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Recovery of flow conditions for optimum electricity generation through micro hydro turbines

Abid A. Khan [a,*], Asim Shahzad [a], Imran Hayat [a], Md Salim Miah [b]

[a] Institute of Space Technology, Pakistan
[b] Military Technological College, Oman

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ABSTRACT

Generation of electricity from existing canals through micro projects have become practical and alternate solution to large scale hydro projects. Run-of-the-River (ROR) is a hydroelectric generation scheme with limited or no water storage requirements, as the turbines use kinetic energy of flowing water streams, canals, or rivers for power generation. In this research, a micro hydropower generation system has been studied for its utilization in existing canal of Pakistan. The work comprises verification of operation of selected water turbine in water flow conditions of Pakistan through computational analysis. Ghazi Barotha Canal with concrete bed and flowing round the year flowing is taken as a test case for analysis. The process followed includes the modeling of turbine geometry and CFD (Computation Fluid Dynamics) analysis for validation of flow potential recovery in selected canal. CFD analysis of the turbine geometry with different configurations of debris protectors is carried out to evaluate the optimal recouping of flow properties for maximum electricity generation. Moreover, it also determines whether the flow properties are recovered within the selected distance downstream, which is ten times the turbine length.

1. Introduction

Electricity is a vital component of infrastructure essentially needed for a country's development. The use of this source of energy has therefore seen a significant rise with technological developments since World War II. Electricity sector in Pakistan is facing its worst crisis in history [1]. Thus efforts are being made to explore all possible resources for rescue from this situation and evaluate the power generation potentials [2,3]. On the other hand small scale hydropower systems or micro-hydro systems along with other green energy sources have gained sufficient popularity as an alternate energy source and different nations has benefited from it [4–8]. It has proved to be a valuable natural source that can replace expensive and fast depleting world's fossil fuel reserves. Pakistan is consuming 28% of its fossil fuel supplies towards electricity generation [9]. Micro-hydro systems can be installed in natural as well as artificial streams and rivers. Hydrokinetic systems use the kinetic energy of flowing water and convert it to electrical energy, hence named as Run of the River (ROR) systems [10]. This means that ROR systems differ from low static head conversion thus require no major constructions or flooding, imparting no serious impact on the environment and aquatic life of the rivers [11]. Most run of the river projects implemented by countries did not require large impoundment of water, thus such projects are often regarded as environmental friendly [12]. Run of the River power generation system offers long operational lifetime with minimal maintenance therefore, payback time on the original investment for such projects is often just a few years [13].

The system under consideration employs a fairly new and emerging concept of shrouded turbine body. Computational fluid dynamics is required to check whether the design is suitable for flow conditions in Pakistan. After generation of system model, it is exposed to flow conditions prevalent at Ghazi Barotha Canal. Ghazi Barotha being the only concrete lined and silt free canal has an average flow speed of 2.3 m/s, physically measured at different possible testing locations. This speed is fairly at border line of input requirement for the selected micro-hydropower system. The water flow requirements for optimum working of the power generation system are tabulated in Table 1. Microsystem geometry (Debris Protector) was modified to accrue maximum benefits out of Ghazi Barotha flow conditions. The flow downstream the turbine enters turbulent regime thus best configuration of debris protector would ensure recovery of the flow parameters to its original laminar state

* Corresponding author.

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Table 1
Water flow characteristics.

Parameter	Value
Minimum depth	1.8 m
Minimum velocity	1.0 m/s
Optimum velocity	2.4 m/s
Maximum velocity	3.5 m/s

so as to ensure installation of next turbine set downstream. The requirement of laminar steady flow being an essential need for optimum results has been emphasized by the authors in different other domains specializations as well [14,15]. Researchers have even used different optimization techniques to accrue best results for their domain areas [16–29].

The selected micro-hydropower system has a horizontal axis reaction turbine, an underwater generator, a shroud body housing the propeller and two floats to keep it submerged in the water flow. The technical specifications of hydropower system are tabulated in Table 2.

2. Hydropower system turbine

The unique characteristic of turbine under study is to use the flow augmentation or diffuser augmentation in its design and thus falls under the category of ducted or "diffuser augmented" turbines [30]. Although this concept is well developed in wind turbines, it is a fairly new and emerging technology in the field of hydroelectric power generation as evident from the turbine model shown in Fig. 1. In conventional open turbines, there is a theoretical limit to the percentage of kinetic energy that can be extracted from the flow. This limit is named as Betz's limit and is known to be 59.3% [31]. In a diffuser augmented turbine, the system is enclosed in a duct or shroud which is designed as a diffuser. Radial flow along the blades is prevented by the duct and high efficiencies up to 90% may be possible. Riegler [31] showed that the theoretical maximum power coefficient for this category of turbine based on its area is 1.96, i.e. 3.3 times higher than the Betz limit. This is possible because flow is drawn in from a greater area upstream than that intercepted by the same sized turbine in open flow [30]. The selected micro hydropower system is a slightly modified form of a conventional diffuser augmented turbine. It uses slots to draw in high energy flow from outside the diffuser for boundary layer control [32]. This allows a short, wide angle diffuser or shroud body which is a more economical arrangement than a longer diffuser as in other diffuser augmented turbines. The selected power generation water turbine has a number of advantages over other conventional Run of the River power generation systems:-

(a) Usable in flows that are otherwise slow for large scale commercial hydropower project.
(b) Bio-fouling is reduced as the turbine is shaded from natural light in shallow water.
(c) Generates relatively more power.

Table 2
Technical specifications of hydropower system.

Parameter	Value
Weight	300 Kg
Dimension	147 × 174 × 197 cm
Rotor diameter	100 cm
Shaft speed	90–230 rpm
Maximum power output	5.0 kW

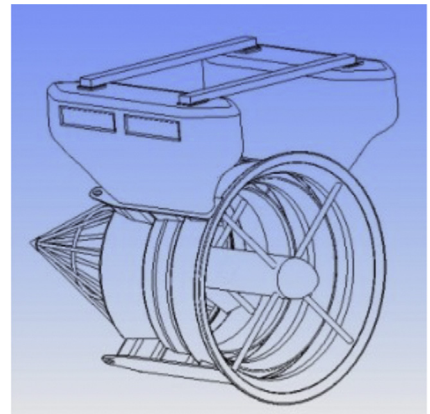

Fig. 1. Smart hydro turbine system.

3. Modeling

In order to analyze the response of selected system in Ghazi Barotha Canal, the system was modeled for computational fluid dynamics (CFD) analysis. A total of four 3D geometries are modeled in commercially available modeling software. Three generated models differ in the design of the debris protectors shown in Fig. 2 whereas; the fourth is without the debris protector as shown in Fig. 16. The reason for modeling four different models is to study the behavior of water flow for different cases and recommend the optimum design based on desired canal flow conditions so as to generate maximum electricity. The first case is the turbine which has a moderately fine wire grill and a circular plate in front, which acts as stagnation point and disturbs the inlet flow as shown in Fig. 7. In the second case the wire grill of the debris protector is removed to draw a comparison between this case and the first case with respect to the flow quality as shown in Fig. 11. In the third case the circular plate of the protector is replaced with a small cone structure to check if it reduces the impact on the inlet flow as seen in Fig. 15 Each part of the turbine was modeled separately and later assembled in a commercial software.

CFD analyses of the four generated models were performed simulating the flow conditions of selected canal. The prepared models were enclosed in a water body domain using canal conditions. The boundary conditions of an open channel flow [33], that is Ghazi Barotha canal, were computed for application to the water domain.

4. Canal flow conditions

Open Channel flows are governed by a well-known relation known as the Manning's equation [34]. The cross-sectional geometry of the selected canal for the study has a trapezoidal shape as shown in Fig. 3 for which the Manning's equation takes the following shape:-

$$V = \frac{1}{n} \times R^{\frac{2}{3}} \times S^{\frac{1}{2}} \tag{1}$$

Where

V is the velocity of flow.
R is hydraulic radius of the Channel cross section computed by dividing the cross section with wetted perimeter
n is the Manning's constant, a function of channel's roughness and material