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DESIGN AND ANALYSIS OF HYDRO TURBINES FOR ELECTRICAL POWER GENERATION

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Article Info

Abstract

In designing a hydropower plant, the design of turbine type depends on the head and water flow. Researchers suggest that Axial/Propeller turbines can perform efficiently in lower heads because of their high specific speeds, Francis turbines can perform efficiently in medium to medium/high heads with high water discharge and medium specific speeds whereas Pelton turbines can perform efficiently in high heads with low water discharge and low specific speeds.

In this paper the output performance of Axial/ Propeller, Francis and Pelton turbines are designed, analyzed and compared using TURBNPRO software for the existing Jams hill Turen More HPP. The site head and water discharge are 117m and 305 m^3/s. The feasibility recommends 4 vertical shaft Francis turbines.

From the results we conclude that if a low head, high specific speed, Axial/Propeller turbine is designed for a medium head site, then its specific speeds exceed its limitations for the same electrical power output per turbine. Similarly, if a high head, low specific speed, Pelton turbine is designed for medium head site, then its runner diameter exceeds its limitations. Four Francis turbines can have the same electrical power output as a minimum of twelve Pelton turbines for the same medium head range

Keywords: *water discharge, energy, head, hydro, renewable.*

Introduction

Hydropower is based on the principle that flowing and falling water has a certain amount of energy associated with it. Conversion of the energy of flowing water into mechanical energy can be done with a wheel or a turbine. A generator is connected to the turbine by a shaft, which converts the mechanical energy into electrical energy. Because the water is recycled by the sun, it makes it a renewable energy source.

Now a days in a time of climate change the world is already facing many issues related to it. Hydropower is environment friendly and does not pollute the air like coal, natural gas and other nuclear power plants. It is also domestic; a country does not have to rely on importing coal and natural gas as their prices are fluctuating. Hydropower generation is among the most efficient renewable energy source. Its production times back to almost ten decades. [1]. Due to the environmental considerations small hydro power projects are emerging [2]. It took more than ten generations by the hydropower to generate electricity efficiently and has thus lies among the best sources of renewable energy. [3]. The operation cost of micro-hydro is low and is environment friendly. [4]. Rural Electrification is mainly provided by the Small Hydro Power plants in developing countries also including India. [5].

Employment opportunities, fighting climate change and rural electrification in both developed and underdeveloped countries are being provided using SHP but it has a high capital cost. [6]. In the countries having emerging economies, 3700 major dams having the capacities of more than 1 MW are being planned or being constructed that can raise the hydroelectric capacity by 73%. of more than 1 MW are being planned or being constructed that can raise the hydroelectric capacity by 73%. [7].

Hydropower turbines

Hydropower turbines are divided into two types

1. Reaction Turbine
2. Impulse Turbine

Reaction turbines

Power is developed in the reaction turbine by the combination of pressure along with moving water. Instead of striking each bucket of the runner via a nozzle, the runner is placed in the water. In sites where the head is low and the water flow is high, reaction turbines are used. Types of reaction turbines are Axial/Propeller and Francis turbine. Compared to impulse turbines, reaction turbines have better performance for high flow and lower head sites. We will be discussing two types of reaction turbines.

Axial/Propeller turbine

The Axial/Propeller Turbine of a runner to which blades are attached. These blades can be in the range between 3 to 6. These turbines perform at a relatively high speeds which makes their specific speeds higher. Its efficiency can be increased by adjusting the guide vane angles and turbine blades. For low head applications, Axial/Propeller turbines are quite efficient.

Limitations of Axial/Propeller turbine

Maximum Unit Flow - Input limited to less than 28,300 m^3/s (1,000,000 cfs)
Maximum Net Head - Input limited to maximum of 67 m (220 feet)
Maximum Unit Size - Runner Diameters not greater than 9,000 mm
Maximum Unit Output - Not greater than 200,000 KW
Specific Speed - Axial turbine application range is 68 to 199

Francis Turbine

A type of reaction hydro turbine. Works on the principles of radial and axial flow. It has an operation ranges of medium to medium/high head specific speeds are lower as compared to Axial/Propeller turbine.

Limitations of Francis turbines

Maximum Unit Flow - Input limited to less than 28,300 m^3/s (1,000,000 cfs)
Site Elevation above sea level. - Input limited to maximum of 4,570 m (15,000 feet)
Water Temperature - Input limited to maximum of 32.7 degrees C (91 deg/F)
Unit Setting - Input limited to a maximum setting above Tailwater of: Atmospheric pressure - Vapor pressure - 0.6 m
Maximum Unit Size diameters - Program will not consider solutions with runner greater than 9,650 mm (380 inches)
Maximum Unit Output - Program will not consider solutions with power output greater than 750,000 KW (1,005,700 Hp)
Specific Speed - Francis turbine application range is 50 to 310 (or 13.1 to 81.3 in US Customary units)

Turbine configuration

Horizontal Orientation - Limited to maximum runner diameter of 736 to 2200 mm (29 to 87 inches) depending on the specific speed
Semi-spiral Case - Limited to vertical units and heads up to 27.4 m (90 feet)
Flume intake - Limited to vertical units and heads up to 27.4 m (90 feet)
Minimum Operating Efficiency - No operation below 60% efficiency

Impulse turbines

In impulse turbine, power is developed only by the pressure energy of the high velocity moving water. This high-pressure energy is provided by the nozzle and is converted into kinetic energy as it strikes the buckets of the runner. In sites where the head is high and the water flow is low, such turbines are used. Due to its simplicity in design and lower cost, impulse turbines are used frequently in small hydro plants.

Pelton turbines

It is the simplest form of impulse turbines. Energy is extracted from the impulse water that is injected by the nozzles to the buckets of the wheel. The runner is above the maximum tail water level so draft tubes are not required in Pelton turbines. These turbines are mainly used for power generation. The use of 1 jet Pelton wheel has recently been designed for Small Hydro Power Plants.

Pelton turbine limitations:

Maximum Unit Flow - Input limited to less than 50 m³/s (1,765 cfs)
Maximum Net Head - Input limited to less than 1800 m (5,905 feet)
Maximum Unit Size - Program will not consider solutions with runner diameters greater than 4,000 mm (157 inches) for vertical units or 3,000 mm (118 inches) for horizontal units
Maximum Unit Output- Program will not consider solutions with power output greater than 425,000 KW (570,000 Hp)
Specific Speed - Pelton turbine limits varies depending on head and number of needles.
The maximum specific speed limits (in SI units) are as follows
1 and 2 Jet Units - 8.5 to 22
3 and 4 Jet Units - 8.5 to 21.1
5 and 6 Jet Units - 8.5 to 19.4
Number of Jets - Minimum: 1, Maximum: 6

Horizontal Orientation - Limited to maximum output of 50 MW, a maximum diameter of 3,000mm and no more than 2-jets
Vertical Orientation - Limited to maximum output of 425 MW, a maximum diameter of 4,000mm and no more than 6-jets

Comparison of Axial/Propeller, Francis and Pelton turbine Limitations

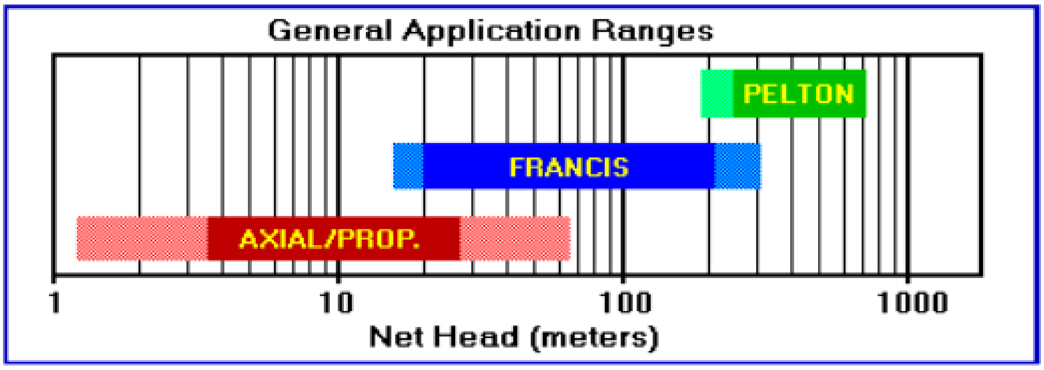


Figure 1: Comparison of Axial/Propeller, Francis and Pelton turbine net head limitations.

From the above diagram it can be concluded that Axial turbines can be applied under 67 m heads. These turbines have the highest specific speeds. Francis turbines can be applied under net heads under 300 meters having a relatively high specific speeds than Axial/ Propeller. Pelton turbines are usually applied to only high heads due to their relatively low specific speeds. However, Pelton units may justify consideration under medium head applications where long penstocks, pressure transients, speed governing or wide operating flow ranges are important issues.

Table 1: Turbine limitations comparison

	AXIAL/PROPELLER	**FRANCIS**	**PELTON**
Maximum Unit Flow	Input limited to less than 28,300 m^3/s (1,000,000 cfs)	Input limited to less than 28,300 m^3/s (1,000,000 cfs)	Input limited to less than 50 m^3/s (1,765 cfs)
Maximum Net Head	Input limited to maximum of 67 m (220 feet)	Input limited to maximum of 300 m (984 feet)	Input limited to less than 1800 m (5,905 feet)
Maximum Unit Size	Runner Diameters not greater than 9,000 mm (354 inches)	Runner Diameter not greater than 9,650 mm (380 inches) Horizontal Orientation -Limited to maximum runner diameter of 736 to 2200 mm (29 to 87 inches) depending on the specific speed Semi-spiral Case - -Limited to vertical units and heads up to 27.4 m (90 feet) Flume intake -Limited to vertical units and heads up to 27.4 m (90 feet)	Horizontal orientation -Limited to maximum output of 50 MW, a maximum Runner Diameter of 3,000mm (118 inches) and no more than 2-jets Vertical Orientation -Limited to maximum output of 425 MW, a maximum diameter of 4,000mm (157 inches) and no more than 6-jets
Maximum Unit Output	Not greater than 200,000 KW	Not greater than 750,000 KW	Not greater than 425,000 KW
Specific Speed	68 to 199	13.1 to 81.3	1 and 2 Jet Units - 8.5 to 22 3 and 4 Jet Units - 8.5 to 21.1 5 and 6 Jet Units - 8.5 to 19.4
Number of Jets	-	-	Minimum: 1, Maximum: 6 8.33 m^3/s for 6 jets

RESEARCH METHODS

Hydropower turbines are basically divided into three types, low head, medium head and high head. Usually Axial/Propeller turbines are used for low head, Francis turbines are used for medium/medium-high head and Pelton turbines for high heads.

- These three turbine types are designed for the existing Jamshill-Turen More Hydropower Project. The feasibility shows 4 Francis turbines to be more feasible, however we have designed Axial, Francis and Pelton turbines and compared the results to find out the reason which makes Francis turbines more feasible for this hydropower project.
- The site has a gross head of 117 meters and a water discharge of 305 m^3/s. These variables will be constant for all the turbine types.
- All the designs for all the turbine types are simulated in the computer software TURBNPRO.
- First, Axial hydropower turbines for this site specifications have been simulated and the results show the reasons behind why it cannot be feasible.
- The feasibility shows 4 vertical Francis turbines, these turbines will also be designed and the output per turbine are calculated.
- Design and Analyze Pelton turbines for the existing site and see how it performs under such site considerations. The Pelton turbines will have three alternatives with designs depending upon water discharge of 15 m^3/s, 20 m^3/s, 25 m^3/s.
- The designs show us the specific speed, rpm, output power per turbine, size of the runner.
- The results are analyzed.

Methodology block diagram

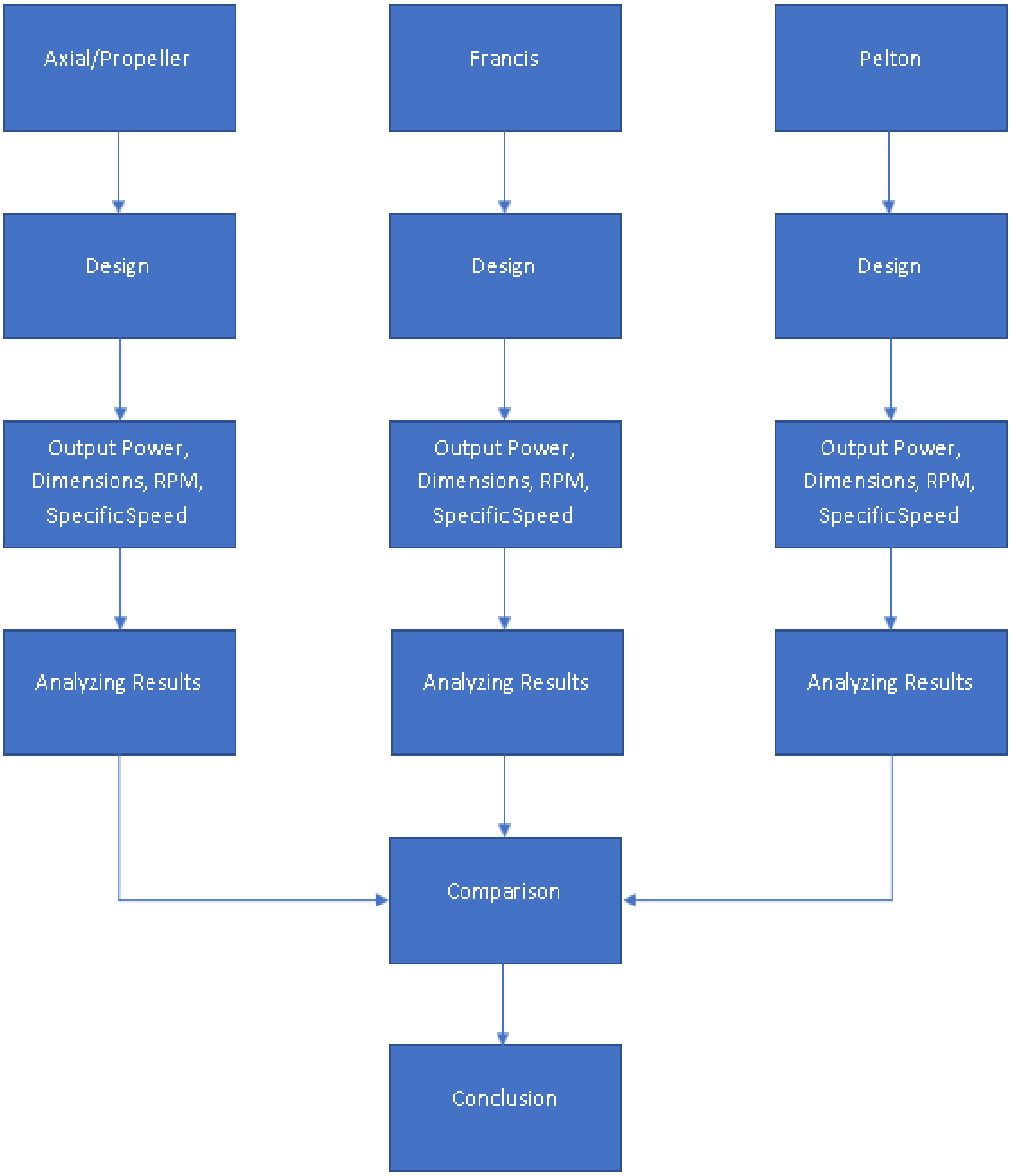


Figure 2: Methodology block diagram.

Data

Our constant input parameters in TURBNPRO are: Gross head, h=117 m and water flow rate, $Q=305m^3/s$.On the basis of these parameters our variable parameters will be decided. Our variable parameters will be:

Dimensions, Rpm, Specific speed, no of jets in case of Pelton turbine, and output power per unit. These parameters will also be dependent on each other.

Equations

Turbine output power

The output power of a turbine is calculated as [8].

$Pt = p * g * Hn * Q * nt$ (watt) (1)

Pt=Power generated in turbine shaft
p=Water density (1000 kg/m^3)
Hn= Net Head
Q=Water flow rate

G=Gravity acceleration constant
nt=Efficiency

Turbine specific speed

After calculating the output power and the rated head, the speeds of the turbine can be economically considered by consulting the manufacturer. The site head and water flow rate determine the type of turbine to be installed. The site head and water flow are also directly proportional to the turbine power and speed. Any turbine, with identical geometric proportions, even if the sizes are different, will have the same specific speed (*Ns*). This specific speed shows us which turbine is feasible according to our site specifications [9].

$$Ns = \frac{N * \sqrt{Pt}}{Hn^{5/4}} \text{ (r.p.m)} \quad (2)$$

Francis turbine dimension

If the net head *Hn*, runner speed *N*, *specific* speed *Ns* and water flow rate *Q* are known. So, the dimensions of Francis can be determined using the following formulas. [10]

$D = 84.5\,(0.31 + 2.49 * \overline{Ns}\,) *$ exit diameter in meters. (3)
$\sqrt{Hn}$

3

$D = (0.4 + 94.5) *$ $\overline{995}$ inlet runner diameter in meters. (4)
D
N

1 $\overline{Ns}$ 3

$D = \underline{\quad D3 \quad}$ inlet diameter in meters. (5)

$2 \quad (0.96+3.8*10^{-4}*Ns)$

Pelton turbine dimension

If the net head *Hn*, runner speed *N*, *specific* speed *Ns* and water flow rate *Q* are known. So, the dimensions of Pelton Turbine can be determined using the following formulas. [10]

$D_1 = 40.8 * \frac{\sqrt{Hn}}{N}$ Circle diameter determining the central lines of the bucket (meters) (6)

$B_2 = 1.68 * \sqrt{\frac{Q*1}{K\sqrt{Hn}}}$ Width of the buckets (meters). (7)

K= no of nozzles.

$D_e = 1.178 * \sqrt{\frac{Q*1}{K\sqrt{g*Hn}}}$ Diameter of the nozzle (meters). (8)

$D_j = 0.54 * \sqrt{\frac{Q}{\sqrt{Hn}}}$ Diameter of jet (meters). (9)

$V_{jet} = 0.97 * \sqrt{2 * g * Hn}$ Velocity if jet determined in m/s. (10)

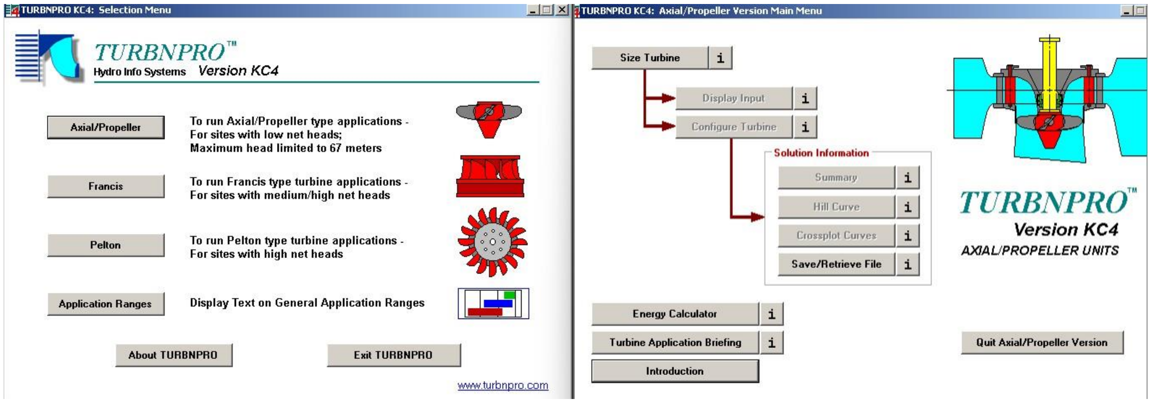
TURBNPRO

The sizing and technical development of hydro turbines is performed in the computer software TURBNPRO. The data is given by the user according to the site considerations. The equipment arrangement and other parameters are also required to be input by the user. TURBNPRO will process the input data and will output the data to the user. This output data will include the sizes, speeds, limitations for the turbines that would have satisfactory results according to the user's requirements. Annual energy production can also be developed for the users by the software.

A typical sequence that the user will follow for running the program is:

1. Input the data according to the site specifications.
   (SIZE TURBINE)
2. The unit size is selected and the arrangement is developed.
   (SIZE TURBINE and CONFIGURE TURBINE)
3. Review the dimensions and the other performance characteristics.
   Print displays.
   (SUMMARY, HILL CURVE, CROSSPLOT)
4. The solutions are saved as a file
   (SAVE/RETRIEVE)
5. The energy that is produced is calculated to the solution that is developed.
   (ANNUAL ENERGY CALCULATOR)
6. Energy production comparison to other solutions is done for the optimization of turbines.

Simulations



To run Axial/Propeller type applications - For sites with low net heads; Maximum head limited to 67 meters

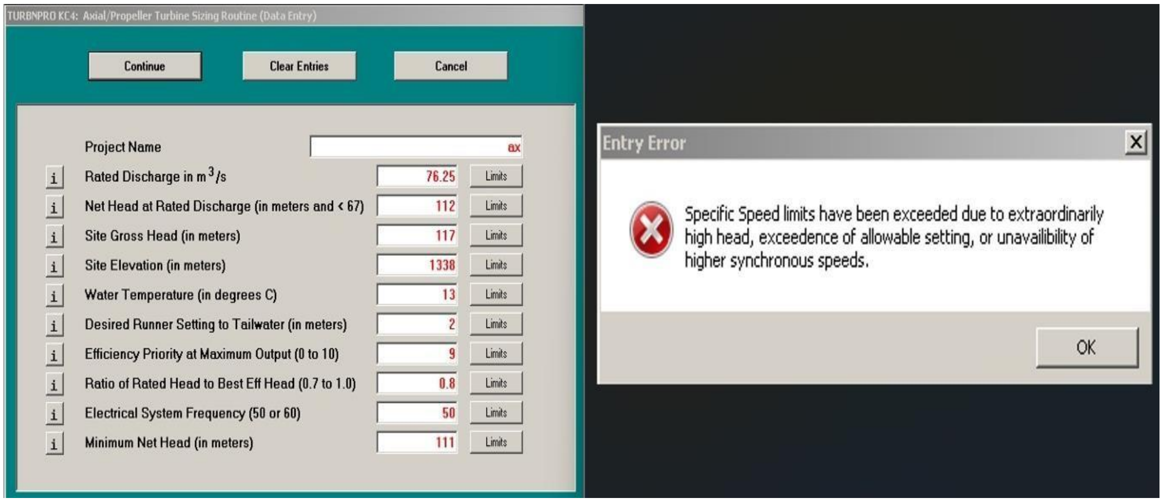
To run Francis type turbine applications - For sites with medium/high net heads

To run Pelton type turbine applications - For sites with high net heads

Display Text on General Application Ranges

Figure 3: TURBNPRO turbine selection.

Axial



Project Name: ax

Rated Discharge in m^3/s: 76.25

Net Head at Rated Discharge (in meters and < 67): 112

Site Gross Head (in meters): 117

Site Elevation (in meters): 1338

Water Temperature (in degrees C): 13

Desired Runner Setting to Tailwater (in meters): 2

Efficiency Priority at Maximum Output (0 to 10): 9

Ratio of Rated Head to Best Eff Head (0.7 to 1.0): 0.8

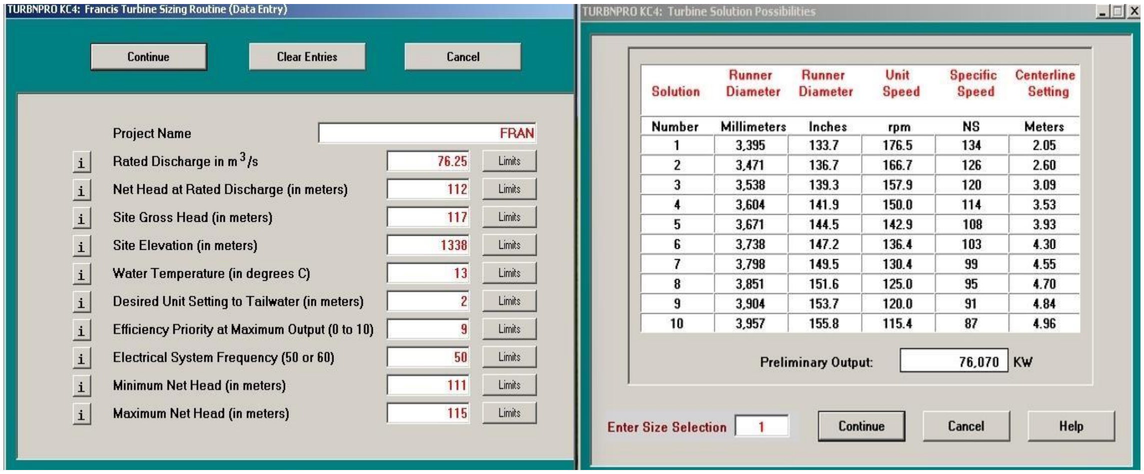
Electrical System Frequency (50 or 60): 50

Minimum Net Head (in meters): 111

Specific Speed limits have been exceeded due to extraordinarily high head, exceedence of allowable setting, or unavailibility of higher synchronous speeds.

Figure 4: Axial/Propeller turbine input/output.

Francis



Project Name: FRAN

Rated Discharge in m^3/s: 76.25

Net Head at Rated Discharge (in meters): 112

Site Gross Head (in meters): 117

Site Elevation (in meters): 1338

Water Temperature (in degrees C): 13

Desired Unit Setting to Tailwater (in meters): 2

Efficiency Priority at Maximum Output (0 to 10): 9

Electrical System Frequency (50 or 60): 50

Minimum Net Head (in meters): 111

Maximum Net Head (in meters): 115

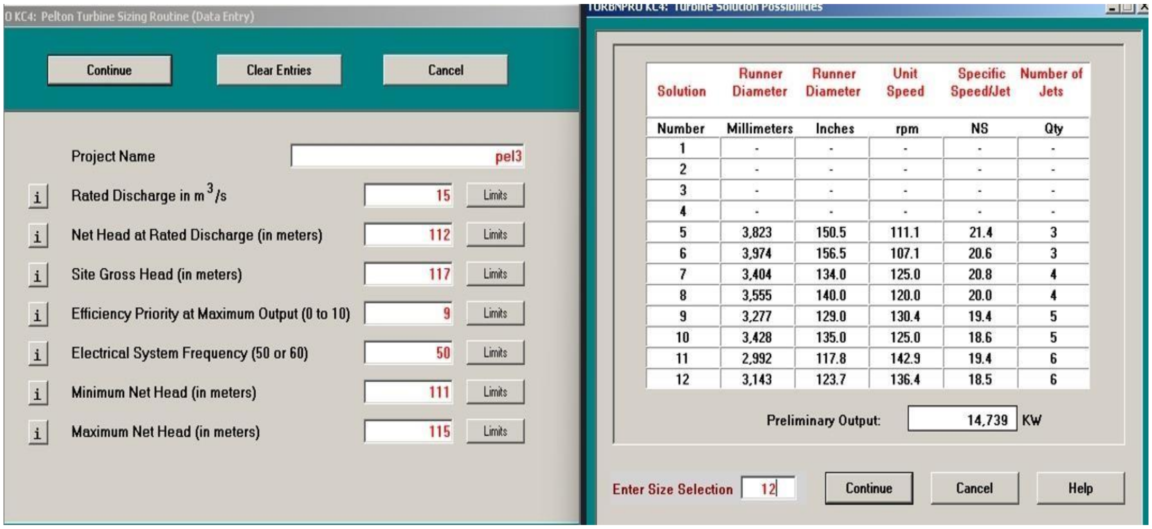
Solution	Runner Diameter	Runner Diameter	Unit Speed	Specific Speed	Centerline Setting
Number	Millimeters	Inches	rpm	NS	Meters
1	3,395	133.7	176.5	134	2.05
2	3,471	136.7	166.7	126	2.60
3	3,538	139.3	157.9	120	3.09
4	3,604	141.9	150.0	114	3.53
5	3,671	144.5	142.9	108	3.93
6	3,738	147.2	136.4	103	4.30
7	3,798	149.5	130.4	99	4.55
8	3,851	151.6	125.0	95	4.70
9	3,904	153.7	120.0	91	4.84
10	3,957	155.8	115.4	87	4.96

Preliminary Output: 76,070 KW

Enter Size Selection: 1

Figure 5: Francis turbine input/output.

Pelton Alternative 1



Project Name: pel3
Rated Discharge in m^3/s: 15
Net Head at Rated Discharge (in meters): 112
Site Gross Head (in meters): 117
Efficiency Priority at Maximum Output (0 to 10): 9
Electrical System Frequency (50 or 60): 50
Minimum Net Head (in meters): 111
Maximum Net Head (in meters): 115

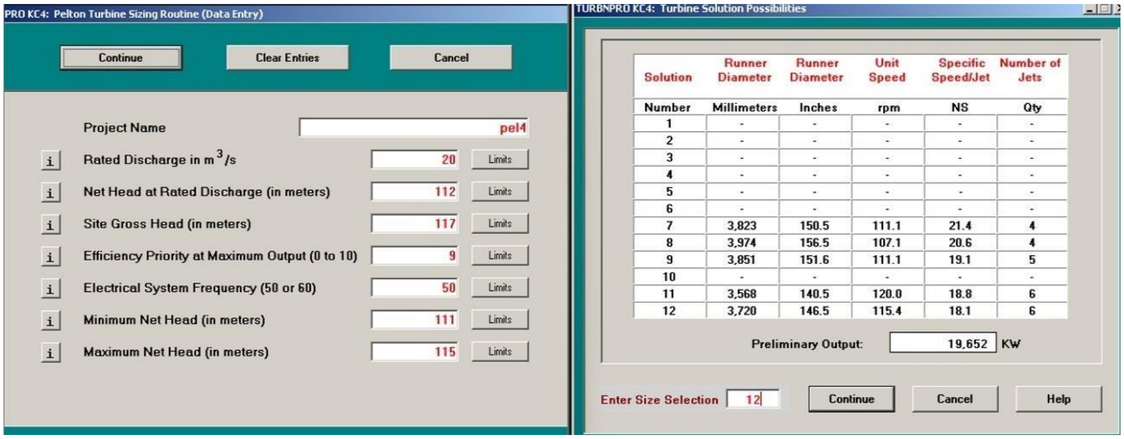
Solution Number	Runner Diameter Millimeters	Runner Diameter Inches	Unit Speed rpm	Specific Speed/Jet NS	Number of Jets Qty
1	-	-	-	-	-
2	-	-	-	-	-
3	-	-	-	-	-
4	-	-	-	-	-
5	3,823	150.5	111.1	21.4	3
6	3,974	156.5	107.1	20.6	3
7	3,404	134.0	125.0	20.8	4
8	3,555	140.0	120.0	20.0	4
9	3,277	129.0	130.4	19.4	5
10	3,428	135.0	125.0	18.6	5
11	2,992	117.8	142.9	19.4	6
12	3,143	123.7	136.4	18.5	6

Preliminary Output: 14,739 KW

Enter Size Selection: 12

Figure 6: Pelton turbine alternative 1 turbine input/output.

Pelton Alternative 2



Project Name: pel4
Rated Discharge in m^3/s: 20
Net Head at Rated Discharge (in meters): 112
Site Gross Head (in meters): 117
Efficiency Priority at Maximum Output (0 to 10): 9
Electrical System Frequency (50 or 60): 50
Minimum Net Head (in meters): 111
Maximum Net Head (in meters): 115

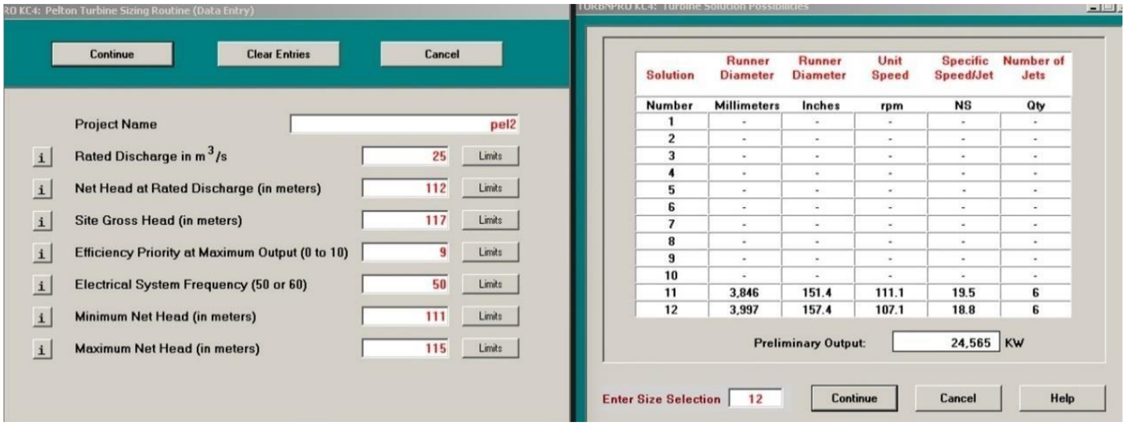
Solution Number	Runner Diameter Millimeters	Runner Diameter Inches	Unit Speed rpm	Specific Speed/Jet NS	Number of Jets Qty
1	-	-	-	-	-
2	-	-	-	-	-
3	-	-	-	-	-
4	-	-	-	-	-
5	-	-	-	-	-
6	-	-	-	-	-
7	3,823	150.5	111.1	21.4	4
8	3,974	156.5	107.1	20.6	4
9	3,851	151.6	111.1	19.1	5
10	-	-	-	-	-
11	3,568	140.5	120.0	18.8	6
12	3,720	146.5	115.4	18.1	6

Preliminary Output: 19,652 KW

Enter Size Selection: 12

Figure 7: Pelton turbine alternative 2 turbine input/output.

Pelton Alternative 3



Project Name: pel2

Rated Discharge in m^3/s: 25

Net Head at Rated Discharge (in meters): 112

Site Gross Head (in meters): 117

Efficiency Priority at Maximum Output (0 to 10): 9

Electrical System Frequency (50 or 60): 50

Minimum Net Head (in meters): 111

Maximum Net Head (in meters): 115

Solution Number	Runner Diameter Millimeters	Runner Diameter Inches	Unit Speed rpm	Specific Speed/Jet NS	Number of Jets Qty
1	-	-	-	-	-
2	-	-	-	-	-
3	-	-	-	-	-
4	-	-	-	-	-
5	-	-	-	-	-
6	-	-	-	-	-
7	-	-	-	-	-
8	-	-	-	-	-
9	-	-	-	-	-
10	-	-	-	-	-
11	3,846	151.4	111.1	19.5	6
12	3,997	157.4	107.1	18.8	6

Preliminary Output: 24,565 KW

Enter Size Selection: 12

Figure 8: Pelton turbine alternative 3 turbine input/output

RESULTS AND DISCUSSION

From the TURBNPRO simulations above.

Francis

Table 2: Francis turbine output

Output Power Per Turbine	76.07 MW
Water Discharge	76.25m^3/s
Specific Speed	134
Rpm	176.5
Runner Diameter (Meters)	3.395
Total Number of Turbines	4

Pelton Alternative 1

Table 3: Pelton alternative 1 output

Output Power Per Turbine	14.73 MW
Water Discharge	15m^3/s
Specific Speed	18.5
Rpm	136.4
Runner Diameter (Meters)	3.143
No of Jets	6
Total Number of Turbines	20

Pelton Alternative 2

Table 4: Pelton alternative 2 output

Output Power Per Turbine	19.65 MW
Water Discharge	20m^3/s
Specific Speed	18.1
Rpm	115.4
Runner Diameter (Meters)	3.720
No of Jets	6
Total Number of Turbines	15

Pelton Alternative 3

Table 5: Pelton alternative 3 output

Out Power Per Turbine	24.56 MW
Water Discharge	25m^3/s
Specific Speed	18.8
Rpm	107.1
Runner Diameter (Meters)	3.997
No of Jets	6
Total Number of Turbines	12

Comparing Output Results of Pelton Alternatives 1 2 3 and Francis

Table 6: Comparison output results of Pelton alternative 1 2 3 and Francis

	Pelton Alternative 1	**Pelton Alternative 2**	**Pelton Alternative 3**	**Francis**
Output Power Per Turbine	14.73 MW	19.65 MW	24.56 MW	76.07 MW
Water Discharge Per Turbine	15m^3/s	20m^3/s	25m^3/s	76.25m^3/s
Specific Speed	18.5	18.1	18.8	134
Rpm	136.4	115.4	107.1	176.5
Runner Diameter (Meters)	3.143	3.720	3.997	3.395
No of Jets	6	6	6	-
Total Number of Turbines	**20**	**15**	**12**	**4**

CONCLUSION

In our research we have designed Axial/Propeller, Francis and Pelton turbines for the existing Jamshill Turen More Hydropower Project. The site has a Gross Head of 117 meters and a water discharge of 305 m^3/s. Its feasibility shows 4 Vertical Francis Turbines to be feasible. The designs were performed on computer software TURBN PRO.

The following points have been concluded from our research.

- The design of Axial/Propeller turbines cannot be made possible because it cannot be even simulated in TURBN PRO as the head of the site is not under the range of Axial turbines. The maximum net head for Axial turbines is 67 meters, if it were to be constructed for this site then its specific speed would have exceeded its limitations. Such high specific speeds will not be feasible for the power house structure.
- 1m^3/s water discharge can generate an average of 1 MW electrical power depending on the efficiencies. With the increase in the specific speed of the turbine, rpm increases and its runner diameter decreases for the same output electrical power.
- Francis turbine shows us a total of 4 units each having an output power of 76.07 MW with a water discharge of 76.25 m^3/s, specific speed of 134, rpm 176.5 and a runner diameter of 3.395 meters.
- From the design of the Pelton turbines, it is concluded that its construction can be possible but not feasible because of its limitations for this site specifications. Alternative 3 shows us that a total number of 12 turbines need to be constructed, each having the power output of 24.56 MW with a water discharge of 25 m^3/s, specific speed of 18.8, rpm of 107.1,6 jets and a runner diameter of 3.997 meters. If we were to decrease the number of units and increase the output power of each unit, then the water discharge per turbine is to be increased. With the increase in water discharge per unit, the runner diameter will exceed 4 meters. Runner diameter exceeding 4 meters is not feasible for construction. Therefore 12 turbines can be our minimum number of turbines for construction but such greater number of turbines will also need a large area for the power house.

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