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Development of a Test Rig for a New Vertical Ultra-Low-Head Hydro Turbine with Calibration of Rectangular Notch for Discharge Measurement

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ABSTRACT

A new vertical ultra-low head hydro turbine has been conceptualized for power generation from water resources on shallow land regions with heads less than 3 m down to 0.5 m. This research reports the development of an experimental setup required for the testing of a newly conceptualized turbine along with the calibration of the rectangular notch used on it and is the novelty of this research. The methodology adopted for the development started with the identification of variables required on the test rig followed by design, fabrication, and testing for the calibration of the notch. The major design point for sizing the test rig was taken for a maximum flow rate of 120 LPS and a maximum upstream head over the turbine of 0.75 m. The overall dimension of the test rig designed was 9 m x 1.2 m x 1.5 m on four different sections assembled with nuts and bolts. The guidelines for installation of a rectangular notch, ISO 1980 was followed for sizing of notch. The trials for all the possible flow rates were found satisfactory as per the concept and tests were covered for calibration. The coefficient of discharge was found to increase from 0.575 to 0.617 for the increasing flow rate and height of the water column over the notch. The uncertainty band of ±0.67% on the measurement of flow for the turbine design condition was calculated. The advanced method and equipment are recommended for more precise results on flow measurement.

1. Introduction

Hydropower is the most economical source of renewable energy [1]. Most of the progress of small hydro-powers was passed over in the 1950s and 1960s. Now again, there exists a high necessity for the deployment of hydropower from low-head resources [2]. Technically hydropower can still be generated from 0 to 3 meters (Ultra-low head, ULH) of hydrostatic heads using non-conventional hydro turbines which fall under the category hydro kinetic or hydrostatic energy conversion [2-4].

Ultra-low head hydro turbines are the unconventional category of hydro turbines that can be mounted on open canal cases or closed flumes. As a result, there are systems in place to use the

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hydropower potential with head changes less than 3 m like old hydraulic facilities and distribution networks for water, walls and weirs in canals for farming is a growing alternative, especially when these obstacles are already in place for other reasons [5-8].

Among the ideas explored, a vertical ultra-low head turbine (VULHT) has been conceptualized for usage on open channel flow sections without (Figure 1) or with (Figure 2) a head-dropped zone (AP ref). The major components of the system are a fine trash rack, fixed guide vane, runner, shaft, gearbox, generator, overflow arrangement, and outlet flow level control mechanism. The turbine is submerged in water with an axial flow case without the draft tube. The water entering from the fine screen and fixed guide vane flows to the runner striking the blades which are fixed and of constant thickness without airfoils on it. This makes the vertical power shaft rotate transmitting the torque to the attached gearbox and finally to the electrical generator as pictured in Figure 1. It also has an outlet flow level control mechanism downstream of the turbine. The water level difference upstream and downstream is the net head acting on the system. The flow over the system is measured through a rectangular notch at the end of the flow line.

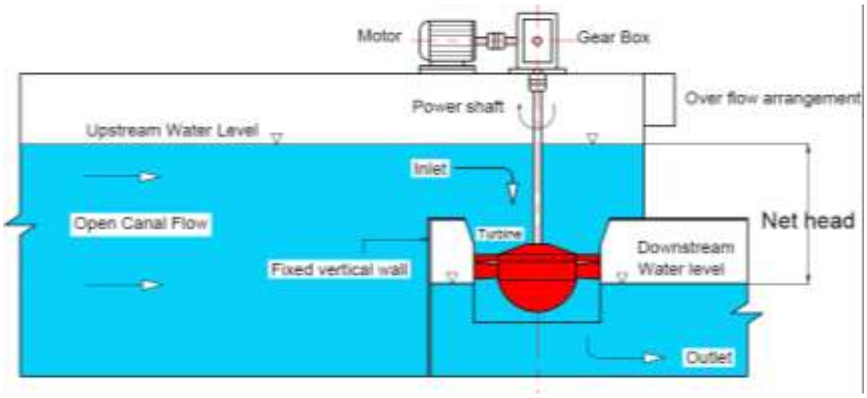

Fig. 1. Schematic diagram of the VULHT concept without a canal head drop [9]

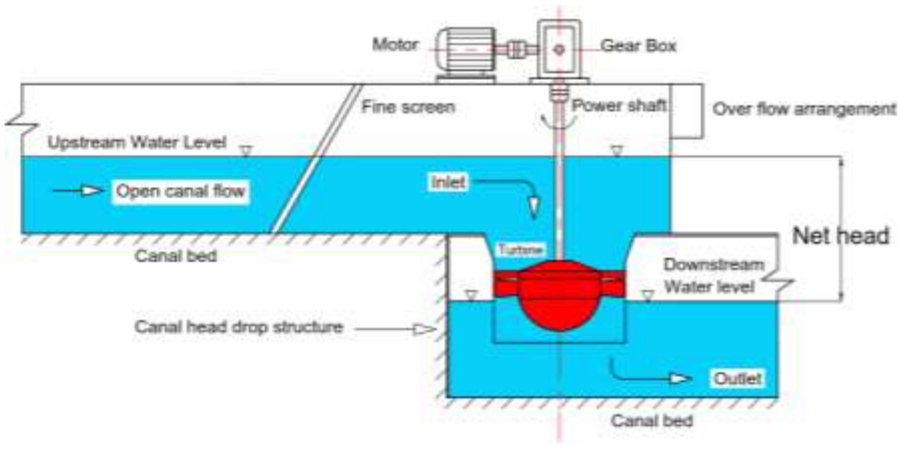

Fig. 2. Schematic diagram of the VULHT concept with a canal head drop [9]

For testing the conceptualized VULHT system, as explained, there is a lack of testing facilities and this is taken as a motivational problem for this research. A test facility with necessary variables is required to develop and is termed a test rig for VULHT. The coefficient of discharge measurement of flow structures is the major parameter for the running of hydro systems. Notches, Weirs, and gates are the common hydraulic structures broadly used for discharge measurement in water engineering networks [10-12]. As the flow measurement is proposed through the rectangular notch, it is necessary to identify the discharge coefficient for available flow rates which is termed as calibration of the rectangular notch. This research reports the methodology and findings of the testing for calibration with results and discussion in detail.

2. Methodology of Test Rig Development

The methodology followed for this research starts from the identification of the problem. The development of the test rig, calibration of the notch, the calculation of uncertainty in measurement, and testing with analysis are followed in sequence. A test rig was required to address the concept of VULHT as a major methodological step. For this, different variables that needed to be included were fulfilled through a test rig development methodology as presented in Figure 3.

Fig. 3. Methodology for development of test rig

2.1 Identification of Variables

According to the concept developed, the experimental setup needs to fulfill the arrangement of different needs. The technology has several uniqueness and thus is new and needs to be tested under different variables as presented in Table 1. As the system is an open flume type, the head, and velocity depend on the flow rate, and is necessary to know the performance of the system for different inlet conditions and canals with or without head drop. In the case of a canal without a head drop, the possibility of flow disturbance was arranged to test with different inlet approach profiles. Similarly, the non-rotating models (NRM) are intentional to predict the upstream head of the actual turbine. The performance of the prototype of the turbine system is necessary to test under different torque, speed, and conditions of submergence using an outlet water level control mechanism.

Table 1
Variables to be included on the test rig

S.N.	Required variable	Means of variation	Method of measurement
1	Flow rate	Number of pumps	Rectangular notch
2	Head	Varies with flow rate	Vertical Steel ruler
3	Flow velocity	Varies with flow rate	Float method
4	Inlet approach profile	Manual Replacing	Predefined geometry
5	NRM	Manual Replacing	Predefined orifice size
6	Torque and speed	The brake dynamometer on the turbine shaft	Torque transducer and tachometer
7	Outlet control height	Manual Shifting on predefined point	Fixed points at equal distance

2.2 Identification of Design Parameters

The overall experiment has been designed to be conducted for a vertical ultra-low head turbine on a single research test rig. The major parameter has been identified for the design of the test rig as presented in Table 2.

Table 2
Design parameters and limits

S.N.	Design parameter	Limits
1	Flow rate	Maximum 120 LPS
2	Head	Maximum 1 m
3	Flow velocity	Less than 1 m/s
4	Flow Reserve time	40 seconds
5	Outlet control height	Maximum 0.5m
6	Height of turbine platform	0.7 m from base
7	Number of segments of test rig	3

2.3 Sizing and Drafting of the System

The maximum flow of 120 LPS and height of 2m are taken for the sizing of different sections of the test rig tank. Considering the flow availability for 40 seconds with the 25% extra volume, the size required is 6,000 L capacity. Similarly, another tank for volumetric measurement of 1,700 Litre capacity receives flow from the outlet of the main test rig tank and has an outlet through a rectangular notch to the reservoir. The different sections of the test rig with its size are listed in Table 3.

Table 3
Size of different sections of the test rig

S.N.	Name of unit	Size (L x B x H m^3)	Remarks
1	Water inlet collection chamber	1.2 x 1.2 x 1.5	3 Sections are joined with
2	Canal section	3 x 0.8 x 1.5	Nuts and Bolts with rubber
3	Turbine section	0.8 x 0.8 x 1.5	gaskets between them
4	Volumetric tank	3.6 x 1.2 x 0.4	Placed separately at the turbine exit

Considering the transportation and installation, the sizing of the different sections was completed with the ease of joining 3 segments with nuts and bolts and one separate section being total of four in number. The drafting was done accordingly using AutoCAD 2019 for the fabrication with all necessary attachments and facilities required for testing.

2.4 Fabrication

The fabrication was followed with the developed drawing on a local fabrication shop with frequent visits for monitoring. All of the structure was fabricated from mild steel material, fixed joints with arc welding, and temporary joints with standard nuts and bolts. The fabrication step was followed to fulfil the requirement on the developed drawing and ended with metal primer coatings on all surfaces of the system.

2.5 Installation

The components were transferred to the laboratory space selected for installation. The selected location was made levelled first and alignment for placing was marked. This made the installation start from the flow measuring section facing the outlet end to the reservoir on one end, the canal section, and the flow receiving chamber at the next end. After that water flow pipelines were in place.

The flow of water is made possible through PVC pipelines of 12 submersible pumps of each 8 LPS capacity that can be controlled individually being 11 pumps for normal operation and one backup.

The water is pumped from a large open underground reservoir to one end of the test rig tank and the outlet is again to the reservoir through the rectangular notch at the other end of the system and is recirculated. The water pumped to the collection end of the tank gets to flow through the several layers of fine wire mesh to the canal being uniform. The 3D model of the test rig used for the experiment of inlet profiles and NRM is shown in Figure 4. Similarly, Figure 5 shows the complete 3D model of the test rig for testing of prototype of the turbine with all of the major components. Figure 6 shows the assembly in progress showing different sections of the test rig during the installation.

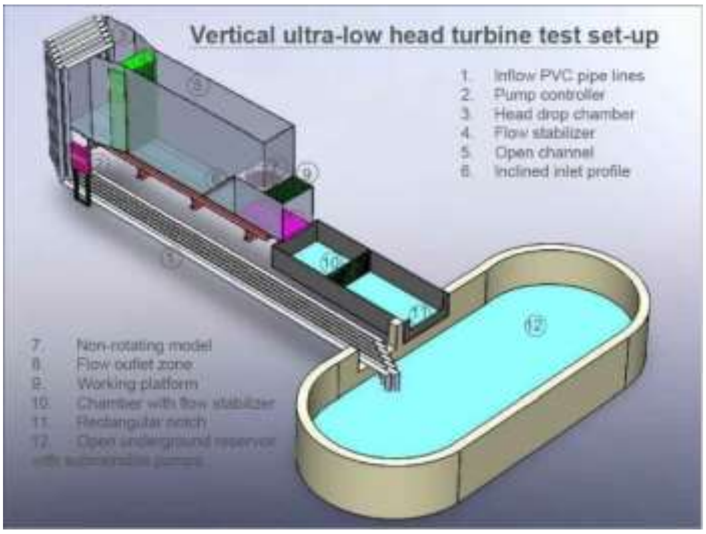

Fig. 4. A 3D model of a VULH test rig for testing of inlet profiles and NRM [9]

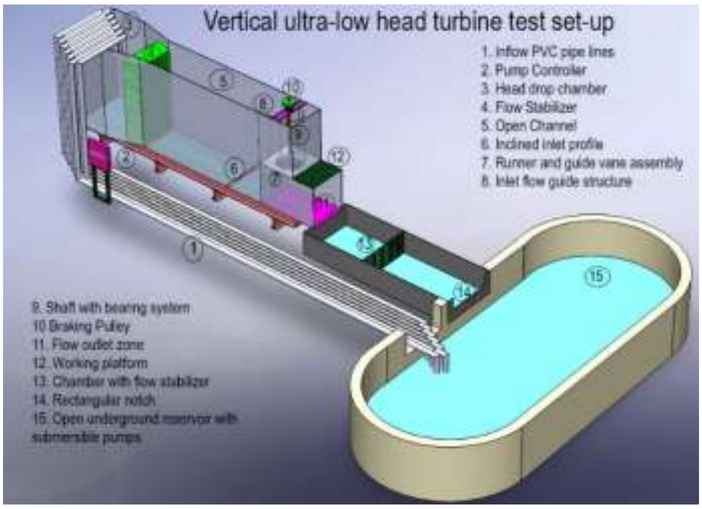

Fig. 5. A 3D model of the test rig for testing a prototype of the turbine [9]

Fig. 6. Fabricated test rig during the installation

3. Methodology of Notch Calibration

The calibration of the notch is to find the discharge coefficient of the rectangular notch for different flow conditions. For the calibration of the notch, three major steps are followed sizing of the notch, measurement from the volumetric tank, and calculation for coefficient for different flow rates.

3.1 Sizing of Rectangular Notch

For the sizing of the rectangular notch, the ISO 1980 Guideline for Rectangular Notch Installation was followed and is listed in Table 4 as per the guideline and the size selected for use on the test rig mentioned in Figure 7 [13,14]. Fabrication of the notch was done with mild steel and fixing by using nuts and bolts with the volumetric tank at the end towards the reservoir.

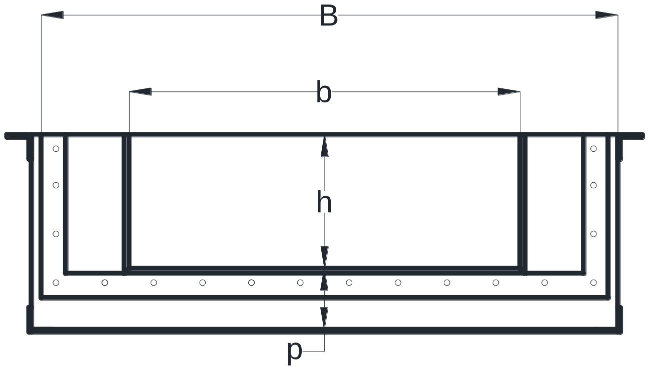

Fig. 7. Parameters on rectangular notch

Table 4
Sizing parameters of a rectangular notch

Terms	Size as per guideline	Selection
Thickness	1-2 mm top (rest thickness needs to be chamfered at > 45^0)	2 mm top on 10mm plate, chamfered 60^0
Water surface downstream	Minimum 0.06m	1m
Measured head (h)	h ≥ 0.03 m	0.275m maximum
Height below notch opening (P)	P ≥ 0.1 m	0.125m
Width of canal (B)	B ≥ 0.15 m	1.22m
Width of notch (b)	b ≥ 0.15 m	0.8m
b/B	0 - 1	0.656
h/P	0 - 2.5	1.2
B-b	≥ 0.2 m	0.42m
Location of head measurement	Upstream direction from the notch at a distance of 4-5 times the maximum head (0.75m)	1m

3.2 Measurement of Theoretical and Volumetric Flow Rate

The flow measurement on the test rig is from a rectangular notch at the end of the tank facing the reservoir. The theoretical flow rate from the rectangular notch is given by Eq. (1) where b and h are the parameters as mentioned in Figure 7 [15].

$$Q_{th} = \frac{2}{3}*b*(2g)^{1/2}*(h)^{3/2} \quad (1)$$

The volumetric measurement involves the time taken to raise the water level on a tank with the known cross-sectional area (A) such that the result obtained is the volume flow rate of water. The time (t) is taken from the stopwatch and the water level (h) on the piezometer that is fixed on it. The volumetric flow is calculated using the Eq. (2).

$$Q_v = \frac{A.h}{t} \quad (2)$$

The time taken for the calculation is an average of three different readings for the same flow rate. So, the process of calibration involves finding the flow rate for theoretical and volumetric flow conditions at the primary level. The same flow rate from the pump was used first through the notch and next closing the notch to fill it for volumetric flow arrangement.

3.3 Calculation of Discharge Coefficient

The calibration of the notch is concerned with the finding of the coefficient of discharge (C_d) for the flow over the notch for different flow rates given by Eq. (3).

$$C_d = \frac{Q_v}{Q_{th}} \quad (3)$$

The actual flow rate from the notch is given by Eq. (4)

$$Q_a = C_d*Q_{th} \quad (4)$$

Further, using Eq. (1) and Eq. (4), the actual flow rate for different conditions can be calculated using Eq. (5).

$$Q_a = \frac{2}{3} * C_d * b * (2g)^{1/2} * (h)^{3/2} \quad (5)$$

The observations for theoretical and volumetric flow covered were calculated to define the coefficient of discharge for a particular flow.

4. Uncertainty in Flow Measurement

The measurement of the discharge in the system through the rectangular notch can be calculated by Eq. (5). The width of the notch used was 0.8 m and the discharge coefficient for the design flow condition of the turbine at 88.7 LPS was found to be 0.615 from the calibration step of the notch. So, the variable was the height of the water column over the notch for different flow rates given by the piezometer reading taken upstream of the notch.

This research work has also identified the sources of uncertainties and quantified them in terms of uncertainty band at laboratory conditions. There are different variables with uncertainties and the uncertainty of separate variables covers both random and bias errors [16,17]. The variable is the measurement on a vertical scale only for the flow calculation through the rectangular notch and requires first-level uncertainty only. With the resolution of 0.5 mm and accuracy of ± 0.7% on the scale for design flow condition, there exists uncertainty in measurement.

The analysis is done for the highest reading point of water column height obtained to gain a general view of the experimental uncertainty. The measurement of actual flow is done across the rectangular notch given by Eq. (5), where height over the column is the single variable. The relative uncertainty in flow rate is given by Eq. (6) and the corresponding absolute uncertainty in flow rate was found to be ± 0.6 LPS for the design flow condition; Q = 88.7 LPS, Δh=0.001 m, and h = 0.155 m.

$$\Delta Q/Q = [(\Delta h/h)^2]^{1/2} \quad (6)$$

$$\Delta Q = \pm 0.6 \text{ LPS}$$

The calculation showed flow of ± 0.6 LPS is uncertain on measurement which is ± 0.67% on the design flow condition.

5. Results and Discussion

A VULH hydro turbine is a new concept for power generation in shallow land regions. For the validation of the technology, an experimental test setup was necessary and this research covers the development of a test rig with calibration of a rectangular notch used for flow measurement. About the concept developed, all the variables were included in the design, and fabrication was done. The installation of all the components of the system was covered and instrumentation was fixed as required. The trial operation was conducted on the test rig running all the water pumps and checking all flow lines from the inlet to the exit of the system. The performance observed was satisfactory and ready to conduct the calibration of the rectangular notch as a further step.

The flow rate from different numbers of pumps from single to twelve numbers was observed to find the theoretical flow rate and five pumps only for volumetric flow rate at the primary level. Due to the limitation on flow collection on the volumetric tank, relations from five pumps were interpolated for all the twelve pumps available. The coefficient of discharge based on Eq. (3) has been plotted for different water column heights at the rectangular notch presented in Figure 8.

The height over notch depends on the number of pumps operated, the higher the number of pumps run, the higher the height over notch. During the test for the quantity of pumps from 1 to 5, the discharge coefficient was found to vary from 0.575 to 0.595 showing different values for each case of flow rate. Figure 8 shows the discharge coefficient increases with the increasing height over the notch almost linear. To know the trend of the variation, the coefficient of determination (R^2) was generated in MS Excel. It is a number between 0 and 1 that measures how well a statistical model predicts an outcome [18]. The value closer to 1 higher is the predicted value either the suggested equation is linear or polynomial. So, an equation suggested with a coefficient of determination is used for the further flow rates of more than 5 pumps and the coefficient of discharge for each case.

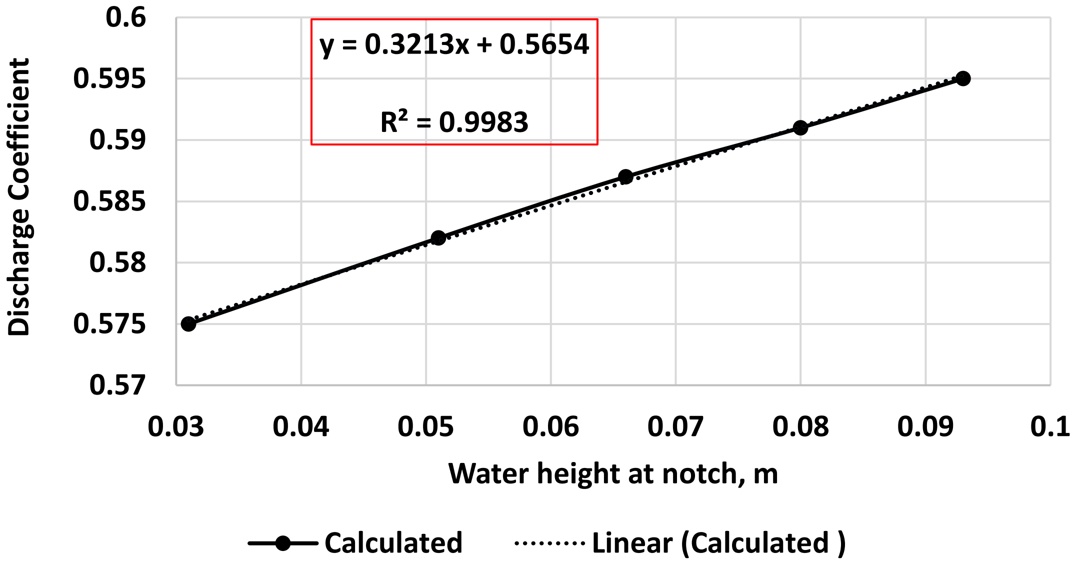

Fig. 8. Variation of discharge coefficient with water height at notch up to 5 pumps

From Figure 8, the suggested equation by MS Excel for the linear case is given by Eq. (7).

$$y = 0.3213x + 0.5654 \tag{7}$$

Where y is the discharge coefficient and x is the water height at the notch in meters which can be written as Eq. (8) to find the coefficient for each height observed.

$$C_d = 0.3213 * h + 0.5654 \tag{8}$$

Similarly, the coefficient of determination, $R^2 = 0.9983$.

This is the value almost near the one. The size of the volumetric tank used for measuring the actual flow in the laboratory is limited to the capacity of flow from 5 pumps but the demand for flow measuring is up to 12 pumps. So, the linear (calculated) equation based on Figure 8, Eq. (7) is used to calculate the coefficient of discharge as in Eq. (8) for more flow rates. The maximum flow rate available is from 12 pumps on the newly developed experimental setup. For each flow condition, the coefficient of discharge is different. The corresponding water column height obtained over the notch is placed on Eq. (8) and the corresponding coefficient is obtained. The variation of notch height due to the operation of pumps in numbers 1 to 12 is presented in Figure 9. It shows the discharge coefficient was found to vary from 0.575 to 0.617 showing different values for each case of flow rate which was found to increase linearly with the flow rate and was used accordingly throughout the experiment after this calibration.

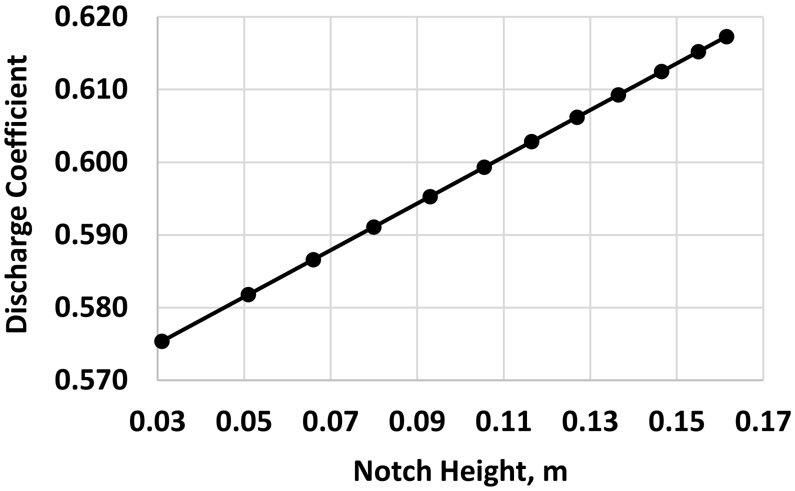

Fig. 9. Variation of discharge coefficient with water height at the notch for 12 pumps

Using the coefficient of discharge obtained for all the flow rates available, the theoretical and actual flow rates can be compared for the same height of the water column over the rectangular notch. The comparison of variation has been plotted in Figure 10 which shows the theoretical flow rate is higher than the actual with the factor of corresponding coefficient of discharge. The maximum theoretical flow rate is 153.32 LPS whereas the corresponding coefficient of discharge and actual flow rates are 0.617 and 94.64 LPS. This summary can be used directly to know the actual or theoretical discharge during the conduction of the further experiment of the turbine over the test rig.

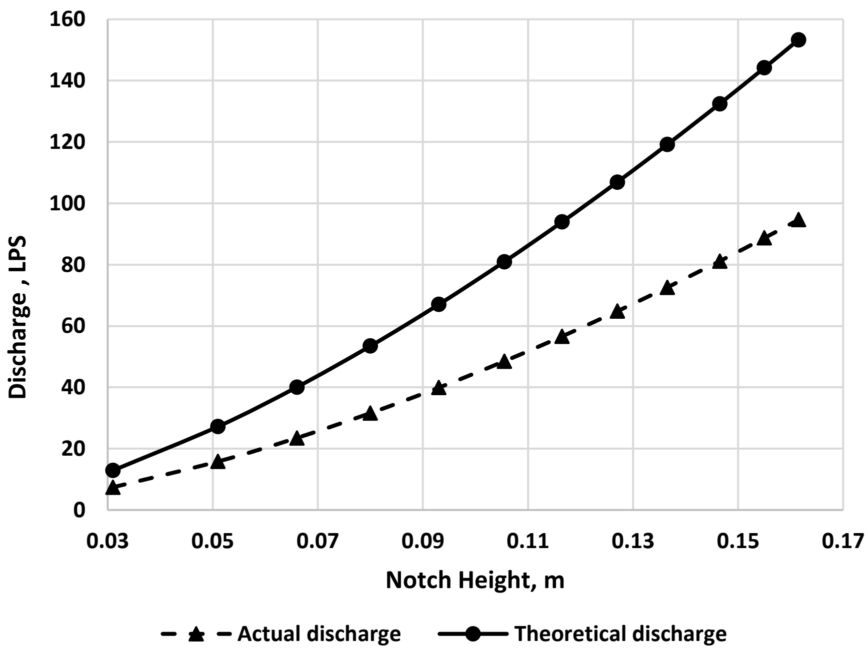

Fig. 10. Variation of actual and theoretical discharge with water height at the notch

6. Conclusion

The research conducted for the development of a new test rig of the conceptualized VULH turbine has been concluded as per the objective defined. The methodology adopted for the development started from the identification of variables required for the development of the test rig. The design parameter was concentrated for 120 LPS discharge and a head of 1m maximum, resulting in the size of all the components. The flow rate on the system was measured through the rectangular notch for which the design was guided by ISO 1980. The calibration of the rectangular notch was followed with the calculation of the theoretical flow and measuring volumetric flow resulting in the coefficient of discharge. Following are the findings from the research concluded.

i. A test rig for the VULH turbine was developed for a maximum flow rate of 120 LPS capacity with testing to 94.6 LPS and a head of a maximum of 1m. The variables proposed for testing were found possible to conduct over the test rig for outlet water level control, inlet approach profile, NRM, and prototype of the turbine. The test performed as a trial for all the flow rates was satisfactory in terms of flow smoothness during the observation.
ii. The calibration of the rectangular notch resulted in a variation in the coefficient of discharge increasing with the flow rate and height over the notch. The relation of discharge coefficient with height over notch obtained from the experiment was found linear with coefficient of determination, R^2 = 0.9983.
iii. The notch height from 0.03 m to 0.162 m showed the coefficient of discharge varying from 0.575 to 0.617 resulting in the variation of actual flow rate from 7.4 LPS to 94.6 LPS.
iv. The uncertainty calculated for the design flow condition (88 LPS for the turbine design stage) on the flow measurement was found to be ± 0.6 LPS which is ±0.67% of the design flow taken.

The limitation of this experimental research is the equipment used for measurement during the experiment. Those are discussed in the uncertainty section. So, as a future scope, more precise methods and equipment can be used for calibration and lowering the uncertainty in measurements that are different from those used in this research.

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