# Increasing Power Density of Kinetic Turbines for Cost-effective Distributed Power Generation

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## Abstract

Kinetic hydropower generation involves the use of underwater turbines in relatively high-velocity rivers. Their design is relatively inexpensive, without the requirement for costly infrastructure such as dams or powerhouses but large power production requires the use of multiple units. Furthermore, with no associated reservoir or spillway, kinetic hydropower has minimal environmental impact. The focus of this study is on the design of the turbine shroud to increase the power density, especially for river deployment. Unlike wind energy, where the large rotor diameters preclude the use of shrouds, kinetic hydropower can take advantage of the shroud geometry to increase the flow speed which results in higher power densities for a given rotor diameter size. This aspect is particularly important for river applications where the diameter of the rotor is limited in size by the cross-sectional dimensions of the river, especially for high velocity applications and to leave room for the upper ice zone during spring runoff in colder climates. A review of kinetic hydropower and shroud development will be discussed. Numerical modeling results of various designs are presented and compared to conventional non-shroud designs. Compared to wind energy and small hydropower, limited commercialization has taken place for kinetic hydropower although the technology has been available for decades. Therefore, a further objective is to raise awareness of the power densities achievable for this promising form of alternative energy.

## 1 Introduction

Rapid growth in energy consumption and environmental concerns over conventional power generation technologies has given rise to a need for alternative energy sources. Kinetic hydropower has been available for decades, however, despite its minimal environmental impact, commercialization has been limited. Diffuser systems for wind turbines have been investigated in detail [1-5] but the large rotor diameters lead to prohibitive costs and complications. Al-Sulaiman et. al. [6] suggest diffuser-augmented wind power may be favorable in countries with small wind power densities. However there is little in the way of studies on the effects of such systems for kinetic hydropower in the open literature. There are design examples of river and ocean kinetic turbine systems under development that use a shroud like that proposed by UEK [7] and Lunar Energy [8]. Numerical modeling shows how the design of a shrouded turbine can lead to a significant increase in energy density and that such technology is feasible.

## 2 Technology Overview

Kinetic river hydropower is a technology that uses the kinetic energy in a river to generate electrical power. Installations are sited at strategic points along a targeted river where the land formation provides a natural flow restriction, resulting in high streamwise velocities. At these locations, one or several turbines are installed beneath the surface of the water for the purpose of electrical power generation. The term “kinetic hydropower” is used to differentiate this technology from run-of-river and small hydropower, which require the construction of dams or powerhouses.

A kinetic hydropower installation is composed of four main components, shown in Figure 1:

- turbine;
- shroud (optional);
- anchoring structure; and
- generator and subsequent power distribution.

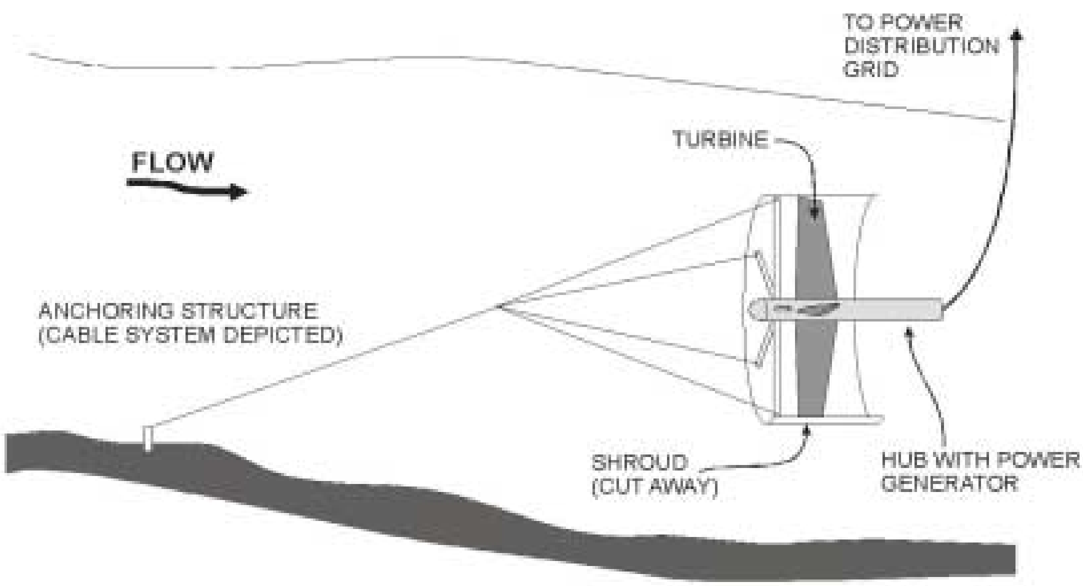


**Figure 1: Technology Overview**

Kinetic hydropower has no reservoir, spillway, or emissions. Therefore environmental impact is minimal, and site selection is far less restrictive compared with other hydro technologies. The initial installation cost and deployment time is relatively short as kinetic hydropower does not require any significant infrastructure, such as dams or powerhouses. The modular nature of kinetic hydropower leads to an easily scalable energy output but with very limited decrease in capital cost per kW. Finally, the consistent river velocities leads to steady energy production, thus eliminating the need for any significant energy storage capacity.

Installation and servicing may be complicated by dangerous river conditions and seasonal ice floes, where applicable. The design must accommodate diverse flow conditions, including seasonal variation in the river flow rate, thus design optimization is compromised. There is no control over the upstream flow conditions or riverbed surface, therefore turbulence, silt and foreign debris are expected at the inlet. The turbine may be designed to move in the vertical direction to avoid debris during spring runoff, similar to the UEK design. Turbulent inlet flow may lead to cavitation on the turbine blades. Finally, the technology poses an unknown risk to fish, vegetation, and other habitants of the river, a risk that must be understood before large-scale deployment is considered.

This paper will focus on the shroud design for river applications.

## 3 Numerical Parameters

The simulations presented here are the first results of an iterative design process. Several simplifying assumptions are made to allow for a broader investigation of the design variables. The findings from these analyses are intended to lead to a more focused study of the design variables under more realistic conditions.

A turbine and hub with the dimensions given in Figure 2 is immersed in a body of fluid. The inlet has a uniform velocity of 3 m/s with high turbulence intensity. The outlet has an imposed average static pressure of 0 kPa. The remaining walls are symmetry planes. The shroud was modeled as a combination of a cylindrical wall and conical wall, as shown in Figure 2. The ratio of the outlet area to inlet area and the cone angle were the design variables.

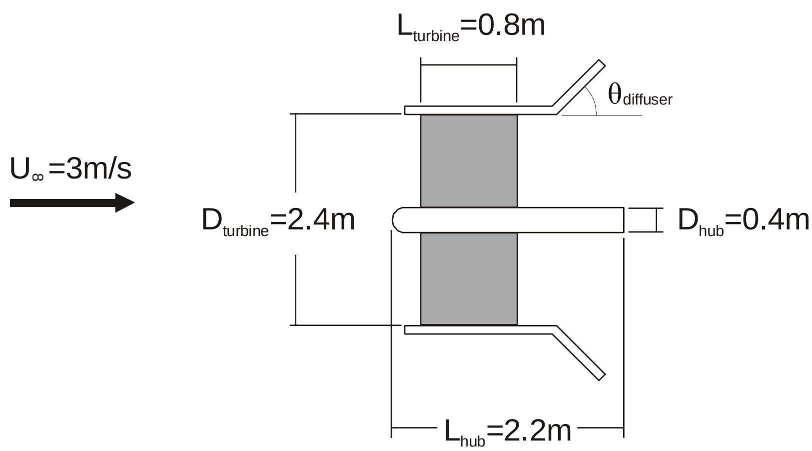


**Figure 2: Turbine dimensions**

## 4 Methodology

Design considerations call for a shroud to enclose the turbine for the purpose of supporting the turbine and protecting the blades; however this component may be used to further advantage by altering its geometry to increase the power available in the fluid passing through the turbine. Installing a diffuser at the outlet, in theory, will increase the pressure drop across the turbine.

The available power in the fluid is given by:

$$P = \frac{\eta \rho u_{\infty}^{3} A}{2}, \tag{1}$$

where $\eta$ is turbine efficiency, $\rho$ is fluid density, $u_{\infty}$ is the freestream velocity, and $A$ is the area of the turbine.

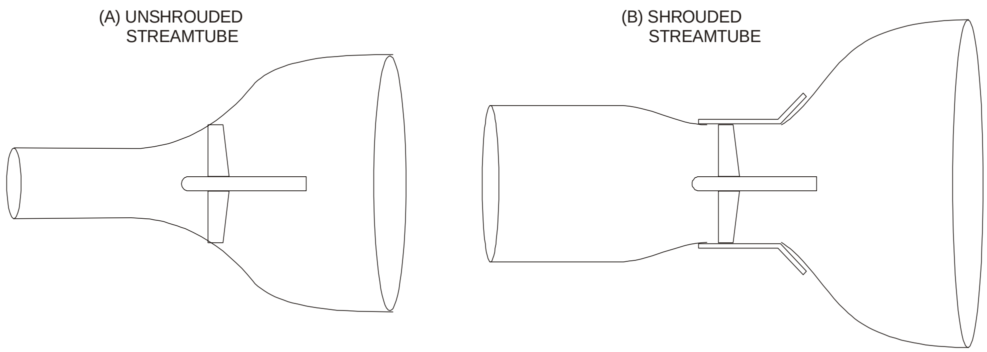


**Figure 3: Streamtubes (a) unshrouded turbine, and (b) shrouded turbine**

For an ideal turbine, the maximum possible efficiency, $\eta$, is approximately 59% [9], commonly referred to as the Betz limit. When a diffuser is installed, the power output is boosted far beyond the output for an ideal turbine with no diffuser. However, the Betz limit is not violated because the streamtube has also changed, as shown in Figure 3. A constant value of 50% is used for $\eta$ in the simulations for a shrouded turbine.

To simplify the simulations, the turbine is modeled as a momentum source. Since the use of a diffuser is expected to increase the flow speed through the turbine, applying a momentum source based on the freestream will not show any power increase. Therefore, we modify Equation 1 to use the mean axial velocity through the turbine:

$$P = \frac{\eta \rho \bar{u}^3 A}{2}, \tag{2}$$

where $\bar{u}$ is the mean axial velocity through the turbine. This will conservatively under-predict the power production, as the momentum source will reduce the mean axial velocity. This is discussed in more detail later.

Power is related to momentum by:

$$P = \frac{\partial S}{\partial t}\left(\frac{l}{t}\right), \tag{3}$$

where $\frac{\partial S}{\partial t}$ is the momentum change, $l$ is the distance through which the momentum change occurs, in this case, the turbine length, and $t$ is the time. Time can be expressed as:

$$t = \frac{l}{\bar{u}} \tag{4}$$

Equations 2, 3 and 4 give:

$$\frac{\partial S}{\partial t} = \frac{\eta \rho \bar{u}^2 A}{2} \quad (5)$$

Dividing through by the volume of the turbine ($lA$) gives:

$$\dot{s} = \frac{\eta \rho \bar{u}^2}{2l}, \quad (6)$$

where $\dot{s}$ is the momentum flux per unit volume. This function is used in the simulations.

The use of the momentum source requires analytic calculations to yield the power and drag from the results of the simulations. Power is given by Equation 2 and the turbine drag is calculated using:

$$F_{d,turbine} = P\frac{t}{l} = \frac{P}{\bar{u}}. \quad (7)$$

The total drag is the sum of the drag on the shroud / diffuser assembly and the turbine drag:

$$F_{d,total} = F_{d,turbine} + F_{d,shroud} = \frac{P}{\bar{u}} + F_{d,shroud} \quad (8)$$

ANSYS CFX-5.7, a commercially available CFD simulator, was used to perform the calculations. The fluid was modeled as incompressible, under steady-state conditions, with a $k$-$\varepsilon$ turbulence model.

## 5 Results

The results from a numerical study of diffuser area ratio and diffuser angle are summarized below for a flow velocity of 3 m/s, a rotor blade diameter of 2.4 m and fresh water at 25$^{o}$C.

*No Diffuser Case*: For comparison, a turbine with a shroud but no diffuser was simulated. The power output was found to be 16.4 kW. The Betz limit for this condition is 34.9 kW based on the imposed free stream velocity. Therefore, with the drag effects of the shroud, the simulated turbine is only 46.9% efficient compared to the theoretical limit as a result of lower velocity in the turbine caused by the drag of the shroud and hub. A constant factor of $\eta = 0.5$ was applied to the mean velocity through the turbine whereas an ideal turbine has a factor of $\eta = 0.59$, applied to the freestream velocity.

*Area Ratio*: The ratio of the diffuser outlet area to the turbine area was the primary variable of interest. Due to the limited space in the river application, it is important to know the relationship between the diffuser size and its benefits. As shown in Figure 4, the area ratio was found to give increases in power initially; however, once the area ratio exceeded approximately 1.56, there were only minimal benefits. Intuitively this is expected due to separation. Total drag responded linearly to area ratio, as shown in Figure 5. Drag impacts the cost of the technology by way of larger support structures. Therefore, any increase in the diffuser size must be carefully balanced with its negative effects.

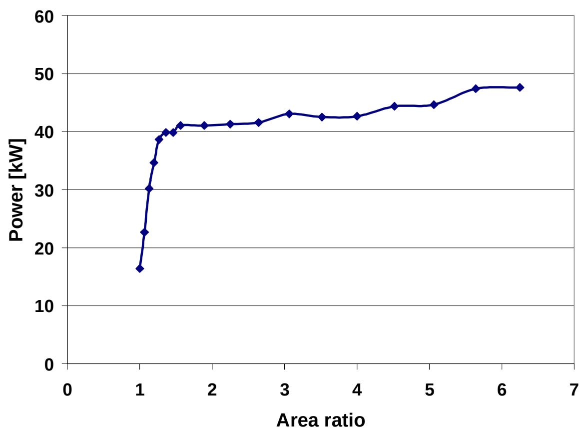


**Figure 4: Power versus area ratio**

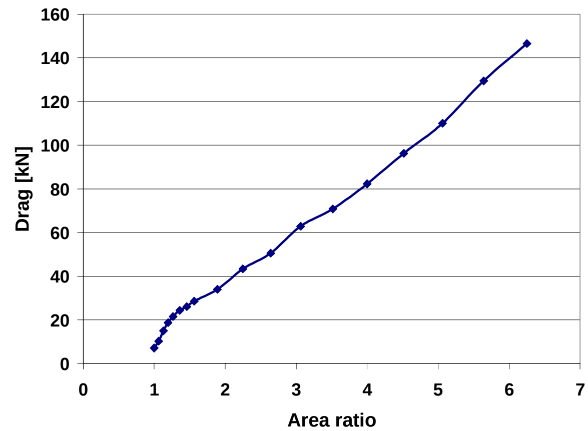


**Figure 5: Total drag versus area ratio**

An area ratio of 1.56 was chosen as the best compromise, translating to an outside diameter of 3.0 meters, compared to a turbine rotor diameter of 2.4 meters. Therefore significant benefit can be achieved with minimal impact on the cross-sectional area.

*Diffuser Angle*: From the results above, an outside diameter of 3.0 meters was fixed, and the angle of the diffuser was varied. Power output was greatest at shallow diffuser angles of 20 to 30 degrees, and dropped off at angles outside of this, as shown in Figure 6. Drag shows a slight drop with decreasing angle, thus the power gained by optimizing the diffuser angle is not offset by any additional drag force. The drag on the shroud assembly decreased significantly at shallower diffuser angles, as shown in Figure 7.


**Figure 6: Power versus diffuser angle**

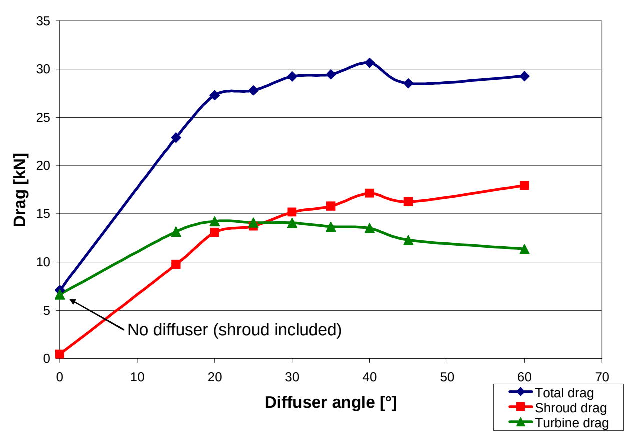


**Figure 7 : Drag versus diffuser angle**

Flow streamlines in Figure 8 and Figure 9 for the 20° diffuser closely match the angle of the streamtube as it exits the turbine. In the 45° case, there is a significant recirculation zone, which is not present in the 20° case. Furthermore, the shallower angle diffuser will have an added benefit of being less susceptible to damage from debris in the river.

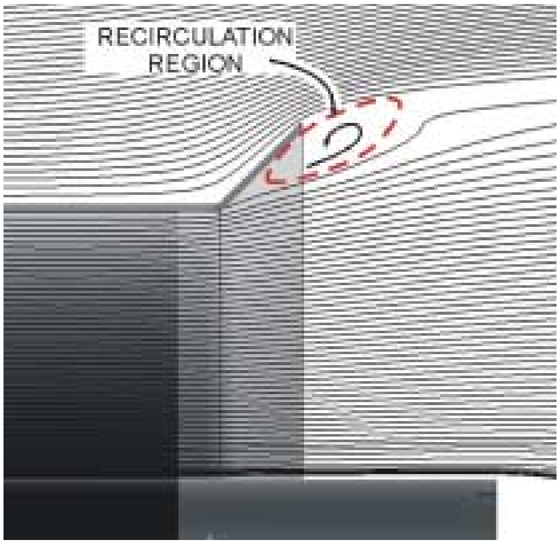


**Figure 8: Streamlines for 45° diffuser**

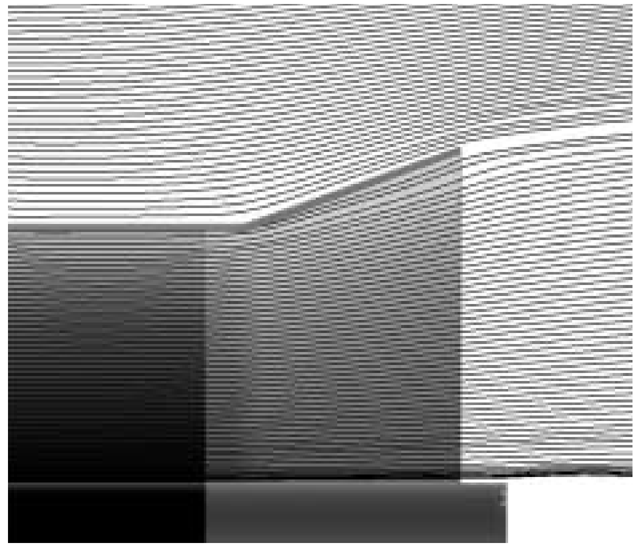

**Figure 9: Streamlines for 20° diffuser**

*Optimum Case*: The optimum diameter ratio was found to be a diffuser with a 3.0 meter outlet diameter and an angle of 20° to the streamwise direction. In this case, power was increased by a factor of 3.1 compared to the turbine with no diffuser. Drag increased by a factor of 3.9.

In this configuration, the turbine produced 51.3 kW of power. For these conditions, the Betz limit calculated based on rotor diameter and the freestream velocity is 34.9 kW. Therefore, relative to the theoretical limit, this configuration has an efficiency of 147%. That is, it produces 1.47 times the power expected from an ideal turbine. Considering the momentum-modeled turbine was shown to have an efficiency less than 50%, this is a significant increase for the numerical study.

The streamlines for no diffuser and for the optimum diffuser are shown in Figure 10. This is analogous to Figure 3.

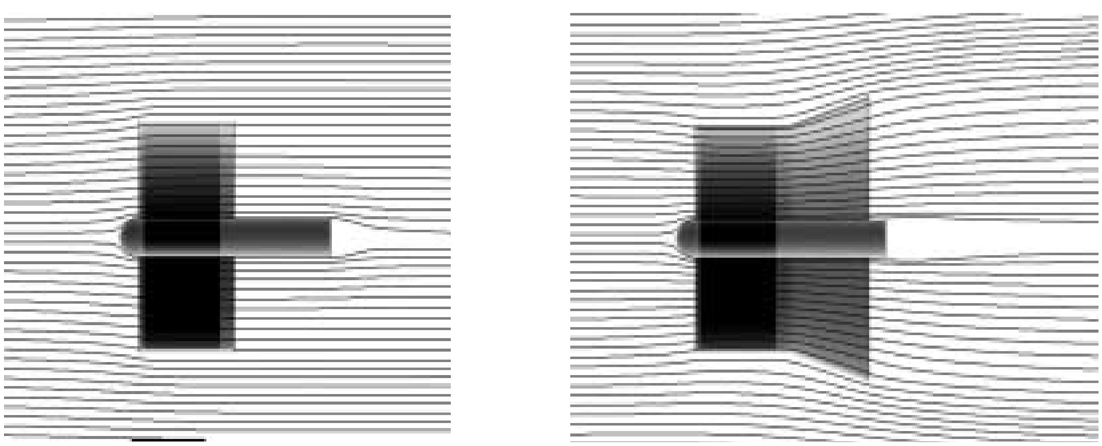

**Figure 10: Streamlines with shroud and no diffuser (left) and optimum diffuser (right)**

The axial component of velocity shown in Figure 11 illustrates the benefit of a diffuser. The maximum axial velocity through the turbine was 2.8 m/s with no diffuser, compared to 4.1 m/s with a diffuser.

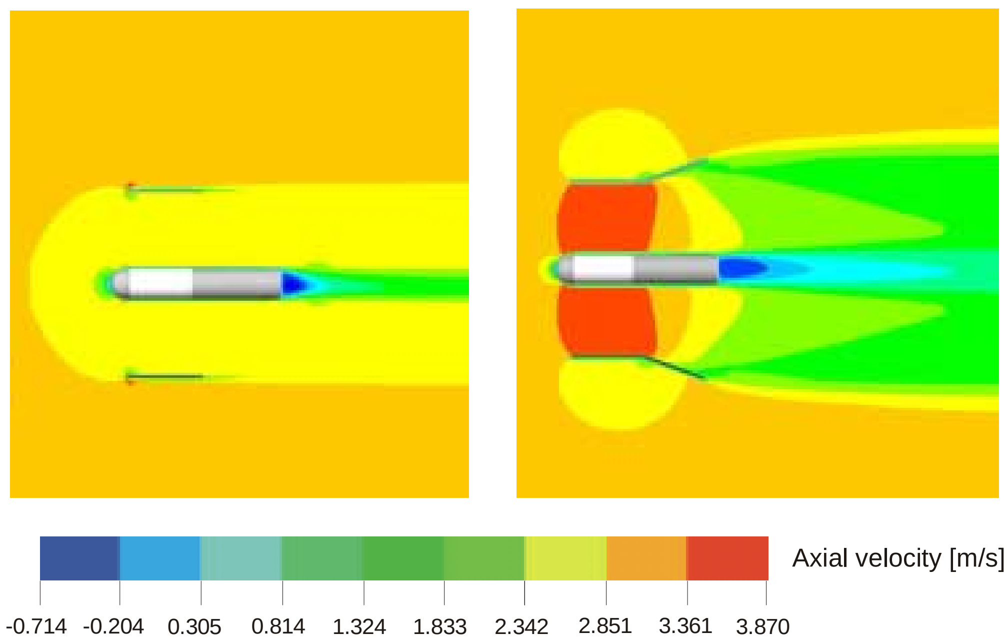


**Figure 11: Axial component of velocity no diffuser (left), selected diffuser (right)**

The results presented here should be interpreted with caution. The simulation shows a power increase by a factor of 3.1, but there are some significant unknowns:

- turbine modeled as a momentum source and it is unknown how well this approximates the behaviour of a real turbine;
- effects of mechanical and electrical conversion losses are not included in the analysis; and
- no performance curves were used for the turbine, and therefore the trends in the results may be exaggerated.

Furthermore, the CFD simulations have not yet been validated against experimental data. The $k$-$\varepsilon$ turbulence model is used. Previous simulations have successfully employed this model [10] but a Reynolds stress model has been found to perform better [11]. Validation is presently on-going.

## 6 Future Study

In this study, the diffuser is modeled as a simple cylindrical wall with a conical section. It is expected that a more streamlined design will perform better, such as a hydrofoil shape. The results of this study can assist in selecting the hydrofoil shape, as one that approximately matches the optimum case presented here will likely perform well. Unlike pipe flow diffusers, there is additional flow available outside the shroud wall. This can be used to further advantage by exploring a multi-section slotted diffuser, similar to an airplane wing. This was found to be beneficial in wind diffuser systems. Bet et. al. [1] suggests further benefit can be realized by oversizing the diffuser to allow some flow around the tips of the turbine. The authors argue this differentiates between flow working at the turbine, and flow working on the pressure drop. This may improve hydro applications as well.

## Conclusions

The design of the shroud enclosing turbine generators for kinetic hydropower can be used to increase the performance and economics of this technology. Numerical simulations presented showed the power increases by a factor of 3.1 with a drag increase factor of 3.9. The use of a well-designed shroud increase efficiency that can lead to reduction in the cost per kilowatt-hour of this technology. However, experimentation has not been performed to validate the numerical simulations presented here. Further study is required.

## Acknowledgement

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