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Full Length Article

Numerical analysis of lift-based in-pipe turbine for predicting hydropower harnessing potential in selected water distribution networks for waterlines optimization

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ABSTRACT

The research models and simulates in-pipe turbine hydropower harnessing possibilities in water distribution networks of the sites under investigation considering in-pipe lift-based spherical turbine. The hydrofoil profile of the turbine is generated using National Advisory Committee for Aeronautics (NACA) aerofoil generator. Consequently, a Computer-Aided Design (CAD) model of the in-line lift-based spherical turbine is then developed and simulated, based on the peak and lean period of the volumetric discharge rates using commercial computational fluid dynamics software (Autodesk Simulation CFD®). The time series of power outputs are computed from the time series of discharge variations. A lift-based spherical turbine with NACA 0020 foil cross-section appears appropriate for extraction of energy in the water distribution pipelines. Furthermore, the minimum and maximum percentage head loss due to insertion of the turbine is about 1.94% at lean flow rates and 9.70% at the peaks for 250 mm pipelines. The available power was found out to depend on the density of the turbine blades material, flow rate, and the pipe diameter. The estimated lean and the peak electric power are about 415 and 1663 W, respectively, using aluminium foil blades while stainless steel foil produces about 242 and 1080 W in the 250 mm pipe.

1. Introduction

The need for saving water and energy had grown as one of the world main concerns over the years and are expected to become more important in the near future [1]. Small hydropower can be retrofitted into a water supply system where the design head of the turbine to be used depends on the excessive hydraulic head of the distribution lines. An innovative energy policy would necessitate the exploitation of the hydraulic power dissipated along the water distribution network. Several technical solutions have been proposed to replace pressure reducing valves with energy production devices [2] in order to allow effective power conversion and a reliable network pressure regulation of water distribution networks [3]. Carravetta reported using pump as turbine PAT's in the literature [4]. Chen researched on a novel vertical-axis water turbine for hydropower harnessing inside water pipelines, posited that the power generated was used for power supply for the data collection systems in underground and congested locations or to maintenance work at remote locations using CFD (Computational Fluid Dynamic) simulation and lab tests [5]. The energy efficiency of water supply systems can be increased through the recovery of hydraulic energy implicit to the volumes of water transported in various stages of the supply process, which can be converted into electricity through hydroelectric recovery systems. Such a process allows the use of a clean energy source that is usually neglected in water supplies, reducing its dependence on energy from the local network and the system's operation costs [6]. According to lucid technology in the patient document with patient no: US 7,959,411 where lift based turbine was proved to be efficient with little flow reduction rate, for the pipes diameter within the range of 610–1575 mm (24–62 in.). Consequently, a research that further adapts lift based turbine to smaller pipe diameter was recommended [7].

From a recent work on five blades tubular propeller turbine for pipe inline installation, it was obtained that the best efficient point (BEP) corresponds to an efficiency of around 64%, held at a rotation speed of 750 rpm, a flow of 16 m^3/h and 0.34 bar (3.5 m) of a head. The maximum mechanical power measured was around 330 W, for

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a maximum flow of 48 m^3/h, 0.48 bar of head and 1500 rpm of rotation speed [8].

The hydropower generation potential of the public universities in southwestern Nigeria, to determine those institutions equipped with the appropriate operational water distribution networks was carried out by considering hydropower potential at service reservoirs due to the possibility of appreciable power potential. Consequently, the water distribution networks of the University of Ibadan, Ibadan (UI), Obafemi Awolowo University Ile-Ife (OAU), and the Federal University of Technology Akure (FUTA) were surveyed for data collections and the volumetric discharge rates were taken in an hour interval for 24 hours [9].

The objective of this study is to model and estimate hydropower possibilities of an in-pipe turbine for water lines optimization based on time series of water distribution discharge rates and the available effective head in the water lines of the selected public universities in southwestern Nigeria. Therefore, this work will make available important data and model for related investigations. The technical feasibility of small hydropower integration will be limited to CAD modeling of existing in-pipe turbine. The turbine considered in this research is lift-based spherical turbine based on its established suitable performance in water distribution systems that do not defeat the original purpose of configuration of effective water distribution to the users at the expense of power harnessing along the water lines.

1.1. Lift based spherical turbine

In-pipe turbines were analyzed by lucid technology pipelines (Lucid, 2014) but large conduit diameters of 610–1575 mm (24–62 in.) were tested. The lift based spherical turbine is a form of turbine configuration that rotates transversely under the power of fluid flowing in the pipe, which is coupled with the appropriate generator to produce electricity. The blade of the spherical turbine curve is in an approximately 180 degree arc in a plane that is an inclined angle relatively to the rotational axis of a central shaft, therefore, the blades of the spherical turbine are airfoil in cross section to optimized the hydrodynamics flow, minimize cavitation and to maximize the conversion from axial to rotating energy [7]. The pictorial representation of this turbine is expressed by Fig. 1.

2. Material and methods

The spherical lift based in pipe turbine was model with Computer Aided Design (CAD) tool Autodesk Inventor 2015 [9] while the minimum and maximum time series of water distribution volumetric discharges taken on the investigated sites using kent volumetric water meters (Elster Kent H4000 model, England) [10] inserted along the energy lines were used as the input parameters for the numerical analysis. The pressure heads were estimated with Global Positioning System GPS (e-Trex GPS, 79; 98 Garmin model, USA) device with Wide Area Augmentation System (WAAS) receiver. The internal diameters of the pipes in the networks were measured to the nearest millimeters, using venier caliper (Mitutoyo 505 series dial caliper model, Japan). Water distribution networks of the University of Ibadan, Ibadan (UI), Obafemi Awolowo the University, Ile-Ife (OAU), and the Federal University of Technology, Akure (FUTA) were considered for data collection being institutions equipped with the appropriate operational water distribution networks in southwestern Nigeria. The numerical power output was derived from each site with the use of computational fluid dynamics software (Autodesk® Simulation CFD) [11].

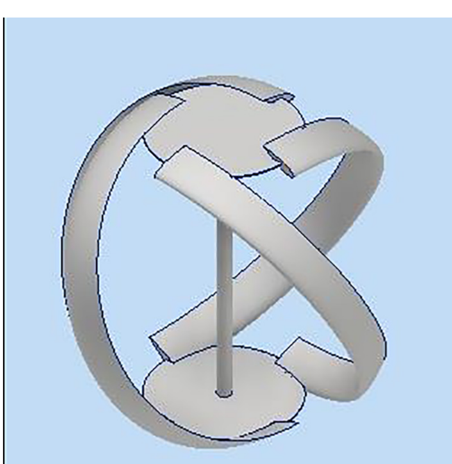

Fig. 1. Lift based spherical turbine [7].

2.1. Basic parameters of the lift based spherical turbine model

The parameters of the modeled lift-based in-pipe turbine are gotten from using the conduit diameter as the presiding parameter of conversion between the existing model and the adaptive model. Parameters are 0.2336 m turbine diameter, 0.1988 m turbine height, and 0.0287 m chord length, 0.1 m hub diameter with turbine shaft diameter of 0.01 m, Blockage ratio 0.11, Number of blades 4, Equatorial solidity 0.18, Average solidity 0.22, blade hydrofoil cross sectional profile takes after the standard of National Advisory Committee for Aeronautics (NACA) four digit symmetric series NACA 0020 using equation (4) to generate the 200 data with the aid of NACA 4-digit series airfoil generator tool, which in turn was exported into the Autodesk inventor during CAD modeling, Blade overlap is 2.

2.2. Simulation of the modelled turbine

The modelled turbine was simulated by importing the turbine CAD model into the simulation software for numerical computation. The CFD numerical computation was done with the use of Autodesk Simulation CFD [12]. Having imported the extraneous features free CAD geometry into Autodesk Simulation CFD as design study, the small edges and sliver surfaces on the impeller were removed with the aid of geometry preparation tool. The suction (inlet) and discharge (outlet) was extended at four hydraulic diameters from the impeller to prevent the boundary conditions from directly influencing the results. Material assignment to each part of the model was carefully carried out. The fluid domain was also created within the pipe which subsequently assigned material to as water. The rotating region that becloud the impeller was also assigned a rotating region to as material which can be preset to a known rotating speed while ramping up the rotating speed to avoid impulsive start up and later to free spinning (turbine mass moment of inertial is required in flow driven analysis) as the case may be. The initial and boundary conditions were also carefully setup at the inlet and outlet to represent the real scenario, while the inlet was set up as observed volumetric discharge in cubic meter per hour for each analysis, The outlet was set as zero static gauge pressure, while monitoring plane was setup to determine magnitude of the parameters at the downstream. Automatic-sizing tetrahedral mesh was used for the analysis. The mesh at the rotating region, inlet surface, and outlet surface were assigned uniform mesh which in turn spread to entire mesh matrixes. The model has about 3.2 million tetrahedral elements. Fluid-cap (entry length) was about two-third of the fluid domain diameter that enabled full development of fluid. Incompressible fluid was assumed, SST – k omega turbulent model was adopted with