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C.F.D. ANALYSIS OF MICRO HYDRO TURBINE UNIT: A CASE STUDY

Priyabrata Adhikary, Pankaj Kr Roy and Asis Mazumdar
S. W. R. E., Jadavpur University, Kolkata, India
E-Mail: priyabrata24@gmail.com

ABSTRACT

Small or micro hydropower projects (SHP or MHP) are emerging as solution for sustainable, eco-friendly, long term and cost-effective water or renewable energy resource for future. According to the International Energy Agency (IEA), approx.22% (2008) of the world's populations, living without access to electricity, 85% of whom live in ruralareas. Of the 1.5 billion people in the world who have no access to electricity, India accounts forover 300 million. Such an energy situation for the poor villagers is unacceptable. It is possible to achieve universal energy access in the foreseeable future, and modern renewable energy technologies can play a crucial role in achieving this goal.This paper describes design and development of low cost micro hydro turbine (converted from commercially available water flow meter) effective for hilly and/or rural area as basic electricity home systems (3V-12V and 7W-10W) for rural and/or hilly area electrification. Water flow rotates the turbine rotor inside stator whose speed of rotation changes with the different rate of flow of water. To the best of the author's knowledge these novel approach for CFD analysis of Micro Hydro Turbine are absent in renewable energy or fluid mechanics literature due to its assessment complexity.

Keywords: small and micro hydropower, hydro turbine, renewable energy, energy recovery, CFD.

1. INTRODUCTION

In India, the total installed power generating capacity during October 2014 was reported as 2, 54,649.5 MW out of which only 40, 798.8 MW is through hydro power. The identified small or micro hydropower potential sites are 19749.4 MW, installed are 3970.4 MW till November 2014 and under implementation are 895.4 MW. The cost of clean-green-friendly small hydroelectricity is relatively low i.e. Rs2.5/KWH (approx.), compared to others and thus making it a competitive source of renewable energy. According to the International Energy Agency (IEA), there was an estimated (approx.) in 2008, 22% of the world's populations, living without access to electricity, 85% of whom live in ruralareas. Of the 1.5 billion people in the world who have no access to electricity, India accounts forover 300 million. Such an energy situation for the poor villagers is unacceptable. It is possible toachieve universal energy access in the foreseeable future, and modern renewable energytechnologies can play a crucial role in achieving this goal. Small or micro hydropower projects are complex, interdisciplinary integrated systems, because there are large numbers of civil, mechanical and electrical components with different characteristics [1-4]. Small or micro hydropower projects (i.e. up to 25MW in India) are much more advantageous than conventional medium or large hydropower projects. Small or micro hydropower plant requires very less flow or head compared to conventional hydropower plants. Reservoir or dam is also not required for small hydropower projects as they are mostly run-of-river type. Environmental and social impacts of small or micro hydropower projects are also negligible compared to conventional medium or large hydropower projects. Small hydropower project schemes are classified as: Run-of-river scheme, Canal-based scheme, Dam-Toe scheme, Pumped storage and In-stream type scheme [1-4].

There are two basic components in all types of small hydro project schemes; i.e., civil works (Diversion and intake, De-silting tank, Power channel, Fore-bay, Penstock, Powerhouse building, Tail race channel etc.) and electro-mechanical equipment (Valves, Hydraulic Turbine, Generator etc.). Most of the components are same in different types of schemes; some components, however, are different. The development of small hydro projects typically takes from 2 to 5 years to complete, from conception to final commissioning. This time is required to undertake studies and design work, to receive the necessary approvals and to construct the project. Once constructed, small hydro plants require little maintenance over their useful life, which can be well over 35 to 50 years [5-8].

Small or micro hydropower project development involves following stages as: Pre-feasibility Analysis; Feasibility Analysis; Engineering and Development; Construction and Commissioning. Small or micro hydropower Plant operation can be divided under four verticals as: Operation Management, Water Management, Maintenance Management and Personnel Management. Similarly, small or micro hydropower plant maintenance is of four types as: Breakdown Maintenance, Routine Maintenance, Preventative Maintenance and Capital Maintenance [5-8].

2. MATERIALS AND METHODS

Hydraulic (or hydro) energy is available in many forms, kinetic energy from flow in rivers and tidal barrages, potential energy from high heads of water retained in dams, kinetic energy also from the movement of waves on relatively static water masses. Many ingenious ways have been developed for harnessing this energy, but most involve directing the water flow through a hydro turbine to generate electricity.

Currently applications of micro (or small) hydro plants have been involved in energy recovery systems such as drinking water distribution system, water or waste water or sewage treatment plant, RO plant, existing irrigation system, rain water harvesting system etc.

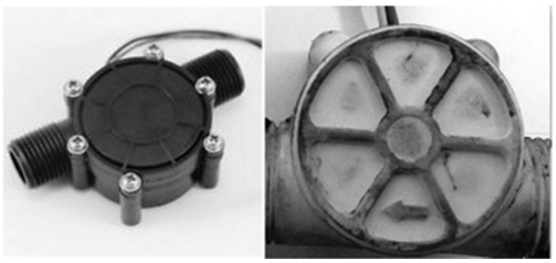

Figure-1. Micro Hydro Turbine (Commercial Flow Meter).

Even a small water infrastructure can generate hydropower - including the systems that deliver water to offices or homes. Anywhere there is excess head pressure in an infrastructure dealing with water; there can be a good opportunity to generate electricity. But micro hydro plant operation must not impact on the primary function (i.e. drinking water pipeline) of the existing infrastructure. Thus, the micro turbine has to be as flexible as possible regarding the available pressures and discharges, while guaranteeing high performances on the largest operation ranges.

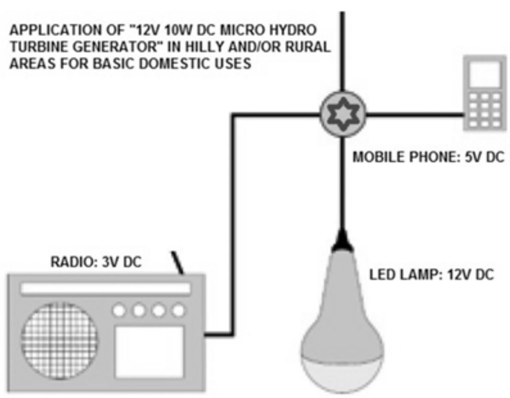

Figure-2. Basic electricity home system (Rural Area)

These 3-12V 7-10W DC Basic Electricity Home Systems / Micro Hydro Units can be used for hilly and/or rural areas for domestic uses (for lighting, radio or mobile phone charging) with flowing streams. Other uses are power generation from rain water harvesting systems, water distribution systems of high rise buildings etc. In renewable energy sector for 12V 10W DC power generation (for basic domestic uses) micro hydro turbine initial cost is minimum compared to solar or wind generators for hilly and/or rural area.

Figure-3. Micro Hydro Turbine (W.T.P. at Murshidabad).

Technical specifications of various commercially available 12V 10W DC Micro Hydro Turbine Unit (converted 1/2” tangential flow meter) is: Output voltage: 5-12V; Maximum Output Current: 220mA; Max. Pressure 0.6Mpa (outlet closed); Maximum pressure 1.2Mpa (outlet opening); Starting pressure 0.05Mpa; Axial clearance 0.2-2.0mm; Mechanical noise ⩽55dB; Material: PVC, Unit Weight: 100gm (approx.).

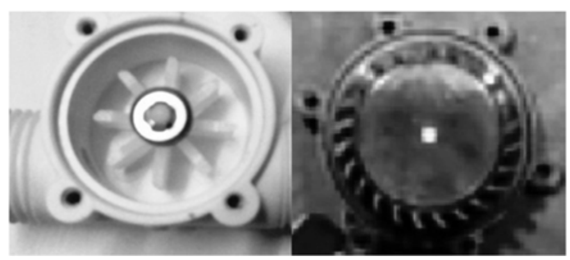

Figure-4. Micro Hydro Turbine runners.

3. THEORY AND CALCULATIONS

The governing equations of viscous flow are based on conservation of mass, momentum and energy which are Langrangian in nature. The governing equations are expressed using equations (notations used have their usual standard meanings) shown below:

Conservation of Mass: $\frac{\partial \rho}{\partial t} + \rho \nabla V = 0$

Conservation of Momentum: $\rho \frac{DV}{Dt} = \rho g + \nabla . \tau'_{ij} - \nabla p$

Conservation of Energy: $\rho \frac{Dh}{Dt} = \frac{Dp}{Dt} + \nabla (k \nabla \mathrm{T}) + \phi$

The numerical analysis of CFD in micro hydro turbine consists of incompressible fluid flow that reduces the conservation of mass and momentum to equations shown below respectively. In addition, the temperature

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effect is negligible during the analysis. Therefore, conservation of energy is ignored during analysis.

$$\nabla \cdot V = 0$$
$$\rho \frac{DV}{Dt} = \rho g + \mu \nabla^2 V - \nabla p$$

4. CFD ANALYSIS

There are many commercial general-purpose CFD programs (Interdisciplinary field of study based on Physics, Engineering, Mechanics, Biology, Material Science supported by both Mathematics and Computer Science) available, e.g. Ansys-Fluent, Ansys-CFX, Star-CD, FLOW-3D, SoldWorks Flow Simulation and Phoenics. A very useful open-source program that can handle CFD problems is OpenFoam. However, the documentation and the user interface are not well developed as those for the commercial codes. Commercial CFD packages contain modules for CAD drawing, meshing, flow simulations, solver and post-processing.

An eco-friendly 12V 10W DC Micro Hydropower Project Model (stand alone) has been designed and planned in a rural drinking W.T.P. at Murshidabad (W.B., India). The CFD analysis for the same was carried out using the ANSYS-Fluent, for analysing the performance. For very complex systems the results are not very accurate, but CFD can still be very useful saving design engineer's time-cost-effort. Experimental validation verifies the codes to make sure that the numerical solutions are correct and compare the results (making a provision for measurement errors).

The ANSYS-Fluent solver solves the Navier Stokes and conservation equations. The equations that we used are not closed, so we need to use Turbulence Modelling to close the equation set and then iterate towards a solution. We used what is called a Reynolds Averaged Navier Stokes (RANS) approach, (or we can use an Eddy Simulation technique which resolves the larger eddies in the flow and is only really required when you have separation or large re-circulating regions). The most commonly used models are the RANS models due to their low cost in terms of compute power and run times. The Eddy Simulation methods can be quite mesh sensitive but will yield much better results for separated and re-circulating flow, but takes much longer run times. There are different turbulence models available in Ansys-Fluent as mentioned below: Spalart-Allmaras Model; k-Ɛ (k-Epsilon) Model-widely used; k-ω (k-Omega) Model; v2-f Model; Reynold's Stress Model (RSM); Detached Eddy Simulation Model (DES); Large Eddy Simulation Model (LES) etc [9-14].

There are many possible reasons for the discrepancy between CFD calculations and experiment. We are modelling the problem as a steady flow that is symmetric about the axis, but experiments reveal that flow is neither steady nor symmetric. Furthermore, we are using a turbulence model. As discussed previously, turbulence models are not universal, and may not be applicable to the present problem. A DES or LES simulation would be required to correctly model the unsteady turbulent eddies [9-14].

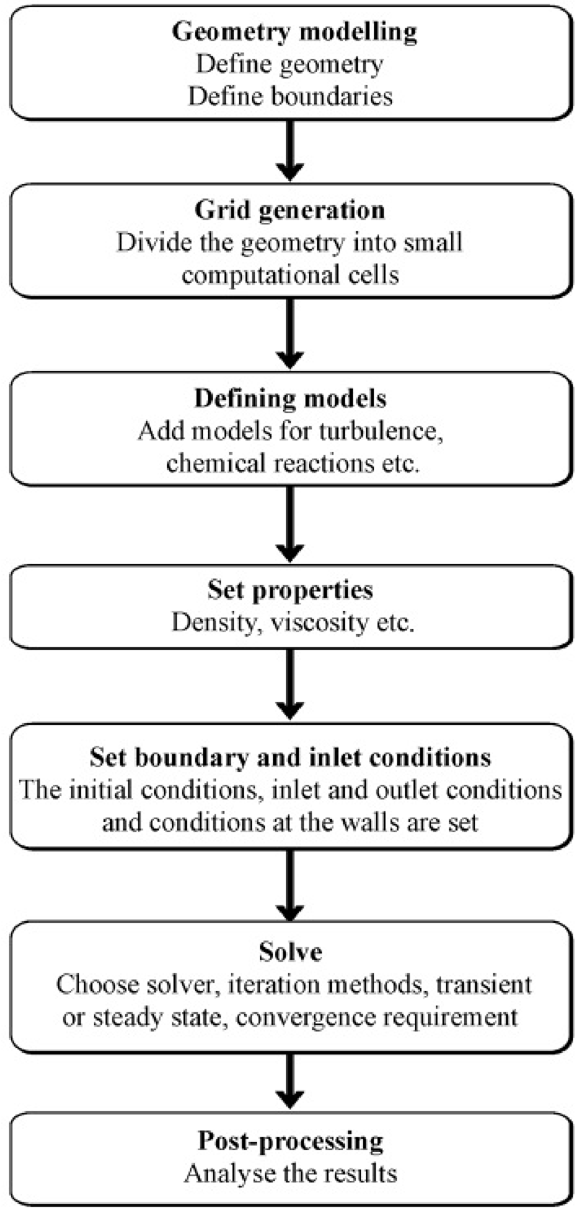

Figure-5. Steps for CFD analysis.

As the size of micro hydro turbine is very small, here a 2D unsteady state computational model (sliding mesh theory) for a micro hydro turbine (8 blades) is proposed, and the **finite volume based-SIMPLE** (Semi-Implicit Method for Pressure-Linked Equations, originally derived by Patankar and Spalding in 1972) solution scheme (algorithm is basically used to solve pressure-velocity coupling equations) and **k-ε turbulence model** are used to obtain the detailed information of flow field in micro turbine, such as velocity and pressure distribution. A second order upwind differencing scheme is used for numerical analysis. Upwind differencing scheme is a modified form of central differencing scheme due to its inability to identify direction of flow. The upwind differencing scheme takes into account the flow direction while computing the value at a cell face. The calculation method is transient hence the time steps are calculated as required. From experimental data, inlet velocity is 64cm/s (m-factor = 7.5) and discharge is 55.2 cc/s. So, the angular velocity comes out to be 3-5 rad/s (approx.).The number of blades is 8 thus for 360 degree rotation one blade will cover an angle of 45 degree each (360/8 = 45) and other will be on its position after it.

In the process of numerical computation, the part of the meshed model which consists of the turbine blade, hub and shaft, is named the turbine rotor. For the fixed rotational shaft, the turbine rotor rotates anti-clockwise. The rotary speed of a turbine rotor is **ω** rad/s, and its initial value is calculated to one $\mathbf{V_{in}}$. In the process of numerical calculation of applying the sliding mesh model, the turbine rotor torque value of different turned angle in the direction of the Z axis is obtained continuously. If the average value of torque at any turned angle is zero the value of will be considered as the valid rotational speed of the rotor under the condition of the value of inlet velocity. The 2D geometry is made of exact dimension as the actual micro turbine has in side view plane. The rotor has 8 blades of 10 mm height and 3 mm thickness (inlet jet diameter 2.5mm).

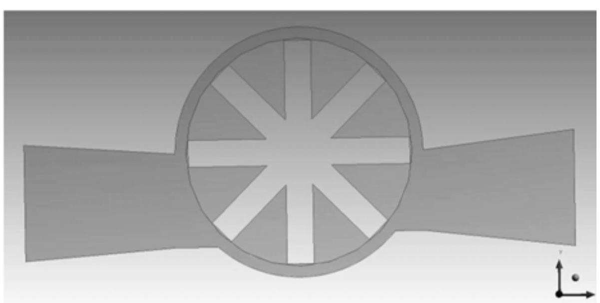

Figure-6. Micro Hydro Turbine - Geometry (Ansys 14.5).

Mesh generation consists of dividing the computational domain into a finite number of discrete regions, called control volumes or cells in which the solution is sought. An unstructured grid was generated for the present analysis; unstructured grid is used where each mesh cell is a block. This provides a tremendous geometric feasibility and allows the most efficient use of computational resources for complex flows.In practical CFD triangles and quadrilaterals are used in 2D geometry and tetrahedral and hexahedral are used in 3D geometry. The grid size range is taken 0.370±0.002 million. Velocity noted at a point 10mm after inlet is 2.39 m/s.

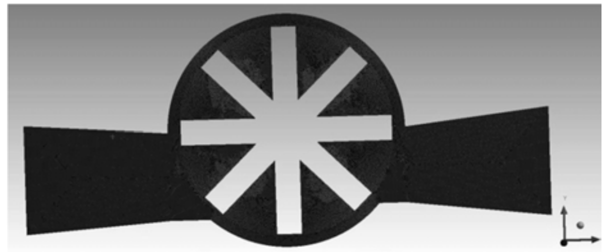

Figure-7. Micro Hydro Turbine – Meshed model.

Single rotating frame model only fits the case without a stationary zone. Multiple reference frames model has a requirement that the boundaries separating a moving region from adjacent regions must be oriented such that the component of the frame velocity normal to boundary is zero. In sliding mesh model (as used here with predicted rotor speed: 506 RPM at 0.01 LPS; 1013 RPM at 0.02 LPS; 1686 RPM at 0.03 LPS; 2527 RPM at 0.04 LPS; 3030 RPM at 0.05 LPS etc), the boundaries between moving and stationary regions are a cross section of the pipe, so velocity normal to boundary is not zero. Since the flow is integrally unsteady, a time-dependent solution technique is required. Grid independency test is carried out to check the sensitivity of result with the change in grid size. A fluid zone is a group of cells for which all active equations are solved. The only required input is the type of fluid material (water at 20ºC having 998.2 kg/CuM density, 0.001003 kg/m-s viscosity is used in our micro hydro unit).The rotor has given mesh motion which is rotational. The parameter is the rotational velocity calculated by the experiment. The angular velocity for the present result is ω=2.5-5 rad/s. The stator is stationary and has only fluid motion through it. The boundary conditions are: Inlet-Velocity Inlet; Outlet-Pressure Outlet; Casing-Wall; Blades-Moving Wall; and Interior.

The maximum and minimum pressure is 0.11 and .08 (vacuum) times the atmospheric pressure. The region of high pressure is observed at the end of the nozzle where the fluid is striking the blades. The low pressure region is behind the blades and at the beginning of outlet nozzle. The pressure is minimal due to formation of vortices there.

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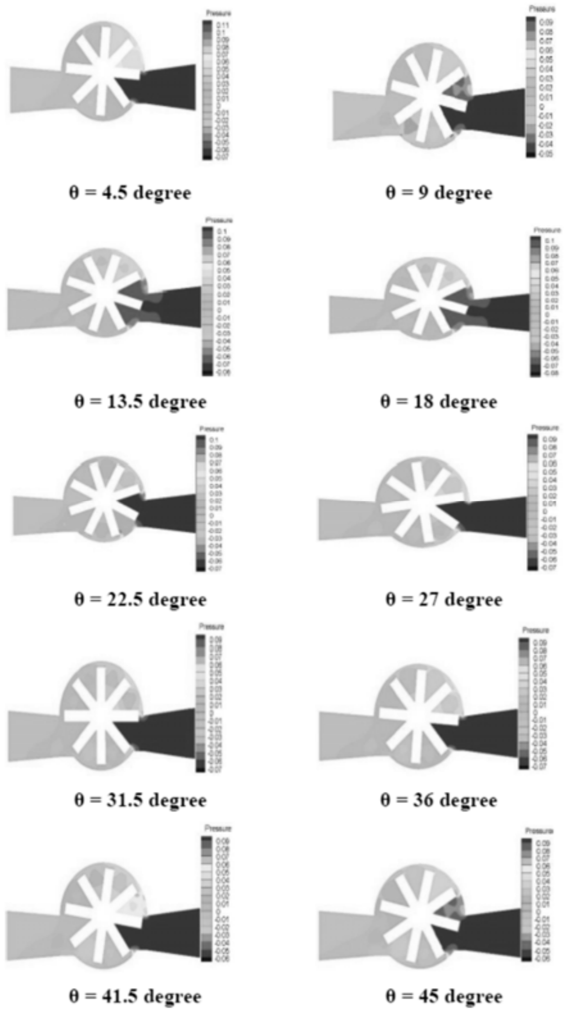

Figure-8. Micro Hydro Turbine - Pressure contours.

The velocity contour shows the maximum and minimum velocity of 1 and -6 (opposite to inlet velocity) of the inlet velocity. The velocity is high at the circumferential periphery and at the edges of the blade in the rotor.

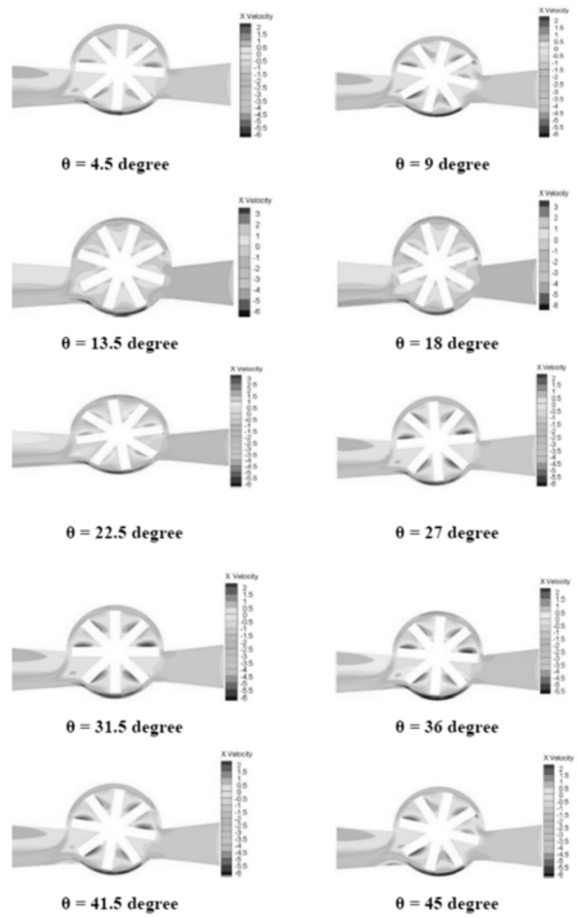

Figure-9. Micro Hydro Turbine - Velocity contours.

The torque at each time step (4.5 degree) is calculated at the inlet velocity of 64cm/s and the angular velocity 2.5-5 rad/s. Power is calculated from torque as (**kW=N-m x RPM / 9.5488**). The pressure and velocity contour at each time step is also plotted to visualize the change happening inside the transient flow as shown. The contour plots are taken up to 10 time step i.e. 45 degree of rotation. The number of blade is 8 and hence after every 45 degree one blade takes the position of other, so the plot will repeat itself. The torque curve is plotted for blade torque over these simulations as shown. The torque is converging to zero. The torque balance is also satisfied in our CFD analysis. The rotor torque is balanced in between the angle of rotation 17.5 to 32.5 in which it almost converges to zero. The value of torque is zero at the 22.5 degree, means balance of torque and hence the inlet velocity and rotational velocity are correct and conformal to each other. Hence the effective power output calculated is in the range of 3W-7W (approx) for various flow rates.

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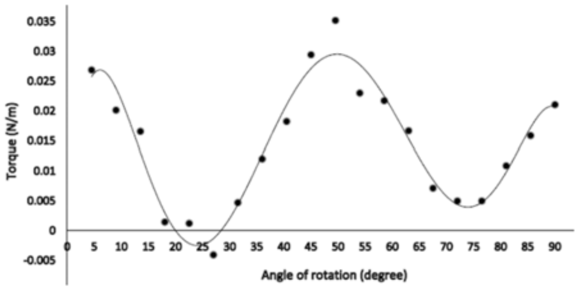

Figure-10. Micro Turbine - Torque vs Angle of rotation.

5. VALIDATION

Results confirm that this CFD study method is feasible and effective. The results of the present experimental research may be useful to similar cost effective hilly and/or rural power generation methods and micro hydro turbine research and development of various ranges (capacity). This experimental study provides a guideline for selecting the most suitable optimal and cost effective micro hydro turbine system for use in different low head and low flow condition, in hilly and/or rural locations in India. These 12V 10W DC M.H.T. units can be used for hilly and/or rural domestic areas (for 12V LED lighting, 3V Radio and 5V Mobile Phone Charging). Other uses include power generation from rain water systems, water distribution systems of high rise buildings, W.T.P. or E.T.P. etc.

Figure-11. Micro Hydro Turbine - Experimental result

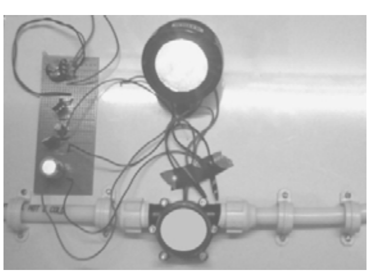

Figure-12. Micro Hydro Turbine - Experimental setup.

6. RESULT AND DISCUSSIONS

Comparison between numerical results and experimental data reveals a good agreement. Micro hydro turbines are not much accurate at low flow rates due to rotor/bearing drag that decelerates the rotor. Almost 5% of minimum rated flow capacity is required. It should not be run at high velocity because premature bearing wear and/or damage can occur. We need to be careful when measuring fluids that are non-lubricating because bearing wear can cause error. With the help of CFD the rotor driving torque (and power) is calculated on blades by using boundary conditions.

7. CONCLUSIONS

The advanced CFD model used in this research solves the Navier-Stokes equations, which are formulations of mass, momentum and energy conservation laws for fluid flows. This CFD model is able of predicting both laminar and turbulent flows. Most of the fluid flows in engineering practice are turbulent, so this model uses the Reynold-Averaged-Navier-Stokes (RANS) equations, where time-averaged effects of the flow turbulence on the flow parameters are considered. Through this procedure, extra terms known as the Reynolds stresses appear in the equations for which additional information must be provided. To close this system of equations, it employs transport equations for the turbulent kinetic energy and its dissipation rate (k-ε model). This research shows the utility of the CFD numerical simulations as a tool for design and optimization of small or micro hydropower performance and flow behaviour through hydro-mechanical devices or hydraulic structures at minimum time-cost-effort. Experimental tests are not always viable because they are very expensive and time consuming as it is much more difficult to analyse different scenarios at various boundary conditions. The flow of a real fluid in contact with a boundary implies velocity variations, pressures gradients and shear stress development which are the important factors to be taken into account in the design, construction, operation and maintenance of any hydraulic machines for small or micro hydropower plants.

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