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# A System and Method for Retrieving Energy Potential through Irrigation Gate of an Agricultural Dependent Hydro Power Plant

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**ABSTRACT**

The modern economics depends on the electrical energy and the share of decarburized electrical energy is the base of 2050 net zero emission targets. Non-fossil fuel and fossil fuel energy resources are the integral part of net zero energy system. The net zero emission activities are affected by increasing demand of electricity and its related CO2 emission in 2021. The contribution of 41.4% of renewable energy as compared to 56.8% of non-renewable energy in the year of 2023 at national level necessities attention of green sources of energy like solar, wind, hydro, waste to energy, small hydropower, etc. Hydropower is one of the reliable backbones of clean energy system which should be used effectively for power generation. The turbine dependent hydropower plant of 45-60 years old requires renovation, modernization, uprating and digitization (RMUD) to resolve socio-economic concerns and increasing demands. This scenario imposes the need of finding solution in existing hydropower plant than investing on new unit. Both high and low discharge should be potentially used for power generation to improve the capacity factor of the plant. Therefore, present work focusses on improving capacity factor of an existing agricultural dependent hydro power plants having reaction type turbine. Reaction turbines operates at high flow and low/medium head conditions. The operational conditions of low flow and low head for reaction turbines may lead to noise, vibration and directed to major catastrophic failure of turbines. There is a need of utilizing the energy potentials balancing power generation and irrigation even during low flow releases. Thus, this paper is an attempt to a design and develop a modified irrigation gate with sliding gate and mini hydropower system at the inlet of existing irrigation diversion gate. Stochastic nature of flows through different hydraulic structures is to be addressed by this modification. A case study of an irrigation dependent hydropower plant Dhom (2X1 MW), MAHAGENCO, Satara, Maharashtra having TWO irrigation gates have been considered. In addition to 2MW, the suggested design can generate 680kW by average irrigation releases of 2.47m$^3$/sec through each gate. The suggested model can be used on any hydropower plant and canal locations.

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## 1. Introduction and Literature Review

To achieve the net zero emission targets, the renewable energy sources are the sustainable solutions. Inadequate non-renewable energy resources and related environmental problems demands green sources such as hydro, wind, solar, etc for power generation. Hydropower adds 16-20% of total power generation at global level. Also, hydropower plant has better capacity factor as compared to thermal power plant and nuclear power plant due to 1. Advantage of operating effectively under varying load and demand 2. Benefit of hydropower plant over limitation of seasonal availability of solar power and wind energy and 3. High ramp rate.

New construction of dam and/or hydropower plant is infeasible solution due to high capital investment, social influence, environmental concerns and other constraints. Thus renovation, modification, up-gradation and digitization in existing hydropower plant shows innovative path. The output from hydropower plant is a function of behaviour of power units under the head and discharge.

This paper suggests the innovative way of using hydraulic structures and hydraulic machines for energy recovery potential for existing agricultural dependent hydropower plant. The closed conduit and inline turbine at the inlet of irrigation canal is suggested as an attempt to generate energy at both high and low discharge. Water regulating mechanism with few modifications is proposed as modernization after irrigation gate in existing hydropower plant.

In case of irrigation dependent plant, the power generation is secondary to irrigation and other mandatory releases. During high discharge, the capacity of turbines restricts the power generation and during low discharge functioning of the turbines restricts the power generation. Thus, selection of turbine accommodating stochastic nature of flows should be done. Following Figure 1 shows the behaviour of different types of turbines under varying discharge. This graph shows better performing Kaplan turbine even under low flow comparing to Francis and other power units.

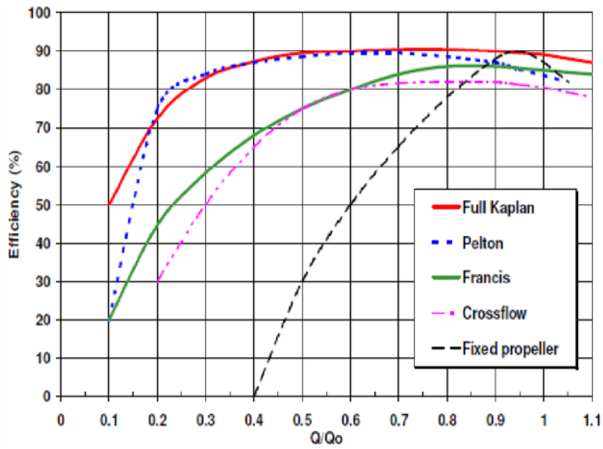

**Fig. 1.** Behaviour of turbines

Different researchers, academicians have attempted and proposed various ways to recover energy from available potential which is given in next part. Yoosefdoost and Lubitz [1] have determined the coefficient of discharge ($C_d$) for sluice gate operating under different flow rate, gate opening, upstream and downstream conditions. Experimental study and HEC-RAS model was prepared to find the Cd. The study can be directly applied for the open channel where measuring and controlling discharge through sluice gate are involved. Selection base for propeller type turbine running at very low head has been proposed by Barsi *et al.,* [2]. Solver and artificial neural network ANN were used for live case study. This study could able to modify geometry of vane and blade by which, the efficiency of the turbine can be answered for any input parameter. The gate model was tested against the different positions to know the coefficient of discharge (Cd) due to increase in the flow area. The increase in area and angle of gate in flow direction was observed helping to reduce hydrodynamic force on gate by Daneshfaraz *et al.,* [3]. Fuzzy logic system has been suggested as Water gate controller by Pangaribuan *et al.,* [4]. Water gate for turbine flow was operated manually creating dependency and involving expenses as well. This problem was converted in automation by the authors suggesting water sensor, microcontroller and actuators.

Mohamed and Abdelhaleem [5] have proposed the sluice gate with an orifice accommodating high discharge and means for an energy dissipation. As compared to traditional sluice gates this arrangement improves the performance in dissipating energy and lowering scour on downstream side. Energy is basic requirement for urban, sub urban and rural areas. Thus, optimal design of propeller of 10kW at low head has been explained by Win *et al.,* [6]. Such solutions paved the path for generating electricity at low head satisfying local demand of the people not connected to main grid. Samora *et al.,* [7] has been observed the pressure reducing valve to be used for electricity generation.

Five blade type tubular propellers have suggested and tested in laboratory for 300kW power. The case study of drinking water system has been considered. The concept of movable weirs against conventional fixed weirs has been suggested by Kim *et al.,* [8]. Also, the dissipation of energy by suggested change has also been studied experimentally. Due to generation of supercritical flow d/s of movable gate, more diverse testing is suggested as a scope of this study. Most effective hydraulic jump has also been studied for both types. Bocko *et al.,* [9] has studied the hydraulic structures such as sluice gate and valves. Firstly, for their proper location, secondly analysis against stresses and loading, thirdly for changes in analysis and finally probable modifications in the existing structure. The irrigation required for rice crop is under low head and low scale water energy. For such cases, provision of other turbines might be uneconomical. Thus, two Darrieus and Savonius type water turbines were suggested by Sahim *et al.,* [10]. After experimentation on two turbines Darrieus turbine with two blades has been suggested.

Water energy to electrical energy conversion by means of Dethridge wheel was experimented by Mugisidi *et al.,* [11]. This waterwheel with very low water head is convenient for irrigation canals. The authors have worked upon the increasing the performance of the Dethridge wheel by changing the shape of the wheel blades. The wheel was tested for various flow rates. Experimental and numerical methods were used to test the developed wheel. A review paper on hydropower development since 20th century was explained by Bekchanov [12]. The present condition and future scope have also been mentioned in the paper. Environmental, social, economic concerns were also provided in this paper. The sluice gate with upstream system having unloaded rotor has been proposed by Farouk *et al.,* [13] to control the water level and dissipating energy as well. The work also provides the solution for power generation passing by water over rotor wheels. Two different types of wheels were tested. Experimental study has been done and compared with the case having no such rotor.

Thus, all above review work suggests converting every loss of water or operation of hydraulic structure for power generation. Two significant motivations behind this study are as, 1. Limited attempt has been seen in the area of modification for existing canal or irrigation channel generating additional power and 2. Also the behavioral changes of hydraulic turbines under stochastic flow condition enforces the attention for novel and feasible solution for existing hydropower plant and/or canal sites. Thus, present design and development is an attempt to find way out for untapped energy potential. Following content will address the solution of additional power generation for existing irrigation dependent hydropower plant than erecting new plant.

## 2. Problem Statement and Objective

There is a crucial need of alternate source of power generation for developing countries considering insufficient power generation and ineffective distribution. Thus, all small opportunities of power generation need to be identified, executed and used for right cause in optimized way. Assessment of energy potential during mandatory releases by modernization of existing plant than erecting new power plant is the feasible solution. Hence suggesting a viable yet innovative way of tapping power at the inlet of existing irrigation gate of agricultural dependent power plant is scope of this study. Objective of this study is to upgrade the capacity factor in view of rainfall, power generation and irrigation releases for an agricultural dependent hydro power plant. Typical case of DHOM hydro Power station of capacity 2 X 1 MW at Vyahali dam at Wai of Satara in Maharashtra is considered.

### *2.1 Characteristics of Dhom Hydropower Plant*

DHOM hydro Power Station of capacity 2 X 1 MW has been erected at Vyahali dam at Satara in Maharashtra. Important landscapes of power plants are mentioned in Table 1.

**Table 1**
Important landscapes of power plants

| | | | |
|---|---|---|---|
| Installed capacity | 2 X 1 MW | Annual design | 10.56 MU |
| Average Rain fall | 1500 – 6250 mm | Energy generation Average inflow of water | 423.91 $MM^3$ |
| Gross dam storage | 382 $MM^3$ | Live storage | 331$MM^3$ |
| Minimum draw down level | 733.08 m | Design head | 18 m |
| Design discharge | 14 $m^3$/sec | Diameter of penstock | 2.5 m |

Right bank of river Krishna has the reservoir along with two distinct passages 1) for Irrigation Discharge and 2) for energy generation. Left bank canal of Dhom splits from right bank canal on downstream side as shown in Figure 2.

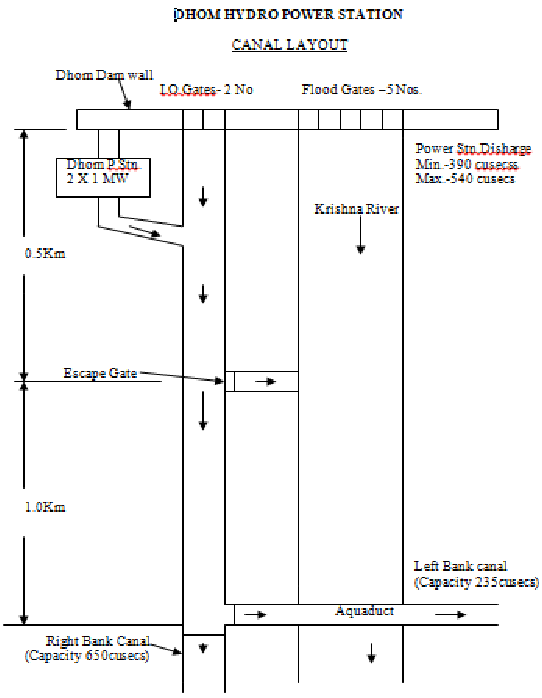


**Fig. 2.** Outline of Dhom canal system

### *2.2 Performance of Hydropower Station*

For agricultural dependent power plant, the power generation is a function of irrigation release. The power generation depends on precipitation of the area as well. The Dhom dam receives, average rainfall in of 970mm. In case of maximum rainfall of 1725mm and minimum rainfall of 580mm, the reservoir has released water towards irrigation without power generation was 108.73 $MM^3$ and 24.78 $MM^3$ respectively. So, if the untapped irrigation release (loss) is converted into an opportunity of power generation, the capacity factor for the power plant would definitely increase. Table 2 shows the irrigation release in $MM^3$ (million cubic meters) and corresponding water loss in MU (million unit).

**Table 2**
Irrigation release and water loss

| Year | Irrigation Discharge Million Cubic Meter (MCM) | Water Loss in Million units | Year | Irrigation Discharge Million Cubic Meter (MCM) | Water Loss in Million units |
|---|---|---|---|---|---|
| 91-92 | 98.543 | 3.425 | 2005-06 | 30.324 | 0.968 |
| 92-93 | 54.346 | 1.864 | 2006-07 | 57.345 | 2.156 |
| 93-94 | 58.241 | 2.432 | 2007-08 | 27.85 | 0.96 |
| 94-95 | 37.421 | 1.296 | 2008-09 | 154.24 | 4.671 |
| 95-96 | 92.357 | 3.361 | 2009-10 | 29.8367 | 0.887 |
| 96-97 | 61.437 | 2.683 | 2010-11 | 52.2128 | 1.165 |
| 97-98 | 165.291 | 5.373 | 2011-12 | 90.8709 | 3.246 |
| 98-99 | 88.541 | 3.186 | 2012-13 | 58.5124 | 1.783 |
| 99-2000 | 27.651 | 0.87 | 2013-14 | 161.318 | 6.973 |
| 2000-01 | 59.563 | 2.453 | 2014-15 | 58.7621 | 2.286 |
| 2001-02 | 86.461 | 3,215 | 2015-16 | 58.898 | 0.96 |
| 2002-03 | 163.435 | 5.427 | 2016-17 | 165.391 | 4.237 |
| 2003-04 | 56.347 | 2.543 | 2017-18 | 46.237 | 2.538 |
| 2004-05 | 48.475 | 1.641 | Avg | 77.40 MCM/year | |

$$Average\ irrigation\ release, = \frac{77.40*10^6}{12*30*24*3600} = 2.47\ m^3/sec \tag{1}$$

$$Power\ generated, = \frac{1000*9.81*14*2.47}{10^6} = 0.339MW \tag{2}$$

The irrigation water released from one gate is 2.47 $m^3$/sec (Eq. (1)) and power generated from this water will be 340kW (Eq. (2)). Dam has two such irrigation gates, this implies that total additional power of 680kW will be generated in addition to existing 2MW.

For this additional power generation, the modernization of existing irrigation channel is proposed. New hydraulic system of having sliding gate conveying water to the inline axial turbine is suggested. The methodology of the proposed modification is explained in next section.

## 3. Methodology

Water controlling structures helps in managing the flow as per requirement and availability of water. The conditions of unsteady flow, varying discharge due to climatic changes and sustainable supply of water demands concrete solution. Thus, water regulating devices like gates addresses this issue with small modification as well. Water controlling structure can be used for retaining the water and regulating the water flow as per requirement and availability.

### *3.1 Modernization – Irrigation Gate with Sliding Mechanism*

The modification in the water regulating structure depends on releases for the irrigation in case of agricultural dependent hydropower plant. The stochastic nature of releases creates two conditions; 1. High rainfall, low irrigation releases could not generate power due to functional restriction of reaction turbine and 2. Low rainfall, high irrigation releases could not generate power due to capacity restrictions of turbines. Therefore, to accommodate the discharge during both high and low release, modification is proposed after the irrigation release beyond existing irrigation gate. Figure 3 shows the modification concept for effective energy recovery.

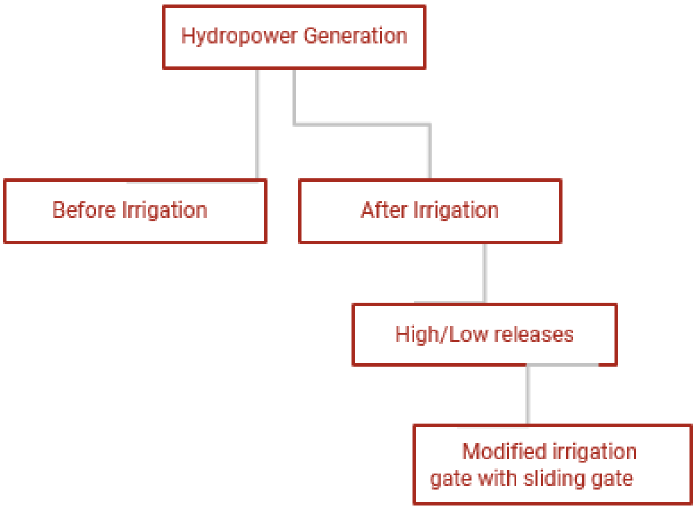


**Fig. 3.** Modification concept for effective energy recovery

Hailu and Thakur [14] have studied the effect of providing different types of opening in the gate such as circular, rectangular and elliptical. When the water is subjected to the hydrostatic and hydrodynamic forces, the development of maximum stress and maximum deformation in each shape of opening has also been studied by the author. Circular opening found with minimum stress and deformation relative to other shapes. This paper emphasizing on design of circular opening in the irrigation gate to accommodate further modification for power generation. The gate design is explained in next section. Figure 4 shows the modified irrigation gate with sliding gate developed in ANSYS software.

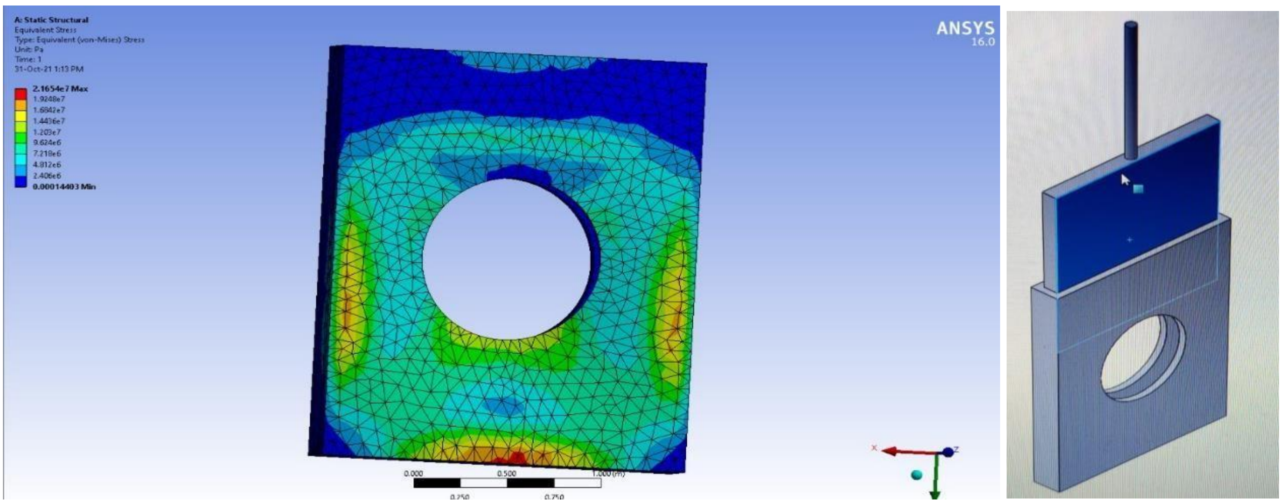


**Fig. 4.** Modified irrigation gate with sliding gate developed in ANSYS software

Proposed solution requires the determination of effect of hydrostatic pressure on the gate. Concerned calculations are performed and explained in the next context.

### *3.1.1 Dimensions of the gate*

The dimensions of gate are tested against maximum stresses, analytically and in ANSYS environment. Sample calculation for the design and analysis in software environment is presented in this section. Assuming the sample dimensions of the gate as 1*1.5m. The gate model referred is shown in Figure 5 [14].

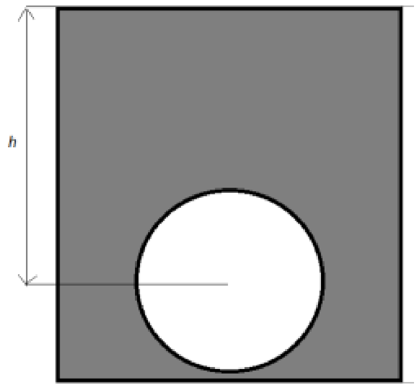


**Fig. 5.** Gate model

Higher discharge will be available if opening is provided at lower part of the gate. Also, the flow after opening should be laminar to avoid further disturbance. Velocity of the fluid flow at opening found at height h below surface of water exposed to atmosphere is calculated (Eq. (3)) assuming $C_v$ = 0.97-0.98 and h = 1m as,

$$V = Cv\sqrt{2gh} = 4.34\ m/s \tag{3}$$

### *3.1.2 Forces on gate*

Hydrostatic and hydrodynamic forces are acting on the gate. Effect of hydrostatic pressure on the gate is considered in the next context. The maximum hydrostatic pressure is at the bottom of the gate. Assuming the operating pressure is the pressure at the bottom of the gate, the pressure distribution at the dam and sliding gate can be evaluated. The operating pressure (Eq. (4)) is

$$P1 = 1000\frac{kg}{m3} * 981 * 1.5 = 14.71\ kPa \tag{4}$$

The pressure distribution in the gate opening at different heights 0.8 and 0.2 from the ground has calculated. The Analytical values of pressure at above heights are P2 is 6.87kPa and P3 is 12.75kPa. The values of pressure obtained by software are P2 is 7.15kPa and P3 is 12.90kPa. The pressure values from software with this small variation is allowed. Assuming, full area of the gate is exposed to hydrostatic force, the average concentrated force exerted at 1/3 of the height can be calculated (Eq. (5)) as [14],

$$Average\ pressure\ (p) = \gamma * \frac{h}{2} = 1000 * 9.81 * 1.5 * 0.5 = 7500Pa \tag{5}$$

Force on the wall can be calculated Eq. (6) as,

$$F = p * A = 7500 * 1.5 * 1 = 11250N \quad (6)$$

Opening gate is underwater, thus the gauge pressure varies to a maximum of 14.71kPa. The resultant force Eq. (7) from variable pressure acting on the opening gate at a depth of h1 is shown in Figure 6. Eq. (8) and Eq. (9) give the different pressure at different heights of h1 and h2-h1.

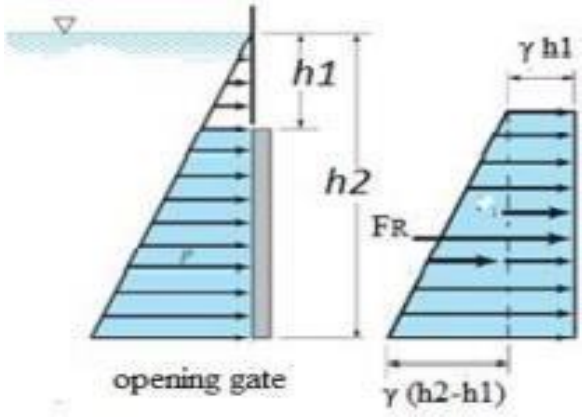


**Fig. 6.** Location of Resultant force [10]

$$FR = (\gamma h1)A + 0.5\,[\gamma(h2 - h1)]A \quad (7)$$

$$FR = 5886 * 0.5 + 0.5 * (20601 - 5886) * 0.5 = 6621\ \approx 6630N$$

where,

$$(\gamma h1)A = 1000 * 9.81 * 0.6 = 5886N \quad (8)$$

$$\gamma(h2 - h1) = 1000 * 9.81 * 2.1 = 20601N \quad (9)$$

*3.1.3 Design of opening handle*

The opening screw is functioning in raising the gate. The resultant force FR = 6630N and pulling height to be 600mm. The force is applied to the gate perpendicularly. By assuming maximum sliding frictional coefficient between the opening gate and guide.

*3.1.4 Design of the screw*

A mild steel screw of the tensile and shear strengths approximately 448MPa and 224 MPa respectively is considered. A very high factor of safety due to the nature of the application and considering the axial tensile, the core diameter of the screw dc is calculated Eq. (10),

$$dc = \frac{\sqrt{6630}}{\frac{\pi}{4} * \frac{448}{10}} = 13.73mm\ \approx 14mm \quad (10)$$

### *3.2 Modification in Irrigation Canal*

The modification is proposed in the existing irrigation canal. Modified irrigation gate with sliding mechanism conveying water to inline turbine. The arrangement explaining this modification is shown in Figure 7. The type of turbine will be Flow and geometrical properties of proposed hydraulic system, site conditions to maintain subcritical flow conditions after power generation and available classification of turbine as shown in Table 3, will be used to decide the type of turbine [6].

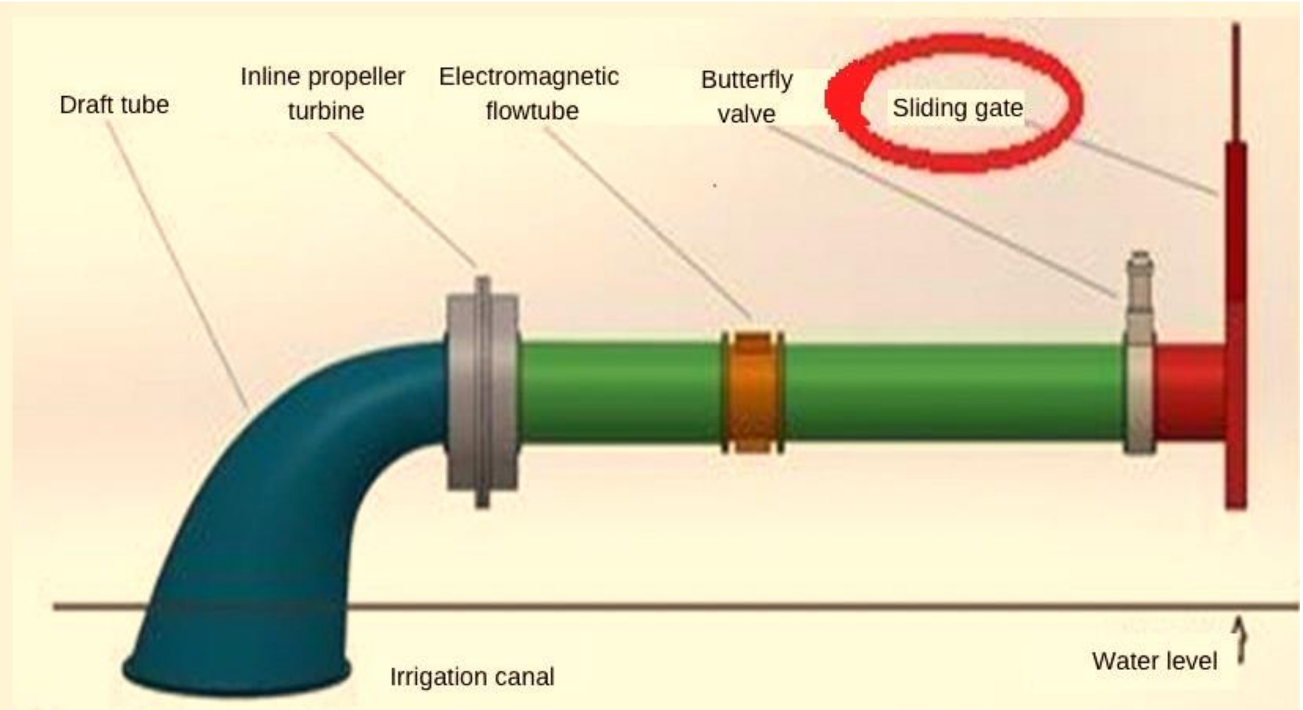


**Fig. 7.** Modified irrigation gate. From left to right – Draft tube, inlet propeller turbine, flow meter, valve, sliding gate

**Table 3**
Classification of turbine type

| Type of Turbine | Turbine Type | Head Ranges(m) | Type of Turbine | Turbine Type | Head Ranges(m) |
|---|---|---|---|---|---|
| Impulse | Pelton | 59<H<1300 | Reaction | Francis | 10<H<350 |
| | Turgo | 50<H<250 | | Kaplan Propeller | 2<H<40 |
| | Cross-Flow | 3<H<250 | | | 2<H<40 |

The proposed closed water conduit can be accommodated with commercially available in inline axial flow propeller or lucid type turbines. The internal diameter and thickness of the annexed leading pipe from penstock section, saddle support for the piping arrangements is formulated as given in [15].

(i) The internal diameter (Eq. (11)) $D_p$ of the leading pipe from the main penstock of the turbine is arrived from the flow rate, pipe length and gross head,

$$D_p = 2.69 * \left(n_p^2 \, * \, Q^2 * \frac{L_p}{H_g}\right)^{0.1875} \tag{11}$$

where
$n_p$ = Manning's coefficient,
Q = Water flow rate ($m^3$/sec),
$L_p$ = Length of penstock (m),
$H_g$ = Gross head (m).

(ii) The wall thickness ($T_p$) of the leading pipe from the main penstock depends on the pipe materials, its tensile strength, pipe diameter and the operating pressure. The minimum wall thickness is recommended (Eq. (12)),

$$T_p = \frac{D_p + 508}{400} + 1.2 \quad (12)$$

where

$D_p$ = diameter of leading pipe in (mm),
$T_p$ = minimum thickness of leading pipe in (mm).

The pipe should be rigid enough to be handled without danger of deformation in the field.

(iii) The saddles are designed to support the weight of penstock full of water. The vertical component (Eq. (13)) of the weight to be supported, in KN, has value of [16]:

$$F = \left(W_p + W_w\right) * L_{ms} * COS\, \emptyset \quad (13)$$

where

$W_p$ = weight of penstock per meter (kN/m),
$W_w$ = weight of water per meter (kN/m),
$L_{ms}$ = Length of penstock between mid-points of each span (m),
∅ = angle of pipe with horizontal.

(iv) Maximum length (Eq. (14)) between supports is given by [16]

$$L_{ms} = 182.61 \frac{\left(\sqrt[3]{D_p + 0.0147^4 + D_p^4}\right)}{P_w} \quad (14)$$

where

$D_p$ = internal diameter of penstock (m),
$P_w$ = unit weight of the penstock full of water (Kg/m).

## 4. Results and Discussions

The hydraulic equipment has suggested an opening at the bottom of the modified gate to allow the maximum flow. The flow beyond the opening to be laminar is to be maintained at laminar state and carried towards the inline turbine. All the required calculations of force and pressure on the sample gate size are presented in the previous section.

i. The analytical calculations for the hydraulic equipment suggested has been carried out considering sample data sample dimensions of the gate as 1*1.5m. Force on the wall is found to be 11250N. The resultant force FR on the gate is calculated as 6630N at the average pressure of 7500Pa.
ii. The hydrostatic and hydrodynamic force limits are observed well for circular opening.
iii. Power generation is secondary to irrigation dependent hydropower plants. Also, stochastic nature of flows is another concern for such plants yet having the opportunity to generate power. Hence, this paper is an attempt to design and develop the hydraulic system having an irrigation gate with a sliding gate followed by an inline turbine in closed conduit at the inlet of the existing irrigation channel.
iv. An agricultural dependent hydropower plant of Dhom (Maharashtra) with capacity 2MW is considered for the application of design and development. 2MW power is generated prior to irrigation.
v. As per data of rainfall, irrigation releases and power generation for 27 years, the additional power generation of 340kW is calculated after releasing 2.47 $m^3$/sec through one gate. From TWO gates 680kW power can be generated additionally.
vi. The irrigation gate having circular opening at the bottom allowing greater discharge is suggested. This gate has a sliding gate arrangement to control the discharge for the inline turbine in the close conduit following the gate.
vii. An attempt to analyze all the hydrostatic and hydrodynamic forces is provided to help further in detailed study of this research work.
viii. The close conduit followed by a gate with an inline turbine can be provided in the existing irrigation channel which is a scope of this study.
ix. The internal diameter and thickness of the annexed leading pipe from the penstock section, saddle support for the piping arrangements is formulated as using [15]. These calculations are considered in the scope of the paper.

## 5. Conclusion

This work is an attempt to provide solution for untapped energy potential as a need of demanding situation of power generation. Modernization is suggested as one of the efficient ways to tap maximum available energy potential from existing hydropower plant than constructing new hydropower plants.

Environmental problems creating drought conditions, increasing $CO_2$ emission from fossil fuels are necessary areas to address on priority. Green sources of power generation are finding place for research and to help achieving net zero emission by 2050. Limited research has been observed in the addressing stochastic nature of discharge through canal/s for power generation. Thus, a case study of Dhom dam having irrigation dependent hydropower plant shows better prospect of tapping energy potential during both high and low release. The calculations have been shown that average irrigation releases of 2.47$m^3$/sec from a single gate able to generate 340kW. Thereby additional 680kW power can be generated from TWO gates in addition to 2MW.

At low discharge, reaction turbine is not able to operate due to operating restrictions which leads to loss of power generation. At high discharge, due to capacity restriction on existing turbine the loss of power has been observed. This stochastic nature of discharge will be well managed by suggested modernization.

A design and development of sliding gate and mini hydropower system is proposed at the inlet of irrigation gate. Irrigates gates along with sliding gates able to control the flow with better efficiency.

The modernization suggested in existing hydropower plant will help to improve the capacity factor with additional power generation of 340kW to 2MW. The proposed irrigation gate is also analysed for hydrostatic forces and size of control structure for future execution.

The methodology suggested in the paper can be employed at canal locations and any hydropower plants to tap the unused potential of water in energy generation.

**Acknowledgement**
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