from results that, around 15 rpm of crank disc, efficiency is showing constancy (47%). To maintain this much of rpm, little physical effort is sufficient to provide oscillating motion to the crank disc.

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