JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

FACULITY OF MECHANICAL ENGINEERING

MSC. PROGRAM IN DESIGN OF MECHANICAL SYSTEM

Title: - Experimental Study on the Parameters Affecting the Performance of Spiral Tube Pump and Numerical Study on Different Water Wheel Paddle Shapes for Locally Developed Stream Powered Spiral Pump System

A thesis submitted to the School of Graduate Studies of Jimma University in partial fulfilment of the requirements for the degree of masters of Science in Mechanical System Design.

By Million Meseret

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Main Advisor: DR. Johnson S. (PHD)

Co- Advisor: Mr. Addisu K/Mariam (MSc.)

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Declaration

I hereby declare that this final thesis, titled "Experimental Study on the Parameters Affecting the Performance of Locally Developed Stream Powered Spiral Pump" is my original work and has not been submitted previously for a degree at any other university, and all source of materials used in this thesis are duly acknowledged.

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Co-Advisor	Addisu K/Mariam	______________________

Approved by Board of Examiners

	Name	Signature and Date
External Examiner	______________________	______________________
Internal Examiner	______________________	______________________
Chairman	______________________	______________________

Abstract

A stream powered spiral pump is a water pumping system that combines to old technologies; water wheel and spiral tube pump. It works based on cascaded manometer principle to pump a portion of water from a stream using the stream's kinetic energy, harnessed by the water wheel. As a result it is commonly categorized under manometric pumps. Mainly under this category there are two types of pumps; coil pump and the spiral pump. Spiral pumps are considered to be a gift from God, because it uses renewable energy source, it has zero emission and operation cost, and it can be manufactured and maintained by local craftsman using available materials. But the problem is because of the emergence of conventional pump it was not well studied so the understanding on this tech was limited. Therefore, this research project's general objective was to conduct an experimental study on the effect of important parameters on the performance of locally developed spiral pump system so that it can be readily design and applied for local irrigation work. In achieving this specific objectives the study were: to conduct a study on paddle shape of water to select the better; to conduct experimental study on the effect of submergence ratio, rotational speed, outer diameter and number of turns of the spiral tube pump; to compare the performance of coil pump and spiral pump; to optimize the parameters of the spiral pump system; and to clearly describe the design procedure of a spiral pump so that it can be readily developed. The study on paddle shape of the conducted numerically using SolidWorks flow simulation. The experimental study on the important parameters was conducted on Jimma Kito River. The comparison of the spiral and coil pump was done using analytical approach. Also the important parameters levels was optimized using Taguchi method. Finally understanding limitation was solved and then seven step design procedure was developed and stated clearly. Accordingly 22.5^0 slanted curved shape paddle found to be high velocity yielding for the spiral pump. Regarding to the important parameters submergence ratio and wheel speed mainly affects the pump discharge while the number of spiral turns mainly affects the head, and the outer diameter affects both. Also the coil pump will be better for the need of higher discharge and the spiral pump will give higher head for the same number of coils. Finally the important levels was given as factors for Taguchi method optimization using Minitab software, and pump running by 35 RPM, at 50% submergence, with 6 spiral turns and 1.5m outer diameter found to be the optimum, yielding 21 liters of water per minute to 4.1 meter head.

Keywords: Spiral pump, water wheel, Taguchi method, important parameters, design procedure

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Acronyms and Abbreviations

BCM	Billion cubic meter
HP	Pressure Head
QP	Pump Discharge
DOE	Design of Experiments
SP	Spiral Pump
CP	Coil Pump
H	Head
Q	Discharge
Do	Outer diameter
Dt	Tube diameter
SCP	Sum of coil pump
P	Power
N	Wheel Speed
A	Paddle cross sectional area
v	Speed
W	Agular speed
n	Number of spiral turns

1. Introduction

1.1. Background

Currently in Ethiopia realising food self-sufficiency and food security is a major concern and focus of governmental policies. In Ethiopia drought is recent history. More than ten million people are in need of assistance according to the Government and humanitarian agencies [1]. The majority of Ethiopia's people are agriculturalists, dependent on rain-fed crops or pastoralists, earning a living through livestock. However, recurrent droughts have eroded their assets: crops have failed and makes farmers too desperate to leave their land. Humanitarian organisations have realised that simply providing millions of tonnes of food aid every few year while life-saving in the short term is doing nothing to address the deeper causes of this chronic disaster [2]. It is must to alter the economy of the country from seasonal rainfall dependent agriculture to irrigation farming. For implementation of irrigation from small scale to large scale water pumping technologies are irreplaceable. There are many types of pumping system in conventional electric and fuel pumps, and non-conventional pumps categories. Among many types of non-conventional pumps of the spiral pump system is the one with greater potential for small-scale irrigation. It can help to alter the rainfall dependant agriculture to sustainably irrigation dependent one.

Spiral tube pump is an old technology created in 1746 by H.A. Wirtz in Zurich, Switzerland. It is incorporated with another ancient technology, water wheel to pump river water to small scale irrigation fields. Spiral tubes pressurizes the water from river to lift it to some head while the water wheel converts the kinetic energy of the river to mechanical energy of rotation that is need by the spiral tube. This pumping system uses no fuel or any other electrical energy sources. And it can be easily manufactured with locally available materials by local craftsman. However it output is not as much as the conventional electric and gasoline pumps so that it is not preferred to large irrigations. Because of this it was not research area for many years in developed countries. So there is few literature regarding to its performance and other matters of spiral pumps. But for developing countries with high river water positional such as Ethiopia has more than adequate reason to examine and study the potential of spiral pump and other similar pump systems.

Ethiopia is resourceful with renewable surface and ground freshwater. According to the current knowledge, the country has about 124.4 billion cubic meter (BCM) river water, 70 BCM lake water, and 30 BCM groundwater resources. It has a potential to develop 3.8 million ha of irrigation and 45,000 MW hydropower production (Berhanu, 2014). Ethiopia manages its surface water through 12 basins, incudes Abbay, Awash, Baro- Akobo, Genale-Dawa, Mereb, Omo- Ghibe, Rift Vally, Tekeze, Wabi Shebele, Dankil, Ogaden and Aysha (USAID, 2020).

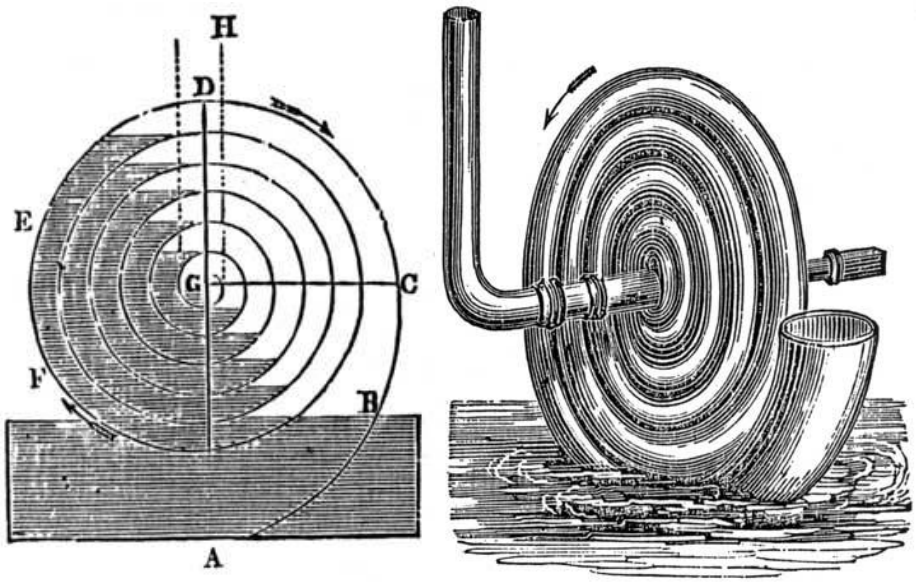

Figure 1.1 Historic Wirtz Pump - 1842 drawing [3]

Figure 1.2 Spiral pump testing on Awetu River

The potential to alter the economy from rain dependent agriculture to irrigation abundant. As noted above the country is home of rivers with 124.4 BCM water flow and irrigable land about 3.6 million hectares out of which only 5% has been developed [5]. Moreover the country is with abundant unskilled labour. So that low-tech labour intensive investment scenarios irrigation comes to be rational and feasible. The problem is the lack of technology for sustainable and reliable water resources management strategy and inefficient utilisation of water resources [5].

As part of the broad water sector reform programme, the Ministry of Water Resources has sought to incorporate drought alleviation in water sector management and investment, thereby addressing drought in a more systematic way, rather than react to drought when it occurs. The overall goal of the water resources policy (WRP) is to enhance and promote all national efforts towards the efficient, equitable and optimum utilisation of the available water resources for significant socio-economic development on a sustainable basis [5].

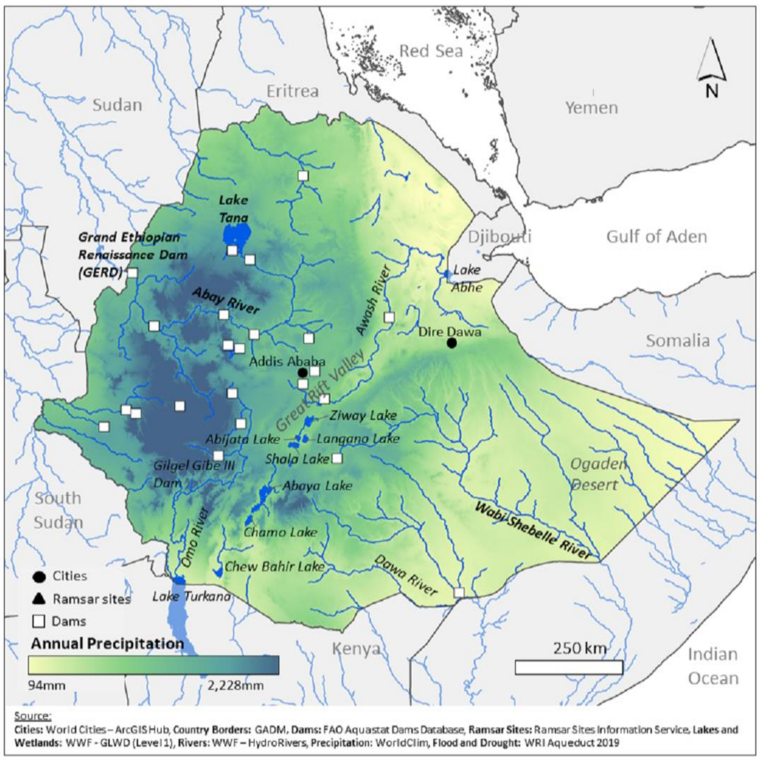

Figure 1.3 Annual Precipitation and Rivers in Ethiopia [4]

Sustainability of the management of water supply schemes is a challenge for the sector. Lack of research and development in the sector has hampered the contribution of the sector to the socio-economic development of the country. [5] Lack of appropriate and affordable irrigation technologies is the major constraint geared towards poor and small farmers of sub-Saharan Africa [6] . Most irrigation equipment used in conventional pressurizes irrigation system in Ethiopia is imported and costly. So appropriate technology must be developed and adapted to suit smallholder farmers. To change the history of drought and famine of the country. These technologies must be appropriate and simple, moreover it should be manufactured using local materials and skill, and have a potential to earn high return on investment.

In line with this, among points of key research areas of Ministry of Water Resource engineering and infrastructure aspects researches with respect to water resources regulation and management is a vital point (MoWR/ESTC 2002). The specific research activities also include;

- Definition of engineering design parameters and standards for water development
- Identification of suitable and appropriate irrigation methods for different scale of irrigation schemes
- Development of different water conservation and management options for surface and Sub-surface water
- Selection of appropriate technologies in the water sector
- Efficient water use methods in arid and semi-arid areas
- Development of irrigation at the village level.

1.2. Spiral pump

According to Naegel (1998) a spiral pump has come to be considered as a “Gift from God” to the farmers [7]. Since it is cost-efficient water pumps powered by renewable energy sources, built out of available materials at the place of use, and repairable by local craftsmen. It harness the kinetic energy of streams for pumping the portion of water to the irrigation fields located above canals and streams.

Originally it is invented in 1746 by H. Andreas Wirtz. And was reinvented by A.E. Belcherb (1972), R. Ohlemutz (1975) and by P. Morgan (1984). A variety of names have been used for the pump, for example, the spiral pump, manometric pump, coil pump and hydrostatic pump [7]. Although this names used interchangeably, in this study each name is used to differentiate the pump system orientation and geometry.

A spiral pump consists of a length of flexible tube wound around the inside or outside of a cylindrical drum/disk which is partly submerged in water with the axis of the drum parallel to the water surface. One end of the pipe is secured to the drum and left open and this forms the inlet. The other end of the pipe is connected via a sealed rotary joint to the delivery pipe. Rotation of the drum causes the inlet end of the pipe to take in alternate plugs of air and water. The ratio of the lengths of these plugs is determined by the depth of immersion of the drum. The plugs then move along the helical pipe towards the outlet and after passing through the rotary joint they travel up the delivery pipe to the header tank. The pressure that is required to force the plugs up the delivery pipe is developed by each water plug acting as a manometer and sustaining a pressure difference across the plug. The sum of all these pressure differences equals the pumping head [8].

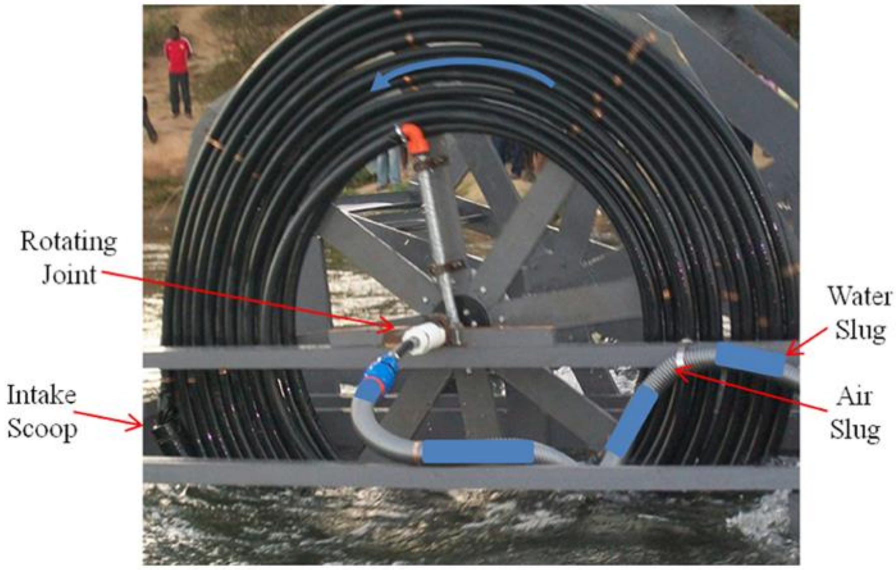

Figure 1.4 Spiral Pump: Air and water Plugs [9]

A first encounter with the spiral pump can hardly fail to impress: essentially, a rotating spiral of pipe, mounted in a vertical plane and arranged so that one open end dips below the surface of a reservoir of water once per revolution, easily adapted to be driven by water power, can be used to pump a useful quantity of water to a height of several metres.

The pump requires only one critical component, a rotating coupling, which connects a turning pipe to a stationary one aligned along the same axis, in a watertight, low-friction manner.

A spiral pump made by forming spiral shape from flexible tube is usually attached to water wheel. So that the water wheel converts the flowing kinetic energy of the stream to rotate the spiral tube attached to it. Therefore we can conclude that a spiral pump system is a corporation of two old technologies|; a water wheel and spiral tube pump. A spiral pump built in such way, which is attached to the spokes of a waterwheel, served for Eight years without a problem providing reliable irrigation at a height of 5.5 m above a stream, at a rate of about 1 l min^{-1} [10].

Figure 1.5 *Spiral Pump*

1.3. Statement of problem

In order to sustain the impact of drought and ensure food security effective water management is crucial. To do so a spiral pump, cost-efficient water pump that powered by renewable energy sources, built out of available materials at the place of use, and repairable by local craftsmen will definitely have great contribution. Also it is what our country's water policy is seeking for. But the problem is up to now we didn't adapt the technology to suit our need and specifications. Based on the literature reviewed there is no any document that shows if a spiral pump or any type of manometric pump is implemented in Ethiopia.

To get the required service from this pump it is must to have sufficient understanding and knowledge on how it works, what will affect it performance and how to increase its performance. This the first problem this study was intended to solve.

The other problem is even on the international level studies on spiral pumps are limited. Because when a spiral pump is compared with fuel or electrically powered pump its performance is lesser. Its advantage over other conventional pump is its zero operation cost and simple construction that can be built with lesser capital. Since developed countries have no problem with money there focus of study is on fuel and electric pumps. That is why the studies on spiral pumps were limited. So there are questions to be answered regarding its performance. The relation between stream velocities, pump size, pump structure and pump position in the rivers with the pump performance is not clearly well defined yet. With limitation of such knowledge it is impossible to made farmers fully beneficial from this impressive technology.

Thus on the completion of this study it is believed that spiral pump technology will be adapted to our countries demography and the understanding regarding to this spiral pump technology is upgraded. So that the achievements of this is solving the local water management problem and contributing something for well understanding of the pump.

1.4. Research Questions

This research has answered the following questions;

1. Does the paddle shape difference has significant effect on energy conversion of water wheel?
2. How does spiral pump important parameters such as; submergence ratio, wheel speed, number spiral turns and outer diameter of the spiral turn affects the pump discharge and head?
3. What is the optimum parameter combination get better pump output?
4. Which is better when compare the typical manometric pumps, spiral and coil pumps?
5. What should be the procedure to design a spiral pump?

1.5. Objectives

1.5.1. General objective

The general objective of this study was to conduct an experimental study on the effect of important parameters on the performance of locally developed spiral pump system so that it can be readily design and applied for local irrigation work.

1.5.2. Specific objectives

- To conduct a study on different paddle shape of water wheel and choose more productive paddle shape for spiral tube pump system
- To conduct experiment to study the effect of submergence ratio, rotational speed, outer diameter and number of turns of the spiral tube pump
- To compare the performance of coil pump and spiral pump to determine effectively working manometric pump
- To optimize the parameters of the spiral pump system

- To clearly describe the design procedure of a spiral pump so that it can be readily used by anyone who is interested on the technology

1.6. Motivation of the research

Recently in Ethiopia having adequate food become harder due to the inflation. This may have both international and local reasons though the solution mainly depends on the increasing of productivity of the agricultural sector. The productivity of this sector mainly hangs on the efficient management of water resource which implies the effective irrigation that enables production more than once in a year. Moreover currently the government policy focus in production of vegetables, fruit and wheat to make the country self-sufficient on feeding the citizen and establishing social stability. Realising such policy without cultivating the water resources of the country effectively, is impossible. As an engineer my duty is empowering my country with technologies that can help achieving the development goals. So that every citizen can have food for him and his family.

1.7. Significance of the study

The benefit of successful accomplishment of this study serves the nations peace and stability beyond helping farmers in their irrigation work. Up front it merits the farmers to harness the nearby river water with less initial capital investment and zero operating cost without polluting the environment. Since the spiral pump operation and maintenance doesn't requires for highly skilled craftsman the work irrigation will be eased. Small scale irrigation will be facilitated. This will certainly implies the following significance;

- Facilitated and eased irrigation work during dry season
- Production of food crops more than once a year
- Minimization of foreign currency expense for conventional pumps and fuel that is going to be used by the pump
- Minimization of polluting gases release fuel using pumps
- Preservation of electric power

Collectively this study can take a part in food security, peace, stability and prosperity of the country.

1.8. Scope of the Study

In this research work the spiral pump is studied as system that contained two system components; water wheel and spiral tube pump. The water wheel has a function of harnessing the kinetic energy of the stream, and a spiral tube pump raises the portion of stream water to the nearby irrigation field. So both parts of the system is studied separately. The study conducted on the water wheel aimed on increasing the wheel speed. So in the study of the paddle shape effect the 3D model of the paddle shapes were developed and numerically simulated using SolidWorks Flow Simulation. On the other hand the study on the spiral tube pump was focused on how the important parameters (submergence ratio, rotational speed, outer diameter and number of turns of the spiral tube) affect the performance of the pump. To do so a prototype was developed base on the 3D model and more than 360 experiments were performed in the river. Then after that those parameter were optimized and the significant parameters were identified once again using the Taguchi approach. And the coil pump and spiral pump performance also compared based on the theoretical relationships. Finally the design procedure for the spiral pump to meet the required output is devised and stated clearly. Here design of the spiral pump system, including the water wheel structure is out the scope since this matter requires real working condition information.

1.9. Limitations of the study

Among many challenge this study faced two of them can be mentioned as its limitations. The first one is unavailability of modern measuring instruments. The technique used for measuring head of pump was traditional that yields only the maximum static head. So finding head was not simple. The other limitation was leakage on the rotatory joint. Since the rotary joint was manufactured locally, some amount of leakage is expected. This leakage has affected the head of pump significantly causing about 17% error from the theoretical. This effected is taken in to account throughout the study.

1.10. Thesis outline

The overall study process and study result report is structured five chapters.

In the first chapter, a general introduction to spiral pumps, backgrounds, problem of the statement, objectives, and the like are presented in this section.

In the second chapter literatures on working principle of spiral pump, water wheel power generation, important parameters and Taguchi method optimizations are reviewed material, an overview of composite material, its constitute, classification, method of manufacturing and merits and demerits are presented.

In the third chapter methodology of the thesis with detail of experimental material and methods and laboratory testing used throughout the studies are presented in detail and literature review concerning to the test also presented.

In the fourth chapter, the result of the experimental studies and consequent analysis are presented. Also numerical simulation results of paddle shapes are shown and discussed, coil and spiral pump compared, Taguchi approach optimization result presented and discussed, finally the design procedure of spiral pump is developed and explained.

In the last chapter five, the summary of the result conclusions drawn from the above analysis and recommendations for future work are suggested.

2. Literature Review

2.1. Working Principle of Spiral Pump

Spiral tube pump uses the kinetic energy of a stream to raise a proportion of its water. To do so it unites two old technologies the spiral tube pump with water wheel. While the waterwheel harnesses the kinetic energy of the river the planar spiral tube that attached to it will raise or pump portion of the water from the river [11].

'Spiral pump', 'coil pump' or 'manometric pump' works by the principle of manometer. A manometer is a device used to measure the pressure at any point in a fluid, manometers are also used to measure the pressure of gas and air. A manometer works on the principle of hydrostatic equilibrium and is used for measuring the pressure (static pressure) exerted by a still liquid or gas [12] [13]. Hydrostatic equilibrium states that the pressure at any point in a fluid at rest is equal, and its value is just the weight of the overlying fluid. In its simplest form, a manometer is a U-shaped tube consisting of an incompressible fluid like water or mercury [14] [15]. A pictorial explanation of how a rotating spiral of pipe can function as a pump shown in is Figure 2.1. It shows three configurations of pipe containing one or more 'plugs' of water. Figure 2.1a shows a U-tube manometer, the simplest pressure gauge, familiar from school physics. Pascal's Law, states that the pressure difference $P_1 - P_0$ is proportional to the height difference, h, between the surfaces of the water in the right and left limbs, respectively. Taking this idea further, Figure 2.1b shows three such manometers connected in series, this arrangement giving an increased pressure difference, $P_3 - P_0$, proportional to $h_1 + h_2 + h_3$. Finally, in Figure 2.1c, we imagine the previous configuration to be 'folded' around alternate vertical limbs, giving the spiral configuration shown, with P_3- P_0 again being proportional to the sum of the height differences [16] [17] [10] [18]. In practice, the spiral would be likely to consist of many more than three turns.

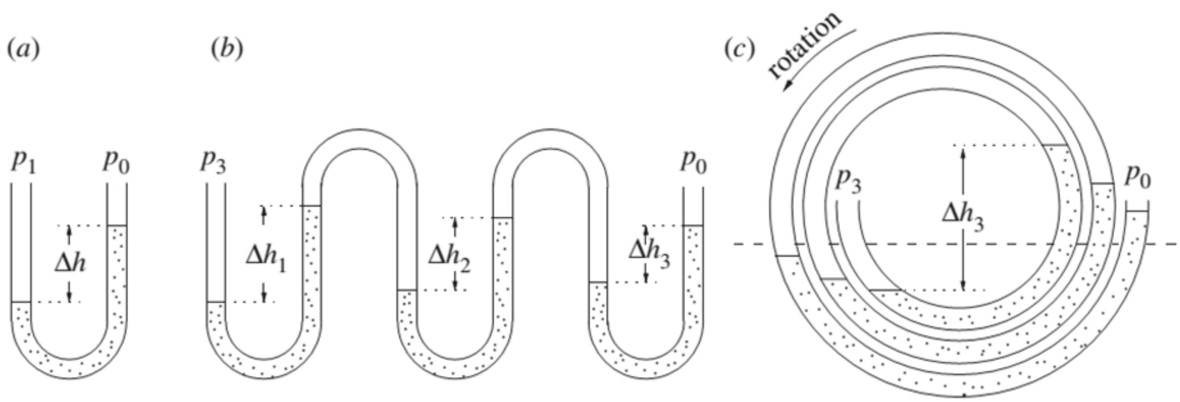

Figure 2.1 Working Principle of Spiral Pump; (a) U shape manometer (b) Cascaded manometer (c) spiral pump [10]

In short with each revolution of the pump, alternating plugs of water and air are forced into the pipe. As the wheel spins it compresses the air in the pipe and creates a pressure head within each coil. A cumulative head is built-up at the inner coil and water is forced out the delivery pipe. In this way the water in each coil was displaced to provide a pressure head. Basically pump follows "Boyle's pressure-volume relationship". In each spiral of the coil, the water plugs occupy the lower part while the air plugs occupy the upper part due to density difference. During rotation they always maintain their respective positions in each spiral. Thus, when the water reaches the end of the coil, it is pushed into the delivery pipe by the air and water in subsequent coil. Thus, the spiral coil pump can be said to be a sort of "positive displacement pump" [19] [20].

2.2. Types of manometric pumps

Mainly pumps considered in the literatures fall into two categories: coil pumps, in which the pipe is formed into a series of turns all of the same radius (the pipe may be imagined to be wound around a cylinder helically) and spiral pumps, an essentially planar arrangement in which the radius of successive turns decreases. But based on their working principle we can name both of them as manometric pump, after their resemblance to a wounded cascading manometer, where the series of loops of the pipe act as manometers separated from one another by the trapped air columns. The total lifting head at the outlet results from the addition of the manometric head difference in each loop [8] [21](as cited in [22]). Several authors have thoroughly studied the hydraulics of this water lifting principle.

The shape of the curved pipe can be either planar, convolved in a three-dimensional cylindrical surface, or in a conical one. Besides, regarding the water stream, the axis of the pipe can be cross-flow or axial-flow. These different shapes give rise to manometric pumps that acquire several names throughout the literature, sometimes being used interchangeably or even as synonyms. For convention of the present work however, cross-flow planar, cross-flow non-planar, and axial-flow non-planar pipes will be referred as spiral pump (SP), Coil pump (CP), and Conical Helix pump (CHP), respectively. Figure 5 depicts different types of manometric pumps [23].

Figure 2.2 From Right to left; Spiral pump, Coil pump, and Conical Helix pump [23]

Based on the spiral pump principle a company called aQysta have manufactured a modern pump with a capacity of 20 meters head and 40,000 litters per day flow rate, called it Barsha pump. it became very effective in Indonesia and Nepal.

Figure 2.3 aQysta Barsha Pump [23]

2.3. Water wheel

In this study a water wheel is incorporated with spiral tube pump to harness the energy of a stream and power the pumping system. So that it is important to understand and increase water wheel efficiency to get better performance of the pump system.

Water wheels were introduced more than two thousands of years ago; they were used for producing energy, grinding grain, forging iron, pumping water, sawing wood and stones, for metalworking and leather tanning. The first kind with a horizontal axle was the stream water wheel, which was described by Vitruvius in 27 BC. Stream water wheels have been later analysed by many engineers and scientists, including Parent, de Borda and Smeaton [24] [25].

Stream wheels are hydrokinetic machines, where change of head at the wheel location is negligible and the torque is provided by the momentum of the water stream. They are used in sites with very low heads or in flowing water, and the kinetic energy of water is exploited. Gravity wheels are used in sites with higher heads, as the water weight is employed for producing energy. Therefore, gravity water wheels exploit mainly the potential energy of water and a portion of the kinetic energy. Three main types of gravity water wheels can be identified: overshot, breastshot and undershot water wheels [26] [27] [28].

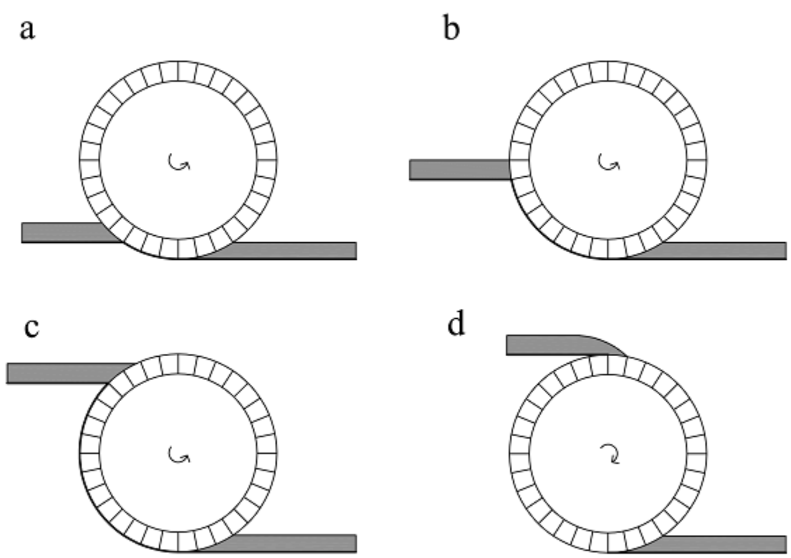

Figure 2.4 Types of gravity water wheels: low breast shot/undershot (a), middle breast shot (b), high breast shot (c) and overshot (d). Undershot water wheels with no channel bed drops are stream water wheels [24].

In 1759 John Smeaton published experimental data on gravity wheels demonstrating the higher efficiency of gravity wheels over the efficiency of impulse stream wheels. In order to link the higher efficiency of gravity wheels with the simplicity of hydrokinetic wheels (stream wheels), in the early 19th century, the French engineer J. V. Poncelet performed a new blade design for the stream water wheels, increasing the maximum efficiency from ' 30% to ' 65%. The blades of the Poncelet wheel were shaped in order to avoid power losses during the impact; the blades were curved in order that the water could flow from the tip of the blade toward the root, pushing against the blades also by its weight. This design was the first effective improvement of the original stream water wheel, [24]. This show how paddle shape of a water wheel affects its efficiency. In addition to this G. Muller suggested a paddle to be curved and slated at angle of 22.5 degrees from to get higher speed [29] [30].

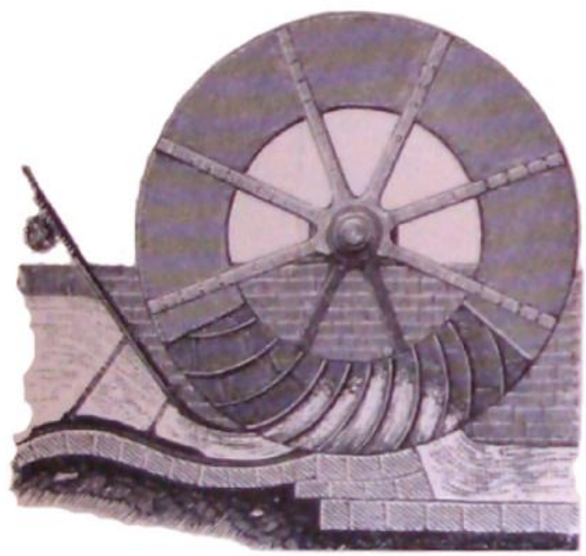

Figure 2.5 An example of Poncelet water wheel [24]

In the Eighteenth and Nineteenth century, additional theories were developed and experimental tests on water wheels However, theories were generally developed separately from experimental tests, and they were usually not validated. Several prescriptions on water wheels design were empirical, and not based on scientific evidence. Furthermore, the experimental tests were carried out more than one century ago, with several uncertainty [24].

At the end of the Nineteenth century, the rising demand of energy, the rapid improvement in the engineering knowledge (especially the design of big hydroelectric plants) and the economic development led to the diffusion of modern turbines (Pelton, Francis and Kaplan turbines and big hydroelectric plants). Therefore, the water wheels used in low head sites especially for self-sustainment were replaced and by then considered bygone and ancient hydraulic machines. Nowadays, due to the new interest in mini hydropower as described before, the scientific research on water wheels is experiencing a revival. This study also joins it for the sake of improving spiral pump performance.

2.4. Power generation in Stream water wheels

After invasion of conventional turbines the studies on water wheels have been ignored for long period of time. As a result recent literatures on water wheels were not abandon. Though the negative impact of conventional turbines on economy and ecology is noticed the need stream wheel raised. Stream water wheels were considered cost effective since little civil engineering work was required for a stream wheel installation. In respect to power generation the power output from stream wheels in slow flowing situations is small; fast flowing streams however exceeds the exception. Besides the speed of the stream the shape of the wheel paddle plays a vital role in efficiently harnessing the kinetic energy of the stream [29] [24].

2.4.1. Power generation of flat paddle shape

Power generated and speed of the wheel can be calculated using conservation of energy and momentum transfer equations. Theoretically the power output of the water wheel is equal to the rate at which energy is transferred from the flowing stream to the wheel. This can be expressed as:

$$Power = {}^{\rho A V^3}/_{2} \qquad \textit{Equation 2.1}$$

Where ρ is the density of water, A is the area of the paddle wheel, and V is the velocity of the stream. This expression gives the power output of the water wheel in terms of the stream velocity and the area of the paddle wheel [31].

The rotational speed of the water wheel can be calculated from the power output and the torque generated by the wheel. The torque is proportional to the product of the radius of the wheel and the force applied to the paddles by the water. The rotational speed can then be calculated as:

$$N = Power\ /(2\pi \times Torque) \qquad \textit{Equation 2.2}$$

In practice, the efficiency of the water wheel will depend on various factors, such as the design of the wheel, the shape of the paddles, and the angle at which they are positioned relative to the flow of the water. Therefore, the actual rotational speed of the wheel may be different from the theoretical value calculated using the above formula.

Also the torque can be calculated by multiplying the force applied on the paddle and radius of the wheel. For paddle slanted at angle θ force can be calculated using the following formula;

$$Force = {}^{\rho A V^2}/_{2} \times (cos\theta) \qquad \textit{Equation 2.3}$$

The perpendicular component of the force is what drives the rotation of the water wheel, while the parallel component is typically minimized by designing the paddle to be angled appropriately.

2.4.2. Power generation of non-flat paddle shape

If the paddle blade is curved, such as a semicircle, the formula for the force on the blade becomes more complex, and it may not be possible to find a simple analytical solution. Approaches such as dividing the blade into small segments or using computational fluid dynamics (CFD) simulations can be used to estimate the force on a curved paddle blade.

Yucheng Liu [32] suggested effective approach to estimate the speed of the wheel. According to Liu the simple approach; assuming the wheel will rotate by the same speed as of the river, and calculating it using Equation 2.4 is incorrect. In this approach first maximum speed of water at the tip of the blade is determined using CFD then this speed is used to determine the speed of the wheel using Equation 2.4.

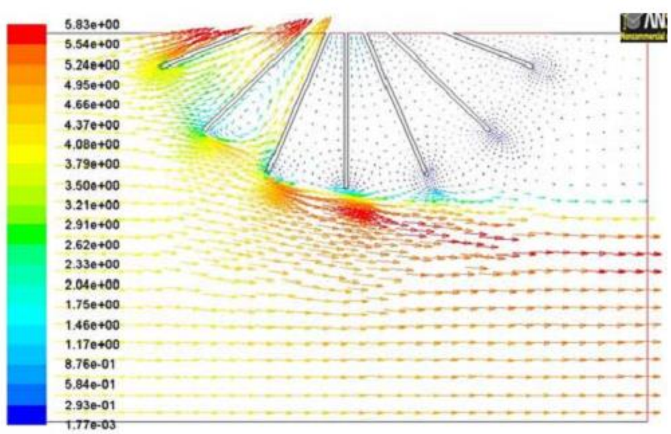

Figure 2.6 Velocity distribution at water velocity of 4 mph for stationary paddles [32]

$$\omega = \frac{60v}{2\pi d} \qquad \textit{Equation 2.4}$$

Where d is the distance from axis of rotation.

2.4.3. Stream wheels in shallow and deep water

Gerald Müller and other researcher had reported an astonishing work on power generation of stream water wheels [29]. This literature stated the theoretical relationship of power generation in stream wheels operating in shallow and deep water. According to this study the power output and efficiencies from stream wheels were however considered to be small when compared with other types of water wheels which employed the potential energy of the flow. Whatever it is the objective of stream wheel in this study is not to generate energy to power a whole city, it is to rotate a simple spiral tube. So that the high power output will not be a concern.

In Gerald Müller's report a vital classification of stream wheels had been made. From theoretical considerations, three different types of stream wheels can be defined, depending on speed of water V_0, the critical depth of the flow d_{cr}, the actual depth of water t_1 and submerged depth of blade d:

1. Shallow water depth in subcritical flow ($d \approx t_1$, $V_0 < V_{cr}$)

2. Shallow water depth in supercritical flow ($d \approx t_1$, $V_0 > v_{cr}$)

3. Deep water ($d << t_1$, V0 < Vcr)

Supercritical flow, i.e. a flow faster than the wave propagation velocity V_w in shallow water of a depth d_1, occurs only rarely in natural river channels.

Based on above classifications the stated power output theoretical relationships is discussed below.

Stream wheels in subcritical flows were only built occasionally. They were considered cost effective since little work on the stream itself was required, power outputs were however low (often less than 1.7 kW for a 3.6 m diameter wheel with 2.8 m width), figure 2.7.

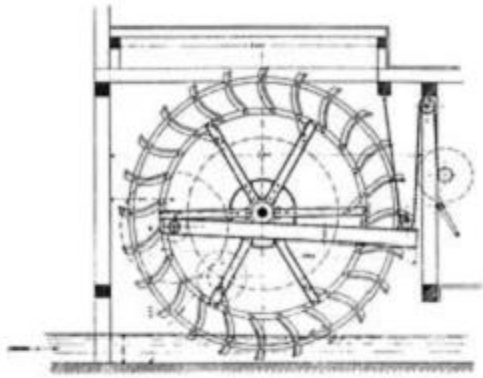

Figure 2.7 Shallow Stream wheel [29]

The assumptions for the theory of the subcritical stream wheel, with the flow being obstructed by a blade of depth d ≈ t:

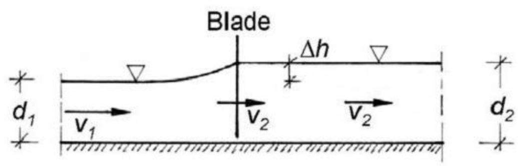

Figure 2.8 Schematics of wheels in subcritical flow [29]

The power is generated by the momentum exchange between flow and blade, leading to a higher water level in front and behind of the blade. The power P is then given as:

$$P = \rho_w b d_2 v_2 (v_1 - v_2)^2$$ *Equation 2.5*

The power maximum occurs for $v_2 = 0.5\ v_1$; with a maximum efficiency of 29.6%. A 1 m deep river channel flowing with a velocity of 1.5 m/s would therefore produce mechanical energy of only 0.5 kW per m width; this indicates the very small amount of energy which can be produced with stream wheels in subcritical flow. The wheel itself in this case acts as a weir, increasing the water level in front and behind of it. This effect should be noted when considering an application of this technology. Experiments on stream wheels led to maximum efficiencies of 30% (taking the efficiency as the ratio of extracted mechanical to available hydraulic energy).

Stream wheels were preferably employed in situations where supercritical flow velocities occurred. A transition to supercritical flow can be generated by small head differences or undershot weirs. The higher velocity of the flow means that smaller water wheels are required and, since upstream conditions in supercritical flow are not affected by an obstacle, higher efficiencies become possible.

It had a power rating of P = 26 - 33kW. The theoretical power output of a stream wheel in supercritical flow can be determined by examining the possible differences in the Total Energy Line (TEL), Figure 2.9:

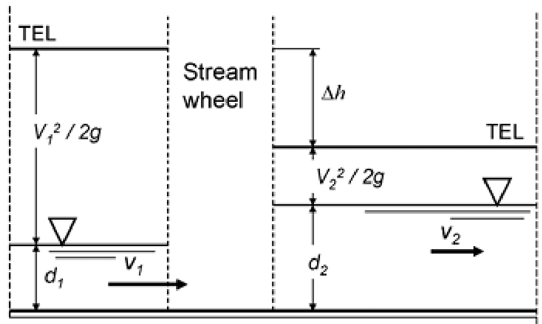

Figure 2.9 Stream wheel in supercritical flow [29]

$$P = \rho_w g Q \Delta h \qquad \text{Equation 2.6}$$

$where$:

$$\Delta h = d_1 + \frac{{v_1}^2}{2g} - \left(d_2 + \frac{{v_1}^2}{2g}\right);\ \Delta h \geq 0$$

$$d_2 = \frac{V_1}{v_2} d_1$$

The water depth behind the wheel assumes the critical depth dcr , for a ratio of wheel speed to initial velocity of water v1 / v2 = 0.56. The maximum theoretical efficiency becomes of 36.3 %.

Water wheel in deep water;

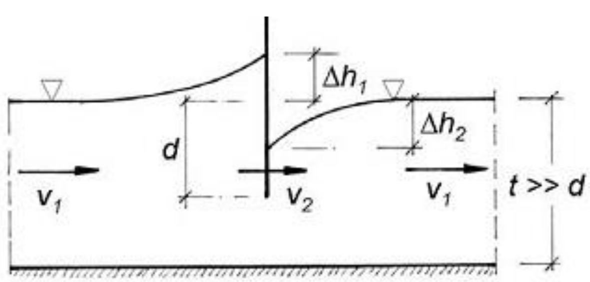

Figure 2.10 Single blade in deep water [29]

$$\Delta h = \frac{{v_1}^2 - {v_2}^2}{2g}; \quad from\ test\ \Delta h_1 \approx \frac{2}{3}\Delta h_1$$

$$P = \rho_w g \frac{b}{2}\left[(d + \Delta h)^2 - (d - \Delta h)^2\right]v + \rho_w b(d + \Delta h_1)(v_1 - v_2)^2 v_2$$

Equation 2.7

In general from this literature the following points can be concluded;

- Subcritical shallow stream wheels power output is less comparatively
- Contrary to the stream wheels in confined water, the number of blades in contact with the water affects the power output, with power increasing for increasing number of blades.
- With respect of construction of blades, they should be curved with a radius which allows for the exit of the blade out of the water with a minimum of energy loss. This is ascertained by keeping the tangent on the blade at its exit point normal to the water surface.

2.5. Important literatures on manometric pumps

Many literature regarding to spiral pump are somewhat old. Finding recent literatures difficult this is because after emerging of conventional electric and fuel Pumps the need for spiral pump and similar kinds has declined in developed countries since they can afford the conventional pumps. But recently in developing countries the search for affordable pumping system has become priority. Even though they are not such recent literatures the following literatures are basic and very important in understanding manometric pumps. Moreover the overall understanding and findings about manometric pumps are reported in these literatures since not many studies conducted after.

2.5.1. Mortimer and Annable, "The Coil Pump: Theory and Practice"

Among many literature the work of G.H. Mortimer & R. Annable called "The Coil Pump - Theory and Practice" is the one which explain the principle of coil pump well with the help of analytical relationships [8]. In this study a simple pump was developed and from laboratory investigation a theory has been produced which satisfactorily predicts the pump's behaviour.

The pump was simple both in construction and operation. It consists of a length of flexible tube wound around the inside or outside of a cylindrical drum which is partly submerged in water with the axis of the drum parallel to the water surface. One end of the pipe is secured to the drum and left open and this forms the inlet. The other end of the pipe is connected via a sealed rotary joint to the delivery pipe. The experimental setup of this study is illustrated in figure …

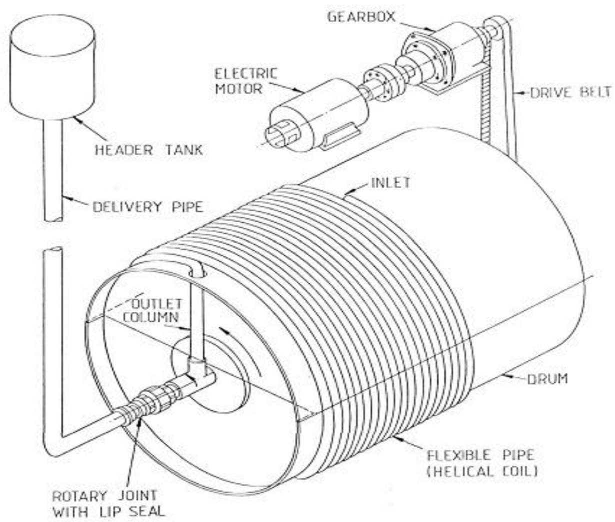

Figure 2.11 Coil pump laboratory setup [8]

This literature clearly explain aspects such as; Rotation of the drum causes the inlet end of the pipe to take in alternate plugs of air and water. The ratio of the lengths of these plugs is determined by the depth of immersion of the drum. The plugs then move along the helical pipe towards the outlet and after passing through the rotary joint they travel up the delivery pipe to the header tank. The pressure that is required to force the plugs up the delivery pipe is developed by each water plug acting as a manometer and sustaining a pressure difference across the plug. The sum of all these pressure differences equals the pumping head.

The pressure developed in the pump is represented by a cascaded manometer. When the coil pump is stationary or rotating the pressure head difference across the pump is developed by means of a cascading manometer which is equivalent to an unwound helical coil; see Figure 2.12.And the overall head difference across the manometer is balanced by the sum of the head differences across the water plugs, that is;

$$H_T - H_A = h_1 + h_2 + h_3 + \cdots\ h_N \qquad \text{Equation 2.8}$$

$$where H_T\ is\ the\ absolute\ presure\ head\ at\ the\ outlate,$$
$$H_A\ is\ the\ atmospheric\ head,$$

$$\text{and} \quad N \text{ is the number of coils or manometric loops,}$$

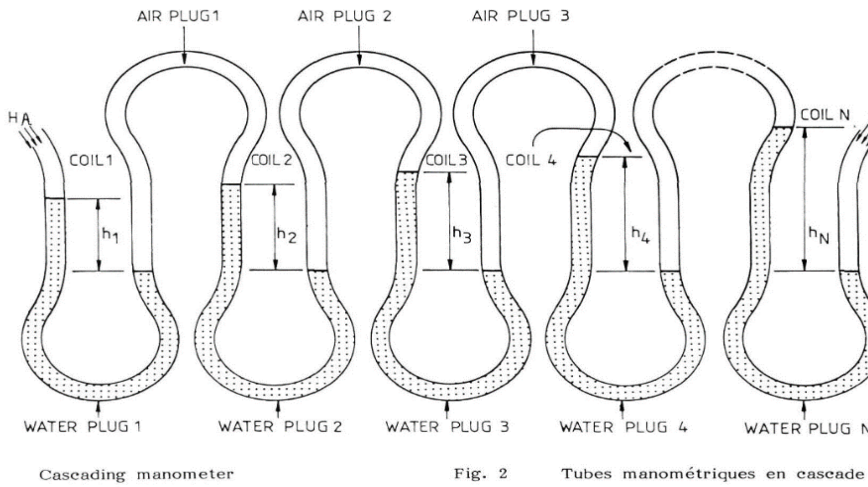

Figure 2.12 Cascaded manometer [8]

The important concept in coil pumps or any other manometric is the contraction of the air plugs that cause the pressure difference. According this literature for calculation on the length of the plugs $P.V^{1.15} = constant$ is valid, where p is the absolute pressure in the air plug and V the volume of the plug.

$$\therefore \; P_1V_1^{1.15} = P_2V_2^{1.15}$$ *Equation 2.9*

Or assuming a constant pipe diameter for the coil

$$H_nL_A^{1.15} = H_nL_{A.n}^{1.15}$$ *Equation 2.10*

Where L_A is length of air plugs.

An air plug travelling along the pipe from the inlet will become compressed by the pressure build up towards the outlet, therefore every point on the pipe will have a different air plug length associated with it. A similar argument can be applied to the water plugs except that the change in plug length is caused by water moving from one plug to the next.

In pump performance study the other important factor is the pump discharge. In this literature the researcher had stated a clear theoretical relationship to predict the steady pump discharge. That is;

$$Q_p = N_s \pi r^2 . L_{w.1}$$ *Equation 2.11*

Where r is the diameter of the helical pipe and $L_{w.1}$is the length of the water plug taken in at the inlet.

With no dynamic losses $L_{w.1} = \theta_1.R$ where θ_1 is the angle subtended by the water plug. However in reality $L_{w.1}$ is better defined as;

$$L_{w.1} = \theta_1.R \pm change\ in\ lengt \quad \text{Equation 2.12}$$

Logically this change in length should be the reduction of the dynamic losses at the inlet. Surprisingly the measured lengths were on average 4% greater than the theoretical length. Further work will be required to explain this enigma but 4% is acceptable error.

Since the coil pump has the ability to work at low speed the researchers decided to build a stream powered coil pump of: 0.25 mm diameter flexible plastic pipe is wrapped around the inside of a 50 gallon oil drum forming 26 coils and it is held in position by a number of inflated car tyre inner tubes. These tubes also provide buoyancy for the drum when it is working in a stream or river. Chevron shaped paddles were used which is made of scrap sheet steel were spot welded onto the outside of the drum and an annular shaped shroud is added to prevent the sideways movement of water, these form the paddles of the waterwheel which powers the pump and details are shown in Figure 8. This paddle arrangement was chosen because laboratory tests indicated that the chevron shape produced more power than a flat surface and also its performance was more stable under a wide range of depths of immersion.

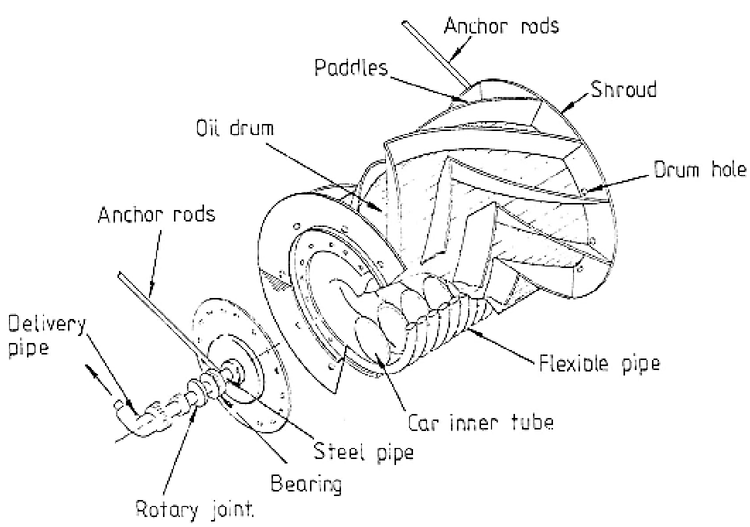

Figure 2.13 Mortimer and Annabel's Stream power coil pump

When this pump got tested in a local stream and it lifted water to a height of 9.50 metres at a rate of 4 l/min when the stream velocity was 0.80 m/s. The pump was operated with a stream velocity as low as 0.40 m/s, but at a reduced performance.

In conclusion this literature was able to predict the behaviour of the pump with sufficient accuracy for most coil pump design purposes. Its suggestion for further work was to continue studies in this so that other useful forms of the coil pump is produced.

2.5.2. Kassab, "Coil Pump Performance under Variable Operating Conditions"

In 2005 Sadek Z. Kassab done an amazing experimental research on coil pump in Egypt [22]. The performance of coil pump under different operating parameters was the main objective was this study. The parameters considered in the present study were submerged ratios, rotational speed and number of coils of the wrapped hose. In this study the effect of pump rotational speed, submerged ratio and change in the number of coils were considered to obtain a clear picture for coil pump performance.

To conduct the study an experiment set up of the coil pump shown in Figure 2.14 is used. As of the report this experimental set up consists of a flexible hose, of inner diameter 19 mm (3/4 inch) wrapped around a P.V.C cylindrical drum, of 1 m total length and outer diameter 20.4 cm.

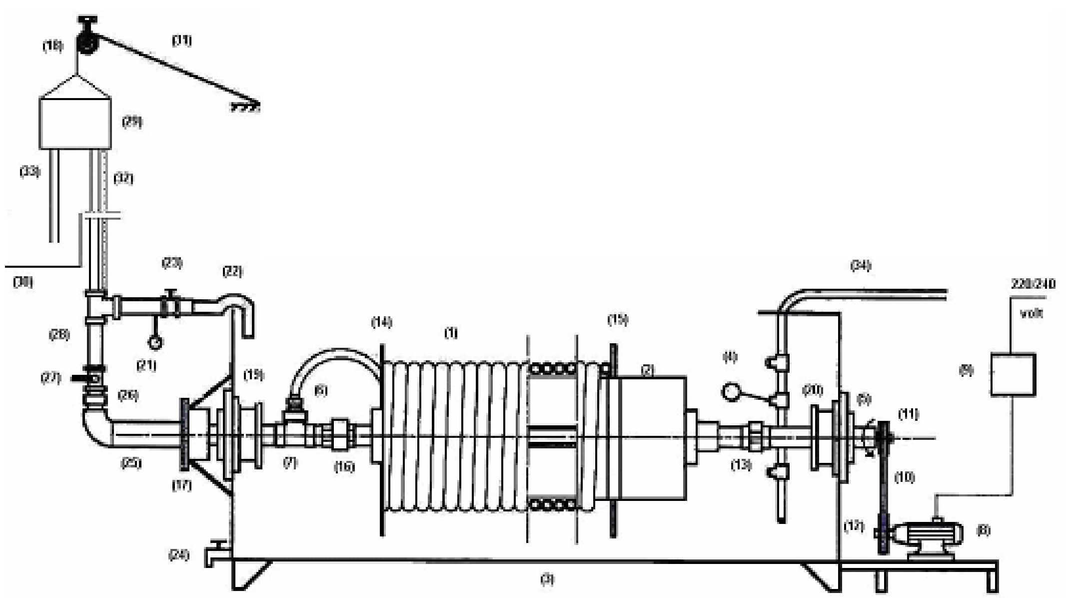

Figure 2.14 Schematic drawing of the experimental setup [22]

The coil pump was immersed in the tank with specified submergence ratio and rotated with given speed. This procedure resulted a water pumped through the delivery pipe. The distance from centreline of the pump to the tip of the delivery pip was recorded to be the pump Head. And the water collected in the measuring tank per certain time was recorded to be the pump discharge. This procedure was replicated with altered number of coil to study the number of coil effect.

Finally the report conduced that; significant effects observed on the pump performance due to the variation in submerged ratio Sr and the pump rotational speed. The presence of air with water for submerged ratios 0-Sr-100% gives the coil pump its pumping action. Increasing the submerged ratio increases the pump flow rate until it reaches its maximum depending on the pump rotational speed, then decreases to zero when the pump is fully immersed. Submerged ratio has a minor effect on the pump maximum static head, it is nearly constant but decreases drastically to zero when the pump submerged ratio reaches 100%. Increasing the pump rotational speed increases water flow rate until it reaches its maximum depending on the working submerged ratio, then the discharge decreases by increasing the rotational speed. Meanwhile slight changes are obtained for the pump static head when the pump rotational speed changes. The number of pump coils is also one of most effective parameters on the coil pump performance. Increasing number of coils increases the pump head while pump discharge is nearly constant. The following graphs were generated to illustrate the effects.

Also the experimental results were compared with the theoretical results from relationships Mortimer and Annable, and Good agreement had been obtained. Especially for lower rotational speeds.

In conclusion this report the following major points are stated;

1. Increasing the pump rotational speed increases water flow rate until it reaches its maximum depending on the working submerged ratio and design parameters, and then the discharge decreases by increasing the rotational speed.
2. Increasing the pump rotational speed has a minor effect on the pump maximum static head.
3. Increasing the submerged ratio increases the pump flow rate until it reaches its maximum depending on the pump rotational speed, then decreases to zero when the pump is fully immersed whatever the value of the pump speed.

4. Submerged ratio has a minor effect on the maximum static head, it is nearly constant but decreases drastically to zero when the pump submerged ratio reaches to 100%.
5. Increase number of coils increases the pump head, while pump discharge is nearly constant.
6. Good agreement is obtained between the present experimental results and theoretical results obtained by other investigators.

2.5.3. Peter Tailer, "The Spiral Pump: A High Lift, Slow Turning Pump"

The literatures mentioned above are concerning the Coli pump. However, this is about spiral pump type manometric pumps. In this study report peter Tailer discussed very important concepts other than his experimental journey such as; Flow over, Blow-back, and Air Lift.

Flow over is flowing water from inner coils backward to outer coils. The flow appears to take place only when the inner coils have insufficient volume to contain the compressed air and water passing to them. Although it must reduce pump output, it is not certain to what extent this internal flow influences the characteristics of the spiral pump. It may maximize the effect of the air columns or cumulative heads of the inner coils.

Blow-back is phenomena that occurs when the pump pressure exceeds the cumulative pressures of the coils. The blow-back pressure is the pressure at which this occurs. This pressure can be determined for each wheel configuration by closing the valve on the pump output and pumping until there is a sudden drop in pressure and a surging of water and air back through the scoop.

Whereas Air lift is the very principle that allows this pump to create columns of water within its coils, that of alternately taking in air and water, also acts to increase the delivery head. The air, which is compressed as it moves toward the centre of the wheel, expands as it goes up the delivery pipe, producing a lift effect on the water. Testing proved this effect by showing that the actual head reached was greater than that indicated by the pressure gauge in the system. The air lift effect was most evident when pumping to heights greater than those indicated by the blow-back pressure. The size of the delivery pipe also appeared to influence the air lift effect.

To conduct the experiment a spiral pump of a 6 foot diameter wheel with of pipe length of 1-1/4 inch inside diameter flexible polyethylene pipe that abled to pump 3,900 gallons of water per day to a 40 foot head with a peripheral speed (flow rate/ discharge) of 3 feet per second was built. With its low torque requirements, the pump was particularly mounted on and driven by a paddle wheel in a current of two feet per second or greater.

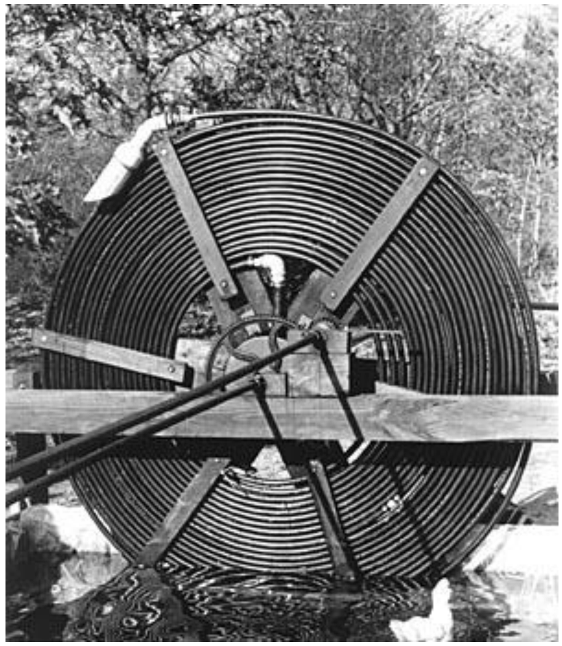

Figure 2.15 Tailer's Writz Pump front view [3]

Unlike other literature this one shown the construction of rotary joint with the help of figure as show on Figure 2.16.

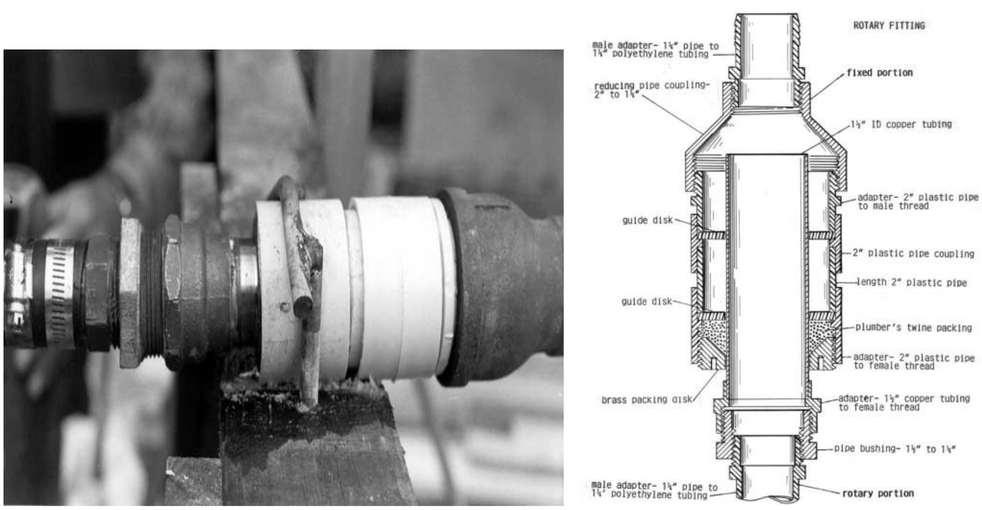

Figure 2.16 Tailer's Rotary joint [3]

Also unlike other literature in a theoretical expression to calculate the pump efficiency is state; that is

$$Work\ out\ (ft - lb) = Q(gal) * H(ft) * 8.34\frac{lb}{gal} \qquad \text{Equation 2.13}$$

$$work\ in\ (ft-lb) = force(lb) * distane(ft)$$
$$= F(lb) * Rev * wheel\ dia.(ft) * \pi$$

Equation 2.14

$$efficiency = \frac{work\ out}{work\ in}$$

Equation 2.15

Where Q is discharge, *H* is height pumped and *Rev* is revolution of the wheel.

After serious of test and calculations about 45% maximum efficiency has reported. In the delivery pipe there are two losses which reduce efficiency, fluid flow resistance and air lift slippage. Fluid flow losses are reduced by larger diameter delivery pipes, but air lift losses are lessened by smaller diameter pipes.

Another great contribution of this study the development of coil design. A theoretical relationship is presented to find h_n (head in n-the coil) and *n* (number of coil) with given value of *H* (delivery head), *D* (outer coil diameter) and *d* (pipe diameter) based on Boyle's low.

$$Boyle's\ low: P_1 \times V_1 = P_n \times V_n$$

$where;$

$P_1 = P_{atm} + D$

$P_n = P_{atm} + H$

$V_1 = \pi \times (\frac{1}{2}d)^2 \times D$

$V_n = \pi \times (\frac{1}{2}d)^2 \times\ h_n$

$$(P_{atm} + D) \times \pi \times \left(\frac{1}{2}d\right)^2 \times D = (P_{atm} + H) \times \pi \times \left(\frac{1}{2}d\right)^2 \times h_n$$
$$h_n = (P_{atm} + D) \times D/(P_{atm} + H)$$

Equation 2.16

To find *n*:

$$n \times \frac{D + h_n}{2} = H$$
$$n = 2H/(D + h_n)$$

Equation 2.17

Peter Tailer in this literature demonstrated the excellent potential of this preindustrial concept when combined with today's available technology. And suggested attractive ways of powering the spiral pump that is to mount it on a paddle wheel placed in a river or stream. A series of paddle wheel driven spiral pumps may be connected to a common delivery pipe for a higher volume output. Alternatively In some circumstances, hand or motor driven spiral pumps could be used to pump to high heads from canals, lakes, or very slow flowing rivers. Low maintenance and ease of construction would make a driven spiral pump a good choice compared to a piston pump.

2.5.4. Naegel, "The hydrostatic spiral pump: Design, construction and field tests of locally developed spiral pumps"

This study report is the most complete in enabling engineers to design and implement the spiral pump. Ludwig C.A. Naegel in Munich, 1998 designed, constructed and tested spiral pump locally. Naegel described spiral pump as cost-efficient water pumps powered by renewable energy sources, built out of available materials at the place of use, and repairable by local craftsmen. This statement really fits to describe the spiral pump and other manometric pumps.

Naegel built a prototype with a 2.0m outer diameter were constructed locally available materials, and different tube materials of different diameters (1.91, 2.54, 3.81, 5.08 and 7.62 cm). To reduce the construction costs, commercially available materials were selected in prototype development process.

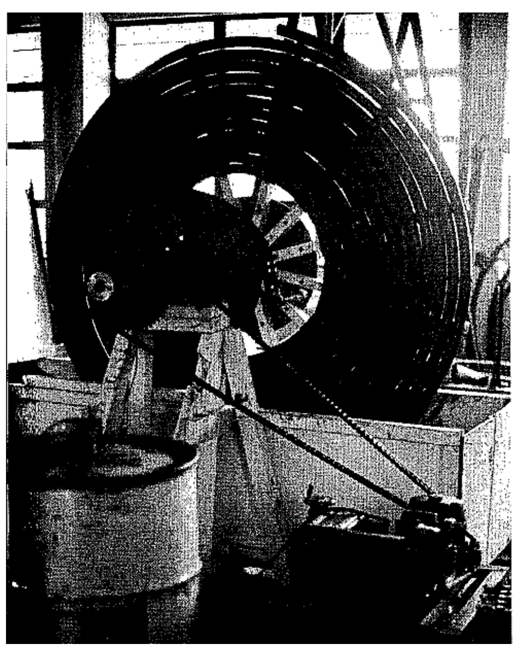

Figure 2.17 Naegel's experimental setup of spiral pump

The testing process is conducted in laboratory. To simulate different flow streams, spiral pumps with different tube sizes and number of coils were immersed into a rectangular water tank and rotated by an electric motor with speed-reduction gears. To determine the influence of the number of coils on the performance of the pump, several different numbers of coils per spiral were tested. To vary the amount of water scooped into the pump, the depth of immersion was changed and water intake spouts were attached. The water delivered to previously determined heights was measured gravimetrically.

After serious of careful testes, the influence of each of the different variation the performance of the pump was determined through a multiple linear and non-linear regression analysis. In nearly 1,600 individual test runs, the following variables influencing the performance of the pump were evaluated and reported as follows,

Delivery volume/discharge in l/min:

$$Q\left(\frac{l}{min}\right) = 0.488td^{1.508}rpm^{0.607}sv^{0.402}H^{-0.257}$$

Equation 2.18

Maximum Head (m):

$$max. H(m) = 0.97scd$$

Equation 2.19

$Where$:

$scd = sum\ of\ coil\ diameters\ (m)$

$td = tube\ diameter\ (cm)$

$sv = scoop\ vlume(l)$

$H = head(h)$

$rpm = rotation\ per\ minute\ of\ the\ spiral\ tube$

In the following graphs the results were presented.

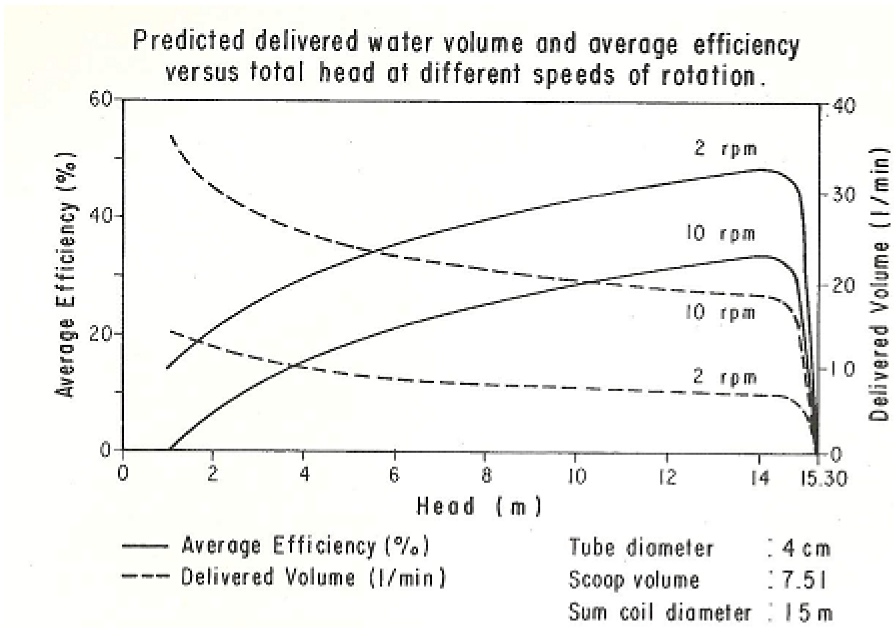

Figure 2.18 Naegwl's Head vs average efficiency and discharge result at different speed [7]

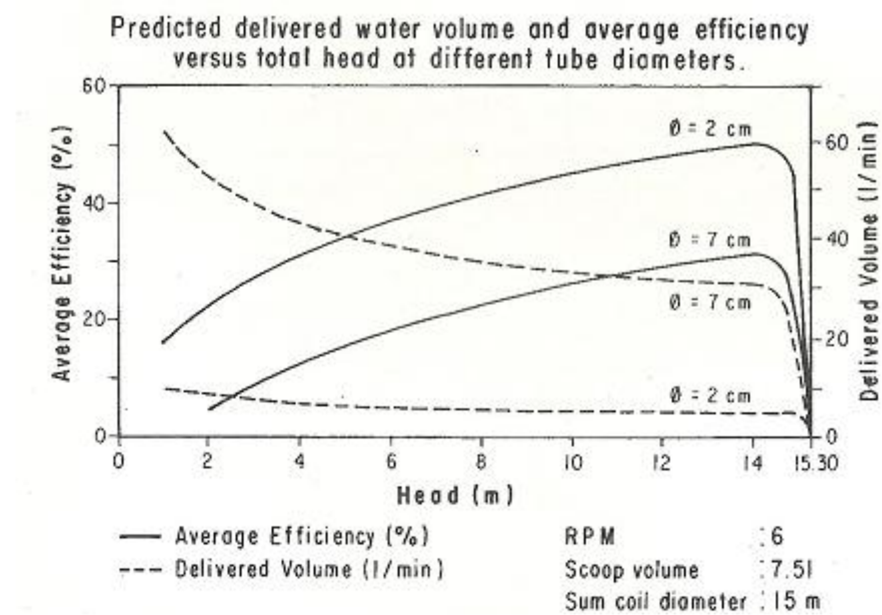

Figure 2.19 Naegel's Head vs average efficiency and discharge result at different tube diameter (Naegel, 1998)

Another interesting thing about this literature is a clear theoretical relationship is stated about power requirements to drive a spiral pump and available energy in the stream.

Accordingly the energy requirement consists of the product of power and time. A specific amount of work can be done quickly using of power, or slowly using less power, but in the end the identical amount of energy is required. The required and the available power have to be determined successfully design a pump. The power P is needed to deliver a water volume Q (l/sec) to a head of H (m) is:

$$P = 9.8 \times Q \times H(watts)$$

Equation 2.20

Where 9.8 is the gravitational constant in m/sec^2. If Q is in m^3/sec, the above formula gives P in KW.

Theoretically, 9.8KW are required to deliver a flow of 1 m^3/sec to a static head one meter. Though the actual power requirement will be higher because of the system inefficiency. For instance spiral pump with a total efficiency of 25% will need four times the amount of unit power.

Also the available kinetic energy in the stream can be calculated using the equation below, the kinetic energy P is proportional to the stream velocity cube.

$$P = 1/2 \times A \times \rho \times v^3$$

Equation 2.21

$were: \rho\ is\ the\ density\ of\ water\ \left(\frac{1kg}{l} for\ fresh\ water\right)$

$A\ is\ the\ area\ of\ cross\ section\ of\ the\ current\ in\ m^2$

$v\ is\ the\ mean\ velocity\ through\ the\ cross\ section\ in\ m/sec$

Pumps driven by hydropower tend to mechanically simple and robust, have long working lives, and require limited and simple maintenance. Moreover it is available 24 h/day.

In conclusion of the result analysis the report stated the most effective combination of parameters. That is high head, slow rotational speed, a scoop volume of 100 to 120% the outer coil, and small tube diameters. This results in a spiral pump with optimum discharge and corresponding high heads.

2.6. Parameters affecting the performance of manometric pump

According to the given literatures the following parameter affects the performance of a manometric pump in general. A serious experimental investigation has been conducted on coil pump types.

Those from existing literatures it is not clear that how those parameters affect spiral pumps. Though, since both coil and spiral pumps share same working principle it is clear that have similar performance affecting parameters.

1. **Spiral tube outer diameter:** when the outer diameter of the spiral turns get larger the, the head generated also get greater [33].
2. **Number of tube turns:** Number of the coils of a coil pump is directly proportional to the head generated [33]. According to Kassab evaluation the performance of a coil pump by varying the number of coils, the submerged ratio and the rotational speed of the pump (N). They found that increasing the number of coils increased the pressure head (HP) while the discharge (QP) remained constant [22].
3. **Tube diameter:** As reported by Mortimer and Annabel the spiral tube diameter doesn't affect the pressure head. Its effect is related to the pump discharge [8].
4. **Submergence ratio (S_r):** As submerged ratio increases discharge increases but has negligible effect on head [1]. As the Submergence approaches 100 percent, discharge (Q_p) increased but there is no significant effect on head (H_P) [22]. Flow rate will be zero when either the pump is fully immersed or completely out of the water.
5. **Wheel velocity (N):** The wheel velocity is directly the output of the stream velocity. Increasing N had negligible effects on HP but increased QP to Q max (for any given Sr) after which the amount of air entering the system began to decrease and QP approached zero. In short With increase in rotational speed, discharge increases till it reaches its maximum value depending on the working submerged ratio then discharge goes to zero at certain maximum speed and submerged ratio, while the maximum static head obtained is not much affected by increase in rotational speed [22].
6. **Stream flow velocity:** the speed of the water is directly proportional to the rotational speed of the water wheel [33].
7. **Blade size and shape:** The size of the plate is directly proportional to the force exerted on blade keeping velocity constant.
8. **Number of blades:** More the number of blade more is the force experienced by the wheel up to a certain limit but decreases after that. More the number of blades, greater is the torque on the water wheel. But after a certain number of blade, the torque decreases due to blockage of water by the subsequent blade. Therefore the number of blades should be

arranged in such a way that only one blade is fully immersed at a time. Therefore the number of blades is found to be 8 by taking the overall view of above point, the angular distance between the spoke is found to be 45 degree.

9. **Number of spiral layers:** According to N.R Patila (2013) study of two layers of spiral tube pump the maximum head (H) and discharge (Q) obtained is around 4.57 m (15 ft) and 1200 lit/hr respectively for single layer Performance. Analysis of Multilayer Spiral Coil Pump Discharge obtained was 2280 lit/hr for double layer of the pump with maximum head 4.8 m. For double layer, discharge is higher than the single layer at all rotational speeds [34].

Among the listed parameters the effect of submergence ratio, rotational speed, outer diameter and number of turns will be studied in this research project. Because they are most important in affecting the discharge and head output of the pump system implicates the other parameters.

2.7. Spiral pump in different countries

For developing countries application of spiral pump or any other type of manometric pump can make a difference. It will be a solution for irrigation problems. Since it doesn't require any electricity or fuel and can be manufactures and maintained by local craftsman. Some Asian countries have applied it on their irrigation field and have been satisfactory with its service.

In Indonesia an experimental research was conducted directly in the field. The waterwheel used a type of undershot flat blade 2 m diameter with 18 pieces of blade. The flexible hose was 38.1 mm diameter with a total coil of 4.55 windings, and an input diameter of 76.2 mm. The highest flow rate was 0.29 m^3/s, the highest spiral pump discharge output was 0.27 l/s with a spiral pump efficiency of 1.54 % and the head was 3.38 m [9].

Among African countries in Zambia Using locally available materials, a team of engineering students from Seattle University designed a waterwheel and coil pump to provide 30 litters of water per minute to a safe gathering area 30 meters onshore and at an elevation of 10 meters above the river. The team also sized a water storage system and designed a series of washbasins for the site [9].

In Pune, India the hand operated experimental setup is designed and constructed to analyse the performance of the spiral coil pump under different parameters. The parameters considered are submerged ratios, rotational speed, layers of coils. For setup of 0.8 m wheel diameter with 7 number of coils, the maximum head obtained is in between 4.3 m to 5 m with maximum discharge 1200 lit/hr for single layer and 2280 lit/hr for double layer of the coil with efficiency range 20% to 74% [34]. Also another study in India Under the operating condition of 0.30 to 0.46 m of water depth with flow velocity of 0.41 ms^{-1} to 0.54 ms^{-1} and carrying distance of 1 m to 20 m, the discharge of 180 to 270lph was obtained [34].

In Egypt an excellent study is conducted on coil pump. The parameters considered in this study were submerged ratios, rotational speed and number of coils of the wrapped hose [22].

The first article that tried to clear state the analytical relationship between the important parameters was conducted in England by G.H. Mortimer and R. Annable. From the old idea of manometric pump and laboratory investigations a theory has been produced which satisfactorily predicts the pump's behaviour. A low cost stream powered version of the pump was built and successfully tested in a local stream [8].

Recently in England specifically in spiral pump a study is conducted. Taking a novel dynamical systems approach, they derive a discrete mathematical model in the form of a mapping that describes its hydrostatic behaviour. This model enables us to explain several aspects of the behaviour of the pump as well as to design one that gives approximately maximal, and maximally constant, output pressure [10].

2.8. Design of Experiments (DOE) Using the Taguchi Approach

Rajnit K. Roy wrote to a great books on Taguchi approach design of experiment. Those are; Design of Experiments Using the Taguchi Approach: 16 Steps to Product and Process Improvement which published on January 2001 and Primer on the Taguchi Method which published on 1989. From those the following points are reviewed in the ways that suits the objective of this study.

According to Ranjit K. Roy Design of Experiments (DOE) is a powerful statistical technique introduced by R. A. Fisher in England in the 1920's to study the effect of multiple variables simultaneously. In Japan, DR. Genechi Taguchi carried out significant research with DOE techniques in the late 1940's. He spent considerable effort to make this experimental technique more user-friendly (easy to apply) and applied it to improve the quality of manufactured products. DR. Taguchi's standardized version of DOE, popularly known as the Taguchi method or Taguchi approach, was introduced in the USA in the early 1980's. Today it is one of the most effective quality building tools used by engineers in all types of manufacturing activities [35].

2.8.1. The need for Design of Experiments (DOE)

DOE can be highly effective to:

- Optimize product and process designs, study the effects of multiple factors (i.e. - variables, parameters, ingredients, etc.) on the performance, and solve production problems by objectively laying out the investigative experiments [36] [37].
- Study Influence of individual factors on the performance and determine which factor has more influence, which ones have less. It is also possible to find out which factor should have tighter tolerance and which tolerance should be relaxed. And many more [37] [38].

2.8.2. Advantages of DOE using Taguchi Approach

The following points are some of the advantages of Taguchi approach [36] [39];

- Experiment planning guidelines are consistent with modern work disciplines
- High emphasis is put on cost and size of experiments
- Size of the experiment for a given number of factors and levels is standardized
- Clear guidelines are available to deal with factors and interactions (interaction tables)
- Uncontrollable factors are formally treated to reduce variation
- Guidelines for carrying out the experiments and number of samples to be tested are defined
- Steps for analysis are standardized
- Standard practice for determination of the optimum is recommended
- Clear guidelines about meaning of error term

In overall Taguchi experiment design technique is to achieve reduced variation (also known as Robust Design) [40]. This technique, therefore, is focused to attain the desired quality objectives in all steps.

2.8.3. Topics in Taguchi Design

As stated by S. Kumar the following points are crucial topics regarding Taguchi design [40];

1. Objectives and Evaluation Criteria

What are the criteria of evaluation? How are each of these criteria measured?

2. Factors

What are the factors that influence the performance criteria? Which factors are more important than others?

3. Noise Factors

Which factors can't be controlled in real life? Is the performance dependent on the application environment? Noise factors are those factors: that are not controllable, whose influences are not known, which are intentionally not controlled. To determine robust design, experiments are conducted under the influence of various noise factors.

4. Factor Levels

What are the ranges of values the factors can assume within practical limits? How many levels of each factor should be used for the study?

5. Interaction between Factors

Which factors are most likely to interact? How many interactions can be studied?

6. Scopes of Studies

How many experiments can we run? When do we need the results? How much does each experiment cost?

Another important issue is Quality Characteristic (QC). It generally refers to the measured results of the experiment. The QC can be single criterion such as pressure, temperature, efficiency, hardness, surface finish, etc. or a combination of several criteria together into a single index. QC also refers to the nature of the performance objectives such as "bigger is better", "smaller is better" or "nominal is the best" [40].

2.8.4. Available Orthogonal Arrays

The following Standard Orthogonal Arrays are commonly used to design experiments:

- 2-Level Arrays: L-4 L-8 L-12 L-16 L-32 L-64
- 3-Level Arrays: L-9 L-18 L-27 (L-18 has one 2- level column)
- 4-Level Arrays: L-16 & L-32 Modified

2.8.5. Factors in Taguchi Approach

Signal Factor: is an input to the system. Its value/level may change.

Control Factor: is also an input to the system. Values/level is fixed at the optimum level for the best performance.

Noise Factor: is an uncontrollable factor. Its level is random during actual performance.

2.8.6. Static and Dynamic system approach in Taguchi Design

Static System Goal is to determine combination of control factor levels which produces the best performance when exposed to the influence of the varying levels of noise factors [35] [40].

Dynamic System Goal is to find the combination of control factor levels which produces different levels of performances in direct proportion to the signal factor, but produces minimum variation due to the noise factors at each level of the signal [35] [40].

2.9. Literature gap

From the literatures reviewed the following points can be gaps to be filled if this study is conducted.

- Coil pump is studied by S.Z Kassab and R. Annable well enough. But there is no recent literature that depicts if there is adequate study is done on how the parametric variables affect the performance a spiral pump.
- Even if both spiral pump and coil pump are manometric pumps their respective performance is not compared in the literatures.
- The previous studies doesn’t consider the effect of the water wheel performance on the overall pump system performance.
- The analytical relationship between different parameters is not clearly stated.
- Literatures have limitation in clearly defined the design procedure of spiral pump system

3. Materials and Methods

3.1. Description of the study area/selected river

The study is conducted in Jimma town; which is found in Oromia regional state, 353km Southwest of Addis Ababa the capital city of Ethiopia. The experimental procedure is conducted in Bosa kito kebele at river Kito with a geographic location of 7.670860, 36.822613. Form general observation and educated conclusion this river can represent the characteristics most of the rivers in Ethiopia. Its speed ranges from 5 m/s to 12 m/s depending on weather and its course. The average 8.5 m/s taken for calculation and simulation purpose.

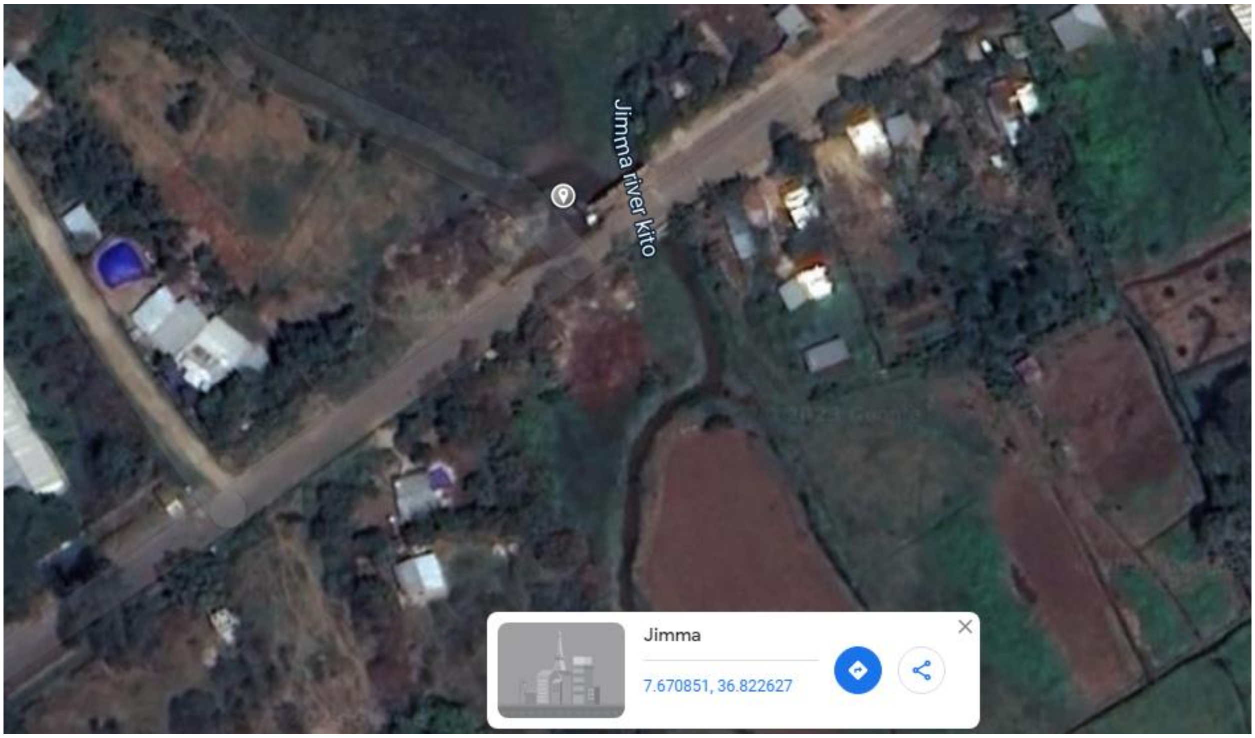

Figure 3.1 River Kito, Source; Google map

3.2. Material and apparatus; Spiral Pump Experimental prototype

This experimental study is conducted on a prototype designed and manufactured by the researcher in universities workshop. The design of the prototype is done based on the literatures suggestion. As mentioned in section 2.7 in many different countries researchers have tried to design and implement different kinds of manometric pipes. Those implementation and the observation have led a base to design and manufacture this study's spiral pump. The Figure 3.2 shows the design of spiral pump wheel structure that developed during the study.

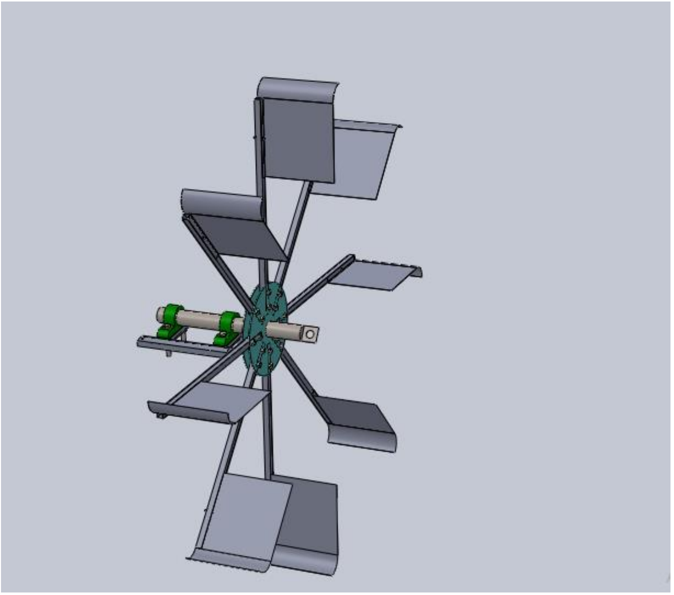

Figure 3.2 3D model of experimental prototype of spiral pump water wheel

Since the manufacturing of this pump is conducted in local workshop, it makes the study more realistic. Because the objective of this study is to grant low cost, locally manufactured pumps to the small farmers. So while conducting this study challenges to develop spiral pump locally is observed also the real problem and capacity of locally manufactured spiral pump are investigated. The following Figures depicts the manufacturing process and the resulted prototype of spiral pump.

Figure 3.3 Manufacturing process of spiral pump prototype in Mechanical engineering laboratory

Figure 3.4 Spiral pump prototype

In developing the prototype manufacturing and designing of most parts of the pump was not complex but designing and manufacturing the rotary joint was too difficult. Till the end of the study developing leakage free rotary joint is unattained. The leakage was minimized to acceptable level and its effect on the result is considered well enough. In the following subheading the design and manufacturing process of the parts of spiral pump is clearly described.

3.3. Parts of the spiral pump

The spiral pump system contains the water wheel and the spiral tube subsystem. The spiral tube subsystem contains a flexible tube and scoop. The water wheel contains paddle, spoke, disk, stage and a bearing. Also the crucial part of the system the tube shaft which use as an axle for the rotating water wheel and as passage to that transfer the pressurized water to the delivery pipe. The other the most crucial part is the rotary joint that connects the whole pumping system with the delivery pipe. Each parts are discussed below briefly;

Figure 3.5 Disassembled prototype of spiral pump prototype

3.3.1. Spiral tube and scoop

This subsystem is where all the pumping principle relies on. Scoop is a wider tube attached on the outer tip of the spiral tube. Its main purpose is to scoop specified amount of water hold it until it inters to the spiral tube. In the spiral tube the water develops pressure with the principle described earlier.

The scope is made from 10cm wide and 12cm log plastic bottle while the spiral tube is made from ¾ inch clear flexible plastic tube.

3.3.2. Paddle

In water wheel system the paddles are the most important parts. Because they are the interface that the work is done on. In other words it consume the kinetic energy of the flowing fluid hitting it. so that as the waterwheel purpose is to convert the kinetic energy in the flowing streaming to rotating energy form, the paddles are the vital parts of the a water wheel. As discussed in the literature review the shape and the orientation of a paddles have major effect in energy conversion efficiency of the water wheel. So in this study to make the pump system more efficient three types of paddle shapes and orientation were studied; the flat paddle, the curved (poncelet type), and the slanted curved paddles using a numerical method. The curved paddle type is selected to be manufactured and tested based on the numerical study result.

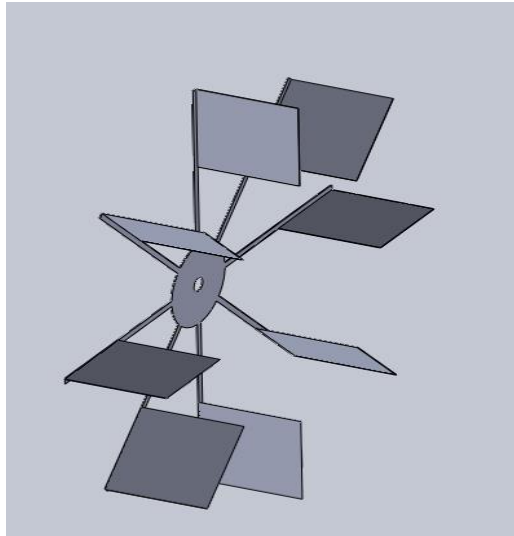

Figure 3.6 Flat Paddle wheel

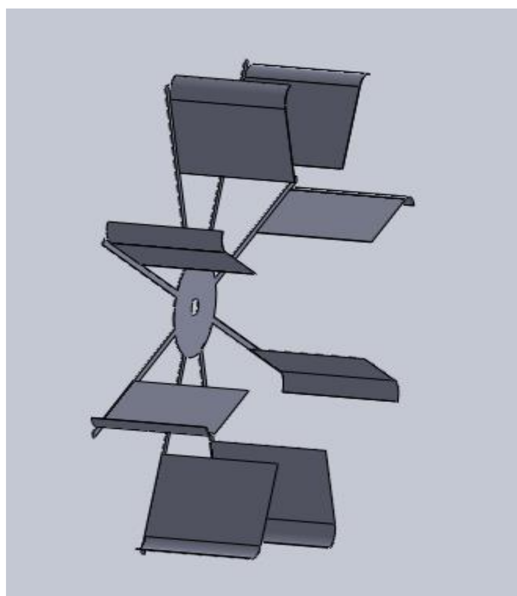

Figure 3.7 Curved paddle wheel

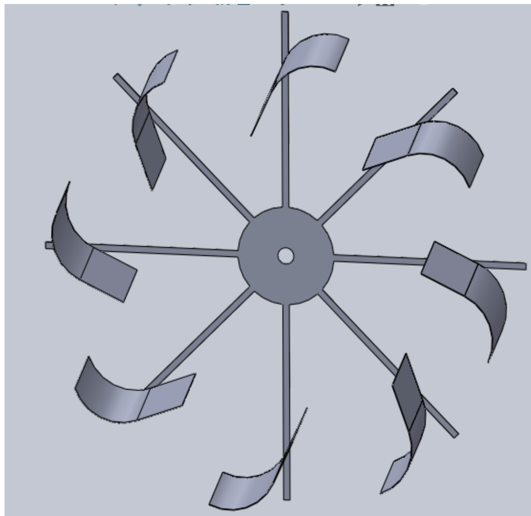

Figure 3.8 Slanted Curved Paddle wheel

Figure 3.6, 3.7 and 3.8 demonstrate the alternatives shape and orientation for the water wheel paddle shapes. In fact there are lot of paddle shape, orientation and number available in water wheel technology the above three are selected based on criteria such as efficiency, ease of manufacturability, cost and maintainability.

The curved paddle type is selected to be manufactured and tested based on the literatures suggestion. This paddle has 25*23cm area, 1.5mm thickness and a curvature with 5cm radius is added at the longest end. Eight paddles are used based on the assumption one paddle in full contact with the stream. It is made up of aluminium sheet.

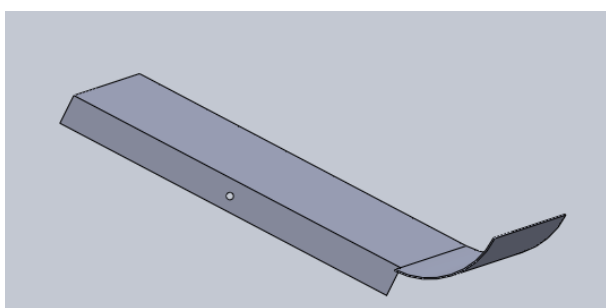

Figure 3.9 Curved paddle

3.3.3. Spoke

Spoke is the structural frame of the water wheel that holds the blade. Also the diameter of the water wheel is mainly implies the length of the spoke. More importantly the spiral tube and the scoop are attached to this part. There are eight spokes to handle eight paddle. Each spoke is 75cm long made from 20*20mm and 1.5 thick RHS.

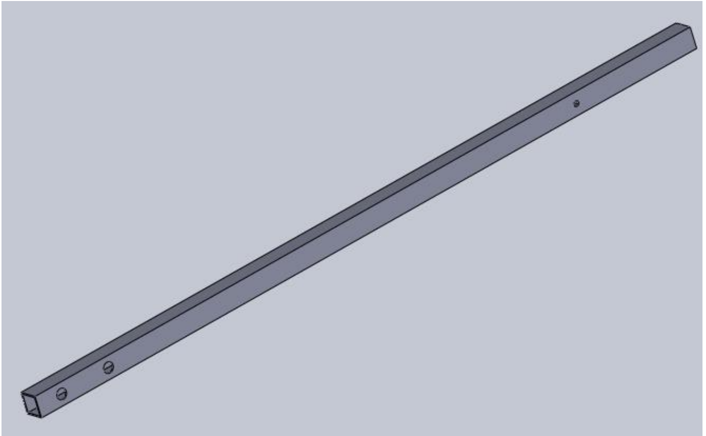

Figure 3.10 Spoke

3.3.4. Holding Disks

This part get to be named holding disk since it has a shape of disk, and has purpose to hold and connect the spoke with the tube shaft. In addition to holding the spoke it serves as fly wheel to store the rotational energy. They are made up of 30cm radius and 3mm thick metal sheet.

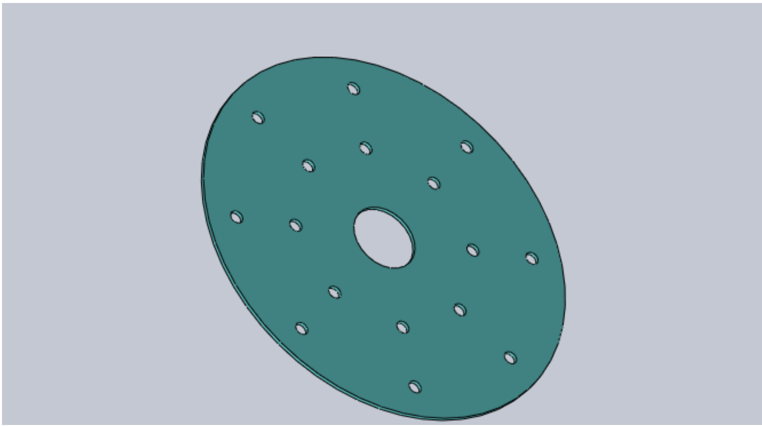

Figure 3.11 Holding disk

3.3.5. Stage

The stage is the base structure where the bearing is attached to. Since this prototype is built for experimental purpose, it is designed to be simple and to be attached on another structure to hold the whole system. This other structure can be a stationary structure built on the banks of the river or floating on the river. This is not the concern of this study. Any of them can be chosen based on the river condition. If the river is deep it is recommended to build a floating structure to seat the pumping system otherwise a stationary structure can be built in the river or on the banks of the river.

The stage is built from 60*40mm RHS.

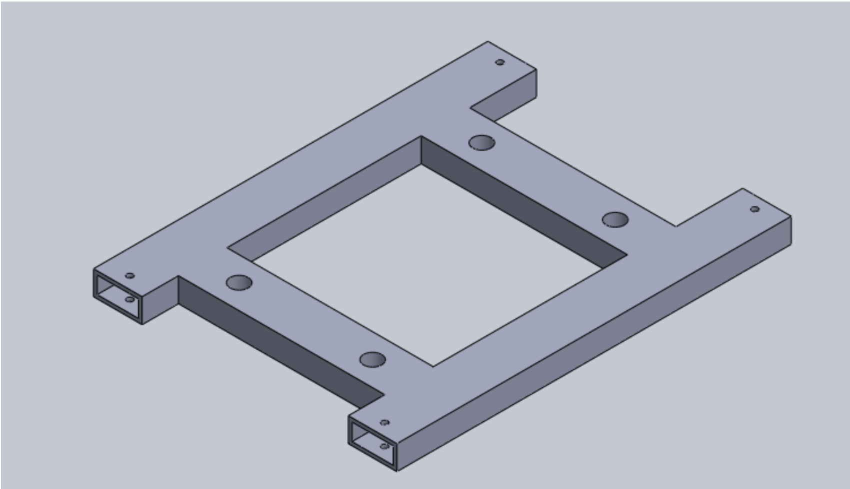

Figure 3.12 Stage

3.3.6. Tube shaft

This part has two purpose. The first one is to serve as a shaft for the rotating water wheel. Secondly it will collect the pressurized water from the spiral tube and pump it to the delivery pip through the rotating joint. It is made up from 2inch diameter galvanized metal tube. At one end of the tube a special feature is added that help to rotate the wheel manually.

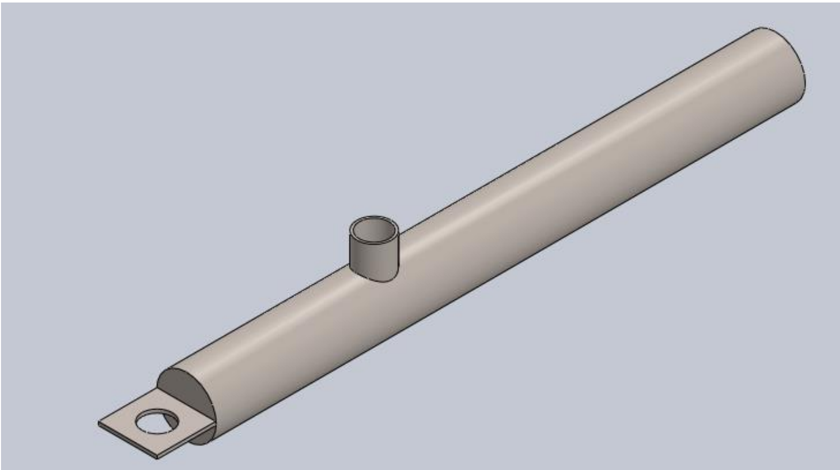

Figure 3.13 Tube Shaft

3.3.7. Rotary joint

The rotary fitting is a critical part of the spiral pump. It connects the rotating tube shaft with stationary delivery pipe while providing a relatively watertight seal to prevent fluid and pressure loss. If a compressed air escapes the pump will be highly affected.

In Ethiopia this kind fitting is not yet well introduced. So it is not found in the market. As a result it is tried to develop it with sealed ball bearing and rubber gasket. Though leakage was inevitable. So that while doing the study loss of pressure due to this leakage is taken in to account.

3.3.8. Delivery pipe

Delivery pipe has unneglectable effect on the performance of the pump. Because the size of the delivery pipe also appeared to influence the air lift effect. In this 4.5m long study ¾ inch flexible plastic water tube is used.

3.3.9. Bearing

The tube shaft has to be support with two efficient bearings. Unless the water wheel performance or energy conversion capacity will be highly affected. The wheel should rotate with much lower torque from the stream. Since water tight bearing is too expensive, in this study two ordinary ball bearings with housing is used. A ball bearing designated 6304-2RS with 55mm inside dimeter is used.

Figure 3.14 Bearing with housing

3.3.10. Fasteners

The parts of the spiral pump is designed to be mostly temporarily fastened so that it can be assembled and disassembled to make it easy for transportation. Therefore, M5 50mm long bolt is used as a fastener mostly.

3.4. Software tools

The following software tools were utilized to conclude the study successfully:

SOLIDWORKS 2019: is used to develop the 3D and 2D geometric model of the pump system design.

SOLIDWORKS® Flow Simulation: As SolidWorks Corporation describes is an intuitive Computational Fluid Dynamics (CFD) solution embedded within SOLIDWORKS 3D CAD that enables you to quickly and easily simulate liquid and gas flows through and around your designs to calculate product performance and capabilities. It is a general parametric flow simulation tool that uses the Finite Volume Method (FVM) to calculate product performance. [41].

Minitab Statistical Software: was used to perform calculations related with Taguchi design of experiment.

MS Excel: is used to process and present the experimental data.

3.5. Testing apparatus

The following four main apparatus was used to measure the most important parameter

3.5.1. A gallon bucket

A bucket with volume of one gallon (3.785 litres) in combination with stopwatch is used to measure the discharge of the pump.

3.5.2. Scaled bar

A scaled bar is a simple wooden bar that have grooves on it showing metric scale. It was planted vertical at some elevation from the river surface. And used to measure the vertical head pumping capacity the pump system.

Stopwatch: A stopwatch was vital apparatus in measuring the discharge, speed of the river and RPM of the wheel.

Scale: a metric scale is used to measure distance quantities whenever it is needed; such us the depth of the stream, width of the stream and as such.

3.6. Methodology

3.6.1. Design of experiment

Design of experiments (DOE) is a systematic and statistical approach to planning, conducting, and analysing experiments in order to gain insights into cause-and-effect relationships between variables. DOE involves designing experiments that manipulate one or more factors or variables, while holding all other factors constant, in order to determine their effect on a response variable. DOE can be used to optimize product design, improve manufacturing processes, and identify key factors that affect product quality or performance. It is a powerful tool for reducing variability, increasing efficiency, and minimizing costs in research and development. Among money types of DOE Taguchi design is selected to design this experimental study.

Taguchi design, also known as the Taguchi method, is a type of Design of Experiments (DOE) that is focused on robust design and parameter optimization. This approach was developed by Genichi Taguchi, a Japanese engineer who emphasized the importance of quality control and cost-effectiveness in manufacturing processes. The Taguchi method involves designing experiments to find the optimal combination of input factors that will lead to a robust and high-quality product or process.

3.6.2. Study variables

The objective of this study is to fill the necessary knowledge gab and make the well performing spiral pump. Therefore anyone who need to use the pump make simple sizing and make it. So as stated in the objective section, the kind of paddle shape that enables the wheel to harness more kinetic energy from the river is studied.

Most importantly how submergence ratio, rotational speed, outer diameter and number of turns of the spiral tube affects head and discharge is studied. So that submergence ratio (Sr), wheel speed (w), outer diameter (Do) and number of turns of the spiral tube (n) are independent variables. Whereas Discharge (Q) and Head (H) are dependent variables.

3.6.3. Sample design and size

To continue experimenting sample value must be selected for each independent variables or factors. These sample values are stated in the table below;

Table 3.1 Study Variable and Levels

Factors	Levels			
Wheel speed (RPM)	5	15	25	35
Submergence Ratio	20%	40%	50%	80%
Number of spiral turns	3	4	5	6
Outer diameter	0.8	1	1.2	1.5

Those levels are selected based on reality or applicability. Meaning the wheel speed maximum level is selected to be 35RPM because in the experiment the wheel was rotated using human power. Based on several trial it observed that the maximum stable wheel speed that can be attained by rotating the wheel with hand is 35RPM. Also with lower stream speed the wheel speed can get slower up to 5RPM and much less.

Regarding to submergence ratio selection of submergence value is based on the depth of river and the water proof characteristics of the bearing. If the bearing is sealed and rust resistant we can immerse the submersion above 50% unless it is advised to immerse the pump near to 50% at maximum.

The number of spiral pump implicates the weight of the water in the spiral tube if the spiral turn number is higher the mass of the system will rise as the wheel turns. So eventually it may stop rotating. Also the depth of the river limits the number of spiral turns.

The outer diameter is mainly restricted by the depth of the river. Most of Ethiopian rivers are mostly shallow for most of the season except in summer.

3.7. Experimental setup

The general experimental setup is shown on the Figure 3.1. As shown the spiral pump system consists both the spiral tube and a simple water wheel. The spiral tube is attached to the wheel using the metal wire. The pitch distant between each spiral turn is specified based on the number of turns. In the Figure 3.15 there are 5 spiral turns with around 120cm distance in between.

The whole system is placed over pre developed wooden structure planted firmly in the river. This structure has four levels. Those levels were suitable to place the stage on it. The primary purpose of these stage were to allow submergence ratio change. When the stage is placed on the top level the submergence level of the pump will be 20%, as the level decrease lower the submergence ratio will increase up to 80%.

The main objective of this experimental procedure is to study the effect of submergence ratio (Sr), Wheel speed (N), number of spiral turns (n), and Do on H and Q. in this experimental procedure the paddle was not needed, because it causes drag while rotating the wheel manually. So that was detached. The after it attached to see how the paddle shape performs. Basically studying the paddle shape experimentally with available resource was very difficult, and full of uncertainties. So that the shape of the paddle was studied numerically using SolidWorks flow simulation 2019 version.

Figure 3.15 Experimental setup on Jimma Kito River

3.8. Test procedure

Experiment is conducted using the following procedure;

1. First, the pump with the certain number of spiral turns is placed at certain level on the wooden structure. This determines the pump Submerged ratio (Sr).

2. The wheel is rotated manually with a certain speed. And this speed was recorded. This speed is the pump wheel speed (W).
3. The delivery pipe outlet was placed at pre-determined vertical distance from the river level. This vertical distance from the river level implies the pump vertical head (H) whenever there is discharge.
4. The pump discharge is collected in gallon bucket. Calculating a certain volume in the gallon bucket gives the pump discharge/flow rate (Q) at certain rotational speed, submergence ratio number spiral turns and head.
5. At the fifth procedure on experimental process was completed. The next will start by altering the number the number of spiral turns or by changing the submergence ratio.

In each step of the experimental procedure serious data recording and documentation was done.

3.9. Method of analysis and presentation

Upon successful completion of the data collection work, the collected data was analysed and interpreted by using Microsoft excel office and Minitab software. Its optimization and analysis conducted using Taguchi method.

3.10. Data quality Assurance

According to (APHA), proper quality assurance procedures and precautions were performed to assure the results' credibility. A field work manual was utilized to check every step of the process in order to improve the data quality. In addition, carefully selected assistants were chosen to handle the data. The acquired data was further double-checked for accuracy and reliability. The major expected error is measurement error. To avoid those errors care full data errors, calibration (standardization) is conducted in data recording documentation process.

4. Result and Discussion

4.1. Effect of paddle shape difference in energy conversion

In stream powered spiral pump water wheel is a system component, which is responsible for bringing the rotational energy needed to the system. So while aiming for efficient locally made spiral pump considering the efficiency of energy conversion is important.

In usage of water wheels for spiral pump application the concern is speed rather than the torque. Yucheng Liu in University of South Dakota worked on Evaluation of Paddle Wheels in Generating Hydroelectric Power [32]. In this study he developed validated approach to determine the speed of a water wheel based on analytical algorithm. Accordingly in this study similar approach is used for different purpose. Unlike Yucheng Liu the purpose of this study was to determine how significant the effect of paddle shape on the speed of the water is. Liu stated that assuming the wheel rotates with the same speed as the water passes through is incorrect.

The speed of water wheel will can be affected by many factor such as river speed, paddle shape, diameter of the wheel, number of paddles, mechanical efficiency the wheel and so on. To alter a river speed require higher investment on the course of the river so it couldn't be an interest in this case. Wheel diameter is parameter preserved for spiral tube meaning it will be determined based on the outer diameter of the spiral tube. Increase a number of paddle to increase the speed also results increased cost of manufacturing. So the soundest parameter for the sake of increasing the wheel speed is to play around with its paddle shape.

In 1820s Poncelet wheel was developed in France. It distinguished feature it curved blade. According to Emanuele it exhibited higher efficiency because of this feature [24]. Also Muller suggested 22.5 degree forward inclination of the paddles and curved paddles with a radius which allows for the exit of the blade out of the water with a minimum of energy loss for higher power yield [29]. Based on these speculation in this study using SolidWorks flow simulation tool is utilized to a numerically asses the speed of water at the tip of different paddle shapes. According to Yucheng Liu the assumption that the speed of river and wheel are similar is oversimplified that may lead to wrong estimation. After finding this speed the speed of the water wheel will be calculated using equation 4.1.

$$\omega = \frac{v}{d}(RPM) = \frac{60v}{2\pi d}(\frac{rad}{second})$$ *Equation 4.1*

A simulations was conducted that mimic flat paddle, curved paddle and slanted curved paddle water wheels to predict the velocity at the tip of the paddle. The result these simulation are shown on Figure 4.1 - 4.3. The simulation setting is also presented on the Table 4.1.

Table 4.1 Paddle shape simulation setting

General setting	**Analysis type - external**
Mesh type	Global mesh
Mesh Size	Coarse mesh
Fluid type	Water
Flow character	Laminar and turbulent, cavitation checked
Wall condition	Adiabatic
Roughness	0 micrometre
Pressure, and temperature	0 1atm, 293 K
Gravity	Y-component = -9.81m/s
Rotation	X-axis = 0 rad/s
River velocity	Z- component = -8.5 m/s

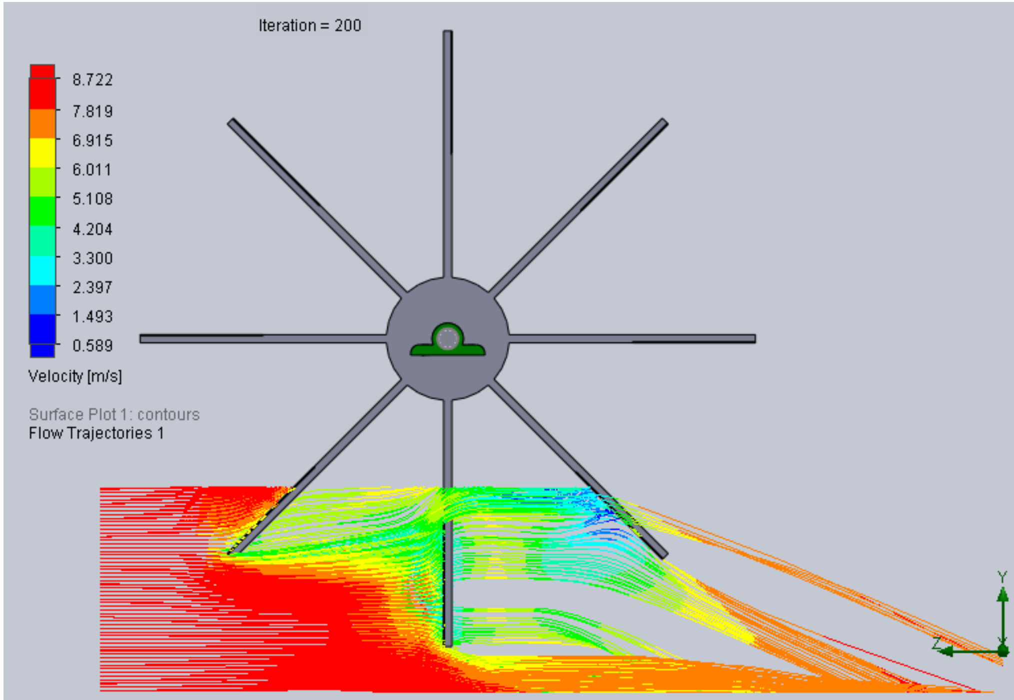

Figure 4.1 Flow speed distribution at the tip of flat wheel

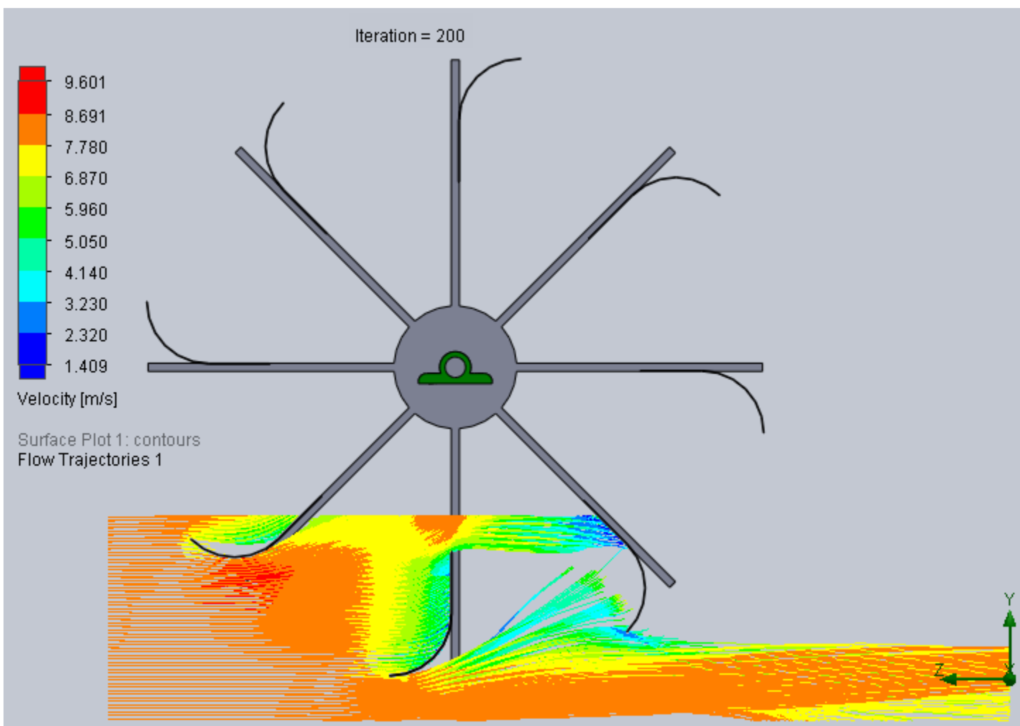

Figure 4.2 Flow speed distribution at the tip of curved wheel

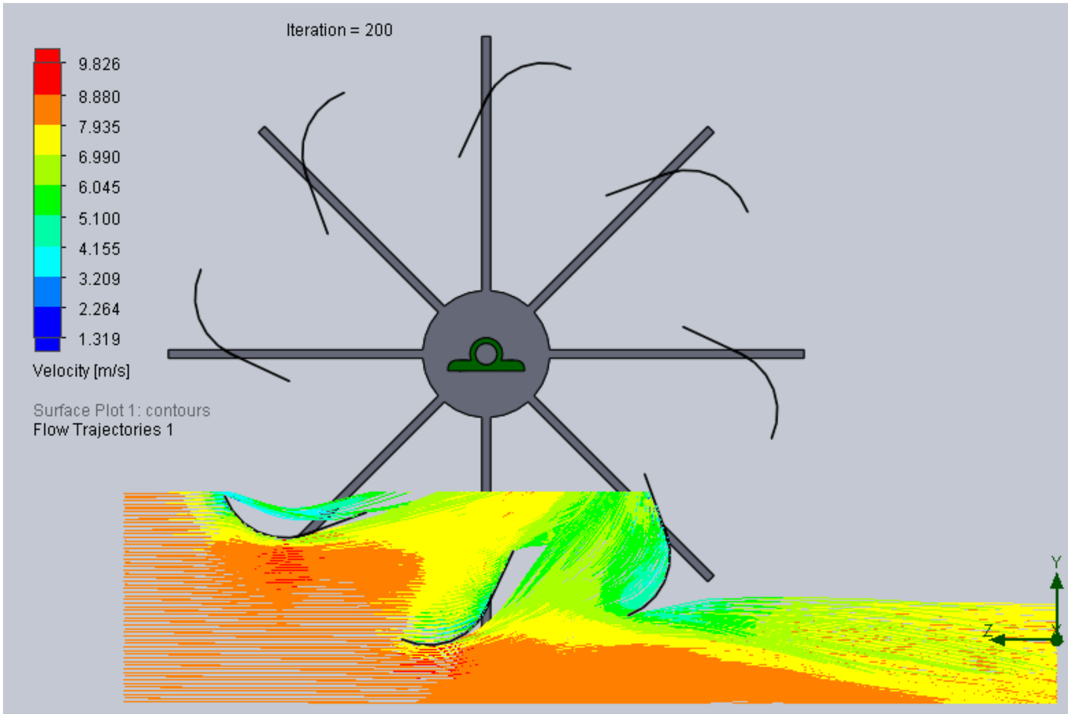

Figure 4.3 Flow speed distribution at the tip of Slanted curved wheel

The above three figures illustrates the velocity gradient when the river water of hits the paddle and pass. On theses simulation result the maximum speed is exhibited on the tip of the paddle. This maximum speed varies with the variation of paddle. As the result shown the maximum speed at the tip of slanted curved paddle is higher.

Table 4.2 Maximum water speed and wheel velocity

Paddle Type	**Max. River Water Speed (M/S)**	**Wheel angular velocity (RPM)**
Flat	8.722	11.629
Curved	9.601	12.804
Slanted and Curved	9.826	13.105

This speed variation resulted more than 1 RPM difference on wheel angular velocity this matters in application of water wheel for spiral pump. In summary the shape and orientation of a paddle in water wheel affects the wheel speed significantly for the purpose of water wheel. So making the paddle curved and installing them at 22.5 degree from vertical yields a greater wheel speed.

4.2. Effect of important parameters on spiral pump performance

The effort to examine the effect of important parameters in the pump's performance took more than 408 serious experimental procedures without including uncertain high number of trials. Each experimental procedure is repeated three times to preserve its certainty and avoid error as much as possible. Also they were much closer to the realistic working environment of the pump. Unlike previous studies the experimental procedure of this study is conducted in flowing river rather in laboratory in stationary tanker of water. The results of each experimental procedure are presented with graphs followed by the respective discussion.

4.2.1. Effect of Variation of wheel speed

In the case of stream powered spiral pump the required energy to rotate the wheel will be gained from the kinetic energy of the stream. This means the user has no control on the speed wheel rotates. It depends on the flow rate of the stream. In such situation it may seems there is no need to study the effect of wheel. However even if it seems it is not true. First of all with the rotation of the pump is crucial part of the pump system. Moreover understanding how the wheel speed affects the pump performance help the designer to decide to select appropriate location on the runway of the stream to install the spiral pump system, so that better performance acquired.

As mentioned in the above paragraph the wheel speed is not parameter that can be controlled by the user in the real situation it is all dependent on the flow rate of the stream. Though since it is important to understand how it affects the pumps performance the variation in wheel speed is established by rotating the wheel manually with almost a constant speed. So the selected variations in wheel speed are in the range a wheel can be speed up manually with stability. So that after many trials 35 RPM is found to be the maximum stable speed that can be attained manually.

The effect of variation of the pump speed on the discharge (Q) and maximum static head (H) of the pump at various submerged ratio, Sr, is presented in Figure 4.4 and Figure 4.5 respectively. These results are for one layer, for outer diameter, D_o = 1.5 m, tube diameter, dp = 3/4 in, number of spiral turns n = 5 turns and at head = 1.5 m. obviously with at zero RPM of rotation no output is expected. But when the rotational speed rises the discharge also rises proportionally. For instance on the 20% submergence ratio for 10 RPM increment in speed around 19 litres per minute increment in discharge is exhibited. At the same submergence ratio with maximum speed of 35 RPM about 70 litres of water is collected per minute, which is about 30 litres per min. The discharge also showed a significant increase with the increase of submergence ratio. With 20% increase in Sr around 67% in discharge is observed. At maximum speed (35RPM) and with 80% immersion the pump yielded 200 litres per minute which is astonishing.

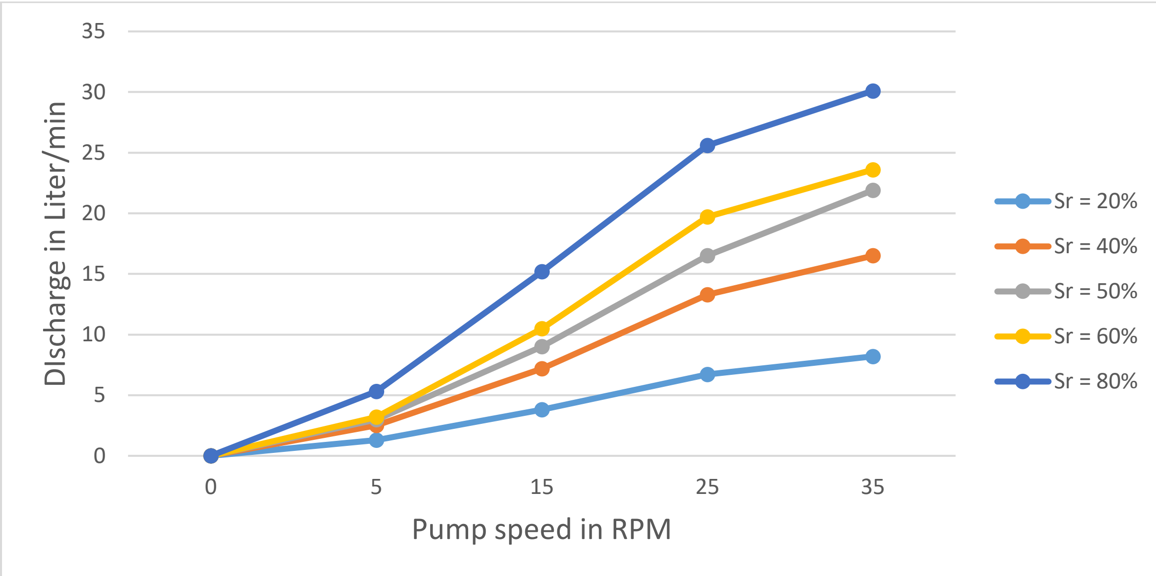

Figure 4.4 Variation of the pump discharge with rotational speed at different submerged ratio

This proves the theoretical relationship that stated by Mortimer and Annabel on equation 2.11 with 5% error. This means the variation of wheel speed affects the pump discharge directly and proportionally in similar manner as of the coil pumps. In other words while the wheel speed increase the spiral pump discharge also increases. This may suggests the installation of the pump should be on location that the stream with higher velocity so that the pump wheel turns with the higher speed possible.

Unlike the discharge the maximum static head of the pump has shown almost no difference when the wheel speed is increasing. As a matter of fact it shown slight decrease at higher submergence, like on 80%. While the speed rises from 5 to 35 RPM the maximum static head stayed around 3.3 meters on average.

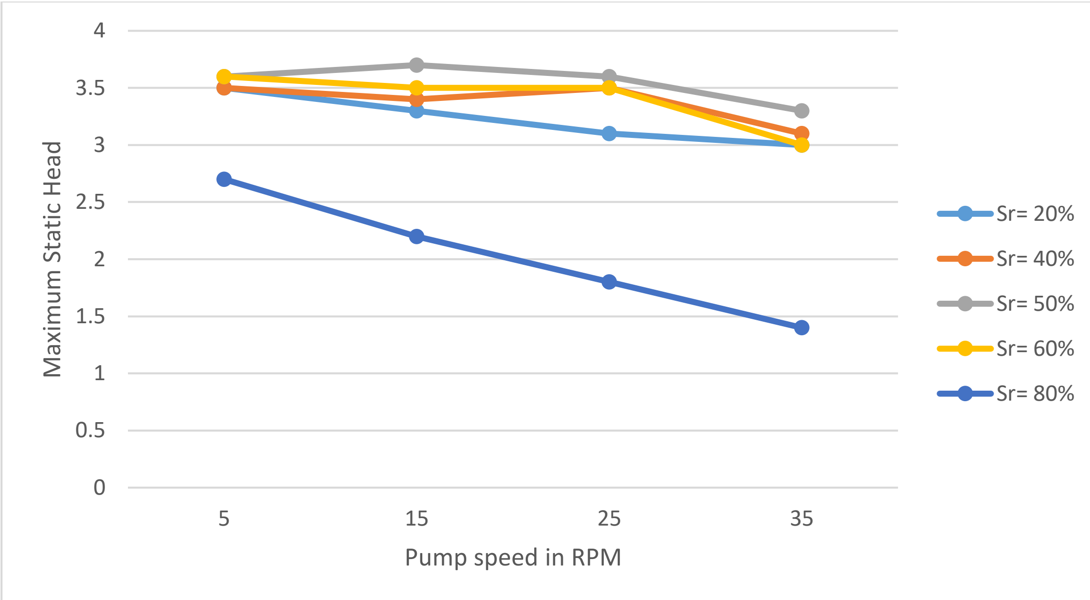

Figure 4.5Variation of max. Static head with rotational speed at different submerged ratios

This result implies the effect of the wheel speed on the pump maximum static head is insignificant, or it doesn't affect it. The pump speed only affects the discharge significantly.

4.2.2. Effect of Variation of Submerged Ratio

Submergence ratio is another important parameter that is labelled to have an effect on the performance of spiral. Because, it implicates the amount of water entered the spiral tube per a rotation. When the spiral pump is 20% submerged, there is a possibility that 20% of the outer spiral tube to be occupied with water if effective scoop is installed. So that as the theoretical relationship suggests the pump deliver such amount of water with a single rotation.

The effect of variation of submerged ratio on the discharge (Q) and maximum static head (H) of the pump at various wheel speed (N), is presented in figure 4.6 and 4.7 respectively. These results are for one layer, for outer diameter, D_o = 1.5 m, tube diameter, d_t= 3/4 in, and number of spiral turns n = 5 turns.

At 0% submergence there was no delivery, obviously. Since there is no inlet water there will not be output. Similarly on 100% submergence zero discharge is observed. This is because the idea of 100% submergence is in the contrary of the working principle of manometric pump. A manometric pump to be functional there must be a plug of air compressed between plug of water. To make this true the pump must rotate with submergence ratio less than 100%.

Other than these two points the discharge of the pump shown increment when the submergence ratio increases. While a pump was rotating at 5 RPM around 1.34 lit/min discharge is recorded at 20% submergence. At same speed the discharge raised to 5.3 lit/min when the submerged 80%. The maximum discharge recorded was 30 lit/min.

So that when submergence ratio approaches to 100% the discharge of the spiral pump increase until it decline and back to zero when the pump is fully submerged. The submergence ratio is directly proportional with pump discharge

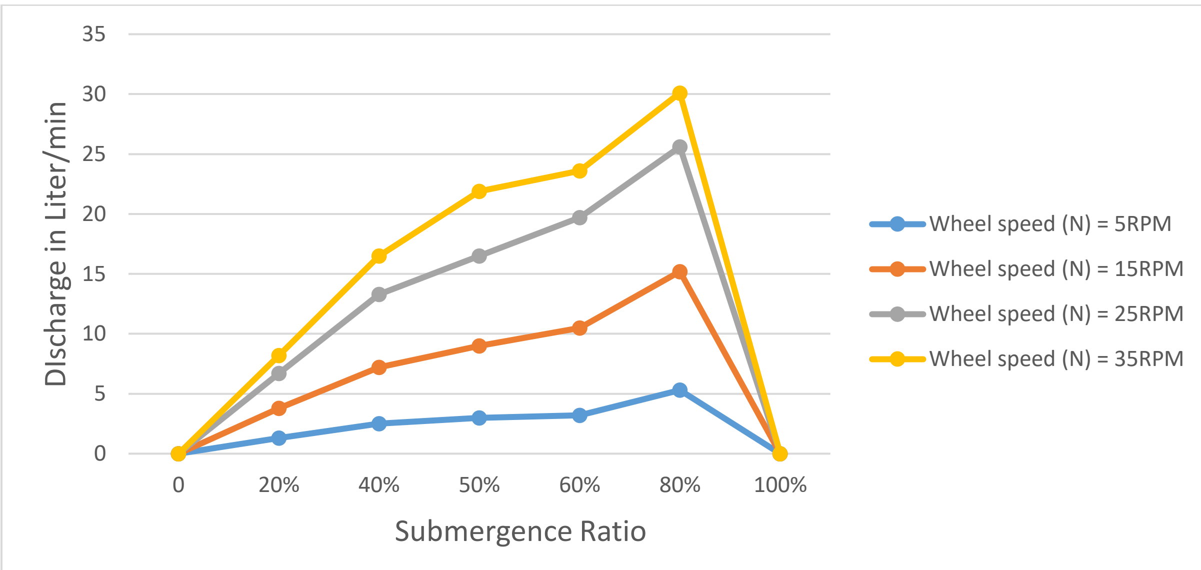

Figure 4.6 Variation of pump discharge with submergence ratio at different speed, H=1.5m

Unlike pump discharge the maximum static head exhibits insignificant increase with the increase of submergence ratio. It is obvious the head is zero at 0% and 100% submergence ratio. At 5 RPM wheel speed the pump head was around 3.5 meters up to about 60% submergence ratio, though around 80% the head declined to 2.8 meters. This is implies the spiral tube was unable to let enough air mass. So that the cumulative head build up lessened.

In general variation in submergence ratio has negligible effect on maximum static head for wider range of submergence ratio. Though when the submergence ratio get closer to 100% it affects the maximum head noticeably.

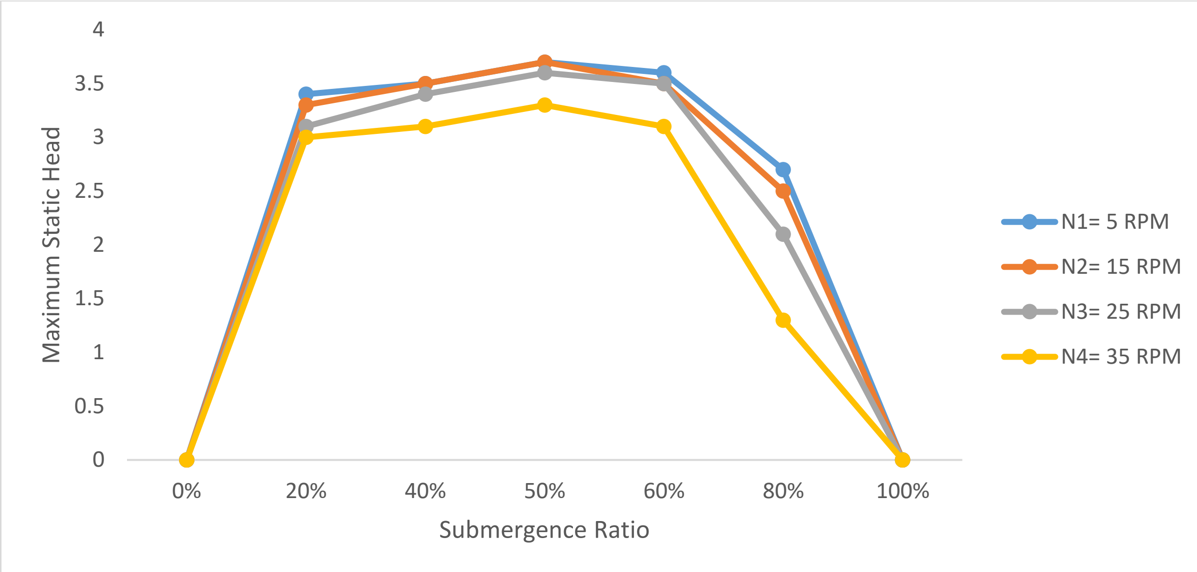

Figure 4.7 Variation of max. Static head with submergence ratio at different speed

So both the speed of the wheel and submergence ratio is directly proportional with pump discharge, and has insignificant effect on the maximum static head. This implies the theoretical relationship by Mortimer on equation 2.11 to be true for spiral type manometric pumps as of coil pumps.

4.2.3. Effect of number of Spiral turns

Number spiral turns (n) variation also depicted an important change on the performance of pump. In case of discharge of the effect was not noticeable, even though the increase in number of spiral turns affected the pump maximum head enormously. Experiment results for one layer, for outer diameter, D_o = 1.5 m, tube diameter, d_t = 3/4 in, submergence ratio 50% for varying spiral turns and with altering wheel speed is presented.

For 5 RPM wheel speed the pump discharge stayed to be around 33 lit/min while the spiral turn number increase from 3 to 6. This result was expected because it is predicted that the number of spiral turns to have no effect on the amount of water induced to the pump or the number of times a certain amount of water induced to the pump system. While conducting the experiment the diameter of outer or the last turn kept unchanged by adjusting the inner turns to let increment in number.

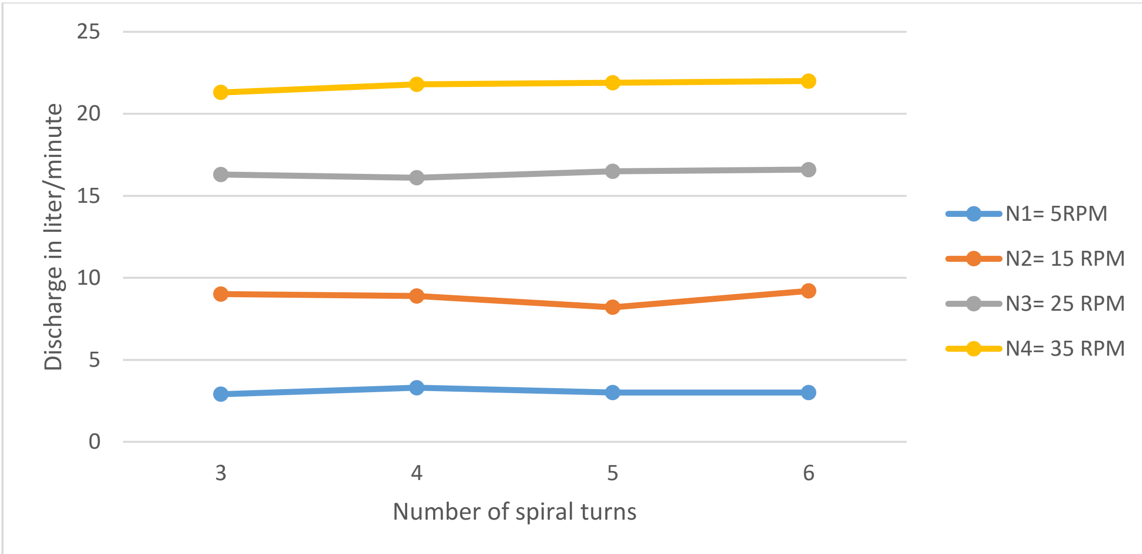

Figure 4.8 variation of pump discharge with number of spiral turns in at different speed, H=1.5m

Unlikely the variation in the number of spiral turns altered the pump maximum static head vitally. As illustrated on figure 4.9 the increment on number of turns from 3 to 6 raised the head from 2.7 meter to about 3.8 meters. If it wasn't for the leakage the maximum static head would be about 25% higher. This means the pump static head is a function of number of the spiral turns of the tube as Naegel reported. This result coincides with the principle of head development on the manometric pump. Accordingly head is developed in cascaded manometric principle. So that if there is higher number of spiral turns there will be higher number of cascaded manometers as a result higher cumulative headed will be developed.

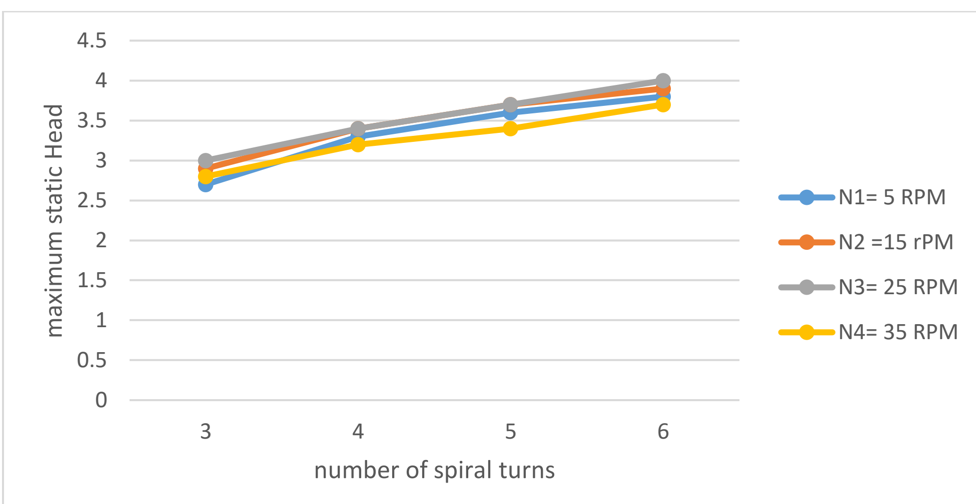

Figure 4.9 variation of max. Static head with number of spiral turns in at different speed

In conducting this experiment diameter of each turn in the spiral is crucial. To generate the same result as represented on figure 4.9. It is important to set the diameter of each turn as follows.

Table 4.3 Diameter of each turns of spiral tube

Number of spiral turns	Diameter of spiral turns from outer to inner
3	1.5, 1.2, 1
4	1.5, 1.2, 1, 0.8
5	1.5, 1.2, 1, 0.8, 0.6
6	1.5, 1.2, 1, 0.8, 0.6, 0.4

4.2.4. Effect of Outer diameter

Outer diameter is an important concept that differentiate spiral tube pump from coil pump. In spiral tubes for each spiral turn increase there will be an increment on the outer diameter. On the contrary in case of coil pumps the outer diameter is always constant. The tube is coiled around a constant diameter cylinder or drum. Based on this understanding the experiment was conducted with 15 RPM speed, at Sr = 50%. According to result shows on figure 4.10 and 4.11 both the pump discharge and the head has shown increase with the increase of outer diameter.

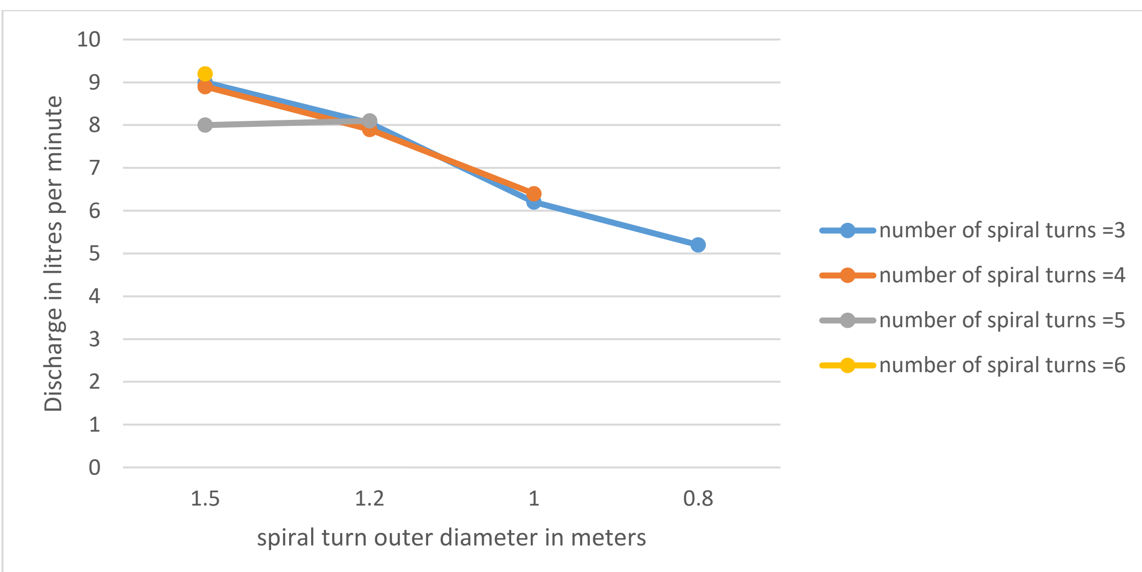

Figure 4.10 Variation of pump discharge with outer diameter for different number of spiral turns, H=1.5m

The maximum static head increased for the increase of outer diameter. At outer diameter of 0.8 m the head was 1.2 meter with 3 number of spiral turns, when the outer diameter get wider to 1.5 the maximum static head elevated to about 3 meters, this is significant. This can be related with the concept of cascaded manometers. The wider diameter refers to larger manometers in the manometers series. So larger manometer results larger head per turn.

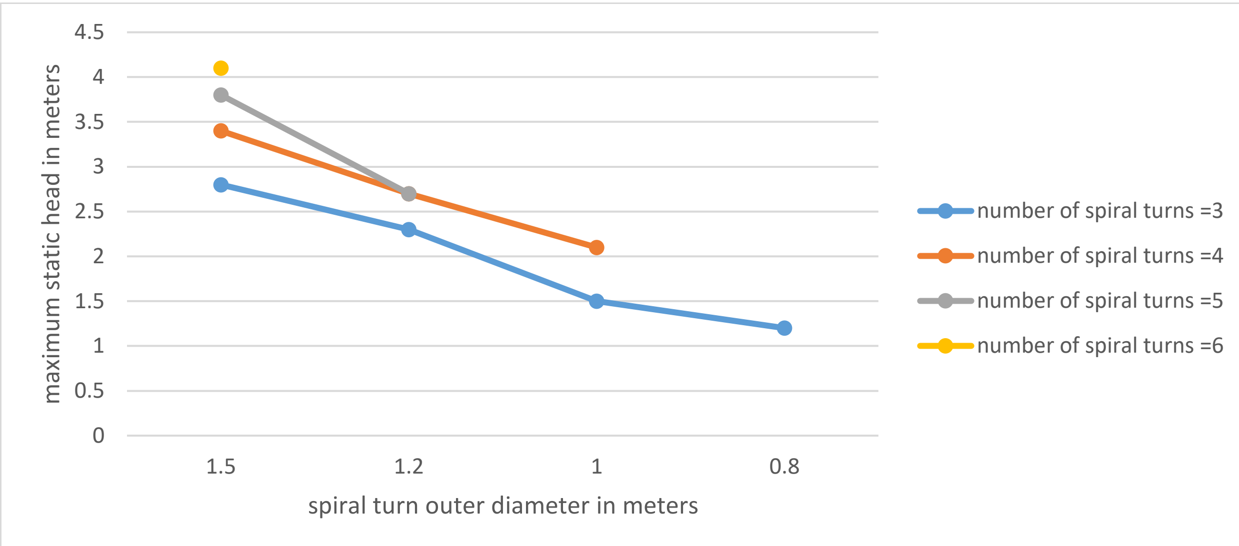

Figure 4.11 Variation of pump max. Static head with outer diameter for different number of spiral turns

Therefore, the outer diameter is the one parameter that affects both pump discharge and head significantly.

4.3. Comparative study between experimental and theoretical results

Mortimer and Naegel had clearly stated the theoretical relation between the important parameters and pump discharge and pump head. In this section the theoretical output prediction based on Equation 2.11 and 2.19 is compared with the field experiment result and presented on the figure 4.12 and 4.13.

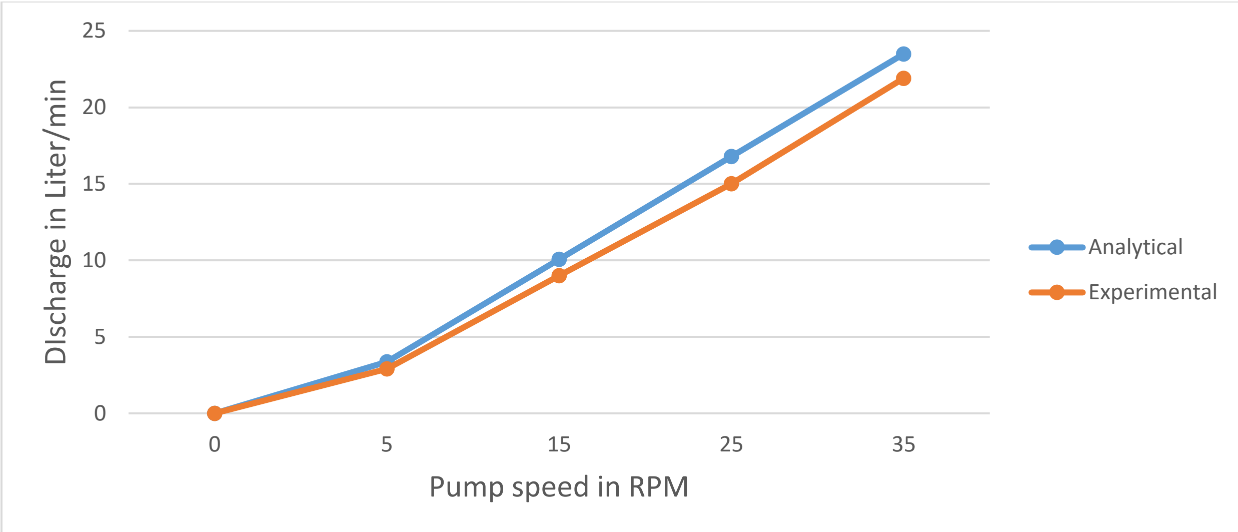

Figure 4.12 Comparison between the theoretical and experimental Pump discharge at different rotational speeds

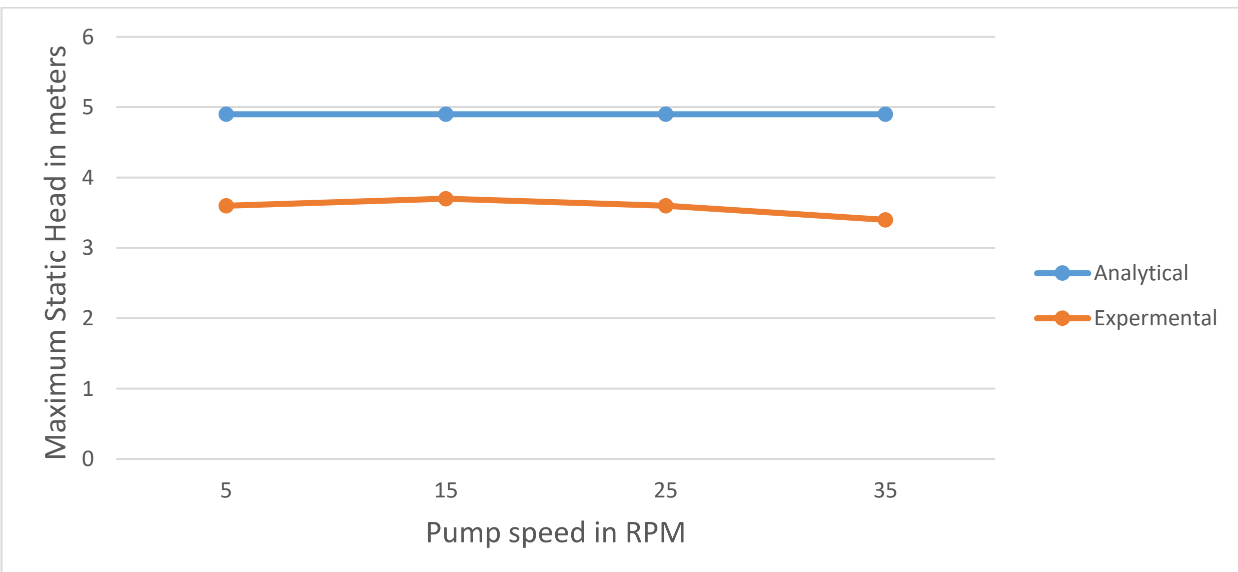

Figure 4.13 Comparison between the theoretical and experimental Pump max. Static head at different rotational speeds

Pump discharge result of the experiment values deviates from the analytical by about 8% error considering the condition of experimenting this value is very less. So it can be concluded the experimental result is validated by the theoretical prediction.

In case of the head 25% error is exhibited. This error because of the air leakage at the rotary joint. So when we consider this situation the error will be acceptable. So here also the experimental result is also validated.

4.4. Optimization of pump parameters based on Taguchi method

4.4.1. Optimization process setup

In recent years, the rapid growth of interest in the Taguchi method has led to numerous applications of the method in a world-wide range of industries and nations. It helps to eliminate variation is during the design of a product and its manufacturing process. Since system design is an initial functional design, it may be far from optimum in terms of quality and cost. In this subheading spiral pump has been made optimum in terms of functional output based on the following application steps:

1. Identification of the quality characteristics and selection of design parameters to be evaluated
2. Determination of the number of levels for the design parameters and possible interactions between the design parameters
3. Selection of the appropriate orthogonal array and assignment of design parameters to the orthogonal array
4. Conducting of the experiments based on the arrangement of the orthogonal array
5. Analysis of the experimental results using the S/N and ANOVA analyses
6. Selection of the optimal level3s of design parameters
7. Verification of the optimal design parameters through the confirmation experiment. This steps has been followed in optimizing both Head and Discharge response.

4.4.2. Parameter design

Since the parameters and the levels have been chosen and worked with in the previous it is better to begin with third step. Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments only. For the purpose of this study L_{16} $_{array}$ used with the four factors having four level as shown in table below:

Table 4.4 Experimental layout using an L16 orthogonal array

Experiment No.	Pump Parameter Levels			
	A	B	C	D

	Wheel Speed (N)	Submergence Ratio (Sr)	Number of spiral turns (n)	Outer diameter (Do)
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	1	4	4	4
5	2	1	2	3
6	2	2	1	4
7	2	3	4	1
8	2	4	3	2
9	3	1	3	4
10	3	2	4	3
11	3	3	1	2
12	3	4	2	1
13	4	1	4	2
14	4	2	3	1
15	4	3	2	4
16	4	4	1	3

The level for each parameters is presented in the table below;

Table 4.5 Parameters and levels

Symbol	Pump parameter	Unit	Level 1	Level 2	Level 3	Level 4
A	Wheel Speed (N)	RPM	5	15	25	35
B	Submergence Ratio (Sr)	-	20%	40%	50%	60%
C	Number of spiral turns (n)	-	3	4	5	6
D	Outer diameter (Do)	meter	0.8	1	1.2	1.5

4.4.3. Experimental result and S/N ratio

In Taguchi Method, we want to optimize the quality of the output of a process or product. The S/N ratio is a measure that we use to evaluate the quality of the output. It's actually a ratio of two things: the signal and the noise. The signal is the part of the output that we want, and the noise is the part that we don't want. The experimental results are then transformed into a signal-to-noise (S/N) ratio. Taguchi recommends the use of the S/N ratio to measure the quality characteristics deviating from the desired values. Usually, there are three categories of quality characteristic in the analysis of the S/N ratio, i.e. *the lower the better*, *the higher the better*, and *the nominal-the-better*.

In the following table the experimental result for the orthogonal array and the S/N ratio is presented separately for Head. It is calculated based on the higher is better since all needed is higher Head.

Table 4.6 Experimental result for Head and S/N ratio

Experiment No.	Pump Parameter Levels				
	A	B	C	D	Response

	Wheel Speed (N)	Submergence Ratio (Sr)	Number of spiral turns (n)	Outer diameter (Do)	Head (H) in meters	S/N ratio
1	5	20%	0.8	3	1.4	2.9226
2	5	40%	1.0	4	2.1	6.4444
3	5	50%	1.2	5	3.1	9.8272
4	5	60%	1.5	6	4.2	12.4650
5	15	20%	1.0	5	2.6	8.2995
6	15	40%	0.8	6	2.7	8.6273
7	15	50%	1.5	3	2.2	6.8485
8	15	60%	1.2	4	2.3	7.2346
9	25	20%	1.2	6	3.6	11.1261
10	25	40%	1.5	5	3.6	11.1261
11	25	50%	0.8	4	1.8	5.1055
12	25	60%	1.0	3	1.6	4.0824
13	35	20%	1.5	4	2.8	8.9432
14	35	40%	1.2	3	1.8	5.1055
15	35	50%	1.0	6	3.2	10.1030
16	35	60%	0.8	5	2.2	6.8485

Similarly in the following table the experimental result for the orthogonal array level combination and the S/N ratio is presented separately for pump discharge (Q). It is calculated based on the higher is better since all needed is higher discharge.

Table 4.7 Experimental result for Discharge and S/N ratio

Experiment No.	Pump Parameter Levels					
	A	B	C	D	Response	
	Wheel Speed (N)	Submergence Ratio (Sr)	Number of spiral turns (n)	Outer diameter (Do)	Head (H) in meters	S/N ratio
1	5	20%	0.8	3	1.4	-3.0980
2	5	40%	1.0	4	2.1	4.6090
3	5	50%	1.2	5	3.1	8.3328
4	5	60%	1.5	6	4.2	10.1030
5	15	20%	1.0	5	2.6	8.2995
6	15	40%	0.8	6	2.7	12.0412
7	15	50%	1.5	3	2.2	19.0849
8	15	60%	1.2	4	2.3	18.2763
9	25	20%	1.2	6	3.6	13.9794
10	25	40%	1.5	5	3.6	22.4770
11	25	50%	0.8	4	1.8	18.0618

12	25	60%	1.0	3	1.6	22.2789
13	35	20%	1.5	4	2.8	18.2763
14	35	40%	1.2	3	1.8	23.4052
15	35	50%	1.0	6	3.2	23.6369
16	35	60%	0.8	5	2.2	23.3463

4.4.4. Analysis of variance (ANOVA) result

Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant. With the S/N and ANOVA analyses, the optimal combination of the process parameters can be predicted.

Table 4.8 Analysis of Variance of S/N ratios for pump head

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Wheel speed	3	0.080	0.0802	0.0267	2.22	0.264
submergence ratio	3	0.197	0.1969	0.0656	5.46	0.098
Outer diameter	3	33.926	33.9256	11.3085	940.82	0.000
Number of spiral turns	3	77.396	77.3962	25.7987	2146.34	0.000
Residual Error	3	0.036	0.0361	0.0120		
Total	15	111.635				

Where;

- DF stands for degrees of freedom, which represents the number of values in the final calculation of a statistic that are free to vary.
- Seq SS stands for sequential sum of squares, which measures the amount of variation in the dependent variable that is explained by each predictor variable in turn.
- Adj SS stands for adjusted sum of squares, which takes into account the effect of other predictor variables when computing the amount of variation explained by each predictor variable.
- Adj MS: Adjusted Mean Square, which is the Adjusted Sum of Squares divided by the degrees of freedom for error.
- F: F-ratio, which is the ratio of the variance between groups to the variance within groups, and is used to test the significance of the differences between the means of two or more groups.
- P: P-value, which is the probability of observing a test statistic as extreme as the one calculated, assuming that the null hypothesis is true. It is used to determine the statistical significance of the F-ratio.

Table 4.9 Analysis of Variance of S/N ratios for pump Discharge

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Wheel speed	3	677.734	677.734	225.911	2315.22	0.000
submergence ratio	3	197.853	197.853	65.951	675.89	0.000
Outer diameter	3	51.709	51.709	17.236	176.65	0.001
Number of spiral turns	3	1.766	1.766	0.589	6.03	0.087
Residual Error	3	0.293	0.293	0.098		

Total	15	929.355

The above tables identifies the significant parameters that have a significant effect on the output which is pump head and discharge. In table 4.8 F and P value shows that number of spiral turns and outer diameter has significant effect on the pump head. The effect of number of spiral turns greatest if we compare its significance with outer diameter. In case of table 4.8 the wheel speed, submergence and outer diameter are significant in deciding the amount of pump discharge. As the F- value suggests the wheel speed has the greater effect then submergence ratio and the outer diameter follows.

4.4.5. Optimal level setting

Based on ANOVA result and S/N ratio Minitab software plotted the following figures that shows the optimal parameter level of the factors.

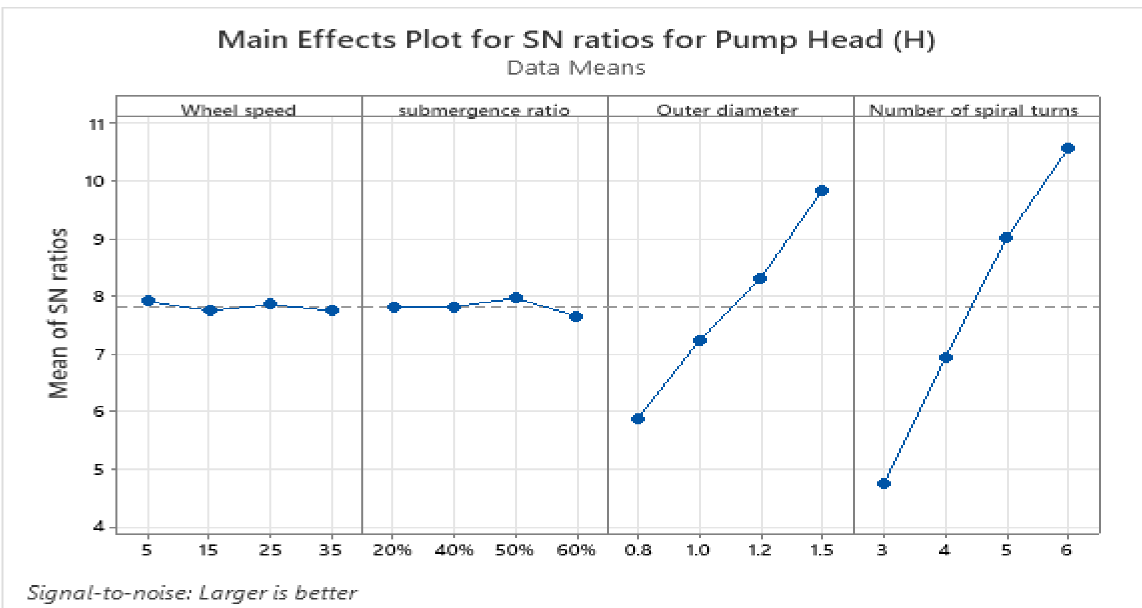

Figure 4.14 Main effects plot for SN ratio for pump head

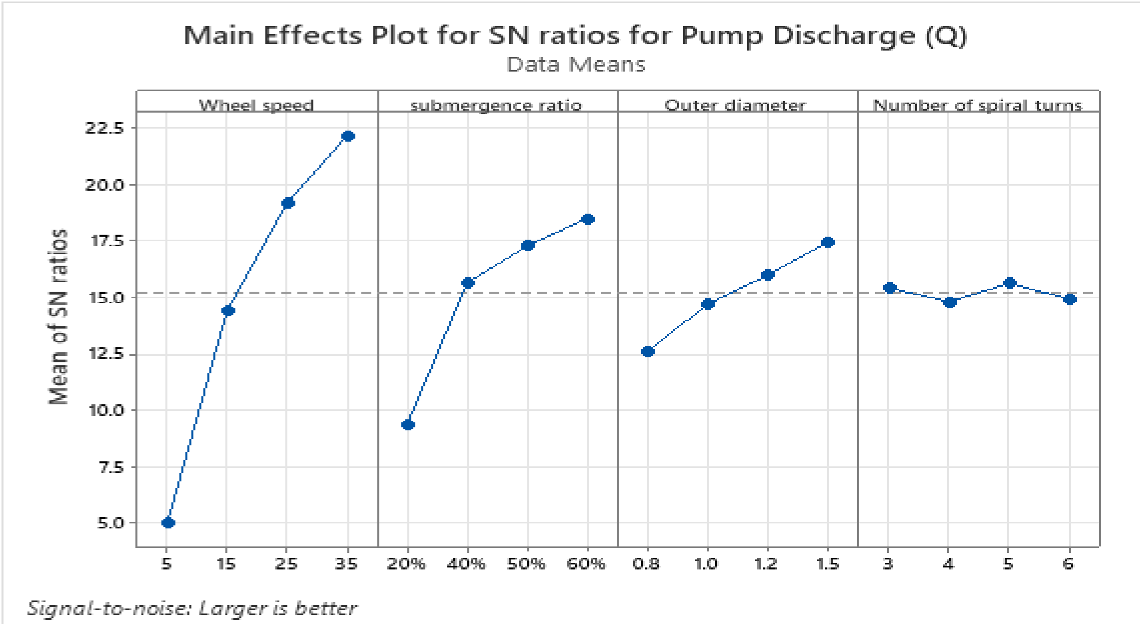

Figure 4.15 Main effects plot for SN ratios for pump discharge

The Taguchi analysis result coincides with the expectation. Since the pump head raise when the number of turns and the outer diameter increases the larger optimal head will be expected on the higher level of these parameter. According to figure 4.14 the optimal level for head is at 6 spiral turns and 1.5 meter the other parameters are subjected for discharge requirements. From figure 4.15 the optimal levels to get larger discharge are 35 Rpm wheel speed, 60% submergence ratio and 1.5 meter outer diameter. The last factor is insignificant in affecting the discharge.

When we consider S/N ration for both head and discharge, meaning if the pump is wanted to give higher result in both head and discharge the optimal level varies slightly based on figure 4.16. It would be 35 RPM wheel speed, 50% submergence ratio, 1.5 meter outer diameter and 6 spiral turns. 50% submergence would be optimal if better head and discharge is required.

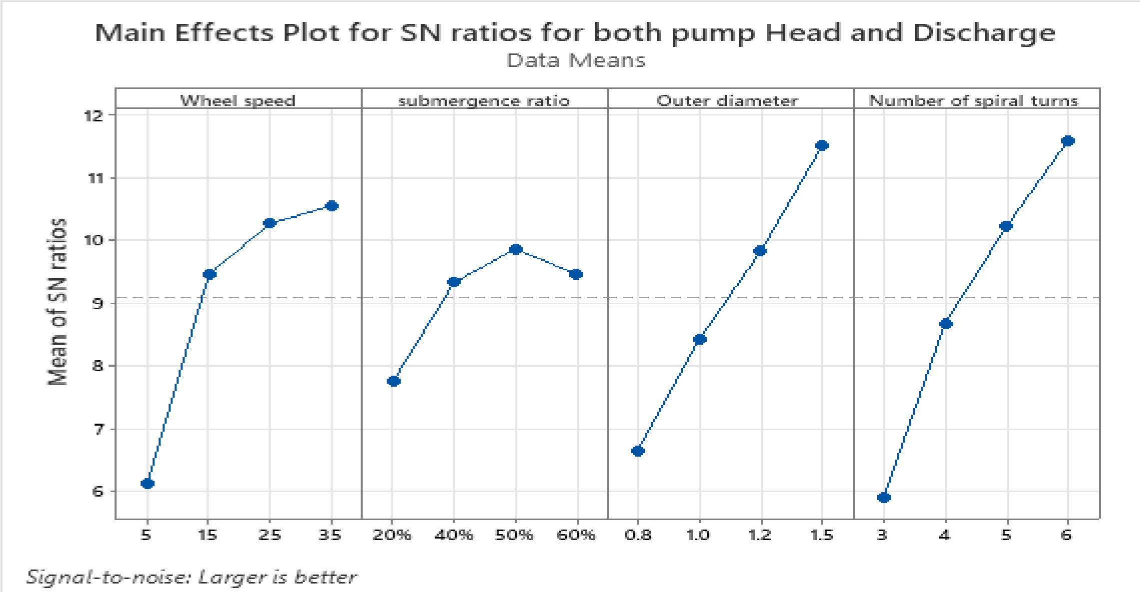

Figure 4.16 Main effects plot for SN ratios for both pump head and discharge

4.4.6. Confirmation test

A test has been conducted to confirm the optimization result. So the pump was at 35 RPM speed, and 50% submergence ratio, 1.5 outer diameter and 6 spiral turns. It gave 0.36 litter of water per second at maximum in at about 4 meter maximum head. If the pump parameter can be maintained it will give 31,104 litters of water at the end of the day. Which is great!

4.5. Comparison between spiral pump and coil pump

Among several alternatives of manometric pumps coil and spiral pumps are the most common and realistic for application in developing countries. Both of the work based on similar scientific principle and can be integrated with water wheel and be stream powered. Even though they are not totally similar they constructional difference and also may exhibit performance difference on different working condition. Understanding there similarity and difference lets to use the variation wisely.

First to discuss the similarity is crucial. Both coil pump and spiral pumps share all the basic parts such as; scoop, flexible tube, tube shaft, rotary joint, delivery pipe, and any other structure to support the flexible tube like spoke. The difference comes on the constructional orientation of the flexible tube. This difference is not simply difference because it leads to performance difference, which is head and discharge difference, when the pumps operates in different condition. Let us discuss these difference separately.

4.5.1. Constructional difference

As mentioned above both type pumps share basic parts and work by similar principle the difference comes on the way the engineer choose to orient the flexible tube. If one choose to turn the flexible tube around a cylindrical drum with constant outer diameter, he constructed a coil pump. But he choose to turn the flexible tube on a planar surface by increasing the diameter of the following turn he definitely built a spiral pump. So while turning the flexible tube in case of coil pumps a horizontal dimension get larger in the contrary in case of spiral pump a vertical dimension get larger. This difference pave a way performance variation. The following figures shows different kind of coil and spiral pumps.

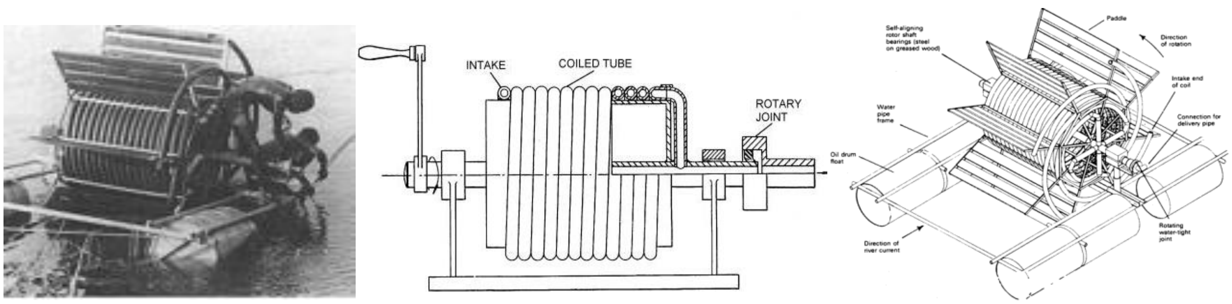

Figure 4.17 Coil pump construction, source: Google image

Figure 4.18 Spiral pump construction, source: Google image

4.5.2. Performance difference

In this context the word performance refers Head (H) and Discharge (Q) so let us see how they are affect by the type of the pump:

4.5.2.1. Head

As discussed in the previous subheading head of the manometric pumps are the functions of number of coils/spiral turns and the diameter of the coil/turns. As a result spiral pumps may give greater head for the same number of turns/coils. Because in spiral pump for each number of turn increase done by increasing the dimeter of the next turn. In the contrary in coil pumps the diameter kept constant. In the following figure a coil pump and spiral pump is compared by theoretical delivery maximum head. On this result for both pumps turning started with 0.5 m diameter then for coil pump this diameter kept until it reaches the eleventh coil, whereas for spiral pumps the turns diameter increased by 0.1 m. This resulted about 5 meter head difference at the last turn theoretically, which is significant.

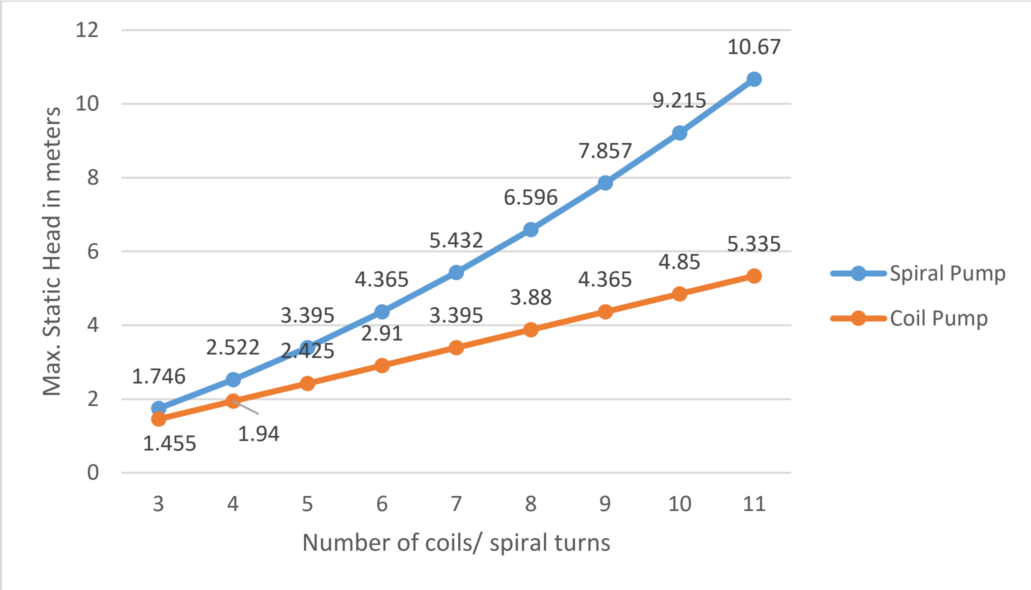

Figure 4.19 spiral pump and coil pump comparison of pump head at different number of coils

So that if the desire is to acquire maximum static head it suggested to select spiral pumps.

Here one thing to consider is the vertical dimension of the pump. For example in the above figure when the eleventh turn reached the outer diameter of the pump have reached 1.5 m while the coil pump outer diameter stayed on 0.5 m. Since the spiral pump getting larger and larger this make it inconvenience for shallow streams. It requires a deep river or sum management on the river runway to make sufficient depth to get the desired discharge output.

4.5.2.2. Discharge

With respect to discharge the coil pumps are better. Because there size are smaller than spiral pump. This lets them to rotate more revolution per a certain time with lesser torque. As a result this higher speed they are capable of delivering higher volume of water per a certain time. So in designing a manometer pump if the demand is higher discharge coil pump is the better choice.

4.6. Development of design procedure for spiral pump

The aim of this development of design procedure is to enable a designing and utilizing, for whoever in need. It can be said this subheading is the conclusion for all reading and experimenting effort. Since this article enables designing and utilizing the stream power spiral pump in corporation with water will become in hand that can be done by through the following steps;

Step 1: Determine the pump specification

First identify to what vertical distance a pump is required to raise the water, Delivery head (H) and how much water to be delivered per certain period of time (Q). In short words specify the Head and the discharge.

Step 2: Find the required power

In this step the required power to deliver the water to specified head with specified discharge will be calculated. To do so this following relationship can be used from equation as stated by Naegel and proved by the experiment.

P is needed to deliver a water volume Q (l/sec) to a head of H (m) is:

$$P = 9.8 \times Q \times H$$

Where 9.8 is the gravitational constant in m/sec^2. If Q is in m^3/sec, the above formula gives P in KW.

Step 3: Calculate the available power

Since the pump is going to be powered by the available kinetic energy in the stream can be calculated using the equation below, the kinetic energy P is proportional to the stream velocity cube.

$$P = 1/2 \times A \times \rho \times v^3$$

$were: \rho\ is\ the\ density\ of\ water\ \left(\frac{1kg}{l} for\ fresh\ water\right)$

$A\ is\ the\ area\ of\ cross\ section\ of\ the\ current\ in\ m^2$

$v\ is\ the\ mean\ velocity\ through\ the\ cross\ section\ in\ m/sec$

Step 4: Design the water wheel

In designing the water wheel there are several factors needs decision. Such as the diameter, number of paddle, area of the paddle and other matters such as construction material. In this study the most relevant parameter is the area of the paddle, since it is the main part to that receive momentum of the stream. To determine the area of the paddle let us set the number of paddle to be 8 so that at least one paddle get to be in contact with the stream at 90^0. The length of spoke or the outer diameter must be determined after the determining the outer diameter of and the number of spiral turns. Here the main focus is to get the required torque from the paddle area only. Therefor letting the required power equation and the available power equation to be equal will render the area of the paddle needed to get the power from available stream power.

$$Area\ of\ wheel\ paddle = \frac{2 \times 9.8 \times Q \times H}{\rho \times v^3}$$

The wheel shape is suggested to be rectangular. The size of height and length of the rectangle can be decided by the designer based on the depth of the stream.

Step 5: Decided the tube diameter and outer diameter of the spiral tube

This is the critical step that requires the situation analysis and decision making ability of the designer. The flexible tube diameter (d) is suggested to be narrower based on the availability. This helps reduce disturbance of water and air plug in the tube. The outer diameter (D_o) spiral turn must be decided by considering the depth of the river. It must be greater than the required submergence ratio, which will be determined in the next step.

$$D_o \gg S_r$$

Step 6: Determine the submergence ratio

Since the wheel speed (N) is determined by the efficiency of the water wheel construction it is not mainly controlled by the designer. Also the flexible tube area is determined by market availability. The left parameter to affect the pump discharge (Q) is the submergence ratio (S_r). So it must be determined by considering the required discharge. So the S_r can be determined by the following relation.

$$S_r = \frac{Q}{\pi \times D_o \times A_T \times N}$$

Were A_T is the cross sectional area flexible tube.

Step 7: Determine the inner diameter and the number of coil

The spiral tube outer diameter (D_o), inner diameter (D_i) and number of turns (n) determines the pump's delivery head capacity so they must be determined in such a way to enable the pump to give the required head (H).

First determine the minimum inner diameter needed from Boyel's law as stated on equation 2.16 by Tailer.

$$D_i = (P_{atm} + D_o) \times D_o/(P_{atm} + H)$$

Then determine the number of spiral turns (n) from equation 2.17.

$$n = \frac{2H}{D + h_n}$$

To add the 20% percent margin.

$$n_{realstic} = n + 20\%n$$

At this stage all parameters that enable the pump to deliver the specified amount of water to specific height per certain period of time is determined. So by taking construction efficiency and other factors in to account the pump should deliver the specified output.

5. Conclusion and Recommendation

5.1. Conclusion

In the end it can be conclude that spiral pump and other similar manometric pumps can be solution for low cost, emission free and simple irrigation pump need. Spiral pump can be built by incorporating it with water wheels so that it can be powered by the river's kinetic energy. This makes the system to require zero cost of energy. So these characteristic of stream powered spiral pump makes it ideal for developing countries like Ethiopia with many rivers.

Based on a results found on this research project the following points are concluded;

- Among many alternatives of paddle shape for water wheel curved shape oriented on the spoke up to 22.5^0 slant from vertical yield higher angular rotation the wheel. Therefor a water wheel for spiral pump purpose should be built with such shape and orientation to make the spiral pump system rotate on higher speed.
- Spiral pump's performance can be affected by many factors. The most important ones are the wheel speed, submergence ratio, number of spiral turns and outer diameter of spiral. The wheel speed and the submergence ratio significantly affects the pumps discharge. The number of spiral turns mainly affects the pump head. The outer diameter affects the both the pump discharge and the head. So based on the irrigation field condition spiral pump can be designed to address the need. For instance if the irrigation field is at elevated position from the river the higher number of spiral tube turns enables the pump to push the water to the desired position.
- Based on the Taguchi optimization method for provided parameter level in the study the pump that run by 35 RPM wheel speed, at 50% submergence ratio, with 6 number of spiral turns and 1.5 outer diameter gives optimum pump out, which delivered about 21 liters/min water to about 4.1 m height. Where the tube diameter is ¾ inches. If the air leakage on rotary joint could be alleviated the head could be higher.
- There are coil pump and spiral pump categories of manometer pump based on their constructions. While spiral pumps have the tendency to give higher head than the coil pump, coil pump has the tendency to give higher discharge. One can select either of one based on his/her need with taking into account the river's condition such as the depth.

Finally this research has provided a seven step simple procedure to design a spiral pump for a certain specification so that it can easily be easily designed and manufactured in local workshop. Having such simple and clear design procedure will assists developing countries such as Ethiopia in the journey to food self-sufficiency and prosperity.

5.2. Recommendation

All type of manometric pump can be best pumping alterative for small scale irrigation farms near rivers. Coil pumps would be more suitable for shallow rivers and higher water discharge requirement. In other hand spiral pumps would be more effective for farms at higher elevation and deep rivers. An engineer can use the design procedure stated in section 4.6 to meet farmers' specification. If a rivers has adequate water volume and speed a meaningfully adequate amount of water can be delivered to the farm.

In the process of designing and manufacturing the pump locally the major problem was developing leakage free rotary joint. Avoid any leakage make the pumping to meet the theoretical prediction on head wise. So it is recommend for a researcher to come up with better performing rotary joint if the pump is need to perform to its capacity. In addition to this studies can be continued in future regarding to the spiral pump on the following aspects;

- Considering effect other parameters such as tube diameter
- Developing a numerical approach to study the behavior and performance of spiral pump to the important parameters
- Development of efficient water wheels and so on.

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Appendixes

Appendix A: Experiment tabular result

Table 0.1 Variation of the pump discharge with rotational speed at different submerged ratio, H=1.5

H= 1.5 m *Number of spiral turns = 5*			*Do = 1.5 m* *Dt = ¾ inches*		
	Pump discharge (litre/min) at different Submergence Ratio				
Wheel speed (RPM)	20%	40%	50%	60%	80%
0	0	0	0	0	0
5	1.3	2.5	2.9	3.2	5.3
15	3.8	7.2	9	10.5	15.2
25	6.7	13.3	15	19.7	25.6
35	8.2	16.5	21.9	23.6	30.1

Table 0.2 Variation of max. Static head with rotational speed at different submerged ratios

Number of spiral turns = 5			*Do = 1.5 m* *Dt = ¾ inches*		
	Max static head (m) at different Submergence Ratio				
Wheel speed (RPM)	20%	40%	50%	60%	80%

5	3.5	3.5	3.6	3.6	2.7
15	3.3	3.4	3.7	3.5	2.2
25	3.1	3.5	3.6	3.5	1.8
35	3	3.1	3.3	3	1.4

Table 0.3 Variation of pump discharge with submergence ratio at different speed,

H=1.5m *Number of spiral turns = 5*			*Do = 1.5 m* *Dt = ¾ inches*		
	Pump discharge (litre/min) at different wheel speed				
Sr	5	15	25	35	
0	0	0	0	0	
20%	1.3	3.8	6.7	8.2	
40%	2.5	7.2	13.3	16.5	
50%	3	9	16.5	21.9	
60%	3.2	10.5	19.7	23.6	
80%	5.3	15.2	25.6	30.1	
100%	0	0	0	0	

Table 0.4 Variation of max. Static head with submergence ratio at different speed

				Do = 1.5 m *Dt = ¾ inches*			
	Max static head (m) at different Submergence Ratio						
Wheel Speed (RPM)	0%	20%	40%	50%	60%	80%	100%
5	0	3.4	3.5	3.7	3.6	2.7	0
15	0	3.3	3.5	3.7	3.5	2.5	0
25	0	3.1	3.4	3.6	3.5	2.1	0
35	0	3	3.1	3.3	3.1	1.3	0

Table 0.5 variation of pump discharge with number of spiral turns in at different speed

H= 1.5 *Sr= 50%*			*Do = 1.5 m* *Dt = ¾ inches*	
	Pump discharge (litre/min) at different number of spiral turns			
Wheel Speed (RPM)	3	4	5	6
5	2.9	3.3	3	3
15	9	8.9	8.2	9.2
25	16.3	16.1	16.5	16.6
35	21.3	21.8	21.9	22

Table 0.6 variation of max. Static head with number of spiral turns in at different speed

Sr = 50%		*Do = 1.5 m* *Dt = ¾ inches*		
	Max static head (m) at different speed			
Number of spiral turns	5	15	25	35
3	2.7	2.9	3	2.8
4	3.3	3.4	3.4	3.2
5	3.6	3.7	3.7	3.4
6	3.8	3.9	4	3.7

Table 0.7 Variation of pump discharge with outer diameter for different number of spiral turns

Sr = 50% *N = 15 RPM*		*H = 1.5 m* *Dt = ¾ inches*		
Outer diameter	Pump discharge (lit/min) at different number of spiral turns			
	3	4	5	6
1.5	9	8.9	8	9.2
1.2	8.05	7.9	8.1	
1	6.2	6.4		
0.8	5.2			

Table 0.8 Variation of pump max. Static head with outer diameter for different number of spiral turns

Sr = 50% *N = 15 RPM*			*H = 1.5 m* *Dt = ¾ inches*	
Outer diameter	Max static head (m) at different number of spiral turns			
	3	4	5	6
1.5	2.8	3.4	3.8	4.1
1.2	2.3	2.7	2.7	
1	1.5	2.1		
0.8	1.2			

Appendix B: Spiral pump prototype part specifications and drawing

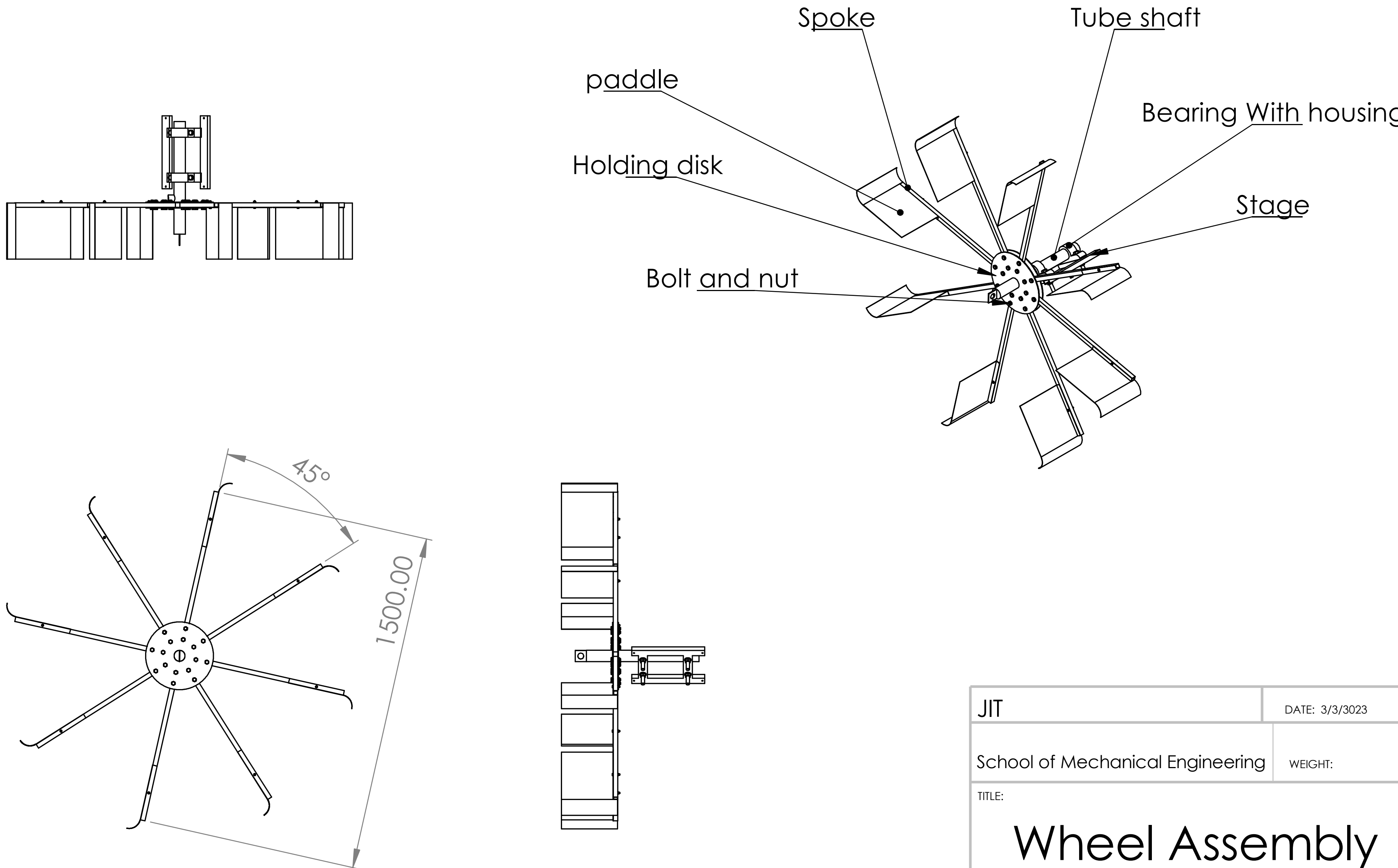
Appendix B-1: Selected and bought materials and parts

No.	**Parts**	**Specification**
1	Bolt and nut 	• Bolt size: M10 diameter with a thread pitch of 1.5 millimeters (Coarse thread) • Bolt material: Structural steel • Bolt strength: Property class 10.9 • Nut size: M10 • Nut material: Structural steel • Nut strength: Property class 10.9 • Thread type: Fine thread (1.5 millimeter pitch) • Finish: Plain

2	Bearing with housing 	• Type: Ball bearing • Bore diameter: 2 inches
3	Flexible plastic tube 	Diameter: ¾ inches Length: 4 m

Appendix B-2: Wheel Prototype Drawing

The drawing the water wheel prototype parts are used for experiment are presented on the following pages.



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School of Mechanical Engineering	WEIGHT:

TITLE:

Wheel Assembly

Drawn by: Million M.	A4

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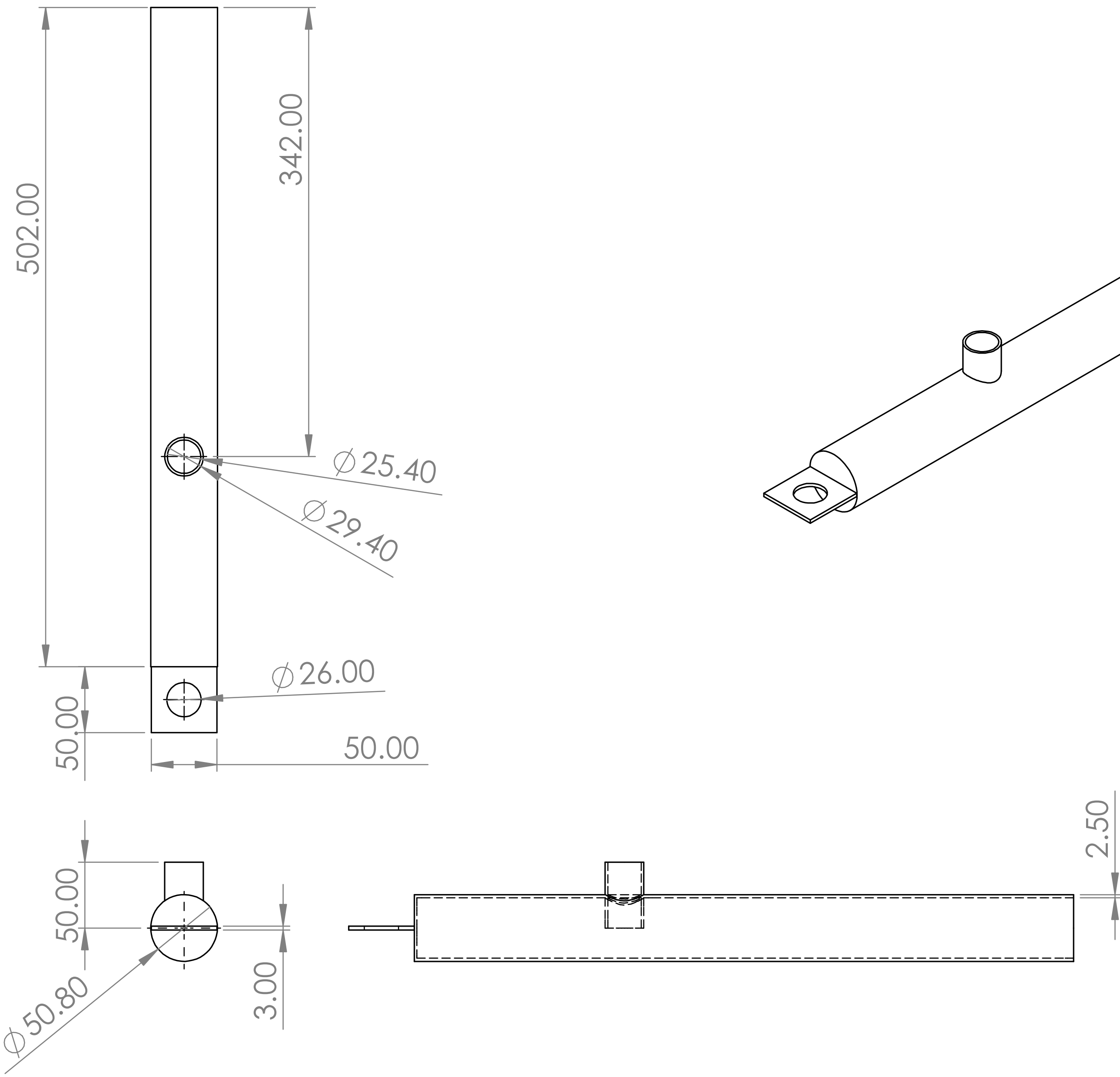

JIT

DATE: 3/3/3023

School of Mechanical Engineering

WEIGHT:

TITLE:

Tube shaft

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A4

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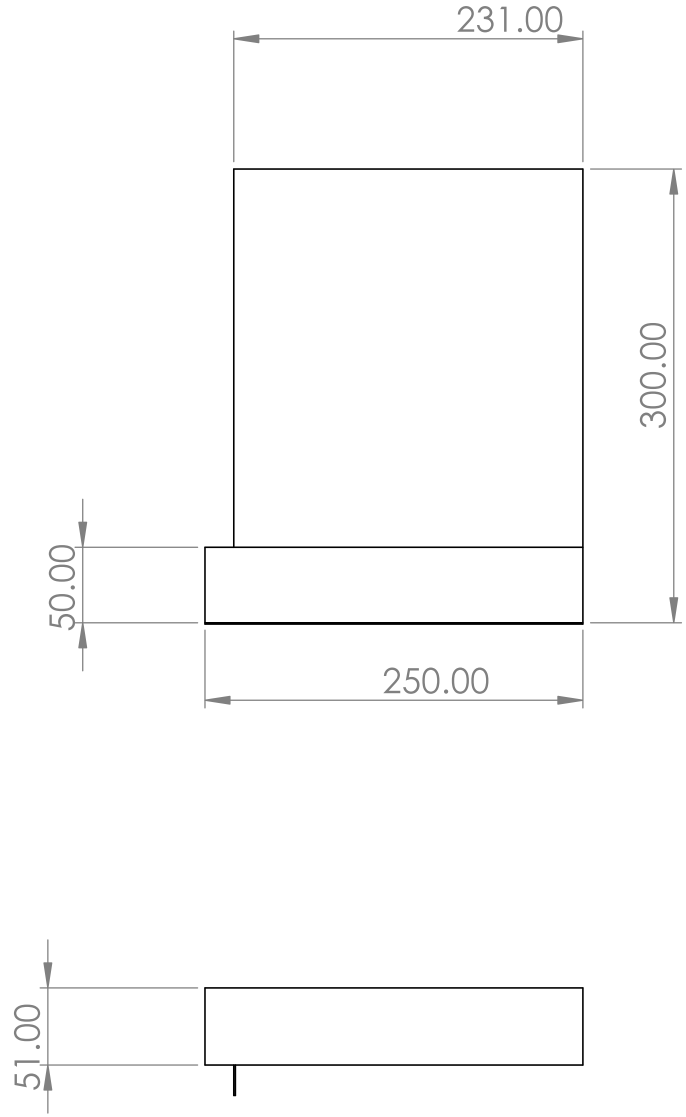

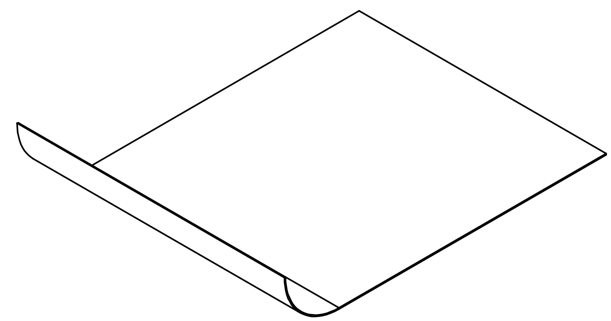

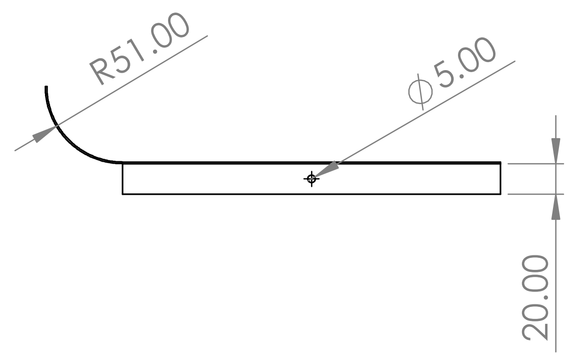

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School of Mechanical Engineering	WEIGHT:
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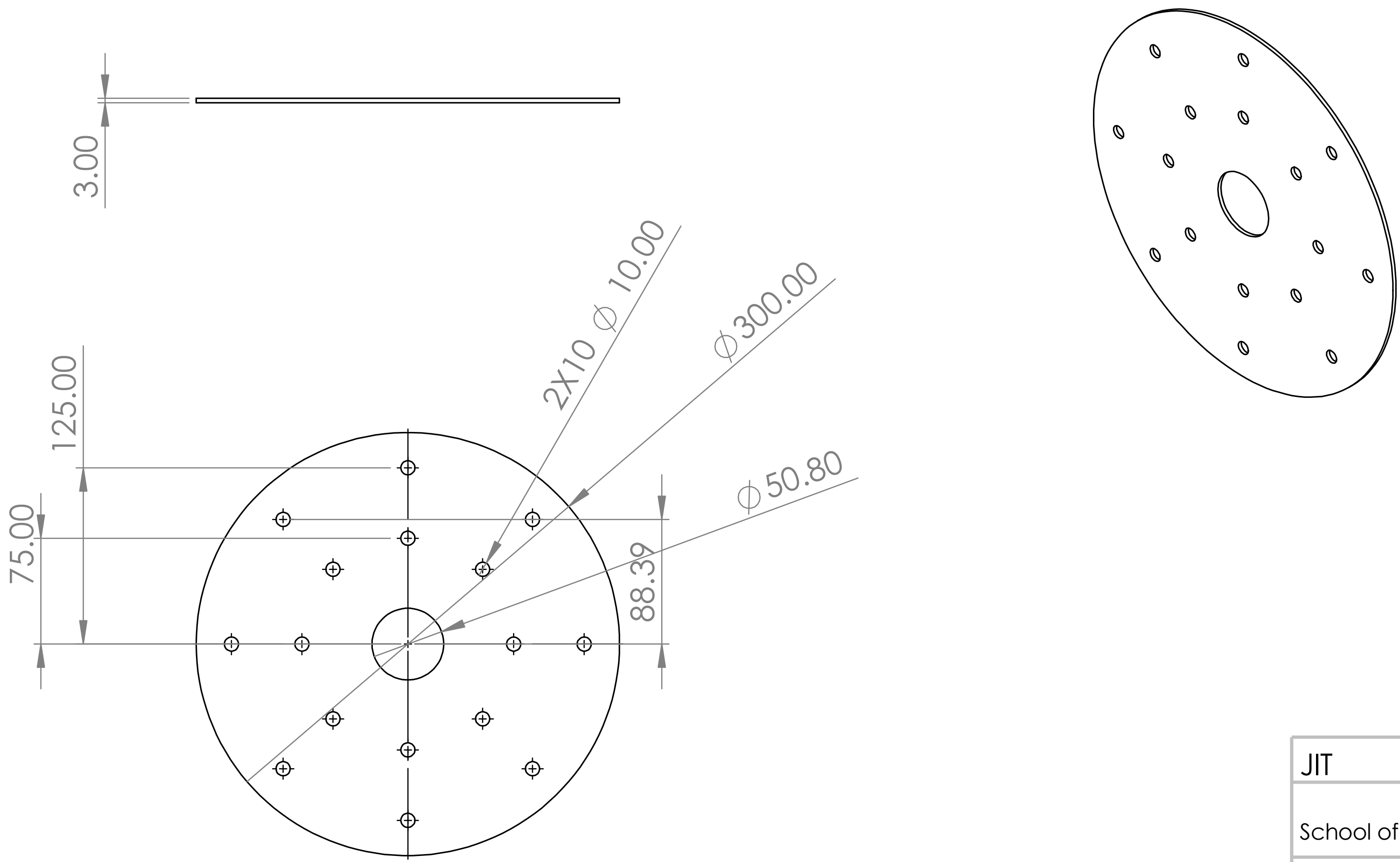

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School of Mechanical Engineering	WEIGHT:

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Holding disk

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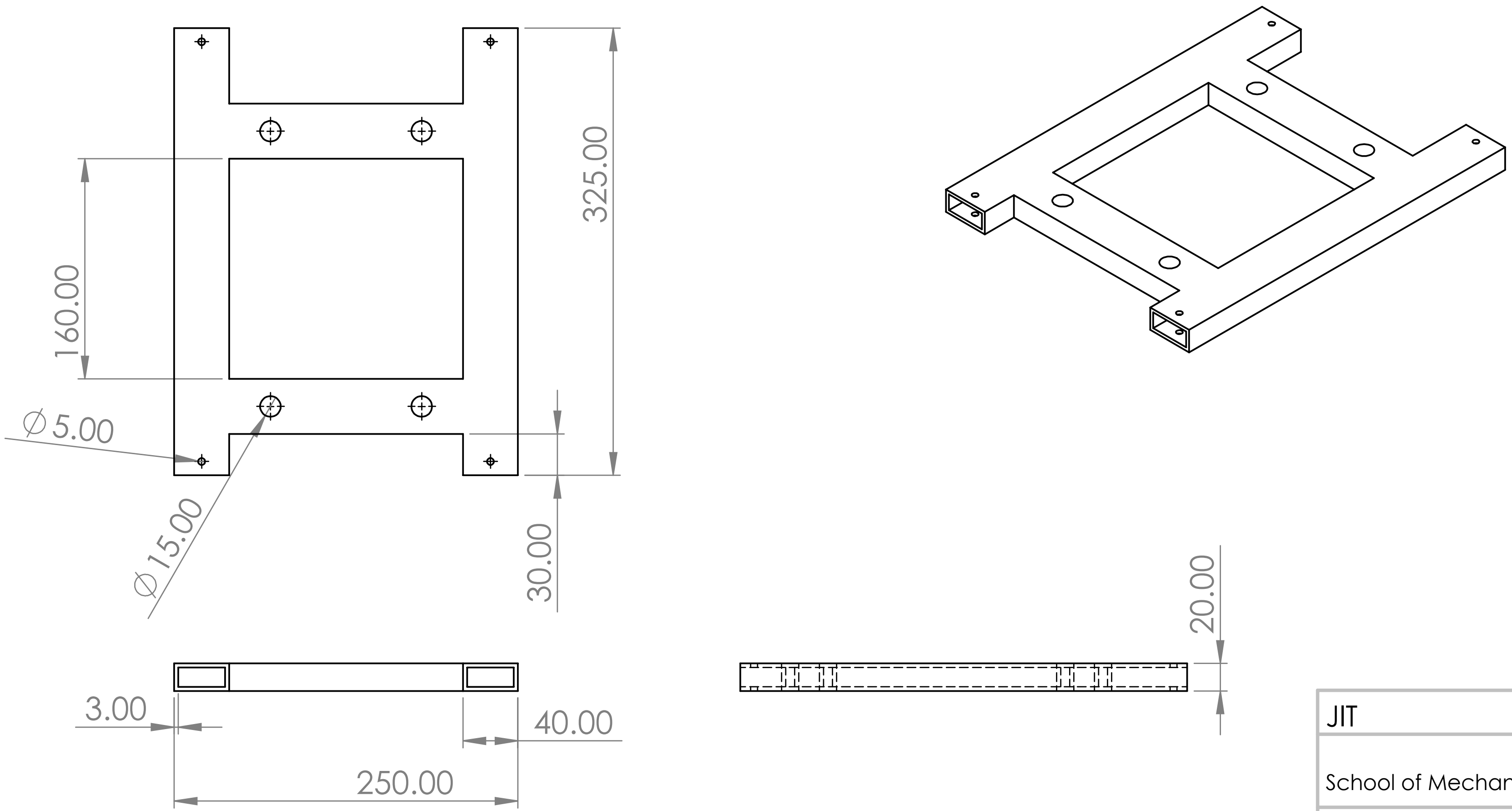


JIT

DATE: 3/3/3023

School of Mechanical Engineering

WEIGHT:

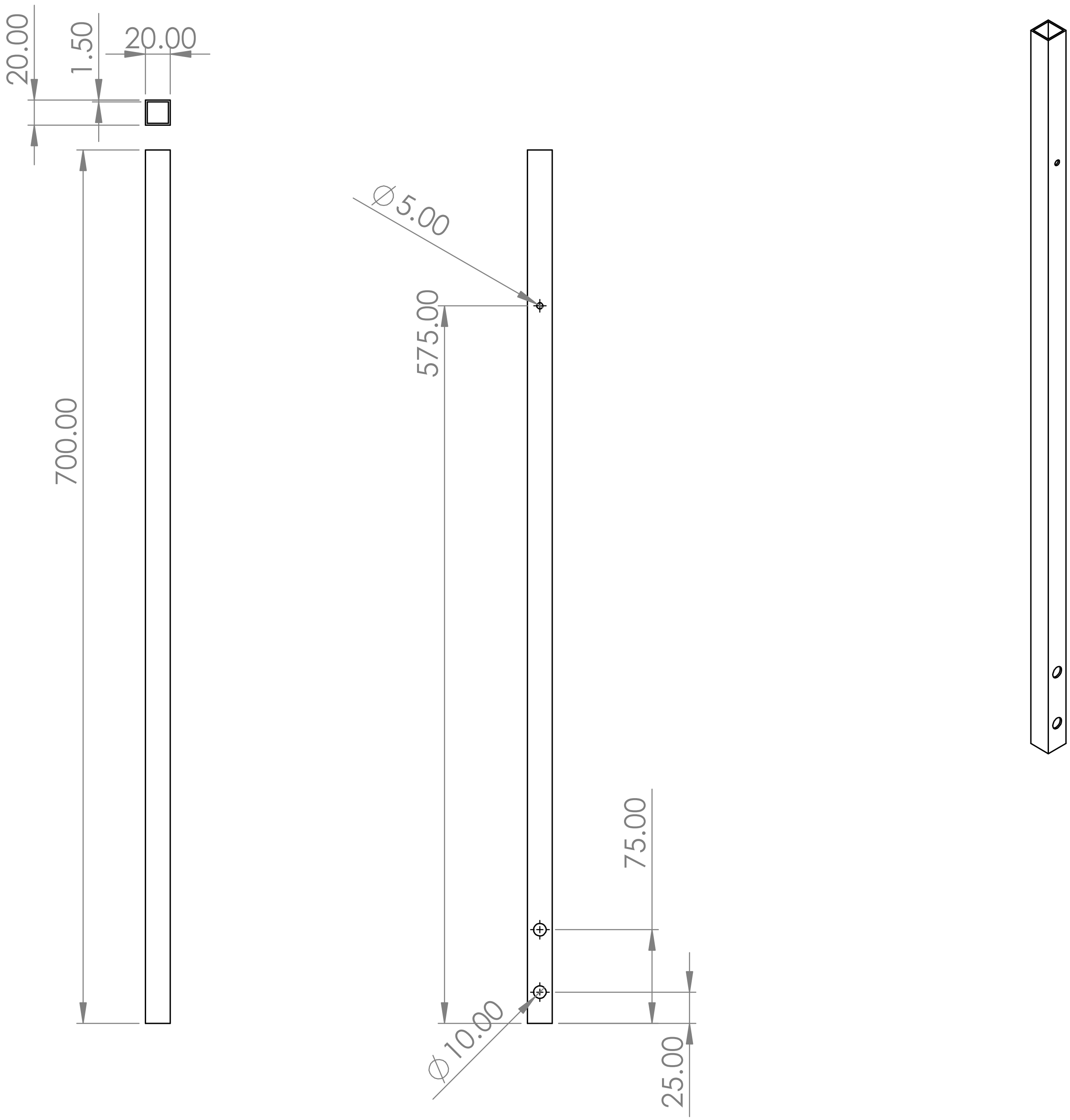
TITLE:

Wheel stage

Drawn by: Million M.

A4

SCALE:1:5 ALL Dimension are in milimeters



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School of Mechanical Engineering	WEIGHT:
TITLE: spoke	
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