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Evaluation of different size savonius wind turbines for water pumping

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Abstract

Wind is one of the renewable energy sources that Ethiopia is endowed with, despite it has been nearly untapped for various purposes. Utilization of this ample energy source to run wind turbine for the purpose of water pumping is can be considered effective from the perspective of cost required to purchase diesel engine to operate pumps, environmental friendly and accessible to remote areas far from power transmission lines. In this study, four savonius wind turbines of different diameters with uniform turbine height (1m) were designed on the basis of Adama's town wind analysis with the presumable discharge capacities and the experiment was laid out in RCBD. The experiment was conducted in March, April and May 2019. The result of the experiment showed that except the largest turbine where the rotor diameter is 1.3m, the rest of the turbines could not pump water for a total head of 7m. The ANOVA showed that there was significant effect of turbine diameters ($P<0.05$) on power coefficient, pumping power, tip speed ratio and discharge. The largest turbine capable to discharge a maximum discharge of 0.036 lit/s and minimum discharge of 0.004lit/s for wind speed ranging from 2.49m/s to 3.77m/s during the experiment. The result of this study depicted that the estimated average power coefficient, tip speed ratio and pumping power of the largest turbine are 0.07, 1.04 and 1.7 watts respectively. On the other hand wind speed variation had less significant effect ($P<0.05$) on the variation of power coefficient, pumping power, tip speed ratio and discharge. According to regression analysis ($P<0.05$), the variation of power coefficient, pumping power, tip speed ratio and discharge significantly (98%, 98.7% , 91.6% and 99% respectively) attributed to the change in wind speed. Furthermore, the variation in discharge is highly (85.2%) attributed to RPM of the turbine ($P<0.0\%$). Hence, to improve the discharge capacity of the largest turbine use of speed up gear ratio can be considered as one best alternative in addition to improvement in manufacturing of rope and washer pump. On the other hand, variation of turbine height (4-10m) has less effect on pumping power consequently on discharge. However, prediction of discharge for different speed up gear ratios has significant effect on discharge. Accordingly for wind speed 3.1m/s where the pump can operate for 107 days, if the speed of the pumping

wheel is three times that of the turbine, the system can discharge 0.047lit/s which is even more than the design discharge.

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Cp- turbine power coefficient

ϱ- density of water/air

g-acceleration due to head

H-pumping head

Q- discharge

V- wind speed

n- surface condition

1. Background and Justification

Many view wind pumping as an underutilized resource for supplying water; however, numerous developing nations have begun to utilize its advantages (Smulders, 1996). The uses provided happen to be ideal purposes for a wind pump due to the small head and low wind power needed, some sufficiently working with a wind speed of as little as 3 meters per second (Smulders, 1996).

Savonius wind turbine is vertical axis turbine type and characterized by s-shaped viewed from the top and turns relatively slowly but yields high torque. Savonius wind turbines use a much simpler concept where the rotors simply cup the wind and use drag force to turn the rotor. Since the rotor is powered mainly by drag force, its maximum speed is that of the wind. Savonius rotors are the vertical-axis drag devices that exhibit high starting torque and are well-suited for pumping water (Sivasegaram, 1977 as cited by Rabah and Osawa). They can be fabricated from readily available, cheap materials such as plywood, oil drums, pipes, and sheet metals (Rabah and Osawa, 1995).

According to Smulders, 1996, to pump 40-100m^3 per day a savonius rotor with a diameter ranging from 2.5 m to 5.5 can be suitable. This amount of water can be used to supplement rainfall (irrigation), domestic use and livestock. However, in this study, the required wind speed is not clearly mentioned.

Thus, use of wind turbine for water pumps can benefit particularly the rural community in the provision of relatively clean water for domestic use, livestock and also for irrigation. Consequently there would a possibility to improve the livelihood of the community interms of both health and economy.

However, size of savonius rotor which can discharge the required amount of water for particular purpose should be a vital aspect from the point of view of available wind speed for a specific location, material cost and capacity in terms of head and discharge. Hence, investigating the appropriate size of the turbine for a given head and estimate the corresponding discharge is justifiable.

1.1.Statement of the problem

Countries like Ethiopia, can secure food production for local consumption and export to earn foreign currency can be attained if the country step up to utilize its resource such as energy and water.

Ethiopia is endowed with abundant water resource which can benefit the demand for domestic use, livestock husbandry and irrigation. The water resources that the country has can be categorized as surface and subsurface water. Specifically, regard subsurface it is estimated that the country would have 2.6- 6.5 billion cubic meter where the resource is still untapped due to the fact that various reasons (Seleshi et al., 2007). One of the bottlenecks for the low level utilization of this resource is supply of energy to pump either from deep aquifer or shallow ones. Nevertheless, likewise the water resource, the country has high potential of renewable energy source such as wind, solar, water which can be harnessed either making use of various technologies which even the country can manufacture at local level. Regard wind, the country has currently started to utilize for electric generation (estimated production 300MW) despite the fact that the total potential to produce electricity from this energy source is 1350 GW (MWE, 2013). The wind turbines that are installed and functional for electric production are imported from abroad and provide the power to the national grid. However, in rural areas where the population density is sparse and difficult to provide electricity from the national grid, provision of clean energy such as wind making use of small scale technologies are very essential. In this regard, the country has planned a program termed as rural electrification.

Apart from producing electric from wind making use of wind turbine, the mechanical energy from wind can merely be used to operate various mechanical devices such as pumps for irrigation and other domestic purpose.

Most farmers who adopt water lifting technologies to irrigate in the dry season get improved household income. Incidents and depth of poverty were found to be lower for households with access to irrigation (Gebrezgi, 2008).

Provision of cheap water pumping technologies based on local resources and technologies can improve cattle and crop productivity. Reliable wind pumping machines can be designed, manufactured and assembled locally in nearly rural towns, or in major urban centres (Wolde-Gihorgis, 2002).

However, in this regard, it has been becoming more common to see the use of diesel operated water pumps for irrigation purpose in different parts of the country. However, initial cost and running cost combined with level of awareness and technical capacity to maintain such technologies are some of the bottlenecks for rural communities in Ethiopia.

Thus, utilization of ample wind energy source to run wind turbine for the purpose of water pumping for small scale irrigation and domestic use is very justifiable in terms of cost required to manufacture and maintain, being environmental friendly and accessible to remote areas far from power transmission lines. Hence, despite there are various types of wind turbines, vertical axis wind turbines are more recommended for water pumping than horizontal axis wind turbines. From the point of view of ease of manufacturing, being made from locally available material and low initial cost, savonius wind turbine is found to be more appropriate to operate the selected water pump for small scale irrigation and domestic use.

1.2. Objectives:

The research objective constitutes the following Major and Specific objectives:

Major objective

- ✓ To evaluate four different size savonius wind turbine for water pumping

Specific objectives of the study

- ✓ To assess the wind potential of Adama town for water pumping
- ✓ To determine the dimensions of savonius wind turbines

- ✓ To determine the power coefficient of each rotor
- ✓ To determine the effect of different wind speed on amount of power produced by each rotor
- ✓ To determine the effect of savonius rotor diameter on amount of discharge for the same wind speed
- ✓ To determine the effect of different wind speed on amount of discharge for each rotor
- ✓ To predict possible power and discharge of the rotor for different conditions

1.3.Scope and limitation of the study

In this study, the performance of savonius wind turbine to pump water for different pumping heads was not covered due to the fact the necessity of large number of prototypes and water wells.

2. Literature Review

2.1.Renewable energy in Ethiopia

Energy for rural development has been an issue of national interest for quite some time. This issue has received significant attention in most developing countries during the last three decades of the twentieth century (Abdalla, 1994; Byrnes, 1998; Lew, 2000) as cited by Wolde-Gohorgies(2002). However, the intensity and attention devoted to rural energy issues in the region varies from country to country. These range from technological innovations and academic interest in well-established research and teaching centers to provision of funding from financing institutions, and finally to growing interests by governments and policy makers in options for addressing the rising costs of modern fuels. In some countries, equal attention has been given to both rural and urban energy initiatives. Over time, notable measures have been taken in planning and implementing rural energy initiatives in parts of the developing world. In contrast, rural energy initiatives in Ethiopia have, however, remained undefined, and largely unattended due to economic resource constraints and low levels of technological advancement (Wolde- Ghiorgis, 2001b).

The rural energy problem in Ethiopia will continue to be one of the chief causes of underdevelopment and poverty unless timely interventions are made. As in many other countries in the region, fuel supply in Ethiopia is mainly biomass-based (94.7% of total energy supply, World Bank, 2001). Household consumption constitutes 89% of the total energy supply. The other sectors of the national economy notably agriculture, transport, and industry account for only 7.2% of total energy consumption. The level of grid electrification is extremely low, and therefore insignificant in direct reference to rural development (WoldeGohorgis, 2002).

The idea of income generation using renewable energy has successfully been implemented in many developing countries. Attractive wind resources are available in north, east and southeastern parts of the country. There are potential sites for electricity generation by wind power for 9-10 month in a year (WoldeGhiorgis, 2000a-d, as cited by WoldeGhiorgis(2002)

According to Shanko (2000) as cited by WoldeGhiorgis (2002) in Ethiopia, there should be a clear policy to sponsor and promote pilot renewable energy technologies (RETs) projects so as to familiarize operators, promoters and consumers with the operations and uses of RETs. The dissemination of RETs should be need-driven, as opposed to donor-driven. The skills needed for designing, installing, maintaining and managing RETs should be taught to energy technicians with general and specialized skills. Community could also be organized as business enterprises to coordinate the sustainable growth of rural energy systems. Manufacturers and assemblers of basic and advanced RETs should also be given incentives to make their activities profitable.

2.2.Renewable Energy Resource potential of Ethiopia

Ethiopia is a nation endowed with huge amount of water, wind, solar and geothermal energy potentials. However, regardless of its enormous potentials the energy system is highly dependent on traditional fossil fuels and biomass and only about 32% of the nation’s population has access to electricity (Mazengia, 2010).

2.2.1. Hydropower potential

With multitude of streams flowing into a number of major river basins that cross the national boundaries carrying millions of cubic meters of waters and soil from Ethiopian highlands to eventually join the Mediterranean or others, Ethiopia is known as the "Water Tower of Eastern Africa". Ethiopia’s plentiful hydropower resources, which are distributed in nine major river basins (where more than 50% of the total potential is in the Blue Nile drainage basin) and their innumerable tributaries are estimated to generate 650 Tera Watt Hour (TWH) (CESEN 1986). Of which, the economically affordable energy and power estimates at 40% of the theoretical potential is about 260 TWh and 26.7 GW, respectively (Ethiopia household energy status, 2000).

Its hydropower potential, for instance, is rated as the second largest potential in Africa next to Congo (Block, 2007). This energy potential is estimated to be between 30GW - 45GW (EEPCo, online; DFIP, 2009; Dalelo, nd). Kloos & Legesse (2010) via a cross reference approximated the gross hydropower potential of the country to be over 74GW and economically feasible potential to be from 16GW to 18.3GW; considering an average plant utilization factor of 0.6 (Mazengia, 2010).

2.2.2. Solar energy

In Ethiopia the average solar radiation is more or less uniform, around 5.20 kwh/m^2. The value varies through time, from a minimum of 4.55 kwh/m^2 in July to a maximum of 5.55kwh/m^2 in February and March; and with location from 4.25 kwh/m^2 in extreme western lowlands to 6.25kwh/m^2 in Adigrat area (Tigrai) (CESEN, 1986) as cited by (Ethiopia household energy status, 2000).

The total exploitable solar energy potential of the country is approximated to about 10^{6}GW having an average insolation of 5kwh/m^2 /day (Dalelo, nd) (Mazengia, 2010).

2.2.3. Wind energy

The Ethiopian Meteorological Agency started wind data collection in 1971 in 39 stations systematically distributed over the territory of Ethiopia. Wind speed is variable in different parts of Ethiopia. Highest speed was recorded at the coastal area of the Red Sea, near the Djibouti border. Wind speeds lower than 3.5 m/sec were recorded in the western part of the country. Medium wind speed between 3.5 – 5.5 m/sec exist over most of the eastern part of the country and the central rift valley zone (CESEN 1986) as cited by (Ethiopia household energy status, 2000).

Wind speeds lower than 3.5 m/sec having energy value less than 500 Mcal/m^2 were recorded in the western part of the country. Medium wind speed between 3.5 – 5.5 m/sec (energy values between 500 and 1500 Mcal/m^2) exist over most of the eastern part of the country and the central rift valley zone (CESEN 1986). This resource is a promising potential for water lifting in the rift valley settlements where water is scarce both for irrigation and domestic uses. With continuous effort to locate promising areas, it can also provide a considerable amount of energy for electricity generation (Ethiopia household energy status, 2000).

The total exploitable reserve of wind energy is also approximated to be about 10GW (EEPCo, online; Wind Energy PPP, 2010; Dalelo, nd) as cited by Mazengia (2010).

An international NGO known as Lay Volunteers International Association (LVIA) as part of its food security activities in Ethiopia installed about 73 wind mills for water supply in rural areas in the Rift Valley since the year 1980. The tower is 16 meters high and the diameter of the rotor is 6 meters. The wind mills deliver 20 to 65 cubic meters of water in a day from a depth of 35 to 85 meter. The model of the windmill that is selected for local production by EBG is based on Tozzi and Bardi’s Italian design. The design employs both casting and welding technology. The mill post guide and the thrust bearing housing are made of cast iron. The other components are manufactured from locally available materials. EBG has locally assembled and installed one such type of wind mill for water pumping in the rift valley for demonstration. The diameter of the rotor is 6 meters with 18 sheet blades made up of sheet metals. Depending on the wind speed of the site and the dynamic head of the bore-hole, the pump size is determined (Ethiopia household energy status, 2000).

In the 1960s more than 100 units of wind mills have been installed for water pumping applications and about 70 of them were still operational as of 2004 (Jargstorf, 2004) as cited by Mazengia (2010).

2.3. Wind power computation

When the price of oil rocketed in the late 20th century, wind energy became a viable choice for sustainable energy and has continued to be a growing field of research (Wind Coalition, 2013) as cited by Ford et al., (2013).

Today, wind power has the potential to reduce the amount of carbon dioxide and related greenhouse gases that contribute to global warming (Congress, 2011) as cited by Ford et al., (2013) .

Even though wind power has many positive aspects, there are numerous disadvantages to overcome as well. Most notably, wind speeds and directions are consistently changing, making it difficult to use wind as a consistent power source . In 2006, the average investment for a wind turbine was between \$1300 and \$1700 for every kW the turbine would produce (Wind Energy). For perspective, a 5kW turbine would cost between \$6500 and \$8500 to build and install whereas a 1 MW turbine would cost as high as \$1.7 million USD (Wind Energy) (Ford et al., 2013)

There has also been an increase of wind power use in developing nations as a source of electric power, or as mechanical energy to pump fresh water from wells (Simon, 2011) as cited by Ford et al., (2013).

In order to properly estimate the anticipated power generation for a wind turbine, certain factors about the area need to be calculated. For example, in order for a wind turbine to be economically viable, there needs to be enough wind at the site to power the turbine. This is referred to as the specific power of a site. According to Ford et al., (2013), the specific power is calculated as follows:

$$P = \frac{1}{2}\rho v^3 \text{---} (1)$$

Where P is the specific power, ρ is the air density (in kilograms per cubic meter), and V is the air velocity (in meters per second), and the specific wind power is measured in watts per square meter swept out by the rotating blades. This can be thought of as the amount of power that could be extracted from the wind by a 100% efficient turbine. However, no wind turbine can extract all of the power from the wind.

The turbine output power, in watts, can be calculated:

$$P_0 = \frac{1}{2}\rho A v^3 C_p \text{---} (2)$$

Where P_o is the output power of the turbine**,** ρ is the air density, A is the swept area of the rotor blades, v is the upstream wind velocity, and C_p is a variable known as the power coefficient.

This coefficient, also known as the rotor efficiency, is the “fraction of upstream wind power that is extracted by the rotor blades and fed to the generator (Patel, 2006).” The power coefficient can be calculated as follows:

$$C_p = \frac{\left(1+\frac{v_0}{v}\right)\left[1-\left(\frac{v_0}{v}\right)^2\right]}{2} \text{--(3)}$$

The power coefficient is calculated using the upstream wind velocity, V_o and the downstream wind velocity, V. The maximum theoretical value for C_p is 0.593; this value is known as the Betz coefficient. In practice, however, a realistic estimation for the maximum value for Cp is closer to 0.5 (Patel, 2005).

The power coefficient is closely related to another coefficient, which is known as the tip speed ratio of the rotor. According to Ragheb (2014), the optimal tip speed ratio, λ, is defined as:

$$\lambda = \frac{\omega r}{v} \text{---(4)}$$

Where ω is the rotational speed of the turbine (in radians per second), r is the turbine radius, and

v is the wind speed. This dimensionless coefficient, along with the power coefficient, can be related to the efficiency of the turbine.

Figure 1 shows the relationship between the power coefficient and the tip speed ratio for different turbine types. There are multiple different curves which represent different types of turbines. Each curve represents the power coefficient as a function of the tip speed ratio. Each curve (except for the ideal power coefficient curve) has a certain tip speed ratio that will give a maximum power coefficient, and therefore a maximum power. It is advantageous to ensure that the tip speed ratio is such that it maximizes the power coefficient.

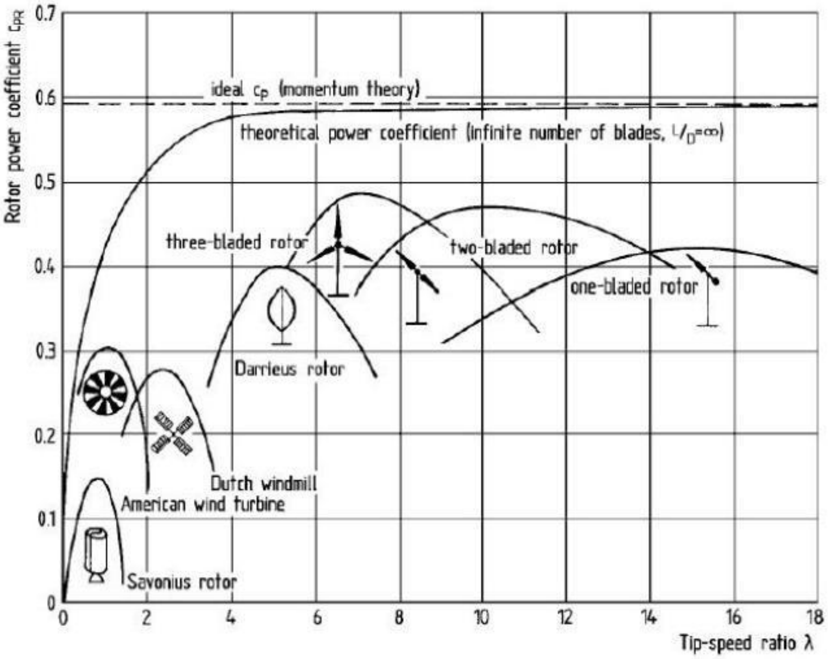

Figure 1. Relationship between rotor power coefficient and tip speed ratio (Wortman,1983) as cited by Ford et al., (2013)

2.4.Savonius wind turbine and design aspects

The viability of a wind turbine depends heavily on the location of the turbine. The site must have enough wind to power the turbine, as well as be clear of obstructions that could cause turbulence. Most commercial wind turbines are designed to be either above obstructions or in an area clear of them. At these heights, the wind is mostly undisturbed and has a higher velocity than wind closer to the ground. However, the wind at any site is not constant, and it varies based on the day. Placing a wind turbine on a hill or in a canyon will serve to enhance the amount of wind power available, which in turn will produce more energy (Wortman, 1983). This phenomenon was implemented in the San Gorgonio Pass, near Palm Springs, California. In order to increase the amount of wind power generated, thousands of turbines were placed on a plateau in between two mountains. The wind flow between the mountains was much higher than in the surrounding area. This higher wind speed, in turn, helped generate more power

(Wortman, 1983). These types of considerations are more relevant when considering a turbine in the third world – a turbine built there would need to be built with limited resources and would likely not be tall enough to avoid turbulent wind currents that can be generated near the ground (Ford et al., 2013).

Wind turbines are mechanical devices that convert wind energy into electrical or mechanical energy (Paraschivoiu, 2002) as cited by Ford et al., (2013). Wind is used to turn the blades, which in turn, are used to generate energy. This energy can either be harnessed as mechanical energy (by using the turning shaft to pump water, for example) or as electrical energy by attaching the shaft to a generator, which can power a device or be used or stored in a battery to be used later.

There are two distinct types of wind turbines, which are based on the orientation of the turbine axis. The first is the horizontal axis wind turbine (HAWT). This type of turbine uses a horizontal axis to suspend large rotor blades, which are turned by the wind. HAWTs are either upwind, where the blades are on the upwind side of the tower, or downwind, where the blades are on the downwind side of the tower. A vertical axis wind turbine (VAWT), unlike a HAWT, does not rely on the direction of the wind to generate power. It relies on a system of blades which lie on a vertical axis and are rotated by the wind.

The Savonius rotor was originally designed by Finnish inventor Sigurd Savonius in 1922. It is classed as a drag-type device, and is understood to have relatively low efficiency but high reliability. Interest in the Savonius rotor and other types of Vertical-Axis Wind Turbines (VAWTs) became elevated duringthe oil embargo and resulting energy crisis. Also, during the 60s and 70s, the Savonius was considered as an example of appropriate technology for rural development in the third world due to its low maintenance requirements. In that the Savonius is low speed and high torque by nature, it is more similar to the windmills of medieval Europe than most contemporary horizontal-axis wind power devices (Andrus, 2012).

The Savonius rotor is less powerful than most HAWTs as it uses drag to rotate itself, and it has a high power to weight ratio. However, the Savonius rotor is particularly useful for situations that do not require a large amount of power (Paraschivoiu, 2002). Also, because of the simple design of the Savonius, it is relatively simple to build.

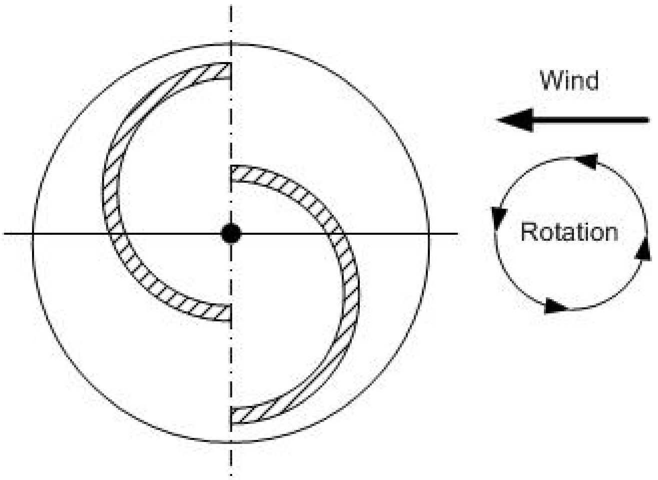

Figure 2. Top view of simple Savonius turbine

The Savonius turbine relies only on drag to turn. As such, the total turning torque of the mechanism can be approximated by considering the drag force on the "cups" to be applied directly on the middle of each cup. The drag force on a surface can be evaluated as:

$$F_d = \frac{1}{2}\rho_{wind} A v_{wind}^2 C_d \text{---} (5)$$

Where ρ_{wind} is the wind density, A is the cross sectional area, v_{wind} is the wind velocity, and C_d is the coefficient of drag on the surface. For a concave semicircle, the drag coefficient is 2.3, and for a convex semicircle, the drag coefficient is 1.2 (Ford et al., 2013).

Hence the torque developed is given by

$$T = F_d * r \text{--} (6)$$

Or

$$T = \frac{P}{\omega} \text{--} (7)$$

Where r is the radius of the rotor.

Aspect ratio/ARs (α)

The aspect ratio represents the height of rotor relative to diameter. The relation is shown by

$$AR = \alpha = \frac{H}{D} \text{---(8)}$$

According to The aerodynamic performance of the Savonius rotor depends strongly on the aspect ratio (AR). Mahmoud and Haround (2012) tested different configurations for aspect ratios (noted a) of 0.5, 1, 2,4,5 by keeping other parameters constant, the results show that the power coefficient increases with the rise in aspect ratio.

Lately, studies with various designs of changed Savonius rotor having low ARs have been reported out (Zemamou et al., 2012). According to Kamoji and Kedare (2009) the rotor with an aspect ratio of 0.7 is having a maximum Cp equal to 0.21.

According to Modi (1984) as cited Zemamou et al., (2012) also conclude that an AR of 0.77 leads to a maximum Cp of 0.24. However, several studies on Savonius new rotors use AR near to 1, generally the of ARs within the range of 1.5–2.0 set good results on the performance of the Savonius rotor.

According to Brusca et al., (2014), to maximize the power coefficient, the rotor’s aspect ratio should be as small as possible. As aspect ratio diminishes there are two advantages: the local Reynolds number rises and simultaneously the rotational velocity diminishes.The advantages of a turbine with a lower aspect ratio are: higher power coefficients, a structural advantage by having a thicker blade (less height and greater chord), greater in-service stability from the greater inertia moment of the turbine rotor.

2.5.Water lifting devices

Water lifting devices are devices that can be operated by different energy sources for the purpose of domestic and agricultural purposes.

2.5.1. Types of water lifting devices

There are number of water lifting devices which can be used for various purposes. Different types of applications require different types of pumps, and each different pump has different characteristics.

According to Gasch & Twele (2012) as cited by Ford et al., (2013), different pumps were compared on the basis of their capacity and application as shown in the chart below.

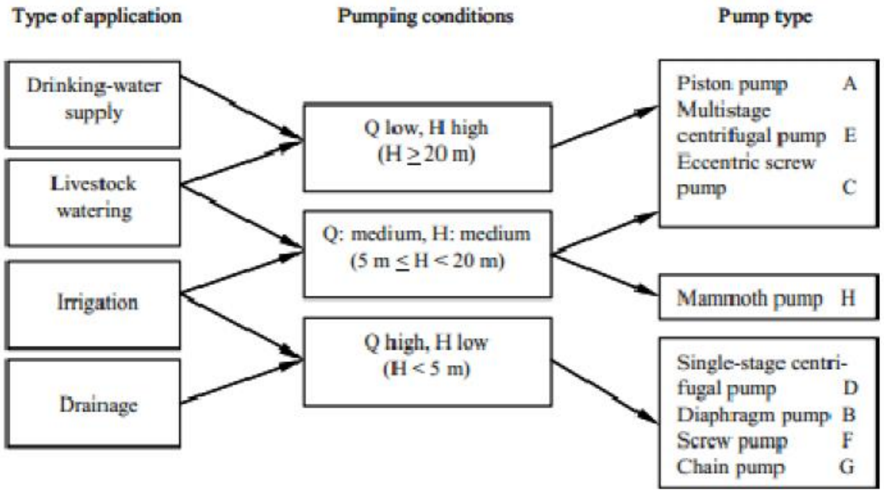

Figure 3. Comparison of water pumps (Gasch & Twele,2012 as cited by Ford et a.., 2013)

Moreover, Gasch & Twele (2012) as cited by Gregory et al., (2013), compared water pumps on the basis of different factors as discussed in the table below.

Table 1. Pump Type Pros and Cons (Gasch & Twele, 2012)

Pump	***Pros***	***Cons***	***Notes***
Piston pump	• For low rotational speeds, a high total head is delivered • Has been successfully applied to many different types of wind pump systems • Starting characteristics can be improved by design measures	• High wear when pumping dirty water • High starting torque required • High dynamic forces due to oscillating piston	• H-Q characteristics show that total head is ideally independent of flow rate
Multistage centrifugal	• Can be used to transmit electrical power • Not sensitive to dirty water • Low starting torque • Turbines and centrifugal pumps are both rotodynamic machines	• Difficult to manufacture if the impellers are small	• Has only been applied to wind pump systems with an electric coupling and a submersible motor • Head increases with more stages
Rope pump	• Can lift water up to the required 30 meters • Mechanically simple to build and repair	• Very inefficient • Can be somewhat unreliable	

2.5.2. Water lifting devices in Ethiopia

Agriculture in Ethiopia is dominated by smallholder rain-fed systems but low and erratic rainfall limits productivity and food security. Consequently, investment in small-scale irrigation has been identified as a key poverty reduction strategy. In addition, given the water resources potential, promoting groundwater use and adoption of household level irrigation technologies is crucial. In its Growth and Transformation Plan (GTP), the

Government of Ethiopia discusses making use of groundwater by supporting farming households in the adoption and use of private hand-dug wells and suitable water lifting technologies (WLTs). How exactly this can be achieved remains unanswered (AG Water Solutions, 2011)

The total number of pumps in use in Ethiopia is not known but _gures for the number of pumps supplied by the RBWR were collected (Table 2). These figures suggest that the use of motor pumps is greater than that of treadle pumps, even though the latter are produced locally.

Table 2. Pumps supplied by Regional Bureau of Water Resources

Type of pump	**Oromia**	**Tigray**	**Amhara**
Motor pumps	19,355	18,448	20,916
Electric pumps	13	ND	ND
Treadle pumps	162	ND	14,731
Rope and Washer	316	ND	ND
Total	19,846	18,448	35,647

Source: Regional Bureaus of Water Resources (AG Water Solutions,2011)

The total number of motor pumps in use could be higher given the number imported from 2004 to 2011 (Figure 4).

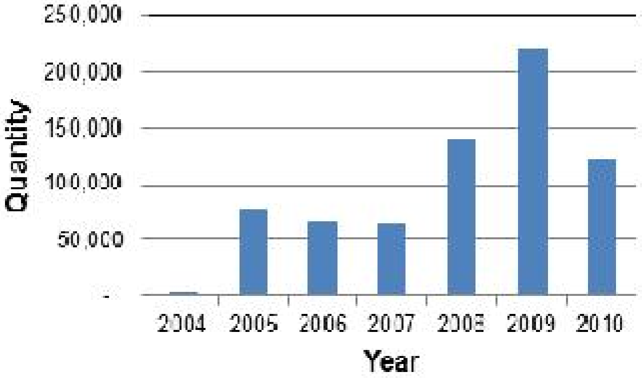

Figure 4. Motor pumps imported to Ethiopia (AG Water Solutions, 2011)

Purchase price can be a hindrance to adoption. This is considerably higher for motor pumps than manual Water Lifting Technologies (WLTs) as shown in Table 2 partly due to import taxes which account for around 37% of the cost. In addition, the average investment cost of water storage facilities, such as shallow wells and ponds, can be prohibitive (AG water solutions,2011).

Table 3. Average costs of WLTs provided by farmers (AG water solutions, 2011)

Pump type	**Capital Costs (Birr)**		**Maintenance costs (Birr)**	
	WLT	Accessories	2010	2011
Treadle pump	3,650	4,000	375	517
Rope and Washer	2,593	200	0	0
Petrol pump	4,751	1,872	953	1,420
Diesel Pump	7,246	1,971	1,792	2,527
Electric Pump	5,000	1,929	13,000	0

As may be expected, access to fuel was found to be an important factor in the adoption of motorized pumps but household labor was not. Most motor pumps are imported by private companies, not through public support programs. Despite the involvement of private enterprises, there are insufficient spare parts and support services for adequate maintenance. The farmers reported that machinery frequently breaks down, and their unfamiliarity with the technologies leads to delays in agricultural activities and contributes to dissatisfaction with
WLTs (Tadesse et al., 2008).

A few wind pumps have been demonstrated through donor funding. Demonstration of PV installations for lighting and village electrification have also been attempted, but these were not sustained (Wolde Ghiorgis, 1990). Old and new micro-hydro power driven flourmills exist in a few farming communities. However, comprehensive and coordinated introduction and use of RETs is yet to be promoted in line with development goals of rural development. (WoldeGohorgis, 2002).

2.5.3. Rope and washer pump

Rope pump: The Rope pump is a lift pump with continuous upward movement of a rope and a number of pistons in a tube. The Rope pump has a relative lightweight construction and is made of locally available materials and can be produced and repaired locally (Arjen et al, 2006).

The Rope pump is an ancient technology that, with new materials and designs, now is a very effective and low cost pump option for water supply and irrigation that is used by families and small communities. It can be produced with locally available materials in local metal workshops. Compared to other low cost hand pumps, the Rope pump has a high pump capacity and can pump from wells of 1 to 35 meter deep. It can be produced in any country and is very simple to install (no black box). If properly produced, installed and maintained, over 90% of the installed pumps may be expected to remain functional, even many years after installation. Because of the before mentioned features, the Rope pump has a high potential for Self-supply. An example is Nicaragua, where over 70,000 Rope pumps were installed primarily for Self-supply. Two reasons for its success in this country were (a) technical improvements that made the pump more effective and attractive and (b) the private sector that took interest in production and sales. The pump became a commercial product so there was a “profit based sustainability”. In Nicaragua the shift from imported piston pumps to locally produced Rope pumps decreased the cost for rural water points by 60%. Close to 20% of the pumps are used for communal wells and 80% for Self-supply (domestic use, cattle watering, small scale irrigation). Due to these pumps, the total accumulated income at family level in the last twelve years was 100 Million US$. This is explained by the fact that families who have a pump on their well earn an average 220 US$ more per year than families using a rope and a bucket. Using a Rope pump saves time, results in less health related cost (water is cleaner since it is not re-contaminated by the bucket) and can provide water for income generating activities such as livestock keeping or garden irrigation (MetaMeta, 2014).

The Rope pump consists of a wheel and an endless rope with small pistons, made of polyethylene (or car tire in home made models) that are attached to the rope at intervals of 1 meter. The pistons fit, with a clearance of around 1 mm, in the PVC pipe called ‘rising main’. The rope and pistons move freely (and not in a pipe) down into the well. At the bottom, the rope is led by a guide box into the rising main. The wheel and handle are mounted on a support structure on top of the well. The rope and pistons are lifted by the wheel. The water is brought up by the pistons and discharged at the surface. When an additional wheel is added it can even be higher than ground level. Rope pumps can be used on open hand dug wells or boreholes with a diameter as small as a 3 inch (75mm). The Rope pump can be classified as a positive displacement pump producing a constant output, unlike the pulsating flow of piston pumps. The weight of the water column is equally carried by all pistons in the rising main. The pressure built up in this tube is only the height of the water column between two pistons (1 m). As a result, the forces on the pistons and the radial water pressure on the rising main are small, making the use of ‘thin wall’ or ‘low pressure type’ PVC pipes possible. In a piston pump (with a foot valve) the pressure would be created by the height of the entire water column. The maximum force on the rope is determined by the volume of the water column in the rising main. The continuous flow not only reduces peak forces on the rope, but also maximizes the effective flow of water through a given tube diameter. Finally, the absence of peak forces and the gradual filling of the pump tube, contribute to good human ergonomics (Arjen et al., 2006)

The Rope pump was introduced in 2004 in Ethiopia by the Japan International Cooperation Agency (JICA). The model first introduced was an A frame model as used in Tanzania and Zambia, which in turn was based on the models from Nicaragua. Lateron also other organizations, including Selam and IDE, worked with Rope pumps and gave trainings to Rope pump producers. According to the results of an inventory done in 2012, there were than 5,639 Rope pumps with hand dug wells systems for drinking water supply in Ethiopia (out of a total of 92,588 drinking water systems). The majority of these Rope pumps are in Amhara (3,699),and Oromia (1,036) as cited by (MetaMeta, 2014).

Evaluations show that 90% of the Rope pumps continue working, even after years of operation. This high percentage is due to the simplicity of the pump. The users understand the working of the pumps and are able to maintain it and, if necessary repair it themselves or with the help of a local workshop ‘around the corner’ (Arjen et al., 2006).

Until 2014, the overall estimate is that over 10,000 Rope pumps are installed, including pumps primarily used for irrigation. Over the years manufacturers and organizations have made several adjustments to the original Rope model. At the same time, different models of well covers and well heads have been developed and tested by different manufacturers and organizations. Similarly, different aprons and methods to drain water away from the well have been installed. The promotion and improvements of the Rope pump is supported by the Ministry of Water, Irrigation and Energy and JICA. There is a high interest in the Rope pump with the Regional Government of SNNPR currently procuring 10,000 Rope pumps for drinking water supply. The Ministry of Agriculture is considering an even larger number of pumps to be obtained for household use and irrigation. However based on the assessments done by JICA and other investigations, it appears that an estimated 33% to 50% of the Rope pumps in Ethiopia are not functioning . Common problems concern technical problems in the pump parts, faulty installation and low quality of aprons and seals causing water to leak back in the well resulting in recontamination of the well water (MetMeta, 2014).

Figure 5. Rope and washer pump (source: MetaMeta,2014)

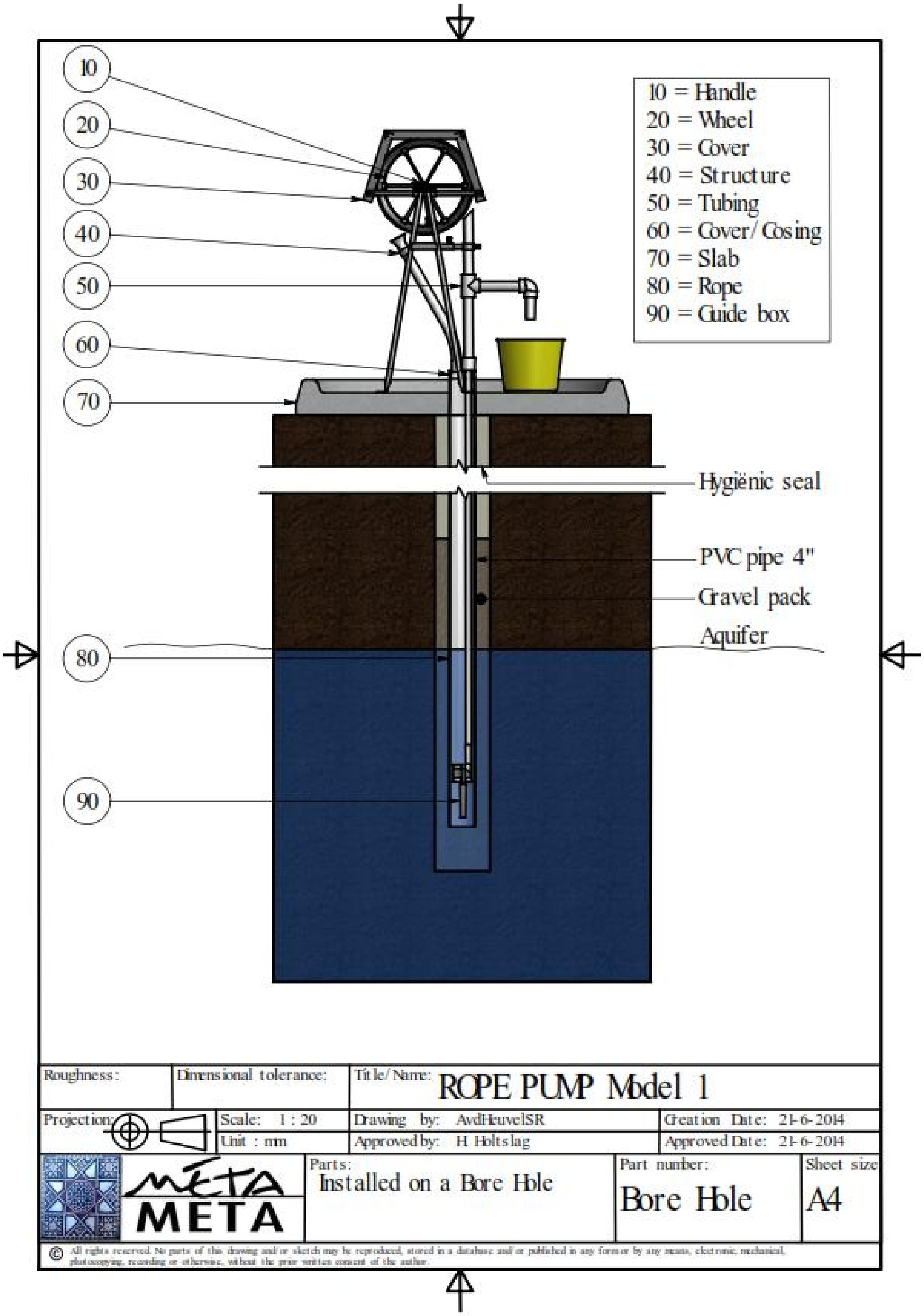

Figure 6. Rope and washer pump technical drawing (MetaMeta, 2014)

According to Arjen et al., (2006), rope and washer pump has the following advanates and disadvantages.

Advantages

- Low cost, a cheap pump on household level (<10 households).
- Absence of dynamic forces (rotating movement).
- Tubes can be made of low pressure PVC tubing.
- The total weight of pump parts is approximately 15 Kg (which is 5 to 10 times less than piston pumps). The pump can be taken from the well without any lifting tool.
- No valves, valve seats, and ball bearings. Therefore less ‘critical’ parts, resulting in higher reliability.
- High overall efficiency 80 – 85% (if well made).
- Technology, without ‘black box’, is easy to understand, produce and maintain.

Disadvantages

- The Rope pump is not 100% closed. At the discharge and return tube, the pump is open to the air and contamination of the rope is possible via contact by hand.
- The Rope pump is not a pressure pump (no pressure in outlet).
- Especially with deep wells, it takes some time before the Rope pump delivers water. (When not in use, the water level in the pump falls back to the water level in the well).
- The Rope pump is NOT designed for communal use by more than 10 households.
- “Stone age” image. Many people know the Rope pump as a self made, low lift pump. This image hampers acceptance by water organizations, institutes and users.

According to Arjen et al.,(2006), rope and washer pump can have a discharge of 35lit/min for depth up to 10m, 20lit/min for depth up to 20m and 10lit/min for depth up to 35m. Moreover, average input power required by rope and washer pump is 50watt. However, the discharge can vary on the basis of input power.

2.6. Wind pumps

How much water a wind pump can pump is rather a difficult to answer exactly, as wind speeds can be quite variable. It must also be noted that local topography, and trees and buildings within the vicinity of the wind pump, can reduce its performance (Jorritsma, 2004).

According to Baumann (2000) as cited by Jorristma (2004), operation and maintenance cost are moderate and they do not need any consumables. Repairs, however, need specialized skilled personnel. Wind pumps are often applied at high head: typically 10 to 100m. They have a robust nature of their construction but quite expensive in relation to their power output. A water storage tank is required to ensure water supply when the pump is not running and to balance the hourly fluctuations in demand. In order to withstand occasional storms, windmills must have a means to limit the power they can deliver.

Water pumping can be powered by different power sources. Kristoferson (1991), as cited by Jorritsma (2004) stated pumping options flowchart for various power sources depending on the water required.

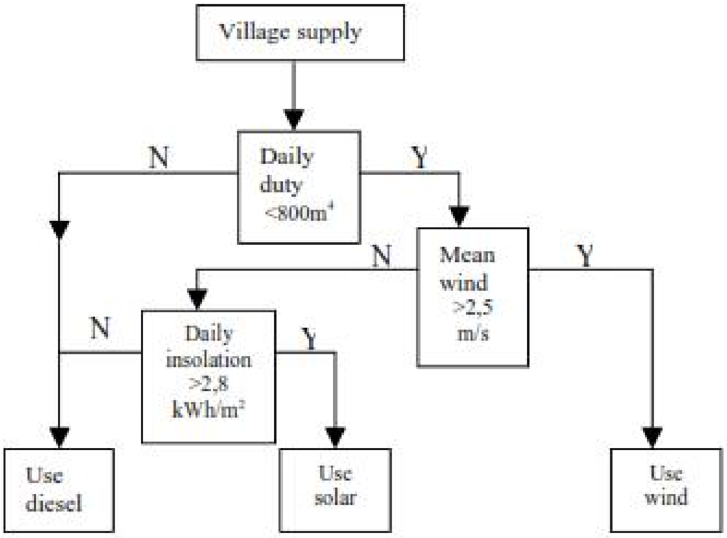

Figure 7. Pumping options flowchart (Kristoferson, 1991 as cited by Jorritsma, 2004)

3. Materials and Methods

3.1.Description of the Study Area

This experiment was conducted around Adama, particularly in ASTU. Adama is located in Oromia region to east of the capital Addis Ababa at about 100km away. Adama lies latitude 8.54^0N and longitude 39.27^0E. The average elevation where the experiment was conducted is 1680m above sea level.

3.2.Prototype production and water well preparation

3.2.1. Design of the turbines

In determining the diameter and height of the turbines or swept area, previous study and mathematical approaches were considered.

The mathematical or theoretical approach to determine basic dimensions of the turbines takes into account power output by turbines computed by eqn.2 and power required to pump an assumed m^3 per second of water for predefined number of days in a year for a given wind speed to(eqn. 9).

Smulders (1996) and Mwangi and Mungai (2006), the power required to discharge a given value from certain depth is computed by:

$$P = \rho g H q \text{---} (9)$$

Where P is power (watts); p is density of water (kg/m^3); g is acceleration due to gravity ($9.81m/s^2$); H is head (m); q is discharge (m^3/s).

Hence, swept area was computed by equating the pumping power (eqn.9) and wind power by assuming the power coefficient of savonius wind turbine through reviewing literatures.

The second approach to determine fundamental dimension of the turbines through reviewing previous study or literature as mentioned above.

Each turbines were made of two half cylinder (rotors) and a single stage; taking into account feasibility in terms of ease of construction, installation and economy or cost were used as means of evaluating the above approaches to select to make use to determine turbines’ dimension. In this study, since the turbines were manufactured from sheet metal (2mm thick), for ease of construction, 1m turbine height for each was selected thereby the diameter of the turbine would be estimated by dividing the computed turbine area by the turbine height (1m).

Hence, to suit the analysis of the turbines output only diameter was made to vary.

Figure 8. Turbines manufactured at ASTU (Photo)

The two basic design criteria for savonius wind turbine, overlap ratio and aspect ratio were determined relying on the estimated rotor diameter and selected turbine height as discussed below.

$$overlap\ ratio\ (\beta) = \frac{overlap\ (e) - diameter\ of\ the\ shaft\ (a)}{rotor\ diameter\ (D)} \text{----------------}(10)$$

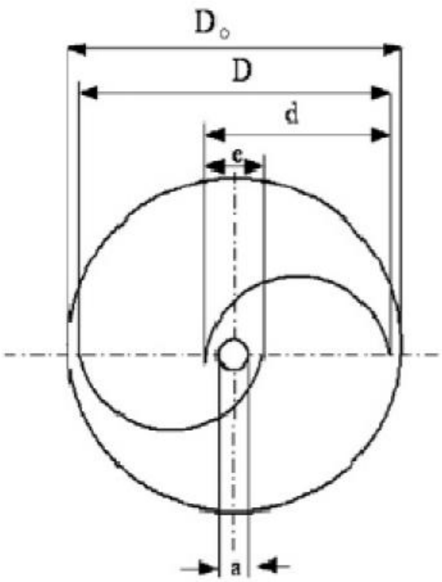

Figure 9. Schematic diagram of savonius rotor

Where: D_o- is the diameter of the upper and lower end plate; D- is the diameter of the rotor ; a is Shaft diameter; e is overlap.

According to Patel et al., (2013), for different overlap ratios of values 0.0, 0.1 0.2; the overlap ratio with value β=0.2 yields high power. Moreover, according Menet & Bourabaa (2012) as cited by Gregory et al., (2013), the optimal overlap ratio was 0.242. Therefore, considering an overlap ratio of 0.2 is justifiable.

Based on the above equation (eqn.10) , the values for overlap (e) and end gap were determined.

Moreover, aspect ratio of each turbine was determined. Aspect ratio for each turbine was determined by dividing the constant turbine height to rotor diameter (eqn 8). Hence, variation among each turbine in terms of capacity is attributed to variation in aspect ratio.

Furthermore, end plate diameter was determined based on Altan et al., (2008) as cited by Wenehenubun recommendation as stated in eqn.11 below.

$$D_o = 1.1D \text{--} (11)$$

D_o=1.1D

Where: D_o is end plate diameter was determined ; D is diameter of the circle inscribe the rotor (turbine diameter).

Finally, the manufacturing of the turbines was conducted by forming a cylinder from a sheet metal of 2mm thickness. The turbines were finally be made by cutting the cylinder half longitudinal and connecting each to form s-shape. AutoCAD was used to draw each turbine as shown in Appendices 2.

3.2.2. Tower prototype

The towers for each turbine were built with the height of 3m just below the bottom end of the turbine. The towers were manufactured from angle iron and to make suitable for transportation joints were made by bolts and nuts.

Figure 10. Tower of 3m height used to support the turbine (Photo)

3.2.3. Prototype of rope and washer pumps

Before producing modified version of rope and washer pumps, the selection of appropriate water pump which can be operated by wind relying on various criteria was assessed using questionnaire (Annex). Only three experts were involved to respond the questionnaire due to the fact that the rest of experts randomly selected had limited knowledge specifically regarding rope and washer pump. Moreover, literatures were reviewed regarding the suitability of various pumps for small scale purpose, economy and maintenance cost.

Likewise the turbine, four rope and washer pumps with the same size (diameter of the washer) were prepared. Among the different rope and washer pumps on the basis of their head and diameter of water transporting PVC pipe, rope and washer pump with pumping head 10m was selected as the total estimated head prepared for this experiment is sum of tower height (3m) and depth of well (4m) and thus total expected pumping was 7m.

Rope and washer pumps normally operated by human or animal power, however, to make suitable for wind turbine, modification of the pumps was made by the supplier as per the design of made by this study. Hence, since the pump requires rotational force around a horizontal axis, to convert the vertical rotation savonius turbine to horizontal bevel gears with driven to drive teeth ratio of 15 to 10 was used.

Figure 11. Assembled tower, turbine and rope and washer pump (photo)

3.2.4. Preparing shallow water wells (test site)

For this experiment 4 shallow artificial wells with 4m depth were dug. To avoid the variation of water level in the well, four plastic jar for each pumps with a capacity of 180 liters were put in the well.

Figure 12. Assembly of the pump and the turbine (photo)

3.3. Computation of tip speed ratio, power coefficient, power output and torque of turbines

Before, estimating the power generated by the turbines, the tip speed of the turbine was computed by multiplying observed RMP and end plate radius (eqn.12).

$$V_t = r * \omega \text{---} (12)$$

Where V_t is turbine tangential speed (m/s); r is end plate radius (m); ω is angular velocity of the turbine (rad/s).

The tip speed ratios of the turbines for different recorded wind speed during the experiment were determined by equation 4.

The tip speed ratio which is the ratio of turbine speed to wind speed is used to determine the power coefficient recommended by Wortman (1983) for savonius turbines as shown in the graph (figure1) theoretically. However, the practical power coefficient of the turbine was determined by equating pumping power and turbine output as shown in the equation 13 below.

$$1.5 * \rho g H q = \frac{1}{2}\rho A v^3 C_p \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(13)$$

Where P is power (watts); p is density of water (kg/m^3); g is acceleration due to gravity (9.81m/s^2); H is head (m); q is discharge (m^3/s). The constant 1.5 is the ratio the gear on the turbine shat to pump shat.

Power generated by each turbines for the selected wind speed was computed for a given tip speed ratio using equation (eqn 2) taking into account the average Cp value computed above for different trials. In addition, the torque produced by the turbine was calculated by taking the ratio of the power generated and angular speed of the turbine.

3.4. Predicting pumping power and discharge under different conditions

Wind turbines can be installed at different realizing the surrounding condition. Thus, the probable pumping power at 8m and 10m for three selected wind speeds were determined and compared with the existing turbine set up.

Moreover, for different pump wheel speed by varying gear ratios or use of speed gear ratio, the possible discharge were estimated relying on the result of regression analysis. Accordingly three different gear ratios were considered to predict the resulting discharge.

3.5.Materials used

Materials required to manufacture the turbine, tower, pump (washer pump) includes:

- Sheet metal, Rectangular pipe, flat iron, pipes, shaft, Electrode, angle iron, bolts and nuts, PVC pipe, washers, rope, bevel gears, bearings.

Materials used to test the turbine includes bucket of 10 liters capacity and stop watch. Moreover, GPS was used to determine the elevation of the experimental site.

3.6.Data collection and Analysis

For the design and manufacturing of the turbines wind speed data for Adama area was considered to conduct frequency analysis. To determine the recurring wind speed of Adama, CumFeq software was used. Considering high return period or higher wind speed value for design of wind turbine can lead to less operational during low wind speed. Hence to make the turbines operational throughout the year and in each months at least, lowest possible return periods such as 2, 3, 4 and 5 years were considered.

The testing of the turbine was conducted for seven days in March and May, 2019. Accordingly, for this specific testing period wind speed recorded at Adama Meteorological Agency was collected which is available in three hours average for the time 6:00-9:00AM, 9:00-12:00AM, 12:00-3:00PM and3:00-6:00PM. Moreover the turbines were installed at 4m (tower height plus turbine height), and hence the recorded wind speeds at this height was estimated by equation12 (Bañuelos-Ruedas et al., 2011).

$$\frac{V}{V_o} = \left(\frac{H}{H_o}\right)^n \text{--(14)}$$

Wheer: V_0 and H_0 are measured at a fixed altitude (generally 10 m) above the ground; ‘n’ is coefficient that varies from 0.10 and 0.40. ‘n’ depends on the surface roughness; Since the experimental site is characterized by ‘small town with trees and shrubs’ for this n=0.3 was considered.

According to Adama Meterological office the elevation of the office where the wind speed is measured is 1648m, and the speed measured at 2m height and hence the total elevation where the wind speed was measured is 1650m, that is equivalent to H_o. In addition, the elevation of the experiment site was measured using GPS and the value is 1680m. The height of the turbine at middle of the rotor is 4m and the total elevation where the rotor is installed is 1684m. Hence, using equation 14 above, the wind speeds which act on the turbines (V) were computed.

During testing, output of each turbine in liters per minute and revolution per minute were recorded. Discharge of the turbine was measured by recording the time required to fill one liter volume. Moreover, revolution per unit time of the turbine was estimated by recording the time required to complete five complete revolution for that particular trial period.

Data collected during this study was analyzed with simple statistics and ANOV (analysis of variance). The experimental design RCBD was used in such a way that the four different turbines were considered as blocks and the seven different wind speeds as treatment to analyze power coefficient, tip speed, power (wind power and pumping power), discharge and rpm developed by each turbine. Two-way analysis of variance (ANOVA) was performed using excel to check the significance of the effect of independent variable (turbine size and wind speed) on dependent variable (power coefficient, tip speed, power (wind power and pumping power), discharge and rpm).

Furthermore, to study the relationship between dependent variable (discharge, rpm, tip speed) and independent variable (wind speed, rpm), regression analysis for discharge versus rpm, discharge versus wind speed and tip speed versus wind speed was carried out statistically.

4. Result and Discussion

4.1. Wind Speed analysis

In this study before designing the wind turbine and estimating output of the turbine, wind data frequency analysis and interpolation were executed as discuss in the section below.

4.1.1. Frequency analysis of Adama's town wind speed

To understand the available wind potential in the region, wind data for Adama was analyzed in terms of frequency of occurrence for selected periods and wind speeds.

A wind pump is certainly the best option when the daily water need is between 100m and $800m^4$ and the average annual wind speed at least 2.5 m/ s(Jorritsma, 2004).

On the other hand, other source revealed that water from wells as deep as 200m can be pumped to the surface by wind pumps. In off grid areas where there is sufficient wind (3-5 m/s) and ground water supply, wind pumps often offer a cost-effective method for domestic and community water supply, small-scale irrigation and livestock watering (Site 1).

Horizontal axis wind turbine has been common around Ziway to operate piston type pumps for various purposes. Experience of around Batu, East Showa regarding wind powered water pumping was considered as Adama (1,712m) and Ziway (1,643m) exist in rift valley and as well their altitude above sea level is relatively closer.

According to 18 years recorded wind speed data of Adama, the data depicted the highest wind speed in Adama occurs during the month November to February and also in months of June and July (figure 13). However, the study was conducted in March and April (2019) where the wind speed is relatively low.

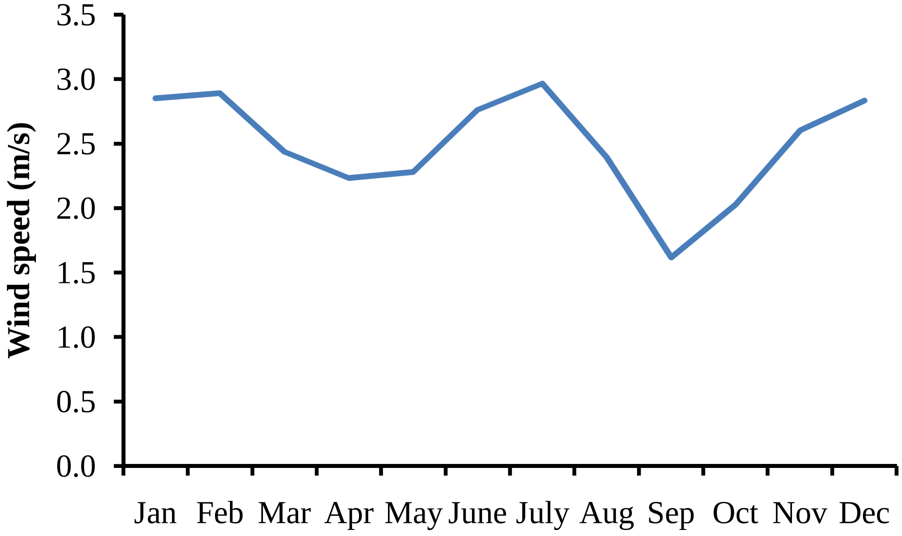

Figure 13. Trend of wind speed of Adama town.

According to this trend of wind speed for Adama town, if the lowest wind speeds occur in months March-May and August-October (figure 14), thus design of wind powered water pump for high wind speeds can limit supply of water during the lowest probable wind condition which might require water storage system.

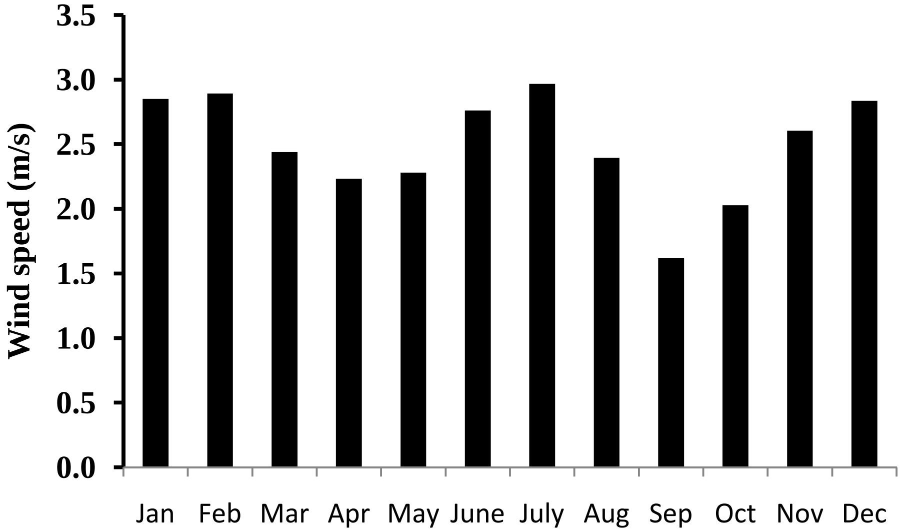

Figure 14. Monthly average wind speed (m/s) of Adama

Cumulative frequency analysis conducted for 193 recorded wind speed data of Adama showed that the cumulative frequency function is generalized Gumbel mirrored type as shown in the equation below.

Freq = 1-exp[-exp{-(A*X^E+B)}]
The exponent E = 0.210
A =-2.05E+001
B = 25.7

Moreover, the analysis depicted that the average wind speed of Adama is 2.67m/s with median 2.7m/s and standard deviation 0.585m/s. The frequency distribution curve of Adama's wind speed data illustrated in the figure 15 below

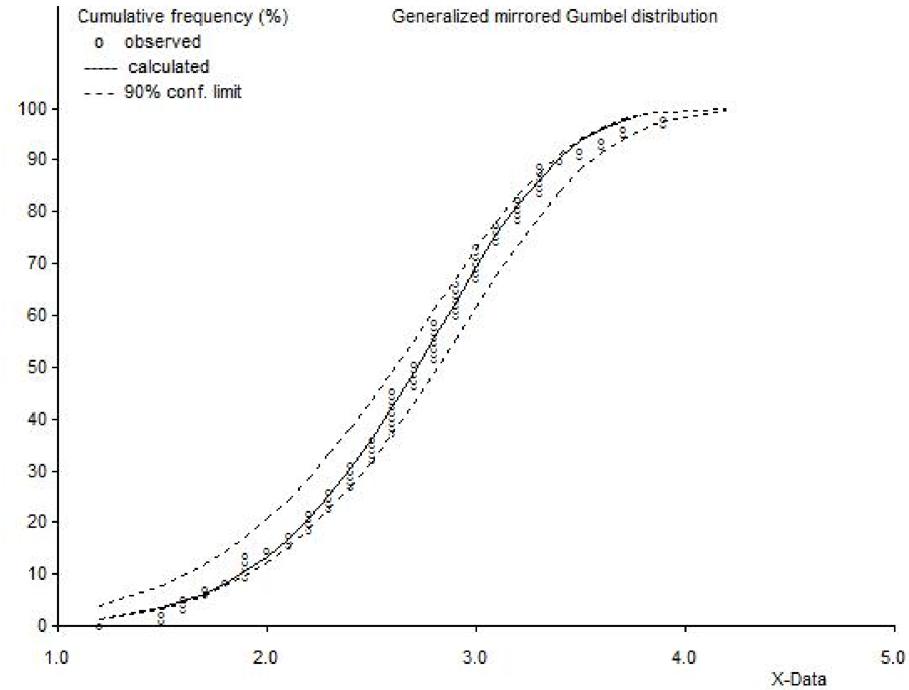

Figure 15. Cumulative frequency curve of Adama town's wind speed data

To make turbines operational throughout the year and each months, lowest possible recurrence periods wind speeds are more essential. According to the output of CumFeq, for 90% confidence limit of return period, the value of wind speed for 2, 3, 4 and 5 years return periods is illustrated in the table 4 below. CumFeq showed that there is no wind speed value for one year return period, and hence the minimum return period was 2 years.

Table 4: Wind speed value for different return periods

Return period	Lower limit (m/s)	Upper limit (m/s)	Cum. feq	Wind speed (m/s)
2 year	2.62	2.80	0.5	2.71
3 year	2.845	3.02	0.67	2.96
4 year	2.96	3.13	0.75	3.09
5 year	3.04	3.21	0.80	3.17

Moreover, the graph (figure 16) for return period indicated that high value of wind speed occurred for large return period and vice versa.

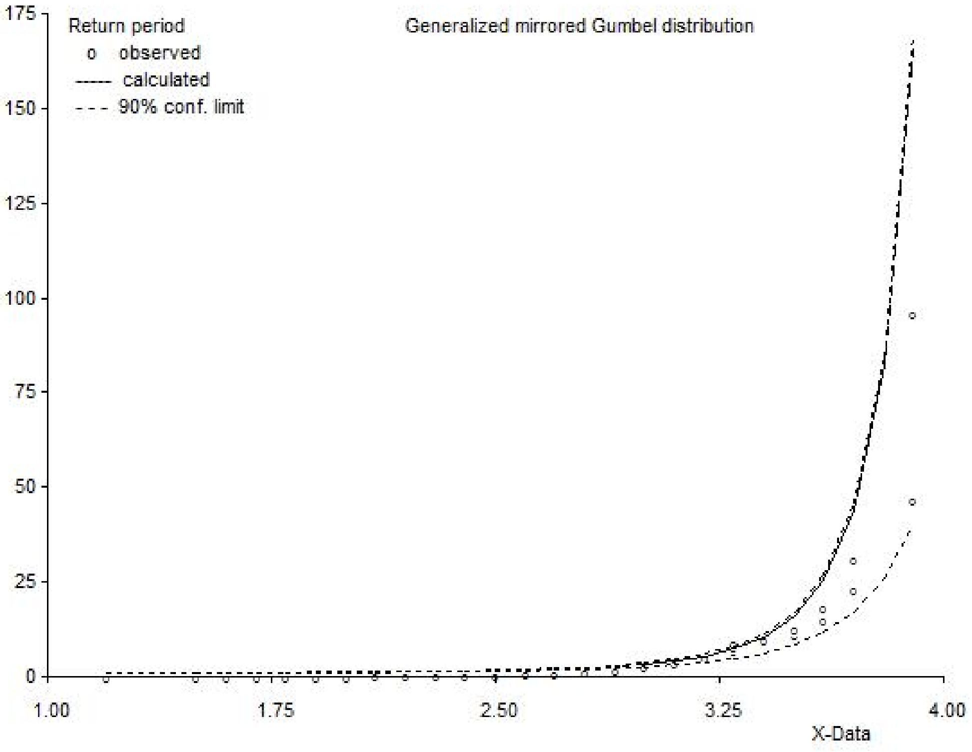

Figure 16: Graph of return period for wind speed.

Apart from cumulative frequency analysis of Adama town's wind speed, the number of days for a given wind speed occurs in a year was illustrated as shown in the graph below considering 14 years daily recorded wind data of the location.

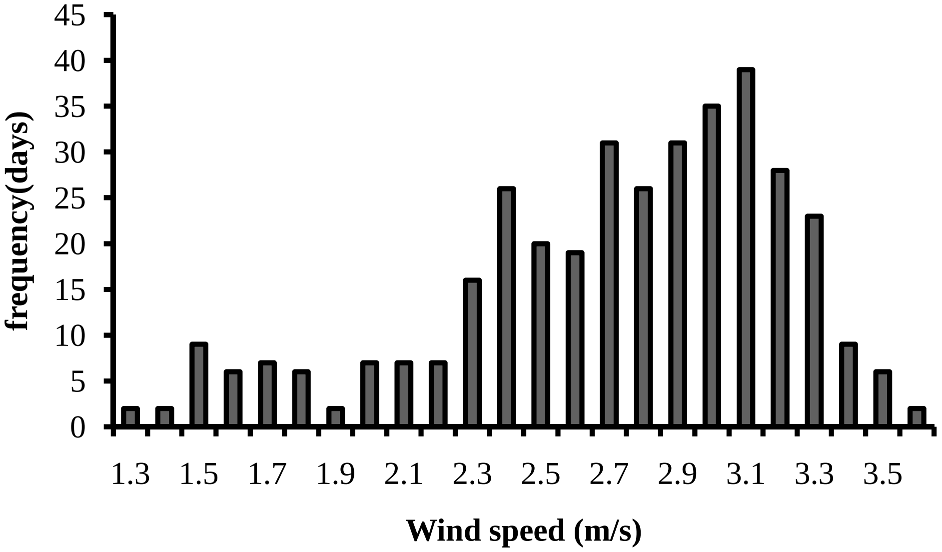

Figure 17. Occurrence of different wind speed in a year for Adama town

From, the graph above (figure 17) and analysis of recurrence time in a year, wind speed 2.67m/s, 3m/s and 3.1m/s where it can occur for 230, 142 and 107 days in a year respectively were considered for the design aspect. Moreover, these wind speed values are more or less close to 2, 3 and 4 years return periods wind speed values respectively.

4.1.2. Interpolation of recorded wind speed

During the 7 days testing the turbines, the corresponding estimated wind speed data recorded at Adama Meteorological office for that particular time is illustrated in the table below (measured at 1650m a.s.l). Accordingly, using equation 14 the wind speed which acts on the turbines at turbine height (1684m a.s.l) for n=0.3 was computed as depicted in the table 5 below.

Table 5: Recorded and interpolated wind speed during experiment

Trials	Recorded wind speed (m/s) at 1650m a.s.l	Interpolated wind speed value (m/s) at 1684m a.s.l
1	3.03	3.05
2	2.86	2.88
3	2.47	2.49
4	3.10	3.12
5	2.58	2.60
6	2.89	2.91
7	3.75	3.77

To compare and contrast the wind speed for different recurrence periods and recorded wind speeds during the experiment, the wind speeds for the different return periods were interpolated for 1684m elevation where the turbines are installed (eqn 12). Consequently, the interpolated wind speed values for 2, 3, 4 and 5 years return periods are 2.73m/s, 2.98m/s, 3.11m/s and 3.19m/s respectively. As shown in the table 5 above, except the wind speeds in third trial and 7 trial, the rest of recorded wind speeds are within the range of wind speeds for recurrence period 2-5 years.

4.2. Water pump selection

The result of the respondents to the questionnaire showed that considering the requirement of the pump for small scale purpose, power required, economy and maintenance cost in general for water lifting, particularly using savonius wind turbine, rope and washer pump was found more compatible. Moreover, the production of this pump is so easy. Specifically, according to AG water solutions (2011), the initial investment and maintenance cost of rope and washer pump is remarkably the lowest among the different water lifting devices.

Rope and washer pumps are manufactured locally, and also operation and maintenance for the pumps is low in comparison with other low cost hand pumps. Moreover, due to the simplicity of the pump design, it can be done by the users themselves, with the few repairs and spare parts available from the local private sector (IRC, 1995) as cited by Hughes et al., (2004).

According to Lambert and Faulkner (1991), rope and washer pump is cheap, easy to make, operate and repair. Moreover, it performs better than more expensive and sophisticated pumps and is suitable for both micro-irrigation and domestic use.

It is generally accepted that the rope-pump has a number of advantages over conventional hand pumps in terms of significantly lower initial cost, increased ease of local fabrication and manufacture, increased ease and lower cost of maintenance and repair (requiring no specialist skills or equipment), lack of reliance on imported specialist components and higher delivery discharge rates (Harvey and Drouin,2006).

Furthermore, Williams et al., (2011) stated that the hand powered rope-pump has been highly successful across Africa and South America mainly due to attributes such as a high achievable head, low starting torque, low installation cost, ease of manufacture and minimal maintenance. These attributes identify the rope-pump as the most appropriate type of pump for automation, providing the remaining system components for automation still allow water to be delivered reliably at low cost.

4.3.Turbine design

Basic requirements such as required discharge and ease of manufacturing to determine the dimension of the turbines were primarily taken into consideration as discussion in sections below.

4.3.1. Turbine diameter

In the theoretical or mathematical approach to determine fundamental dimensions of the turbine specifically diameter, power coefficient (Cp) of savonius wind turbine was estimated based on the finding of Óskarsdóttir (2014) and Ajayi (2012). According to Óskarsdóttir (2014), for horizontal axis wind turbine type the optimum Cp value is 0.3. However, on other hand other studies, Ajayi (2012) revealed that the maximum Cp value of savonius wind turbine is less than 0.2 and hence since this value is the maximum value that can be attained by these turbines, Cp value of 0.2 was considered to compute the swept area of the turbine.

Regarding water supply and community size, Rajagopalan (1996) illustrated that for community water supply (500 persons), the required discharge is 20m^3/day (0.23liters/s). Considering 7m pumping head and mean daily wind speed for Adama 2.67m/s, the power required to pump water was computed (eqn..) as depicted in the table below. Consequently, swept area or rotor area of the turbine computed from pumping power and wind power illustrated in the table 6 below.

In addition, swept areas of the turbine for different discharges (for 75%, 50% and 20% of the above discharge) for the same aforementioned head (7m) were estimated as illustrated below (table 6). The selection of the largest turbine diameter was executed relying on the analysis made in the table below apart from criteria set for selection in terms of manufacturing and cost.

Table 6.Estimating diameter of the largest turbine.

No	**Discharge (lit/s)**	**Swept area (m^2)**	**Pumping power required (watt)**	**Number of persons (community size)**	**Diameter of savonius for 1m turbine height**
1	0.23lit/s	6.75	15.79	500	6.75
2	0.175lit/s	5.14	12.02	375	5.14
3	0.115lit/s	3.37	7.90	250	3.37
4	0.046lit/s	1.35	3.16	100	1.35

Hence, the values of turbine dimension obtained from theoretical approach for 0.23lit/s and 0.17lit/s are relatively impractical in terms of installation, construction and cost for small scale purpose. Hence, a dimension for 100 person water supplies that is 0.046lit/s was found appropriate from the point of view of easy of manufacturing, installation and cost for small community size. Moreover, Smulders (1996) as cited by Gregory et al., (2013), a savonius wind turbine with diameter ranging from 2.5- 7 m can be used to discharge 20m^3/day (almost for 500 head) and lift water from deep wells (>30m). Hence, 20% of this recommended turbine size becomes 0.5-1.4m or 0.5-1.4m^2 swept area for 1meter turbine height. However, this turbine dimension is for deep wells (head >30m), and thus in this experiment where it was set to pump water for 7m head, the turbine size can be even less than the above range.

Thus, mathematically, taking into account estimation of turbine diameter discussed above (table 7), by assuming the first two largest turbines to discharge 0.046lit/s (for 100 people) and the rest two smallest turbines to discharge 0.023lit/s (for 50 people), the swept area of each turbine was estimated as follows.

Table 7.Computed swept area of the turbines

Discharge (m^3/s)	**Wind speed (m/s)**	**Pumping head (m)**	**Pumping power (Watt)**	**Computed turbine swept area (m^2)**	**Number of days the turbine can operate in a year**
0.000046	2.67	7	3.2	1.3	230
0.000046	3	7	3.2	0.95 (app. 1m)	142
0.000023	2.67	7	1.6	0.7	230
0.000023	3.1	7	1.6	0.4	107

The table 7 above showed that the first turbine with estimated swept area 1.3m^2 can have the capacity to discharge water (0.046lit/s) which can serve 100 people for a wind speed 2.67m/s and above which occurs for 230 days, accordingly the turbine can operate the pump for 230 days in a year. The second turbine with swept area 1m^2 could discharge 0.046lit/s which is estimated to serve 100 people for a wind speed of 3m/s and above for 142 days in a year. Similarly the third and forth turbines with swept area 0.7m^2 and 0.4m^2 each can discharge 0.023lit/s (to serve 50 people) for a wind speed of 2.67m/s and 3.1m/s for 230 and 107 days in a year respectively.

On the other hand, according a research conducted in Kenya by Rabah and Osawa (1995), a swept area of savonius turbine 0.95m is capable to operate water pump at 2m height. Hence, from the theoretical approach (mathematical method) and previous studies as discussed above, for 7m head and to discharge the above selected amount (0.046lit/s and 0.023lit/s) for different community sizes, for this experiment four savonius wind turbines rotor diameter (D) 0.4m, 0.7m, 1m and 1.3m were selected.

4.3.2. Turbine overlap, aspect ratio and end gap

The study conducted by Patel et al., (2013) illustrated that for different overlap ratios of values 0.0, 0.1 0.2; the overlap ratio with value β=0.2 yields high power. According Menet & Bourabaa (2012) as cited by Gregory et al., (2013), the optimal overlap ratio was 0.242. Therefore, considering an overlap ratio of 0.2 is permissible.

As discussed above, given overlap ratio 0.2, shaft diameter 500mm, turbine diameter mentioned above (0.4m, 0.7m, 1m and 1.3m), the overlap (e) was computed using equation 9 and the result is summarized in the table below including the rest of basic turbine dimensions. Thus, end plate diameter, overlap, diameter of each rotor and end gap of each turbines were determined as depicted in the table 7 below.

Table 8. Basic dimension of the turbines

Turbine rotor dia.(mm)	**overlap ratio**	**overlap (e)**	**Each rotor dia (mm)**	**End gap (mm)**	**End plate diameter (mm)**	**Turbine height (mm)**	**Aspect ratio (h/D)**
400	0.2	130	265	20	440	1000	2.5
700	0.2	190	445	35	770	1000	1.4
1000	0.2	250	625	50	1100	1000	1
1300	0.2	310	805	65	1430	1000	0.8

4.4.Evaluation of turbines output

In this experiment, except the largest turbine, the rest of three turbines could not pump water, despite the fact that the second largest turbine rotated without pumping water for some of the trials where the wind speed was relatively peak (highest value). Moreover, little rotation of the rest of turbines for short period of time was observed in this experiment. Hence, this is clear indication how the size of savonius turbine affect pumping capacity. Nevertheless, in some days, where the wind speed had been very high during night time, discharge from the two smallest turbines was also observed. In this case, since the measurement of wind speed at Adama Meterologicala station is conducted staring from 6:00AM (morning) until 6:00PM (evening), it became difficult to estimate at what peak wind speed the two smallest turbines capable to pump water or operate the rope and washer pump. Hence, the basic outputs, particularly for the largest turbine which could help to estimate the performance were discussed in the sections below.

4.4.1. Power coefficient, Pumping power and tip speed ratio of the turbine

Since only the largest turbine with rotor area 1.3m^2 is capable to discharge water for certain recorded wind speeds, power coefficient and pumping power were estimated and analyzed as discuss below for this specific turbine only. Nevertheless, for the second largest turbine, for some wind speeds (>3m/s), without pumping water, the turbine was rotating slowly and hence, the analysis of tip speed ratio was carried for these two turbines as discussed in section below.

4.4.1.1. Power coefficient of the turbine

The power coefficients of the largest turbine for different wind speeds were computed as shown in the table 9.According to the computed Cp, the average Cp of the turbine is 0.07 (7%), however, some trials it has been observed that the value of Cp is as low as 4% and as high as 9%. Power loss in power transmission or bevel gears (poor gear meshing), poor manufacturing of the pump, gear reduction and lack of hourly wind speed data might be considered as main reasons for low Cp value.

However, according to Óskarsdóttir (2014), the efficiency of a Savonius turbine is poor and has very limited power outputs but its advantage is that is reliable and can be maintained rather easily. Large Savonius turbines that have high efficiency need a lot of material, making them unfeasible when it comes to being cost-effective over the long run. According to this author, the savonius has the lowest power coefficient of up to 0.3 and it operates only over a specified blade tip-speed-towind speed ratio of 0.8 to 0.85. For this reason, the Savonius rotor is only cost-effective where not much power is needed, for example for water pumping or driving a small generator.

Table 9. Power coefficient of the largest turbine

Recorded Wind speed (m/s) (1650m a.s.l)	**Interpolated wind speed (m/s) (1680m a.s.l)**	**Pumping power (watts)**	**Computed Cp**
3.03	3.05	2.06	9%
2.86	2.88	1.55	7%
2.47	2.49	0.43	3%
3.10	3.12	2.29	9%
2.58	2.60	0.57	4%
2.89	2.91	1.72	8%
3.75	3.77	3.72	9%

From the experiment conducted for 7 days for different wind speeds as illustrated above the average Cp value of the turbine is 7% which was used to determine the turbine power.

On the other hand, the analysis of Cp trend with respect wind speed as shown in the figure 18 the Cp value of the turbine had been increasing with certain wind speed value and later it seems constant for relatively highest wind speed values. The study conducted by Robin et al., (2017) indicated that the power coefficient of a turbine increases with the increase in wind speed up to certain levels where the Cp becomes maximum and then starts to decline. Moreover, experiment conducted by Qasim et al. (2012); Azevedo and Mendonça (2015); Mahmoud et al., (2012); Jang et al., (2019); Kavade and Ghanegaonkar (201&) showed that the Cp of a turbine increases with wind speed up to certain level of wind speed.

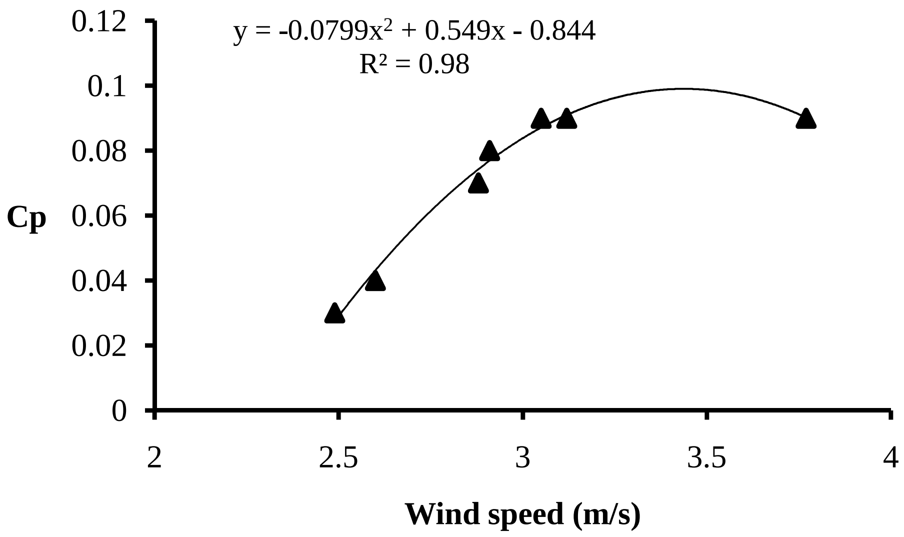

Figure 18.The effect of wind speed on savonius turbine power coefficient

Hence, regression analysis (table 10) carried out to investigate the relationship between wind speed and power coefficient showed that 98% of the variation in Cp is attributed to wind speed and the rest 2% variation in Cp value is attributed to other factors ($P<0.05$) such as precise measurements of wind speed, since the wind speed measurement was 3 hours average rather than hourly wind speed.

Table 10.Regression analysis wind speed and power coefficient

Regression Statistics	
Multiple R	0.993
R Square	0.986
Adjusted R Square	0.979
Standard Error	0.004
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.003746	0.001873	139.1558	0.000201
Residual	4	5.38E-05	1.35E-05		
Total	6	0.0038			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.8444	0.0783	-10.7808	0.0004	-1.0618	-0.6269	-1.0618	-0.6269
X Variable 1	-0.0799	0.0080	-9.9456	0.0006	-0.1021	-0.0576	-0.1021	-0.0576
X Variable 2	0.5490	0.0505	10.8712	0.0004	0.4088	0.6892	0.4088	0.6892

The analysis of variance (table 11) illustrated that turbine diameter or rotor diameter has significant effect ($P<0.05$) on Cp value of the turbine. For turbine diameter less than 1m or rotor area $1m^2$ the Cp of the turbine is zero since there was no recorded discharge whereas for turbine diameter 1.3m or rotor diameter $1.3m^2$ the average Cp of the turbine value is 0.07. on the other, despite there was an increase in Cp for the increase in wind speed, the analysis of variance showed that the change in Cp value due to change in wind speed is less significant (P,0.05).

Table 11. ANOVA table of the effect of turbine diameter and wind speed on Cp

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Diameter	0.027868	3	0.009289	53.81379	3.46E-09	3.159908
Wind speed	0.001036	6	0.000173	1	0.455201	2.661305
Error	0.003107	18	0.000173			
Total	0.032011	27				

4.4.1.2. The effect of turbine size and wind speed on pumping power

The two-way analysis of variance showed that there is significant difference among turbines ($P<0.05$) where the pumping power is the highest for the largest turbine whereas the variation of pumping power for different recorded wind speeds is less significant (table 12). Moreover, the pumping power of the largest with rotor area of the turbine $1.3m^2$ is as low as 0.43watts and as high as 3.72watts for lowest and highest wind speeds respectively.

Table 12. ANOVA table of the effect of turbine size and wind speed on pumping power

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	15.229	3	5.076	16.028	2.53E-05	3.160
Columns	1.900	6	0.317	1	0.455	2.661
Error	5.701	18	0.317			
Total	22.830	27				

The analysis of regression ($P<0.05$) to correlate the pumping power and wind speed showed that 98.7% of the variation of the pumping power is attributed to change in wind speed (table 12). The analysis depicted that pumping power increases with the increase in wind speed. Accordingly, the pumping power of the turbine is expressed as natural logarithmic function of wind speed as illustrated in the figure 19 below.

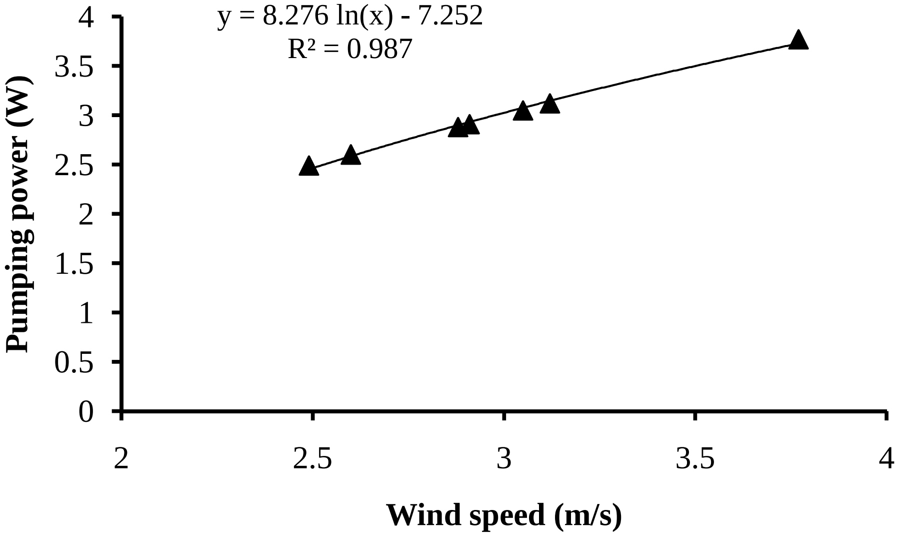

Figure 19.The effect of wind speed on pumping power

In this experiment, the highest computed pumping power was 3.72watts and the minimum was 0.43watts, however, according to Nederstigt and van der Wal(2011) , the power required for rope and washer pump is 50watt. Such power might be necessary to pump water from deep wells, specifically according to Mohamed (2019) indicated that rope and washer pump has the capacity to discharge water from 40m deep wells. Thus, in this experiment with very low pumping power, notably low discharge was obtained which might be not only due to notably low pumping power but also low pumping head. As discussed above (section 4.3.1.1) power loss in power transmission or bevel gears (poor gear meshing), poor manufacturing of the pump, gear reduction and lack of hourly wind speed data might be considered as main reasons for low Cp value consequently low pumping power.

Thus, for existing experimental set up (for largest turbine with rotor area $1.3m^2$) through reducing loss in rotating part of the system, improving bevel gear meshing, exact wind recorded wind speed and rather than gear reduction use of pump shaft speed multiplication might be considered as means to obtain the required and recommended (50watts) pumping power for rope and washer pump.

4.4.1.3. The effect of turbine size and wind speed on tip speed ratio

Since the two larger turbines were seen to rotate despite the second largest turbine could not pump water, their speeds for a given trail period was used to determine the tip speed ratio (equation 4). The tip speed ratio of the two turbines at different trails is explained in the table 13 below.

Table 13. Tip speed ratio of the turbines

Trials	Wind speed (m/s) at turbine height (1684m a.s.l)	Speed of turbine 1 (radius.) [m/s]	Speed of turbine2 (dia.) [m/s]	Tip speed ratio of turbine-1	Tip speed ratio of turbine-2
1	3.05	2.9	-	0.95	-
2	2.88	2.07	-	0.72	-
3	2.49	1.92	-	0.77	-
4	3.12	4	1.44	1.28	0.46
5	2.60	2.38	-	0.92	-
6	2.91	2.32	-	0.80	-
7	3.77	6.95	1.57	1.84	0.42

The average tip speed ratio of the largest turbine which is capable to pump during these trials is 1.04. On the other hand, the computed tip speed ratios of the turbines (0.72-1.84) are within the range stated by Eddahmani (2017) for savonius wind turbine.

The two-way analysis of variance showed (table 14) that the variation in tip speed ratio of the turbines for different recorded wind speeds is less significant ($P<0.05$); whereas, the variation in tip speed ratio among the turbines is significant.

Table 14 .ANOVA table of the effect of turbine size and wind speed on tip speed ratio

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	5.710	3	1.903	61.349	1.19E-09	3.160
Columns	0.186	6	0.031	1	0.455	2.661
Error	0.558	18	0.031			
Total	6.454	27				

Regression analysis of wind speed versus tip speed ratio (table 15) depicted that 91.6% of the variation in tip speed ratio is attributed to wind speed ($P<0.05$).

Table 15. Regression analysis of wind speed and tip speed ratio

Regression Statistics	
Multiple R	0.936
R Square	0.877
Adjusted R Square	0.815
Standard Error	0.180
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.919	0.459	14.215	0.015
Residual	4	0.129	0.032		
Total	6	1.048			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1.646	1.104	1.492	0.210	-1.418	4.710
X Variable 1	1.411	1.918	0.735	0.503	-3.916	6.737
X Variable 2	-0.120	0.761	-0.158	0.882	-2.234	1.994

Accordingly, as in the figure 20, tip speed ratio of the largest turbine increased quadratically with the increase in wind speed.

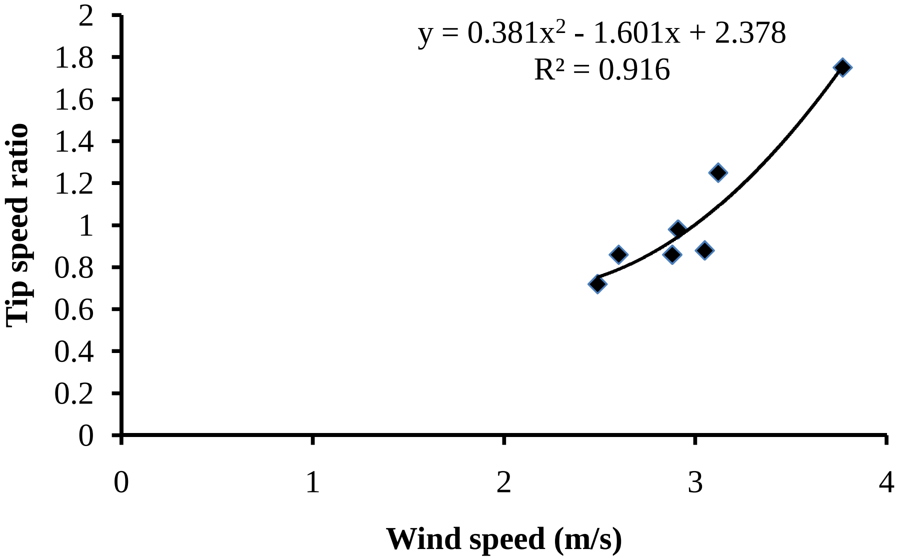

Figure 20. The effect of wind speed on tip speed ratio

4.4.2. Discharge and RPM of the turbine

Discharge is one the main performance criteria to evaluate the turbines where it depends on turbine size, wind speed and which in turn RPM of the driving wheel or RPM of the turbine as discussed in the sections below.

4.4.2.1. The effect of wind speed on discharge

The turbine has various capacities to discharge water for a total head of 7m (suction head of 4 m and discharge head 3m). Testing of each turbine for pumping at different time indicated that except the largest turbine the rest of the turbine could not discharge water. Turbine size had significantly different effect ($P<0.05$) on discharge of water (table 16). On the other hand, wind speed has less significant effect ($P<0.05$) on discharge by the largest turbine.

The discharge obtained from the largest turbine is 0.036 lit/s for the highest recorded wind speed and 0.004lit/s for low recorded wind speed.

Table 16 .ANOVA table of the effect of turbine size and wind speed on discharge

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	0.0014	3	0.0005	16.0276	2.53E-05	3.160
Columns	0.0002	6	2.99E-05	1	0.455	2.661
Error	0.0005	18	2.99E-05			
Total	0.002152	27				

The discharge obtained by the largest turbine is considerable lower than that of expected during turbine design and selection. For instance, during turbine design phase for wind speed 2.67m/s the expected discharge was 0.046 lit/s. However, for relatively similar wind speed (2.6 m/s), the actual discharge obtained from the turbine was 0.006lit/s. That means, it is almost 12% of the expected discharge or this discharge rather than serving 100 people, it can serve up to 12 people only. The main reason for such low discharge might be gear ratio (reduced pump shaft speed), loss in gears (poor meshing) and poor manufacturing features of the pump specifically the wheel and its support which was modified from human driven to wind turbine driven system.

On the other hand, the turbine's discharge output for the highest recorded wind speed (3.75m/s) is 0.036 lit/s. This discharge again 79% lower than the expected discharge from the system for wind speed of 2.67m/s or it can serve only 78 people for 230 days in a year.

As discussed above, in addition to the reasons mentioned above for low output, such low discharge output might be due to wind speed recording or availability from Adama meteorological office is 3 hours average within 3 hours intervals only during day time and thus the natural wind speed variation cannot be controlled during the experiment. Moreover, the other experimental site is full of tall grass, vegetation and nearby buildings near the experimental site can be hampering to obtain the recorded wind speed from the station. It is obvious that, according to recommended wind turbine installation site requirements, the site should be far from tall vegetation and buildings.

Regarding the trend of the discharge with respect to wind speed, it has been observed that the discharge obtained increased with the increase in wind speed as shown in the figure 21 below

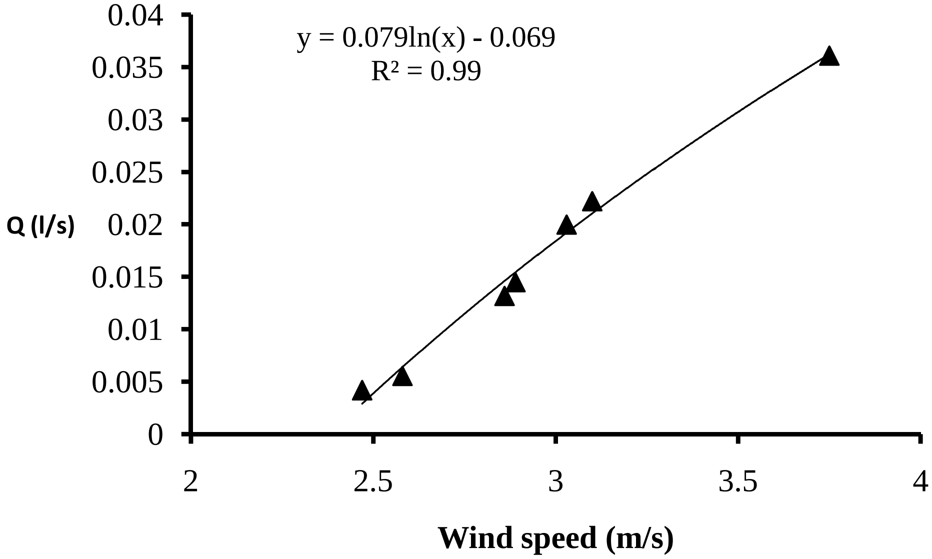

Figure 21.The effect of wind speed on discharge

Moreover, the regression analysis (table 17) which was carried out to correlate wind speed and discharge depicted that 98.9% variation of the discharge is attributed to wind speed ($P<0.05$). The graph discharge versus wind speed showed that the discharge is a natural logarithmic function of wind speed.

In other word, taking into account low discharge of the turbine of the reasons mentioned above, of the existing set up of the system, the regression analysis illustrated that the output of the turbine in terms of discharge is highly dependent on wind speed.

Table 17. Regression analysis of wind speed and discharge

Regression Statistics	
Multiple R	0.994964
R Square	0.989954
Adjusted R Square	0.987944
Standard Error	0.0012
Observations	7

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.000709	0.000709	492.6931	3.45E-06
Residual	5	7.2E-06	1.44E-06		
Total	6	0.000716			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.069	0.004	-17.798	0.000	-0.079	-0.059	-0.079	-0.059
X Variable 1	0.080	0.004	22.197	0.000	0.071	0.089	0.071	0.089

4.4.2.2. The effect of Wind speed and turbine size on turbines’ RPM

In this section, despite the second largest turbine (rotor area 1m^2) was observed to rotate without discharge for two recorded wind speeds (3.12m/s and 3.77m/s), the analysis of variance to study the effect of turbine size and wind speed on the turbines’ RPM was studied as discussed below.

According to ANOVA (table 18),

Table 18. ANOVA table of turbine size and wind speed effect on RPM

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	8876.176	3	2958.725	25.17845	1.16E-06	3.159908
Columns	1673.161	6	278.8602	2.373072	0.072523	2.661305
Error	2115.184	18	117.5102			
Total	12664.52	27				

Moreover, for the largest turbine, wind speed and the resulting RPM was correlated as shown in the table 19 below using regression analysis. It is obvious that with the increasing wind speed, the RPM of the turbine was increasing as shown in the figure 22.

Table 19. Regression analysis of wind speed and turbine RPM

Regression Statistics	
Multiple R	0.982
R Square	0.964
Adjusted R Square	0.957
Standard Error	2.999
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1203.92	1203.92	133.87	8.46E-05
Residual	5	44.96	8.99		
Total	6	1248.89			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-0.117	2.734	-0.043	0.967	-7.145	6.910	-7.145	6.910
X Variable 1	0.106	0.009	11.570	8.46E-05	0.083	0.130	0.083	0.130

The analysis regression showed that 85% variation in turbine's RPM is the due to wind speed and the rest 15% variation in RPM is attributed to other factors which affect RPM, such measurement error.

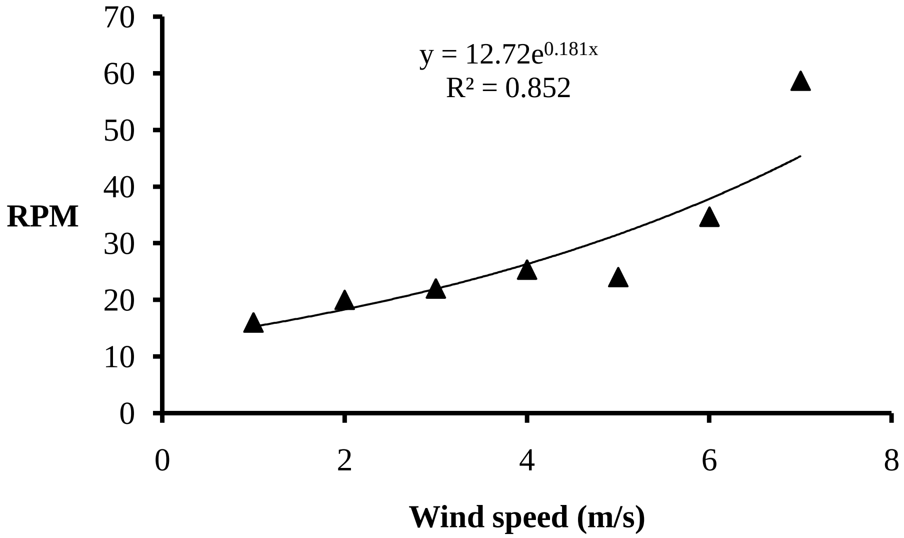

Figure 22. The effect of wind speed on RPM

4.4.2.3. The effect of RPM on discharge

In the section rather than considering the RPM of the shaft used to drive the pump, turbine's RPM was considered to analyze its effect on discharge.

According to the analysis of variance (table 20) showed that the variation of discharge due to RPM is less significant and whereas the variation in discharge due to turbine size is significant ($P<0.05$).

Table 20.ANOVA table of turbine size and RPM on discharge

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Rows	0.0014	3	0.0005	16.0276	2.53E-05	3.160
Columns	0.0002	6	2.99E-05	1	0.455	2.661
Error	0.0005	18	2.99E-05			
Total	0.002152	27				

The discharge obtained from the largest turbine was found increasing with increasing in RPM logarithmically as shown in figure 23.

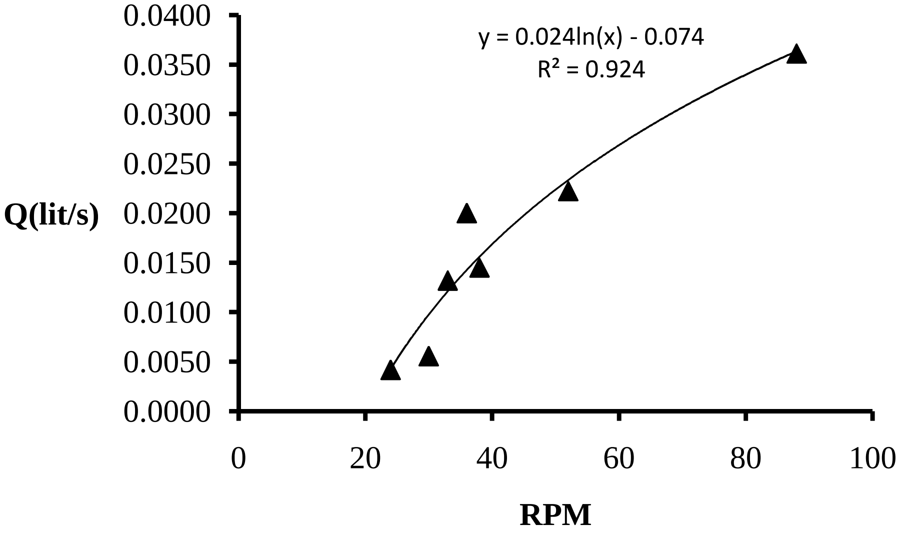

Figure 23.The effect of RPM on discharge

In addition, the analysis for regression (table 21) which was carried to study the relationship between RPM and discharge depicted that 92.4% variation in discharge is attributed to RPM and the rest nearly 8% variation in discharge is due to other affecting factors including measurement precision.

Table 21. Regression analysis of RPM and discharge

Regression Statistics	
Multiple R	0.961
R Square	0.924
Adjusted R Square	0.909
Standard Error	0.003
Observations	7

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0.0007	0.0007	60.9715	0.0006
Residual	5	5.43E-05	1.09E-05		
Total	6	0.00072			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-0.0743	0.0117	-6.3509	0.0014	-0.1044	-0.0442	-0.1044	-0.0442
X Variable 1	0.0247	0.0032	7.8084	0.0006	0.0166	0.0329	0.0166	0.0329

According to Lambert and Faulkner (1989) the preferred range of RPM for rope and washer pump is 30-50RPM. However, since gear reduction and poor meshing gears, the RPM of the shaft used to drive the pump is lower than the recommended and required RPM.

If poor gear meshing of the bevel gears which transmit power from the turbine to the pump shat disregarding, from gear ratio used in this experiment 15 to 10 (driving to driven), the RPM of the shaft becomes 16, 20, 22, 25.3, 24, 34.7 and 58.7 rev/min for recorded wind speeds 2.49m/s, 2.6m/s 2.88m/s, 2.91m/s 3.05, 3.12m/s and 3.77m/s respectively. Hence, the wheel of rope and washer pump was rotating with RPM nearly below the recommended values which results in poor discharge.

4.5.Predicting pumping power and discharge under different conditions

As discussed in the above sections, the effect of RPM on discharge and the effect of wind speed on pumping power and discharge were discussed through regression. Since wind speed varies with the surrounding surface conditions and height and consequently affects pumping power. Thus, probable pumping power for different turbine heights for different recurrence wind speed and the resulting discharge; and probable RPM through selected speed up gear ratio (2, 3 and 4 times) and the resulting discharge was discussed in the sections below.

4.5.1. Predicting pumping power and resulting discharge for different turbine heights

Assuming the average computed power coefficient of the largest turbine (0.07 or 7%) discussed above for the largest turbine, the power generated by the turbine for the selected wind speeds which were used for design purpose as discussed in section 4.2.1 (2.67, 3, 3.1m/s with occurrence days 230, 142 and 107 days per year respectively) was computed as shown in the table 22 below.

Table 22. Power of the wind for the largest turbine for different wind speeds at different heights.

Recurrence Period (days/year)	**Wind speed (m/s) at 4m height**	**Wind speed (m/s) at 8m height**	**Wind speed (m/s) at 10m turbine height (4m)**	**Expected pumping Power of wind for the largest turbine (Watt)**
107	3.1	3.1	3.1	2.6
142	3	3	3	2.3
230	2.67	2.67	2.67	1.6

Assuming the surrounding condition observed at this particular experimental site for surface condition (n), according to the table above, the wind speed at different turbine heights did not show significant difference and consequently on pumping power. Despite the for this experiment the turbine height was 3m, installation of the turbine up to 10m height could not produce considerable pumping power. Hence, the installation of the turbine at shortest tower height cannot be considered as main source of low pumping power.

4.5.2. Predicting discharge for gear ratios

One of the means to improve power is speed multiplication of the driven. Considering the above wind speeds (2.67, 3 and 3.1) and approximated respective recorded RPMs of the turbine for these wind speeds of this experiment, the probable discharge when the gear ratio of driving to driven or ratio of number of teeth of turbine shaft to pump driving shaft is 1.5 (reversing the existing set up gear assembly), 2 and 3 was analyzed as discussed below.

Table 23. Estimated RPM of the turbine for different gear ratio

Wind speed	**Recorded RPM of the turbine**	**RPM of the turbine 1.5 times (reverse the assembly)**	**RPM of the turbine (2 times)**	**RPM of turbine (3 times)**
2.67	30	45	60	90
3	36	54	72	108
3.1	52	78	104	156

As discussed in section 4.3.2.3 from turbine RPM versus discharge regression analysis, discharge is a natural logarithmic function of RPM. Thus, from the regression equation, it is possible to predict the discharge as illustrated in the table 24 below.

Table 24. Predicted discharge for different gear ratio for different recurrence wind speed of Adama

Wind speed	**Recorded Discharge**	**Discharge (1.5 times) [lit/s]**	**Discharge (2 times) [lit/s]**	**Discharge (3 times) [lit/s]**
2.67	0.0056	0.017	0.024	0.034
3	0.02	0.022	0.029	0.038
3.1	0.022	0.031	0.037	0.047

By using speed up gear ratio, for instance by reversing the existing gear ratio, it is possible to obtain 0.017, 0.022 and 0.031 lit/s for 230, 142 and 107 days in a year or this can serve 38, 47 and 66 people respectively. On the other hand if the speed of pump shaft it multiplied twice, the estimated discharge would be 0.024, 0.029 and 0.037 for 230, 142 and 107 days in a year or it can serve 53, 62 and 81 people respectively. With very high speed multiplication (three times), for 107 days, it is possible to discharge 0.047 lit/s which is even higher than the designed discharge of the turbine for 100 people that is 0.046lit/s. Thus, improvement on the existing coupling system of savonius wind turbine and rope and washer, specifically on gear system only would have the possibility to obtain the desired discharge.

5. Conclusion and Recommendation

5.1. Conclusion

The study can be considered as milestone as it showed hand operated rope and washer pump can be driven by savonius wind turbine with the necessary modification on the pump for coupling
In this study, it is observed that only the largest turbine with rotor diameter of 1.3m is capable to operate rope and washer pump. Thus, turbine size combined with wind speed affect the output of the pump.

The average power coefficient of the turbine was found to be 7% where the minimum and maximum Cps were observed for relatively minimum and maximum wind speeds. The minimum Cp value is due to loss in different parts of the system and precise measurement of wind speed data.

The study showed the maximum and minimum pumping power to discharge at 7m head (shallow wells) are 3.72 watts and 0.43watts. From the analysis conducted, for 7m pumping head, the average discharge of the turbine can approximately serve 36 people which is lower than the designed discharge (for 100 people).

The discharge from the rope and washer pump was found to be highly dependent on wind speed which in return RPM of the turbine. Thus, for the existing experimental set up, use of speed up gear ratio can improve the capacity of the turbine.

This technology would be more beneficial if there will be reservoir to store water during peak wind speed particularly during night time, apart from improvement on gear system and manufacturing modified pump. Hence, this could be insurance for water supply during low wind speed.

5.2.Recommendation

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To obtain more discharge either for such shallow wells or more depth, it is better to consider higher gear ratio between turbine shaft to pump driving shaft. Hence, reverse the gear ratio for the already installed turbines or even higher gear ratio than used ones and investigating every output could be considered as further research.

The experiment was conducted in area where there are obstacles for wind speed; hence, further research to determine best possible performance of savonius turbine for water pumping is very essential taking into account surrounding condition.

The study revealed that, manufacturing error or dissimilarity among the pumps was one of the challenges to come up with clear variation among the turbines. Hence, experiment with improved manufactured pumps would be essential.

In this study, it has been clearly seen that wind speed data during testing period was interpolated from 3 hours interval recorded data. Hence, detail investigation is very crucial with wind speed measurement conducted during the test. Moreover, further investigation on performance of each turbine is very essential in terms of wind speed throughout the year.

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Annex

Questionnaire

Adama Science and technology University

Evaluation of different water pumps

Objective of the study: to evaluate different locally available water pumps from economic, technical, environmental and cultural point of view.

Institution…………………………………………………………..

Respondent…………………………………………………………

Educational level……………………………………………….

1. *What type of water pump do you know/ have suitable to be operated by wind turbine?*
    a. *……………………………………*
    b. *……………………………………*
    c. *…………………………………..*
    d. *…………………………………..*
    e. *……………………………………*
2. *Are you manufacturing all or either of these pumps in industry or importing?*
    a. *Manufacturedlocally……………………………………………………………… ………………………………………………………………………………………*

b. Imported

………………………………………………………………………………………………..

3. How many water pumps you have distributed for the past 5 years? (for each type)

4. Who is you customer? (NGO, Farmers, GOV)

5. For the distributed water pumps water is their power source?

6. The discharge of the pump according to their increasing order

7. The head of the pump according to their increasing order. (keep uniform the power requirement)

8. Reply the following questions in relation to maintenance and technical training, put tick mark for your choice

1. Strongly agree 2. Agree 3. Disagree 4. Strongly Disagree

S/No	Activity	Pump_1	Pump_2	Pump_3	Pump_4	remark
1	The pump is suitable for lifting ground water for shallow depth					
2	The pump is suitable for lifting deep ground water					
3	The cost the pump is reasonable					
4	Running cost of the pump is high					
5	The pump needs different accessories					
6	The pump is easily manufactured locally					
7	The pump has different complex parts					
8	Training is necessary to operate and use the pump					
9	The maintenance of the pump is easy					
10	The pump can be maintained by local expert					
11	The spare parts needed for the pump are					

	readily available					
12	The pump can be operated by wind speed					
13	Attachment of the pump to wind turbine is simple					
14	The pump can be used for different locations (different wind speed)					
15	The pump provides high discharge					
16	The pump head is high					

Key:

1. *Pump-1= Rope and washer pump*
2. *Pump-2= Piston pump*
3. *Pump-3=centrifugal pump*
4. *Pump-4=gear pump*

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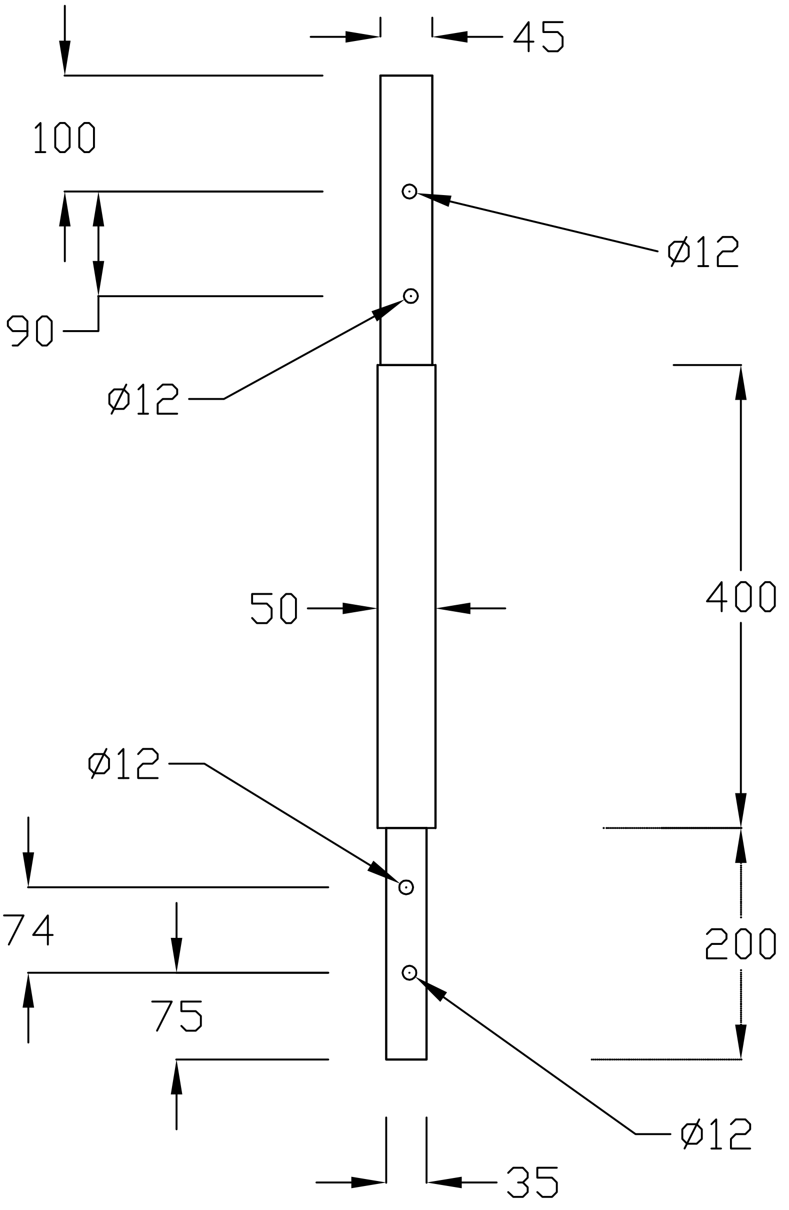

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Shaft design (unit in mm)

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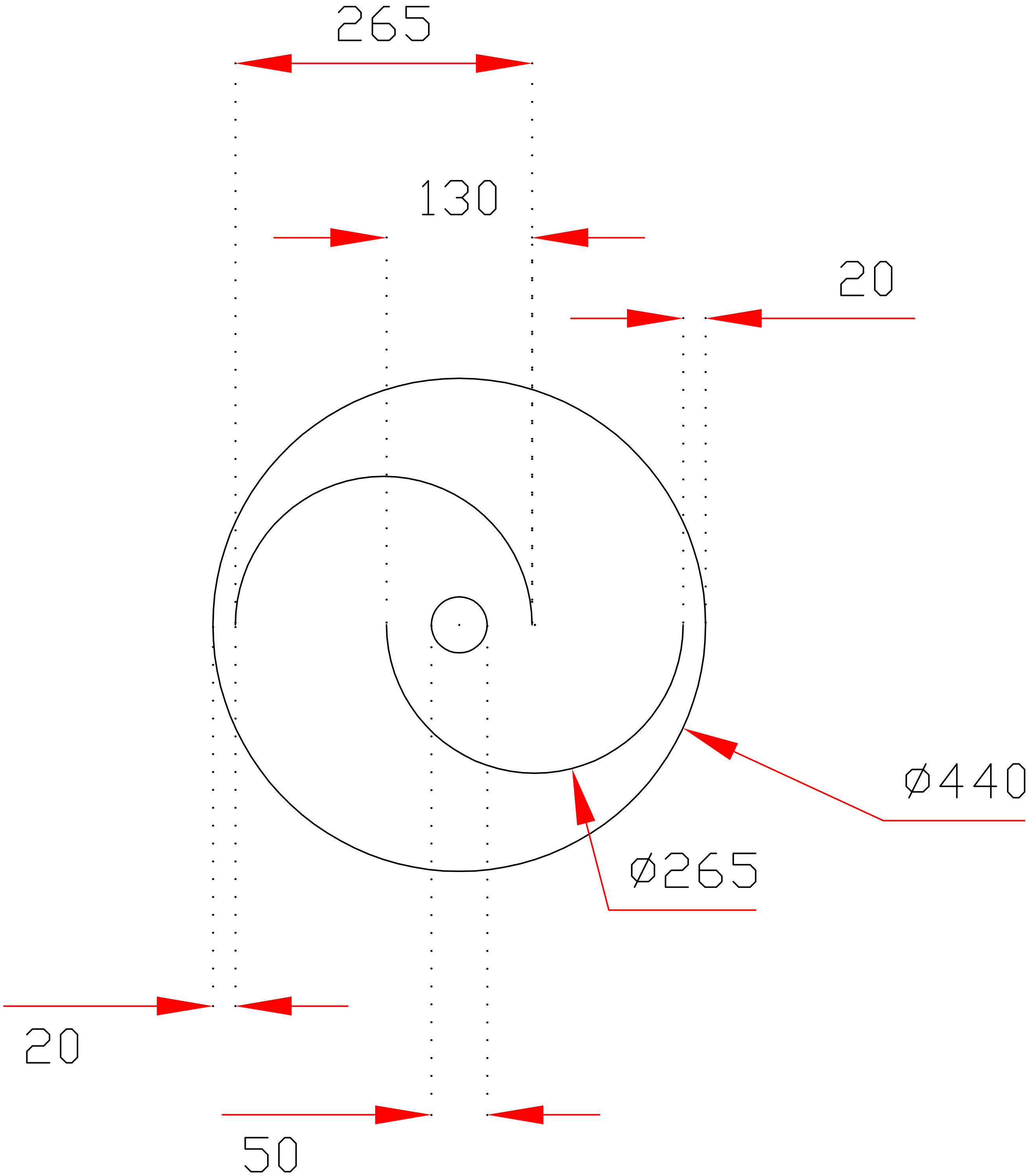

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Turbine__1 (mm)

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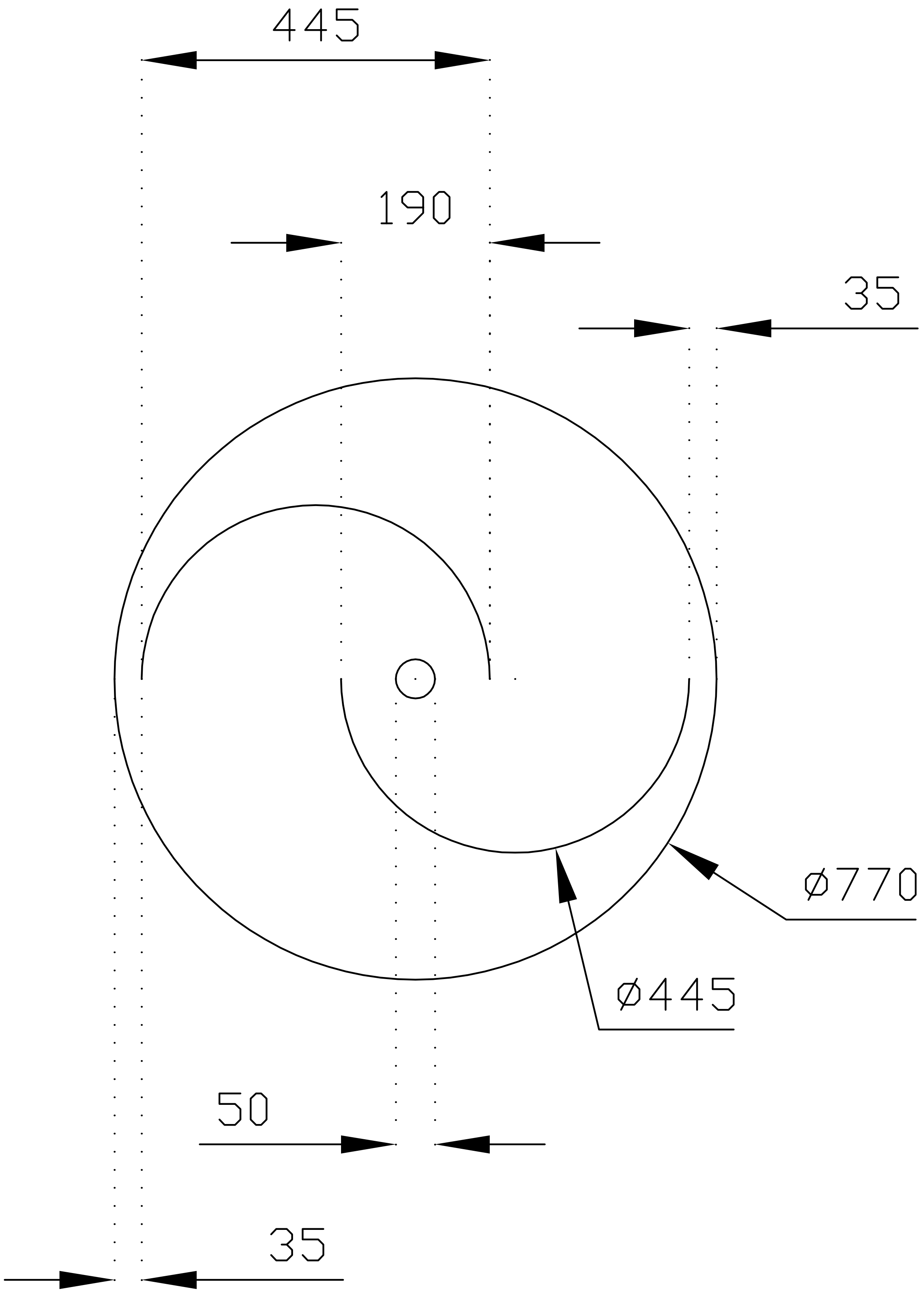

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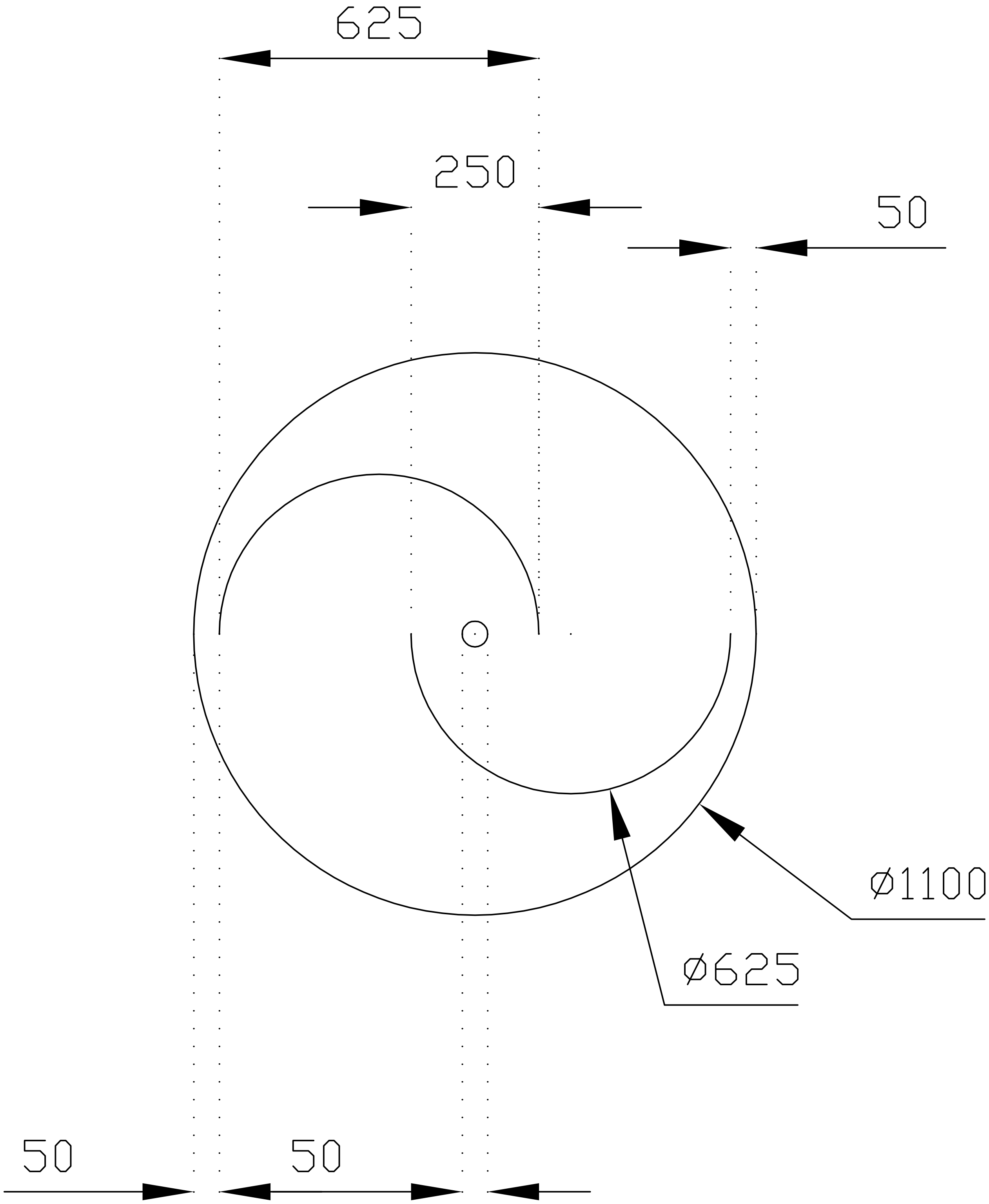

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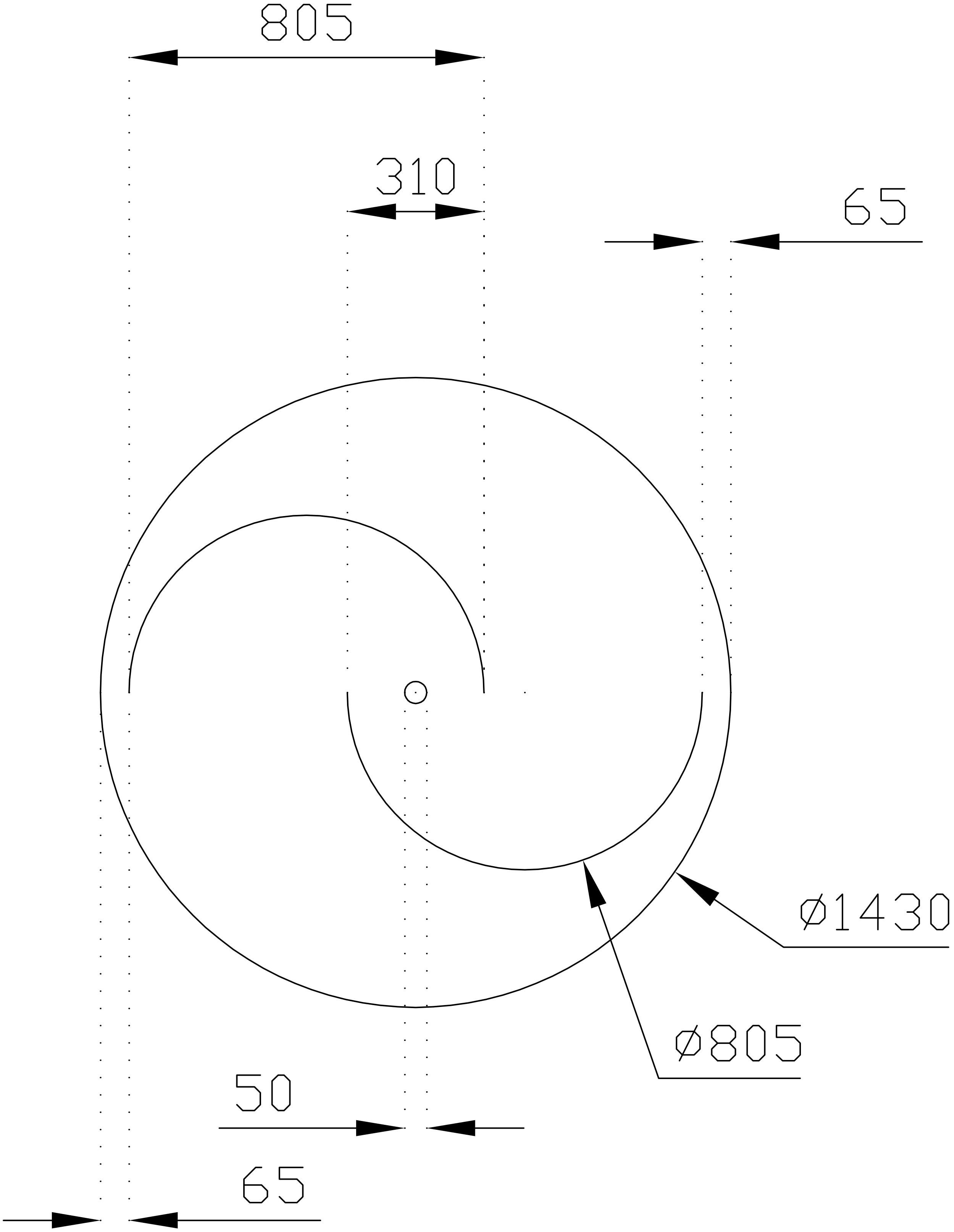

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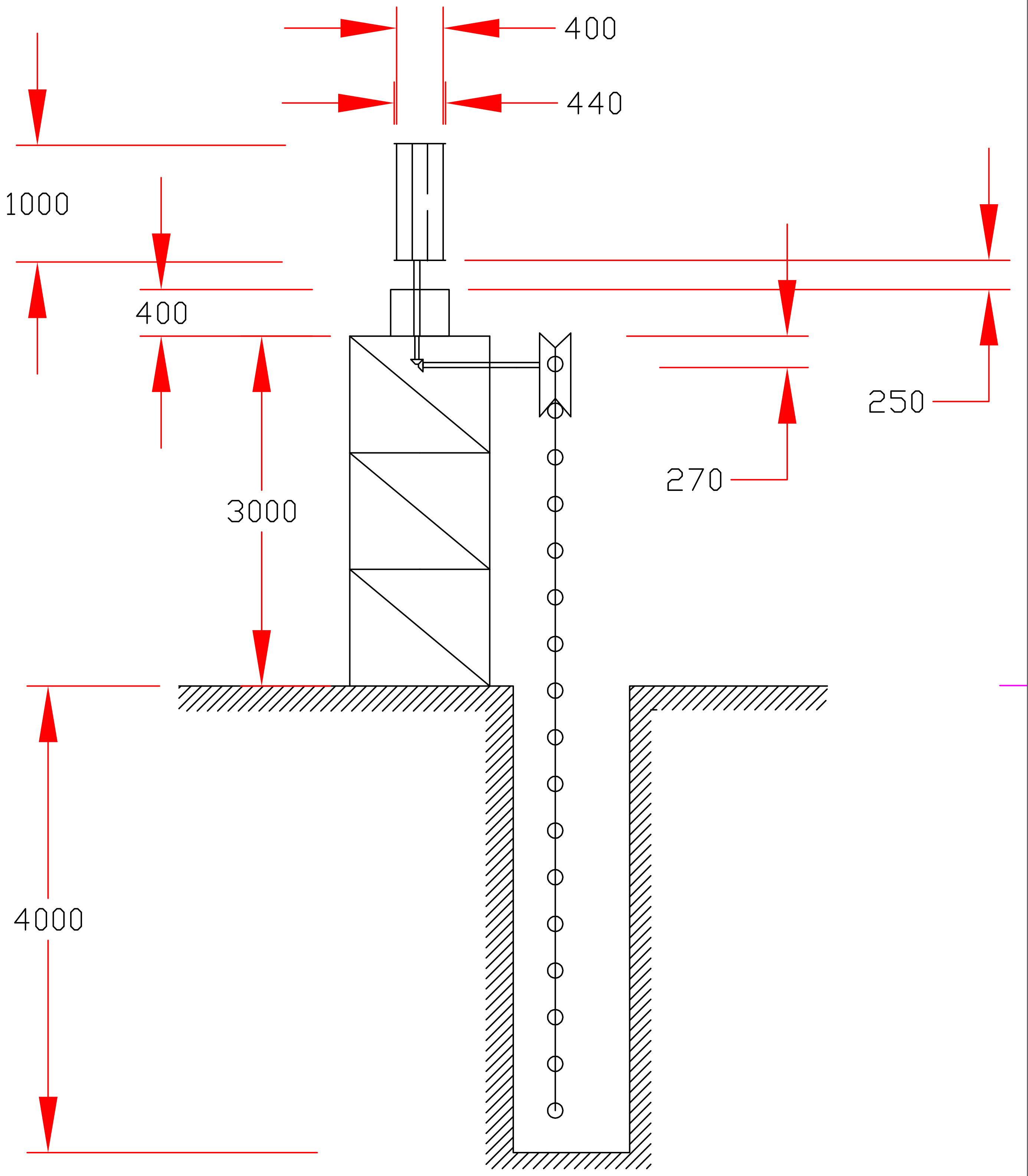

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Savonius turbine_1 (mm)

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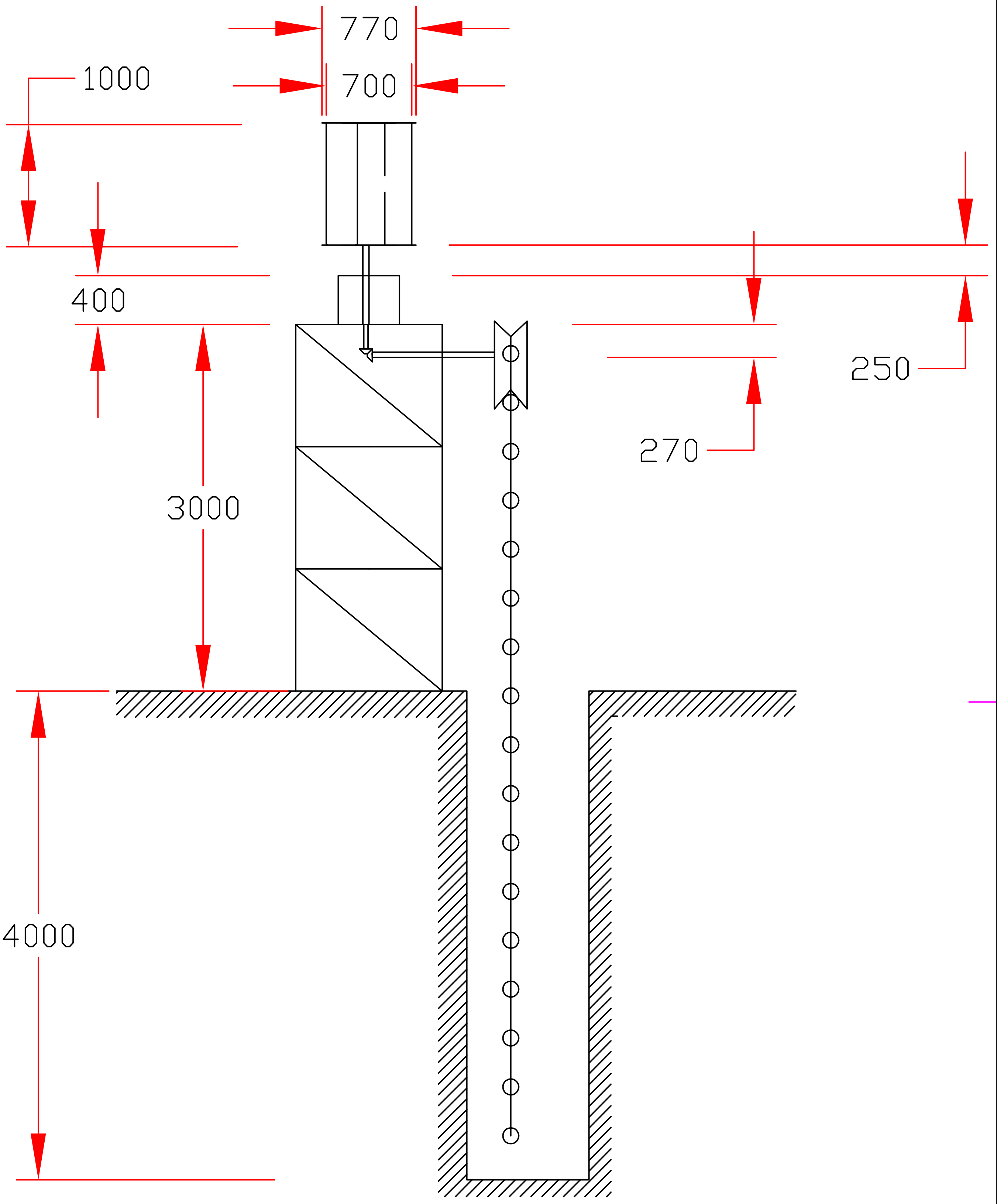

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Savonius Turbine_2 (mm)

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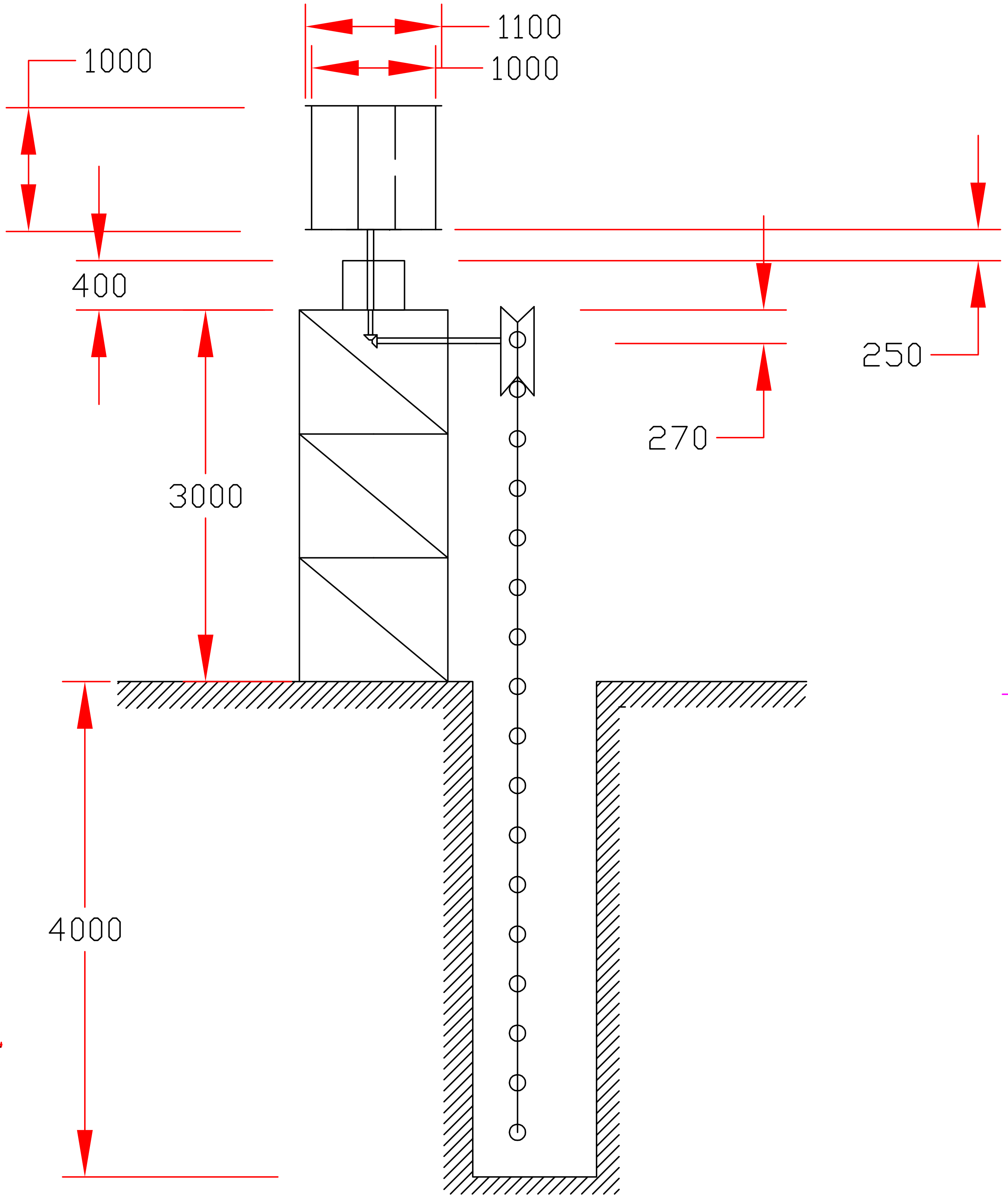

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Savonius turbine_3 (mm)

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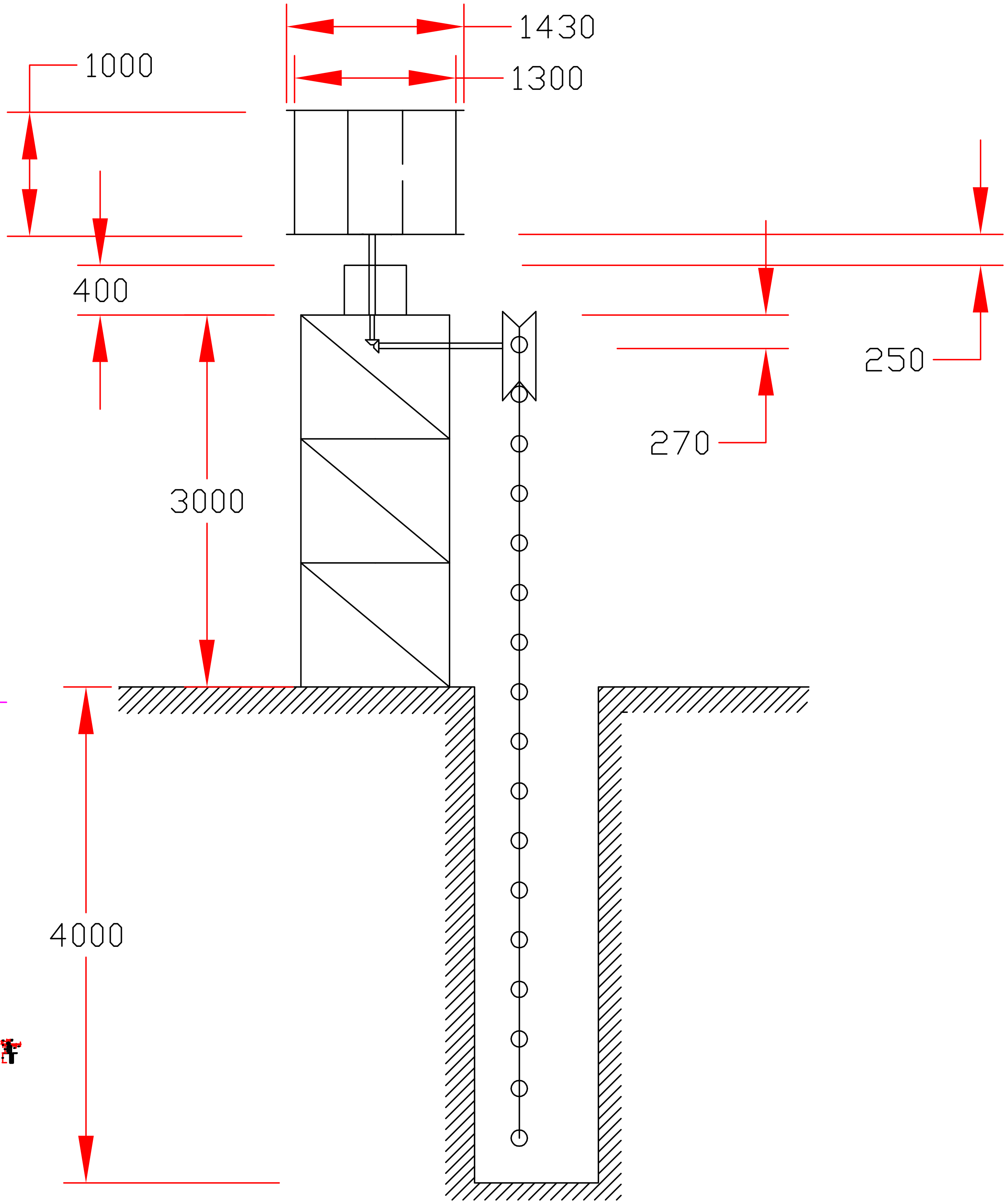

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Savonius Turbine_4 (mm)

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