Investigation and Design of Undershot Hydrostatic Pressure Converter for the Exploitation of Very Low Head Hydropower Potential in Pakistan

M. M. A. Bhutta[1], A. Naveed[2], M. A. M. Qureshi[3], A. A. Bhatti[4], S. A. Ahmad[5]

[1,2]Mechanical Engineering Department, University of Engineering & Technology, Lahore-Pakistan
[3]Industrial and Manufacturing Engineering Department, University of Engineering & Technology, Lahore-Pakistan
[4]Petroleum & Gas Engineering Department, University of Engineering & Technology, Lahore-Pakistan
[5]Mechanical Engineering Department, NFC Institute of Engineering and Fertilizer Research, Jaranwala Road, Faisalabad, Pakistan
[1]bhuttathermo@yahoo.com

Abstract-In this paper, different types of zero head or run of the river scheme micro hydro turbines with their design methodologies have been discussed. These are considered to be ideal for hydropower production with very low head (VLH) differences between 0.5 and 5 m. Punjab has a total low-head hydel potential of 600-1000 MW on canals and barrages. Already developed technologies are much costly and are suitable for large potential sites only. For sites with low potential need is to develop a novel technology that can be manufactured locally to use this potential. These small resources, if exploited efficiently, can contribute to overcome the short fall of electricity in rural areas of the province of Punjab. A design of Undershot Hydrostatic Pressure Converter (U-HPC) for a specific site in Punjab has been also been presented.

Keywords-Hydrostatic Pressure Converters, Hydropower, Micro Power Plants, Very Low Head

I. INTRODUCTION

Hydropower is a renewable, non-polluting and environmentally benign source of energy. Pakistan is rich in both large and small hydropower resources. The electrification access in Pakistan was 62.4% in 2009, leaving more than 63.8 million inhabitants without access to electricity. Electricity consumption per capita is estimated at 465 kWh per year. Whole country is facing severe energy crisis. Within these conditions, small hydropower plants with locally manufactured turbine technologies can contribute a large to improve the current situation.

The hydropower is categorized in some divisions. Power ranging upto 10 KW is considered as Pico Hydro Power and from 10 KW to 300 KW is considered as Micro Hydro Power. [i]

Various techniques have been developed to harness the energy of flowing water. In 18th century, to extract water energy water wheels were used. [ii] Finally the advancement in the water wheel desoign brought the new projects like Poncelet and Zupinger water machines [iii]. The water wheels have 33 to 66 percent cost of the conventional turbines [iv]. Overshot water wheels are recommended for 2.5 to 10 m water fall, Breastshot water wheel for 1.5 to 4 m and Zuppinger water wheel from 0.5 to 2.5 m water fall. [v].

Middle shot water wheels with high filling ratios and large cells show low revolution per minute in comparison to the wheels with low filling ratios and smaller cells. The efficiencies of such type of water wheel ranges up to 85 percent [vi]. A. U. R. water turbine is after name of its inventor Aliter Ure Reidand was patented after his name in 1975. The details of the design of this engine was published with the design of new technology known as Salford Transverse Oscillator [vii]. Archimedes Screw is a used to uplift water from lower level to upper level and using this concept in reverse a technology was developed to produce power and is known as Archimedes Screw 287BC-212BC [viii]. A submerged type of the turbine is known as Sundermann turbine. This turbine is suitable for unilateral flow direction. This machine is designed by an Austrian engineer. The high velocity by the specific path at the mid of the vortex produced is used by a router mounted at the middle of vortex. Efficiency upto 50% has been shown by a prototype constructed. Due to fixed shrouds inside the machine itself and other specific arrangements make the technology known as Aqualienne to have filling ratio of one. The efficiency of such machine has been claimed up to 80 percent and range of head is among 1-5. Salford Transverse Oscillator is application of positive displacement machine for the scenario of run of the river [viii]. Staudruck machine is the machine for which initial design was with some defects and were removed by the later design known as rotary hydrostatic pressure machine. Marcel K and Wright investigated a non-rotating very low head water turbine and compared the results with a rotating hydel turbine with same size. They found that non-rotating turbines may be a good option for initial exhibiting and optimization of very low head turbine implementation in future [ix]. A. Alidai and I. W. M. Pothof developed a model to find the efficiency for a hydro turbine connected to a siphon. They found very low efficiency. For a head of 1.25 m and a flow rate of 4500 cubic meter per second the power generated is 4 MW [x].

A. Hydrostatic Pressure Converters

Hydropower machines may exist which are predominantly driven by hydrostatic pressure acting on a non-horizontal working surface, moving with a horizontal component. Such an operational mechanism has not been analyzed theoretically.

The two forms are defined as:

'Type One' HPCs:

Hydropower machines where the working surface extends from the channel bed to ***the upstream water surface***. Such machines include the undershot waterwheel operating in non-impulse conditions, the Salford Transverse Oscillator, the Sundermann Turbine and the Archimedes Screw.

'Type Two' HPCs:

Hydropower machines where the working surface extends from the channel bed only up to the downstream water surface. This is possible by mounting or rotating the working surfaces or blades beneath a central hub or dam like structure which retains the head differential. Such machines include the *Zuppingerrad*, the *Aqualienne* and the *Staudruckmaschine*.

1) 'Type One' HPCs

The theory is ideal, being based on the fundamental geometry of such machines, whilst assuming no design related losses such turbulence. The ideal models used in this theory do not account for the change in kinetic energy observed between the upstream and downstream of actual `type one' HPCs such as the Salford Transverse Oscillator. This increase in kinetic energy is assumed to be the result of a process which does not directly contribute to the power output of `type one' HPCs.

II. Force and Power Calculations

A. Force Calculations (For Type One)

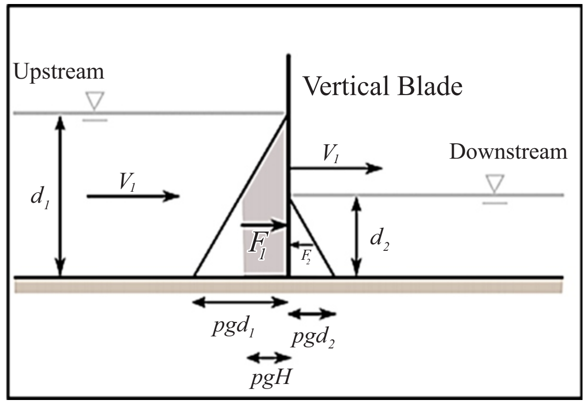

Fig. 1. Type one' HPC nomenclature

Fig. 1. depicts a simple vertical blade which extends from the channel bed to slightly beyond the upstream water surface. Here V_1, d_1, F_1 are upper stream velocity, upper stream total depth and net force acting on blade from upper stream side. Similarly V_2, d_2, F_2 are lower stream velocity, lower stream stream total depth and net force acting on blade from lower stream side.

This blade is the working surface on which the hydrostatic pressure of the water acts, and has width W into the page. The blade is shown to be partially submerged in the downstream, the depth of which, d_2, is between zero and the upstream depth, d_1

$$F_1 = \rho g \frac{d_1^2}{2} w \tag{1}$$

$$F_2 = \rho g \frac{d_2^2}{2} w \tag{2}$$

$$F_1 = \rho g \frac{d_1^2 - d_2^2}{2} w \tag{3}$$

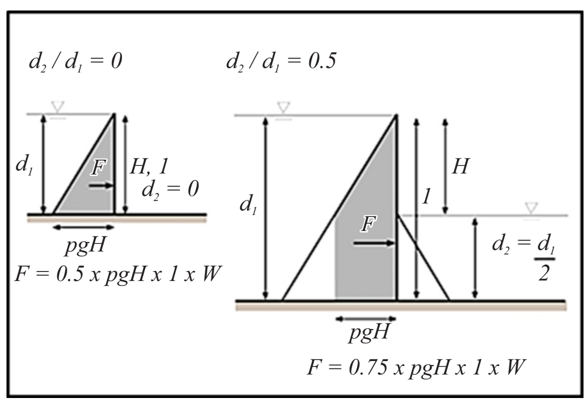

Fig. 2. Type one' HPC, demonstration of relationship between force and the ratio d_2/d_1

The relationship between the ratio d2/d1and the force applied to the blade is thus critical. As the ratio d_2/d_1tends towards a value of 1, the maximum pressure ρgH is applied to an increasing proportion of the blade area. Technically, the maximum pressure will be applied over the entire length of blade when d2/d1equals 1, however this is trivial as the head and thus the pressure differential at this point would equal zero.

B. Power and Efficiency Calculations

If the blade upon which the force is exerted extends from the channel bed to the upstream water surface and the upstream depth is to be maintained, then the blade must move with the same velocity as the upstream water, v_1. Accordingly, the output power, P_{out}, of a `type one' HPC is as under

$$P_{in} = \rho g\,(d_1 - d_2)(v_1 d_1 W) \qquad (4)$$

$$P_{out} = F v_1 = \rho g \frac{d_1^2 - d_2^2}{2} W v_1 \qquad (5)$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{1}{2}\left(1 + \frac{d_2}{d_1}\right) \qquad (6)$$

The efficiency, η of a `type one' HPC is shown in above equation. This equation shows that the efficiency, just like the force and output power equations, is a function of the ratio d_2/d_1. The implications of this are shown in the Fig. 3 & 4.

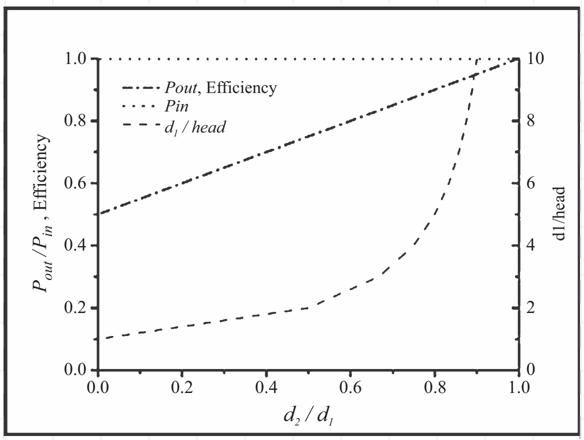

Fig. 3. Type one' HPC theory with constant head and flow rate, but variable d_2/d_1 ratio

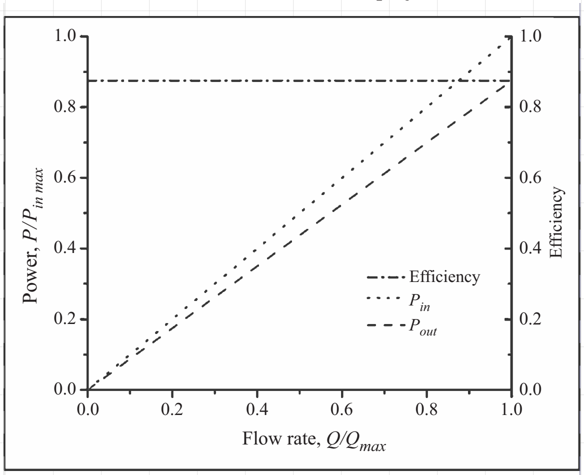

Fig. 4. 'Type one' HPC theory with ratio d2=d1= 0.75, constant head and variable flow rate

C. Evacuation and the resulting kinetic energy change

When considering actual `type one 'HPCs such the ***Salford Transverse Oscillator***, the velocity of the downstream flow, v_2, would be greater than that of the upstream, v_1, as the downstream water depth is less than the upstream, whilst the flow rate is common. This is demonstrated by equation

$$v_2 = \frac{d_1}{d_2} v_1 \qquad (7)$$

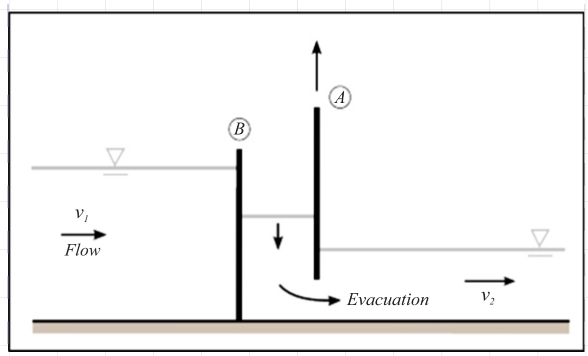

Fig. 5. Depiction of `evacuation' process

The power associated with the evacuation process per unit width, P_{evac}, is shown in Equation given below. When plotted along with the P_{out} estimate from the ideal theory against the ratio d2/d1asin Figure-5.8, it can be seen that the P_{evac} accounts for the remaining input power, P_{in}, which was not exploited by the `type one' HPC.

$$P_{evac} = \rho g \left(\frac{d_1 - d_2}{2}\right)\left(\frac{d_1 - d_2}{d_1} v_1 d_1\right) \qquad (8)$$

Fig. 6 is graph plotted using the relations (equation 4, 5, 6 & 8) of power input, power output and power loss related to evacuation process.

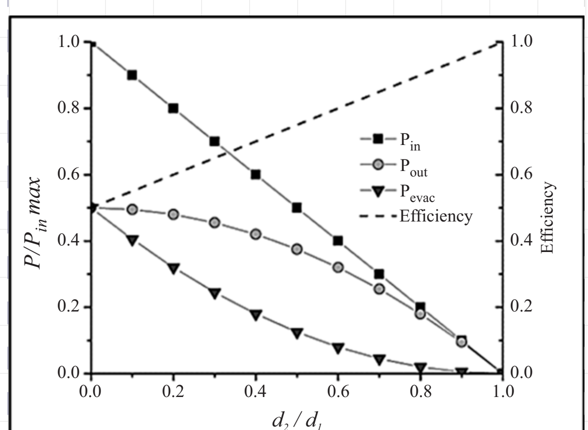

Fig. 6. Power associated with `evacuation' resulting in increased flow velocity [xii]

III. Site Analysis and Design Calculations for U-HPC

A. Site Overview (Gogera Branch Lower)

Gogera Branch Lower is an irrigation canal in Punjab with the region font code of Asia/Pacific. It is located at an elevation of 195 meters above sea level. Its coordinates are 31°25'60" N and 73°31'60" E in DMS (Degrees Minutes Seconds) or 31.4333 and 73.5333 (in decimal degrees). Its UTM position is CQ67 and its Joint Operation Graphics reference is NH43-02.

1) Site Parameters

Available Head= 1.58 m

Average Flow Rate = 66 m^3/s ($66x10^3$ liter/s)

Estimated Power Potential= 1.0 MW

Fig. 7. Gogera Branch Lower, Faisalabad District, Punjab, Pakistan

B. Design Calculations

1) Shroud Length

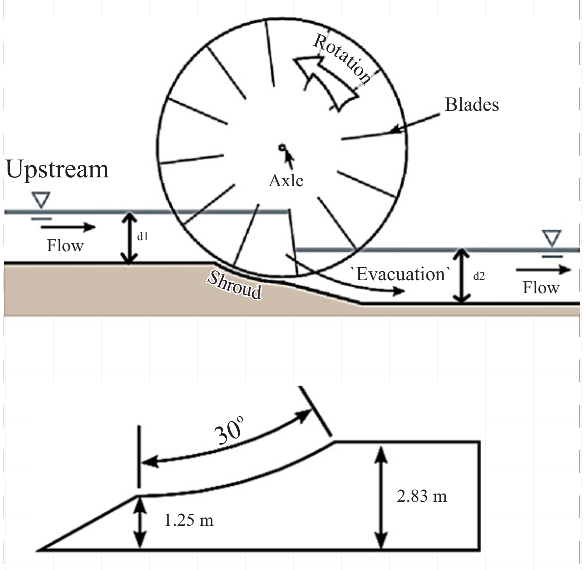

Fig. 8. Shroud Length

$H=d_1-d_2=1.58$ m

$d_1= 2.83$ m

$d_2= 1.25$ m

Blade Length=L= 1.58 m

Number of Blades = n= 12

Blade space (Arc Angle) =$\theta=30^0$

($360/12=30^0$)

Then Shroud Arc Length= S= L$x\theta$=1.58xΠ/6

S=0.827 m

2) Channel Design & Upstream Velocity v_1

Total No of passages= n =6

Total flow rate = Q_T= 66 m3/s

Flow through each passage = $Q_1=Q_T/6$=11 m3/s

Width =W= 5 ft =1.54 m

Now at upstream level, $Q_1= A_1v_1= (d_1W).v_1$

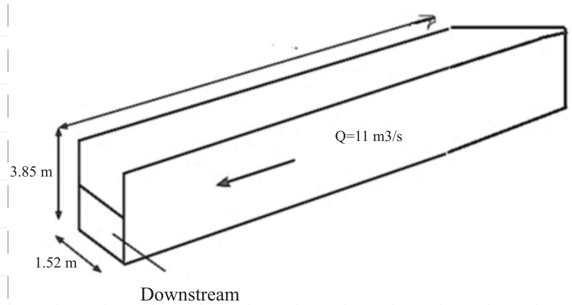

Fig. 9. Channel Design

11= 3.83x1.54xv_1

Upstream velocity v_1=1.86 m/s

1) Resultant Force on Blade

$F=\rho g\ [d_1^2-d_2^2]/2.W$

ρ=1000 kg/m^3

g= 9.81 m/s^2

d_1=3.83 m

d_2=1.50 m

W= 1.54 m

So,

F = 1000x 9.81x [3.83^2-1.25^2]/2 x1.54

F = 48,694.8 N

Force = F= 48.694 kN

Power Input (Ideally available on site)

$P_{in} = \rho g\ (d_1-d_2)\ v_1\ d_1\ W$

P_{in} = 1000x 9.81x 1.58x 1.86x 3.83x 1.54

P_{in} = 170.042 kW

4) Power Output at Full flow rate

Power Output is given by:

$P_{out} = F.v_1 = g\,[d_1^2 - d_2^2]/2.W.v_1$

P_{out} = 48,694.8x1.86 W = 92,572 W = 92.571 kW

P_{out} = 92.571 kW

Efficiency = P_{out}/P_{in}

η= 90.57/170.042 = 54.40 %

IV. Graphs and Relations for Various Flow Rates in Comparison With:

A. Power Output Consideration

TABLE I
POWER BASED ON IDEAL THEORY AND CONSIDERING LEAKAGE EFFECTS

Q/Q_{max}	P/P_{in} max
0	0
0.167	0.165
0.333	0.33
0.5	0.5
0.666	0.658
0.833	0.823
1	1

Q_{total}	$Q_{leakage}$	Vb	$P_{out,\ leakage\ adjusted}$
3	2.341	0.659	6.76
6	2.341	3.659	55.6
9	2.341	6.659	76.4
12	2.341	9.659	99.9

Fig. 10. shows the relation of flow rate with power input. Power input increases with increase in flow rate.

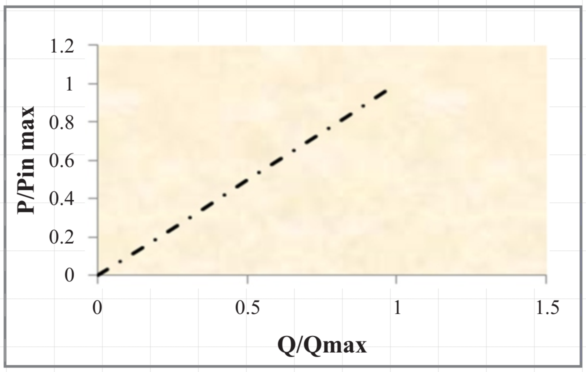

Fig. 10. Power input at various flow rates

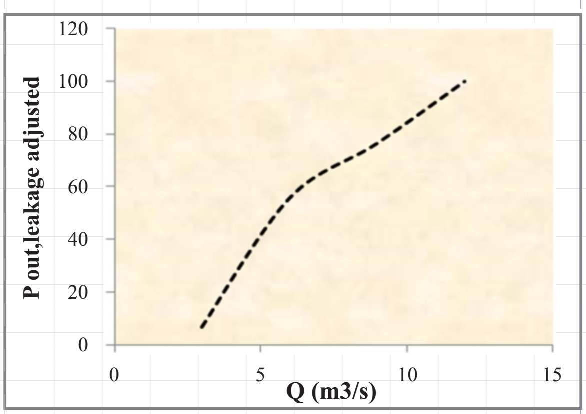

Fig. 11. Power output with leakage losses at various flow rates

B. Efficiency Consideration

TABLE II
EFFICIENCY BASED ON IDEAL THEORY & CONSIDERING LEAKAGE EFFECTS

$Q(m^3/s)$	$\eta_{(Ideal)}$	$Q_{leakage}$	V_b	η
0	0	2.341	0.659	3.97
3	0.72	2.341	3.659	32.5
6	0.72	2.341	6.659	45.8
9	0.72	2.341	9.659	57.76

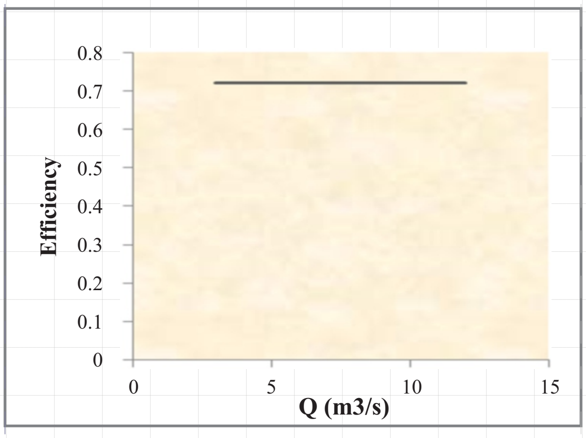

Fig. 12. Efficiency (Ideal) at various flow

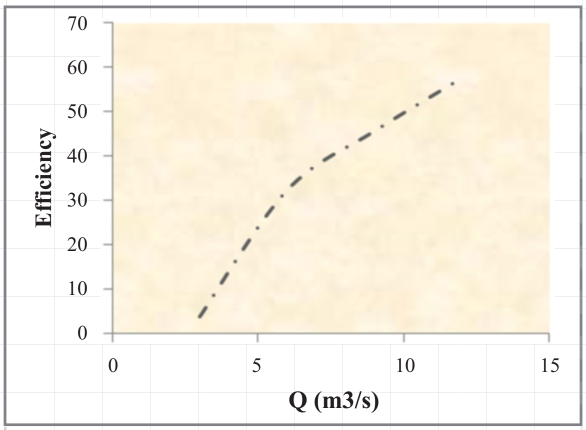

Fig. 13. Efficiency (leakage) at various flow rates

Fig. 12 shows variation of efficiency with respect to the flow rate. As the flow rate increases the efficiency increases but the rate of increase is not uniform. Initially the efficiency increase is more, then the rate of increase decreases gradually. The reason is that at higher flow rates the turbulent losses and eddy formation losses are more. Fig. 13 shows the variation of efficiency corresponding to the leakage losses. Since leakage losses are related to the geometry and it remains constant so efficiency change due to leakage losses is not prominent.

V. Calculations for Power Output & Efficiency After Considering Leakage Losses

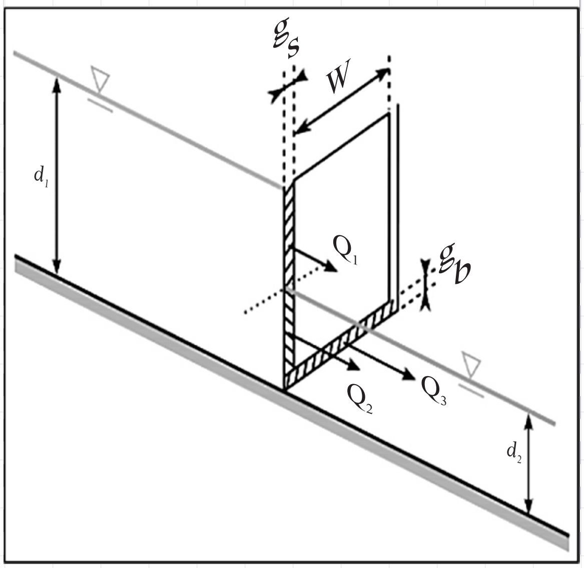

Fig. 14. Analysis of Leakage Losses

$Q_{leakage}$ = *(velocity of flow) x (area of gap)*

$$Q_1 = \left(\int_{d2}^{d1} \left(\sqrt{2gd} \right) dd \right) gs =$$

$$\frac{\sqrt{2g}\left(d_1^2 - d_2^2\right)^{1.5}}{1.5}\left(g_s\right)$$

$$= \frac{\sqrt{2 \times 9.81}\left(3.83^2 - 1.5^2\right)^{1.5}}{1.5}(0.05)$$

$Q_1 = 0.525\ m^3/s$

$$Q_2 = \sqrt{2g(d_1 - d_2)}\left(d_2 g_s\right)$$

$$= \sqrt{2 \times 9.81(3.83 - 1.5)}(1.5 \times 0.05)$$

$Q_2 = 0.507\ m^3/s$

$$Q_3 = \sqrt{2g(d_1 - d_2)}\left(g_b\left(W + 2g_s\right)\right)$$

$$= \sqrt{2 \times 9.81(3.83 - 1.5)}\left(0.025(1.54 + 2 \times 0.05)\right)$$

$Q_3 = 0.227\ m^3/s$

$Q_{leakage}$ = 2 (0.525 + 0.507) + 0.227

$Q_{leakage} = 2.341\ m^3/s$

$Q_{wheel} = Q_{total} - Q_{leakage}$

$Q_{wheel} = 9 - 2.341 = 6.659\ m^3/s$

$$V_b = \frac{Q_{wheel}}{Wd_1} = \frac{6.659}{1.54 \times 3.83}$$

Vb = 1.13 m/s

$$P_{out;\ leakage\ adjusted} = \rho g \frac{d_1^2 - d_2^2}{2} v_b$$

= 1000 X

$$9.81 \frac{3.83^2 - 1.5^2}{2} 1.13$$

$P_{out;\ leakage\ adjusted}$ = 68.83 KW

$$\eta_{leakage\ adjusted} = \frac{P_{out,leakageadjusted}}{P_{in}}$$

$$\eta_{leakage\ adjusted} = \frac{68.83}{170} = 40.4\ \%$$

VI. Gear Box Losses

There is a disadvantage of this technique that it gives low rpm. To enhance the rpm of the converter as per requirement by the electric generator to produce electricity in accordance to the particular frequency a sophisticated gear box is required between the shaft of the converter and the shaft of the electric generator. So, gear box losses must be taken into account. Let the gear box be four stages with coaxial shafts assembly then its efficiency would vary between 80 to 90 percent [xi].

$P_{out;leakage,gearlossadjusted}$ = (68.83) (0.90)
= 61.95 KW

$$\eta_{leakage,\ gear\ loss\ adjusted} = \frac{61.95}{170} = 36.44\ \%$$

VII. Conclusions

From the review of the literature on hydropower converters for very low head differences i.e. below 2.5 m it is found that the Undershot Hydrostatic Pressure Converter are most suitable for very low head at various sites in Punjab. Furthermore, combined with its potential for improved sediment transport and fish passage, the U-HPC could satisfy the demand for a new economically and ecologically acceptable technology. A typical design of U-HPC for Gogera Branch Lower irrigation canal in Punjab has been made that shows a potential of 1 MW at 40.4% efficiency.

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