American Journal of Renewable and Sustainable Energy
Vol. 3, No. 4, 2017, pp. 27-35
http://www.aiscience.org/journal/ajrse
ISSN: 2381-7437 (Print); ISSN: 2381-7445 (Online)

Technical Details for the Design of a Penstock for Kuchigoro Small Hydro Project

Obinna Ajala Chinyere[1, *], Nkiru Rosemary Obasih[2], Emmanuel Osiewundo Ojo[1], Chidozie Okonkwo[2], Edward Udoka Mafiana[2]

[1]National Agency for Science and Engineering Infrastructure (NASENI), Idu, Industrial Area, Abuja, Nigeria
[2]National Engineering Design Development Institute (NEDDI), Nnewi, Nigeria

Abstract

The penstock constitutes a major expense in the total Small-Hydro budget. It is therefore important that the pipe used is carefully chosen to minimize both lifetime running costs and initial purchase cost. Basic Design parameters for the penstock were gotten through field survey in 2015 for parameters like the gross head and flow to be 15m and $0.26m^3/s$ respectively. The penstock was designed using the Un-Plasticised Polyvinyl Chloride (uPVC) material owning to its benefits over steel pipes, such as cost, roughness value, ease of installation, transportation etc. After subjecting different sizes of uPVC pipe internal diameter through iterative process to get the best diameter that produces a percentage head loss of less than 4% European Small Hydropower Association (ESHA) standard, the 442mm diameter penstock was selected because it has the least head loss of 2.5%, even though the 397mm diameter also met the condition having a 4% loss. Parameters like the friction loss, net head, thickness of pipe, safety value, wave velocity, diameter of vent, operating pressure were gotten to be 0.38, 14.62m, 27mm, 4.1, 384m/s, 0.07m, 8.2bar respectively. Finally the cost benefit analysis was computed to show the effect of using a larger diameter penstock over the smaller diameter that gave a cost benefit ratio of 1.4, an indication that shows that for every extra one naira (Nigerian Currency) spent on the penstock, a benefit of 40kobo (Nigerian Currency) is achieved. This shows that the larger pipe diameter if used will yield positive returns on the long run.

Keywords

Head Losses, Friction Losses, Diameter of Penstock, Cost

Received: May 21, 2017 / Accepted: July 24, 2017 / Published online: Septembe 18, 2017

1. Introduction

More than 60% of communities in Nigeria are still not connected to the National Grid [2]. The cost of extending the grid is currently high, compared with the cost of installing off-grid electricity generation plants. Water resources for the development of SHP abound in all states of Nigeria, in fact flowing water bodies classified as “small” in Nigeria can generate between 100 – 200Kw [11]. Opportunities thrive in Hydropower schemes development as a viable source of energy for electricity generation. Hydro power, a renewable source of energy that utilizes the elevation difference in altitude to generate energy, using the available flow as the fuel that powers the turbine. The generation of energy from water can be explained by the law of conservation of energy. The potential energy of flowing water is converted to kinetic energy in the penstock, which turns the blades of the turbine to produce mechanical energy.

The penstock is a conduit or tunnel connecting a reservoir/forebay to hydro turbine housed in power house

---

* Corresponding author
E-mail address: obixi@yahoo.co.uk (O. A. Chinyere), rovian2003@yahoo.com (N. R. Obasih), emmacyosy13@gmail.com (E. O. Ojo), dozine79@gmail.com (C. Okonkwo), mafianaedwardudoka@yahoo.com (E. U. Mafiana)

building for power generation [10]. The penstock constitutes a major expense in the total Micro-Hydro budget. It is therefore worthwhile to select an appropriate pipe diameter to minimise both lifetime running costs and initial purchase cost. Conveying water from the intake to the powerhouse -the purpose of a penstock may not appear a difficult task, considering the familiarity of water pipes [4]. However, deciding the most economical arrangement for a penstock is not so simple.

A penstock is characterized by materials, diameter, wall thickness and type of joint. The material is selected according to the ground conditions, accessibility, weight, jointing system and cost [4]. The diameter is selected to reduce frictional losses and therefore energy losses within the penstock, which also depends on a trade-off between penstock cost and power losses Selecting as small a diameter as possible to minimize cost and selecting as large a diameter as necessary to minimize losses [3]. A simple criterion for diameter selection is to limit the head loss to a certain Percentage that is a loss of power (head) of 4% is usually acceptable [4]. The wall thickness is selected to accommodate the pressures encountered during plant operation.

This work seek to address basically the design of penstock for kuchigoro Small hydropower Project (SHP), with specific objectives to calculate for the required length of penstock, selection of suitable penstock material, iterating for optimum diameter that will reduce losses, cost benefit analysis etc.

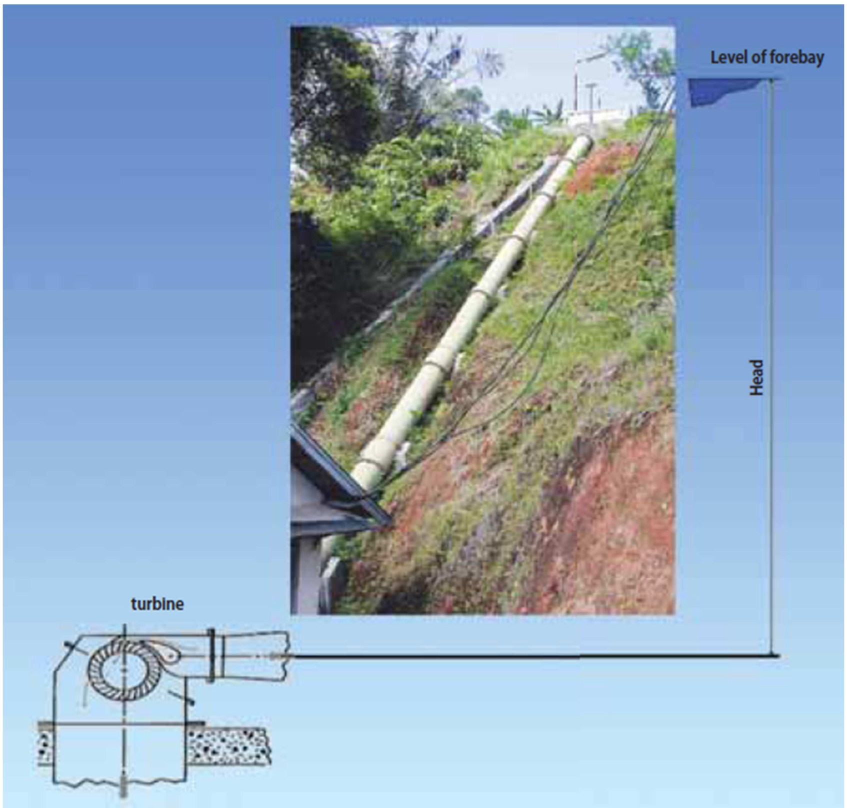


Figure 1. Showing a penstock to a turbine [8].

2. Materials and Methods

2.1. Study Site

The Geologic setting of the project site – in Abuja Municipal Area Council (AMAC) Federal Capital Territory (FCT), Abuja lies within longitudes 07° 24` 20`` and Latitudes 08° 54` 47``, with farming as the major occupation of the people.

2.2. Material

Factors to consider when deciding which materials to use for a particular penstock design [3]. Required operating pressure and diameter, Method of coupling, Weight and ease in handling and accessibility of site, Local availability of pipe, Maintenance requirements and expected life, Nature of terrain to be traversed, effect on pipe of water quality, climate, soil, and possible tampering.

The following materials are likely to be used for the penstock of micro-hydro schemes. Mild Steel, Un-Plasticized Polyvinyl Chloride (uPVC), High Density Polyethylene (HDPE), Asbestos Cement, Glass Reinforced Plastic (GRP).

Having carefully gone through the properties of the listed materials, taking factors like environment (Smooth terrain), friction loss, surge pressure, ease of installation (Spigot and

Socket Jointing) and cost of pipe (cheaper than steel pipe), the uPVC pipe is therefore recommended for the design.

2.3. Methodology

The basic technical details were carried through field survey to ascertain the basic requirements like the flow and head for the Kuchigoro Small Hydro Project (SHP) in AMAC, FCT Abuja Nigeria in 2015. The flow was gotten using velocity area method and the head was estimated by the help of the area contour map and altimeter. The data was analyzed using mathematical equations as available in the literatures. Hence to accomplish the objectives of this study, the methodology is divided into three parts:

i) The first part will iterate different internal diameters by trial and error method using the Microsoft-excel platform to get the best diameter that will limit head loss or power loss by 4%.

ii) The second part will also use Microsoft-excel platform to address factors like the pressure wave velocity, surge head, total head, safety factor and area of vent that can cause failure and damage of pipe if neglected. This part will only consider diameters that met the 4% power or head loss factor.

iii) The third part will address the cost benefit analysis as well as the trade-off between cost and the size of the internal diameter.

2.3.1. Economic Diameter of Penstock

The economic diameter equation serves as a guide to aid us with close diameter we can optimize by adding or removing from it through iteration to get the best diameter that will limit the 4% power loss. It is given by [6]:

$$D_e=C_1\ C_2\ Q_0^{0.43}\ H_0^{0.14} \tag{1}$$

where

D_e-Economic Diameter

C_1-Energy Cost Coefficient (1.2 - where energy cost is low; 1.3 – where energy cost is high or where there exist no alternative source)

C_2-Penstock material coefficient (1.0 for steel; 1.05 – 1.1 for wood; 0.35-0.4 for plastics)

Q_0-Design Discharge

H_0-Design Head of Plant

2.3.2. Losses in a Penstock

Water losses energy as it flows through a pipe, fundamentally due to the following:

a) Friction against the pipe wall

The friction against the pipe wall depends on the material roughness and the velocity gradient nearby the wall. Therefore as the Reynolds number increases the friction loss will also increase.

Given as [3]

$$\text{hfriction loss} = \text{hwall} + \text{hminorloss} \tag{2}$$

Where hwall is mathematically represented as [1]

$$\text{hwall} = \frac{fL0.08Q^2}{d^5} \tag{3}$$

Where f = friction factor

L = length of pipe

d = Inner diameter of pipe work

b) Minor losses (losses due to turbulence)

Water flowing through a pipe system, with entrances, bends, sudden contraction and enlargements of pipes, racks, valves etc. experience losses in the following ways.

i) Loss of head by sudden contraction (Kc): Due to sudden contraction, the streamlines converge to a minimum cross-section called the vena contrata and then expand to fill the downstream pipe [9].

Table 1. Head loss co-efficient for sudden contraction [3].

d_1/d_2	1.0	1.5	2.0	2.5	5.0
Kcontration (Kc)	0	0.25	0.35	0.40	0.50

(Where d1/d2= ratio of large to small pipe diameter)

ii) Loss of head at the entrance (Ke): An entrance to the pipe is otherwise an extreme case of sudden contraction from a forebay to the mouth of the penstock.

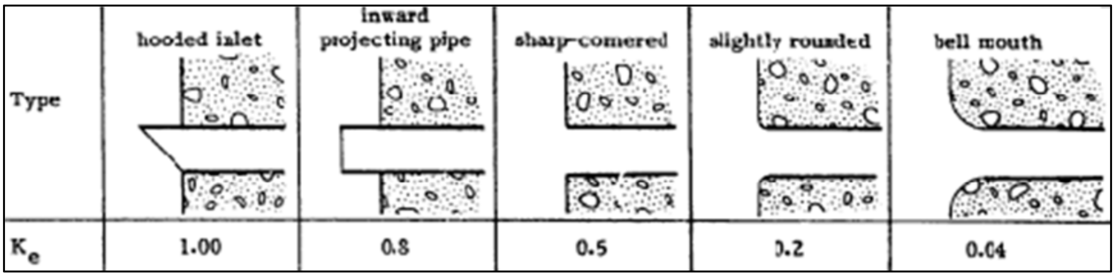
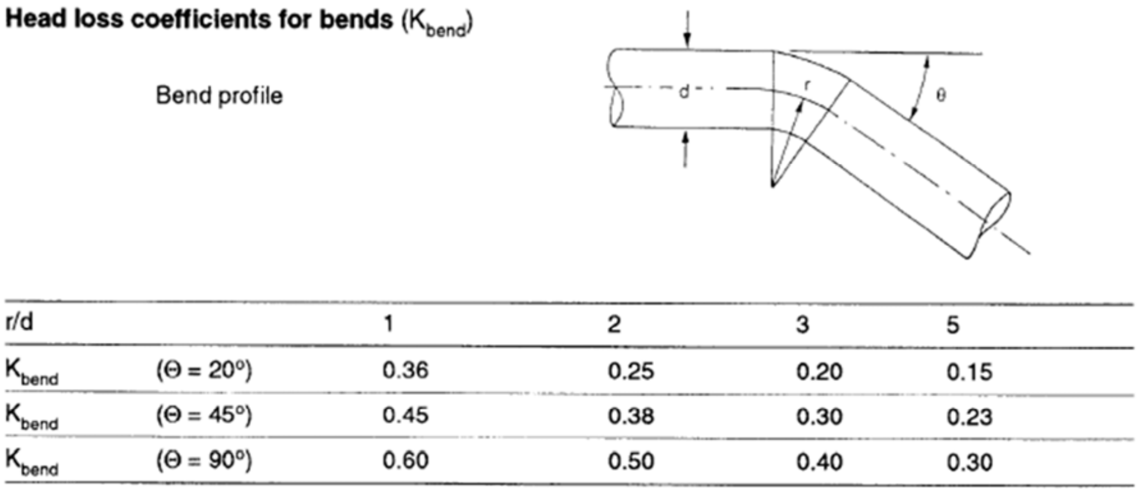


Figure 2. Losses at entrance [3].

iii) Loss of head in bends (Kb): pipe flow in a bend, experiences an increase of pressure along the outer wall and a decrease of pressure along the inner wall [1]. This pressure unbalance causes a secondary current that leads to losses.



Head loss coefficients for bends (K_{bend})

Bend profile

r/d		1	2	3	5
K_{bend}	($\Theta = 20^{\circ}$)	0.36	0.25	0.20	0.15
K_{bend}	($\Theta = 45^{\circ}$)	0.45	0.38	0.30	0.23
K_{bend}	($\Theta = 90^{\circ}$)	0.60	0.50	0.40	0.30

Figure 3. Loss of head in bends [1].

iv) Loss of head through valves (Kv): valves or gates are used in MHP to isolate a component from the rest, so they are neither entirely closed nor entirely open. The loss of head produced by the water flowing through an open valve depends on the type and manufacture of valve.

Table 2. Losses through fully opened valves [3].

Type	**K_v**
Spherical	0
Gate	0.1
Butterfly	0.3

Hence the losses due to turbulence are the sum of all the losses due to turbulence explained above [7].

$$\text{hminor} = \frac{V^2}{2g}(\text{Ke}+K_{b1}+K_{b1}+K_{c1}+K_{c2}\text{……..}+\text{Kv}) \quad (4)$$

c) Losses due to surge or water hammer:

These are sudden and temporal high pressure which results from sudden blockage of the water flow. They are also known as water hammer pressures. The surge pressure in the steel pipe is three times higher than in the PVC pipe, due to the greater rigidity of the steel.

2.3.3. Head

This is the vertical distance through which the water falls or drops in the turbine. There are various forms of head which are net head, total head, gross head and the surge head. Given in [9]

$$\text{hnet} = \text{hgross–hfriction} \quad (5)$$

$$\text{htotal} = \text{hgross+ hsurge} \quad (6)$$

The power generated by using the potential energy of the flowing water is given by the following formula [4]:

$$P = 7QH \quad (7)$$

Where;

P is the power in watts

Q is the discharge, passing through the turbine in m^3/s

H is the net head of the water in m

2.3.4. Moody Chart

The moody chart is a graph in non-dimensional form that relates the Darcy-weisbach friction factor, Reynolds number and relative roughness for fully developed flow in a circular pipe. It can be used for working out pressure drop or flow rate down such a pipe. The relative roughness being the ratio of the mean height of roughness of the pipe to the pipe diameter or $\frac{k}{d}$ and $\frac{1.2Q}{d}$[9]

Where k = Relative roughness = 0.01

Q = flow in m^3/s

d = Internal diameter in metres (m) or millimetres (mm).

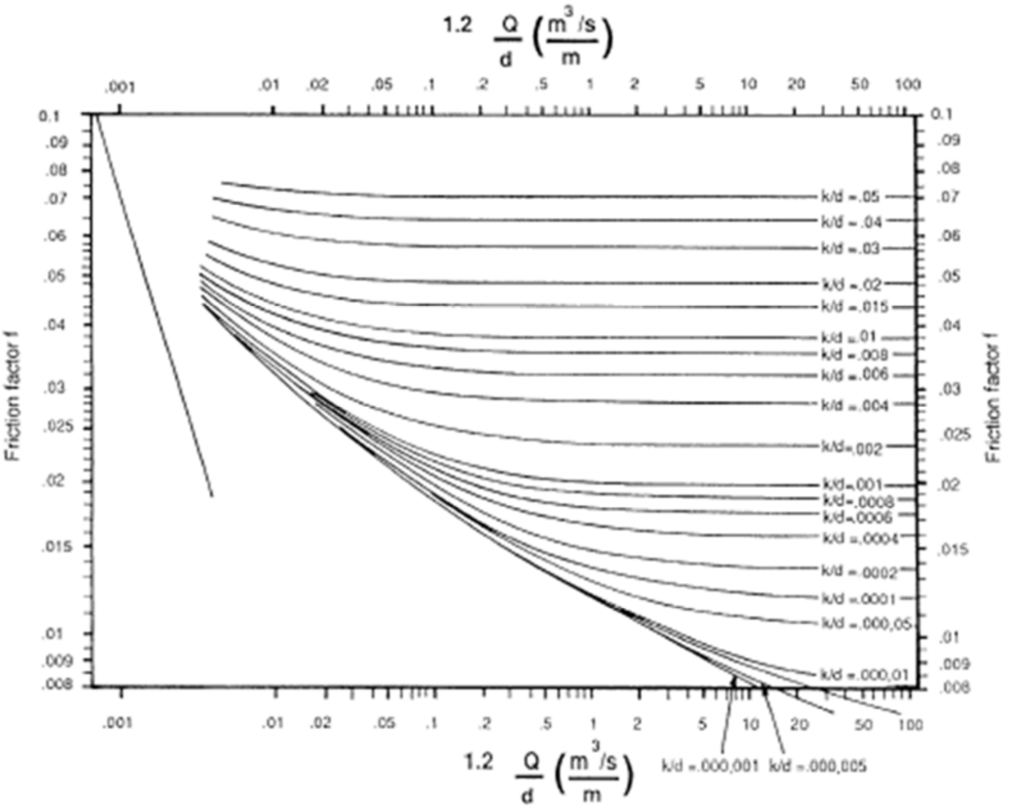


Figure 4. Moody Chart [5].

2.3.5. Velocity of Water in the Penstock (V)

A smaller pipe diameter means a higher velocity of water and higher pressure losses. The lower velocity will also result in less surge head or water hammer. For low heads SHP projects the velocity should not exceed 1-3m/s to maintain head losses and surge pressure within acceptable limits [3].

$$\text{Hence } V = \frac{4Q}{\pi d^2} \qquad (8)$$

Where V= velocity of water

Q = discharge

d = diameter of pipe.

2.3.6. Percentage Loss of Head Due to Friction and the Net Head (HNET)

This is the ratio between head loss due to friction to gross head multiplied by100. Percentage Loss of above 4% is usually not acceptable according to the European small hydro association thereby making the penstock diameter not suitable.

$$\text{Given as } \%\text{loss} = \frac{hfriction}{hgross} * 100 \qquad (9)$$

2.3.7. Operating Pressure

Total pressure in penstock = atmospheric pressure + absolute pressure (10)

Where absolute pressure

$$P = hpg \qquad (11)$$

Where h = net head,

P = density of water

g = 9.8

2.3.8. Pressure Wave Velocity (a)

This is the speed with which the pressure surge travels along the pipe. The pressure wave velocity arises from the effect of surge or water hammer.

Mathematically given as [5]:

$$a = \frac{1400}{\sqrt{1+\left(\frac{2.1*10^9*d}{E*t}\right)}} \qquad (12)$$

where

E = Young's Modulus of elasticity of uPVC = 2.8 $*10^9 N/m^2$

t = Pipe material thickness

d = pipe diameter

1400 = wave velocity or speed of sound in water approximately given as 1400.

2.3.9. Surge Head

This is the ratio of the pressure wave velocity multiplied by the velocity of water in the penstock over the acceleration due gravity. The surge head together with the gross head will produce the total head of the scheme.

Mathematically given as [1]:

$$\text{hsurge or maximum surge pressure} = \frac{av}{g} \tag{13}$$

2.3.10. Safety Factor (S.F)

This is the ratio of maximum stress or ultimate tensile strength to the working stress. For penstock design a safety factor of less than three should not be accepted for any penstock design.

Mathematically given as [1]:

$$\text{S.F} = \frac{t*S}{5*htotal*10^3*d} \tag{14}$$

Where; t = pipe thickness

d = internal diameter of pipe =

f = friction factor of pipe material from moody chart.

S = ultimate tensile stress of uPVC = 28 $*10^6$N/m^2

h_{total} = total head.

2.3.11. Air Vent

Air has to be permitted to enter or leave the penstock at specific points along its length, otherwise, as the penstock empties, the pressure within will fall below atmospheric pressure and the pipe may collapse. To prevent this possibility, a simple air vent i.e. a pipe section open to the atmosphere is located at the upper end of the penstock, possibly in the forebay wall itself. Hence we have [3]:

$$\text{Area of vent} = \frac{Q}{400c\sqrt{p}} \tag{15}$$

Where c = co-efficient of discharge through inlet.

c = 0.5 for ordinary inlet valves

c = 0.7 for short air-inlet pipes.

P = maximum negative pressure difference the pipe can accommodate.

Where;

$$\text{P} = \frac{2E*t^3}{f*D^3} \tag{16}$$

WhereE= young modulus of uPVC = 2.8$*10^9$N/m^2

t = pipe thickness

D = internal diameter of pipe

f = friction factor of pipe material

Hence diameter of pipe

$$\text{d} = 2\sqrt{\frac{A}{\pi}} \tag{17}$$

3. Result and Discussions

3.1. Result

Table 3. Showing standard sizes ofuPVC pipe and their wall thickness [1].

Nominal Diameter	uPVC pipe withMaximum working pressure (10bar)		
		Internal diameter	Minimum wall thickness
inches	mm	mm	mm
6	160	140	9
9	225	198	13
11	280	246	16
11	315	277	18
14	355	312	21
16	400	352	23
18	450	397	25
20	500	442	27

Table 4. Summary of basic data from feasibility survey on Kuchigoro2015

Flow rate	Gross head	Vertical horizontal distance	Terrain type
0.26m^3/s	15m	73.48m	Smooth not too rocky

Hence the economic diameter [using equation (1)] becomes

$$D_e = 1.2*0.38*0.26^{0.43}*15^{0.14} = 0.403\text{m} = 400\text{mm approx.}$$

From Pythagoras theorem the length of the penstock is estimated

$$\text{Length of pipe} = \sqrt{horizontaldistance^2 + hgross^2} = \sqrt{73.48^2 + 15^2}$$

Length of pipe = 75m

Table 5. Iterating for different diameter.

Internal Diameter(mm)	$\frac{k}{d}* 10^5$	$\frac{1.2Q}{d}$	FrictionFactor (f)	Pipe wall friction (m)	Velocity of water(m/s)	Minor losses (hminor)(m)	Friction losses (hfriction)(m)	Percentage loss of head(% loss)
277	3.6	1.12	0.015	3.73	4.3	0.57	4.29	28.7
312	3.2	1.00	0.0135	1.85	3.4	0.35	2.20	14.7
352	2.8	0.89	0.013	0.98	2.7	0.22	1.19	7.9
397	2.5	0.79	0.0125	0.51	2.1	0.14	0.65	4.0
442	2.3	0.71	0.012	0.29	1.7	0.09	0.38	2.5

Table 6. Comparism between two penstocks uPVC internal diameter.

S/N		Unit	PVC	PVC
1	Internal Diameter	mm	442	397
2	Internal diameter	m	0.442	0.397
3	Wall thickness	mm	27	25
4	Wave velocity	m/s	384	390
5	Estimated Surge Head	m	66.0	86.6
6	Estimated total head	m	81	99
7	Effective wall thickness	mm	27	25
8	Calculated safety factor		4.1	3.5
9	SF acceptable		Yes	Yes
10	Area of vent	m^2	0.04	0.003
11	Diameter of vent	m	0.07	0.06
12	Operating Pressure		8.2	9.1

Table 7. Cost benefit Analysis of using 442mm pipe over 397mm pipe.

S/N			uPVC	uPVC
1	Internal diameter	mm	442	397
2	Net head	m	14.62	14.35
3	Estimated power	kW	26.6	26.2
4	Estimated Annual Energy	kWh	233,016	229,512
5	Annual revenue	₦	6,321,724	6,226,661
6	Annual benefit derived from using 442mm Diameter penstock over 397mm diameter (Internal)	₦	95,063	-
6	Estimated cost of material	₦	5,250,000	5,120,000
7	Extra cost from using 442mm over 397mm internal diameter pipe	₦	130,000	-
8	Cost benefit comparism		1.4	-

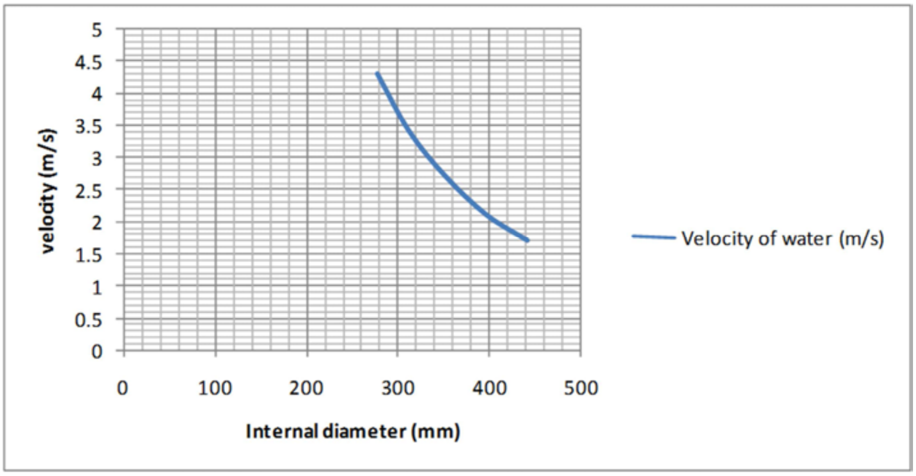


Figure 5. Showing the relationship between velocity and internal diameter.

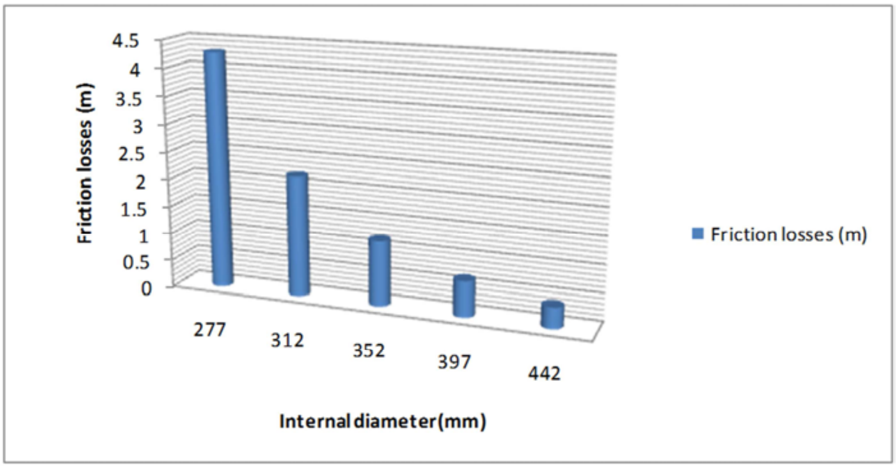


Figure 6. Showing the relationship between friction losses and internal diameter.

3.2. Discussions

i) Iteration for suitable diameter: Equation (1) gives the economic diameter of the penstock to be 400mm approximately, which serves as a guide diameter to choose penstock sizes between ±100mm above and below the 400mm for our iteration process to get the best penstock size that meets the 4% loss of power condition. From (Table 3) using the internal diameter that falls at the maximum working pressure of 10 bar to cushion the effect of pressure surge and safety against the penstock from bursting, if water hammer arises. Table 5 iterated different penstock of varied internal diameter and thickness using the Microsoft excel platform as a tool to help simplify the bulk and long iteration processes. Factors like the friction factor, pipe wall friction, velocity of water; minor losses and percentage loss of head were considered for the iteration process to get the best pipe diameter that will not exceed the 4% ESHA standard for losses. From the analysis in table 5, two penstock of internal diameter 397mm and 442mm percentage loss of head did not exceed the 4% requirement, while other penstock internal diameters exceeded the 4% loss bench mark and makes them not suitable for the project, due to the percentage of head loss and power, that will result in loss of revenue due to a shortfall on the net head of the project if used. Hence the adoption of the 397mm and 442mm diameter penstock for further analysis. Also in terms of maximum velocity of flow in the pipe not exceeding the 3m/s the 397mm and 442mm penstock also met the requirement. Figure 5 shows the relationship between velocity and the internal diameter. It shows that as the diameter of the penstock increases, the velocity reduces and vice versa. A drop in velocity in the pipe reduces head loss, that is, a smaller pipe diameter means a higher velocity of water, higher pressure losses and high tendency for water hammer. Figure 6 shows how friction losses increase with smaller pipe diameter, resulting to head loss that leads to power loss. It is worth stating that, selecting a penstock diameter is a trade-off between cost and power losses; selecting a smaller diameter as possible to minimize cost and selecting as large a diameter as necessary to minimize losses. The penstock diameter is directly proportional to cost and inversely proportional to losses, that is the higher the diameter the higher the cost and the higher the diameter the lesser the losses and vice versa.

ii) Failure prevention parameters (pressure wave velocity, surge head, total head, safety factor and area of vent): From table 6, the wave velocity of 442mm and 397mmm are 384m/s and 390m/s. the 442mm has a lower wave velocity given it the advantage over the 397mm. considering the total head which is directly proportional to the surge pressure, that is the higher the total head the higher the surge pressure. The 442mm diameter has a lower total head of 81m as against the 99m for the 397mm diameter gives it an advantage over the 397mm in terms of surge control that may lead to water hammer. Also from table 6 both penstocks has acceptable safety factor above 3 which is acceptable by the ESHA standard. We can safely state that technically and operational wise either of the 442mm and 397mm penstock can be used for the Kuchigoro SHP project, as both penstock diameter met the basic technical requirement of percentage loss not exceeding 4%, velocity in the penstock maintain between 3m/s for low head scheme and a safety factor above the 3 ESHA standard, even though on the basis of losses and surge control the 442mm has advantage over the 397mm penstock.

iii) Cost benefit Analysis: Table 7 shows cost comparism between the two penstock internal diameters of 442mm and 397mm. from the analysis the 442mm penstock has a higher cost price than the 397mm diameter, though with a ₦ 95,063 benefit over the 397mm due to higher energy produced, resulting from a very low head loss percentage of 2.5% as against the 4% loss of the 397mm diameter, making it in terms of benefit the 442mm diameter has advantage over the 397mm, even with the extra cost of ₦ 130,000 from the 442mm internal diameter. The cost benefit ratio from table 7 is 1.4, meaning that for every one naira spent on purchasing the 442mm extra internal diameter penstock over the 397mm, a benefit of 0.4 kobo is achieved, that is, a 40% return or benefit on every one naira. Considering cost benefit analysis and the other technical advantage the 442mm internal penstock diameter pipe is selected over the 397mm internal diameter pipe.

4. Conclusion

The 442mm internal diameter with wall thickness of 27mm uPVC penstock amongst other sizes gives the best cost-benefit ratio and best design requirement in terms of the 4% loss, and safety factor of above 3, though more expensive than the other penstocks options in terms of cost in the interim, but on the overall the cost benefit ratio from calculation favours the use of the 442mm penstock with a 1.4 cost benefit ratio.

References

[1] Adam, H., Andy, B., Priyantha, H., & Allen, H. (1993). MH Design Manual: A guide to Small – Scale water power schemes.

[2] Ajani, E. A., Olasupo, O. A., Oyelade, O. L., Olusunle, S. O. O. and Adewoye, O. O., (2009), Developing Local Manufacturing Capacity for SHP Equipment - NASENI Experience. Owerri: FUTO.

[3] Alien, R. (1990): MHP source book: A Practical guide to design and implementation in developing countries.

[4] ESHA (1998): Layman's Guide book on how to develop a Small Hydro Site.

[5] Fox, R., McDonald, A., & Pritchard, P. (2004). Introduction to fluid mechanics: Sixth edition. John wiley and Sons, Inc.

[6] HRC Training manual on SHP (2006), Hangzhon Regional Center (HRC) for SHP, Domestically called, National Research Institute for Rural Electrification, China.

[7] Kunwor, A. (2012): Technical Specifications of Micro Hydropower systems design and itsImplementation, feasibility Analysis and design of LamayaKhola Micro Hydro Power Plant.

[8] Klaus, J., Ekart, H., & Heinz, U. (2009). ASEAN Centre for Energy (ACE): Good and Bad of Mini Hydro Power.

[9] Rajput, 2006: A text book of fluid mechanics and hydraulic machines in SI units.

[10] Singhai, M. and Arun, K. (2015): Optimum Design of a Penstock for Hydropower Projects-International Journal of Energy and Power Engineering (Vol. 4).

[11] UNIDO-RC-SHP, (2008), *Manual and Reports from UNIDO Regional Centre for Small Hydro Power*, Abuja: UNIDO.