An Evaluation of Blockage Corrections for a Helical Cross-Flow Turbine

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Summary: The ability to accurately evaluate hydrokinetic turbine concepts at small-scale in experimental facilities is important for the development of new devices. Problems introduced by working at lab-scale include operation in a transitional Reynolds number regime and cross-sectional blockage. These factors are shown to influence performance characteristics of a helical cross-flow turbine tested over a range of inflow velocities in two experimental flumes. Published blockage corrections are applied in an attempt to match performance under conditions of varying blockage (constant inflow velocity) and varying inflow velocity (constant blockage).

Introduction

Small-scale testing of hydrokinetic turbines informs design decisions (e.g., number of blades, solidity, hydrofoil profile) during device development. This requires that performance characteristics of a small-scale device be reflective of full-scale performance and independent of the test facility. The presence of confining fluid boundaries in experimental flumes (and in natural channels) is known to influence performance by increasing mass flux through the turbine swept area [1]. Operation of a turbine in a transitional Reynolds number regime has also been shown to introduce a velocity dependence that results in a family of characteristic performance curves [2]. Research on corrections for cross-sectional blockage of a model in a flow (primarily for wind tunnel testing) has been conducted since the 1930s, starting with Glauert [3]. Pope & Harper provide rules for blockage corrections for bluff bodies and also "unusual shapes" [4]. An iteratively solved blockage correction based on actuator disc theory derived during a study on tidal turbine performance in a closed tunnel section is presented by Bahaj et al. [5]. Werle [6] describes a relation between peak performance and blockage (a conclusion also reached in [1]) and assumes that all points on a characteristic performance curve behave similarly to arrive at a correction based solely on the ratio of turbine swept area to channel cross-sectional area. Other blockage corrections have been proposed, but require parameters not generally quantified during experimental testing (i.e., wake diameter).

The focus of this study is to compare the performance curves of a small-scale helical cross-flow turbine tested in two experimental flumes at different velocities and blockage ratios. The blockage corrections of Pope & Harper, Bahaj et al., and Werle are applied to the experimental results and compared.

Methods

The small-scale turbine experiments referenced herein are previously described [2]. Experimental apparatus and the geometry of the flumes at the University of Washington (UW) and Bamfield Marine Science Centre (BMSC) lead to experiments with blockage ratios, defined as

$$\varepsilon = \frac{(A_{Turbine} + A_{Rig})}{A_{Channel}}, \tag{1}$$

that range between 9% and 19%, where A_{Rig} is the cross-sectional area of the test rig supporting the turbine. Turbulence intensity for experiments at the UW flume is 3% compared to 10% at BMSC. Velocities range from 0.55 – 0.70 m/s (UW) and 0.55 – 1.0 m/s (BMSC) with average water depths of 0.5 m (UW) and 0.8 m (BMSC). Chord length Reynolds numbers are transitional in both cases (10^4-10^5).

All blockage corrections relate the equivalent unconfined "free" velocity (U_F), coefficient of performance ($C_{P,F}$, and tip-speed ratio (λ_F) to blocked "tunnel" values measured in an experiment [5] (U_T, $C_{P,T}$, λ_T) as

$$U_F = U_T \sqrt[3]{\frac{C_{P_T}}{C_{P_F}}},\; C_{P_F} = C_{P_T}\left(\frac{U_T}{U_F}\right)^3,\; \lambda_F = \lambda_T\left(\frac{U_T}{U_F}\right) \tag{2-4}$$

where,

$$C_P = \frac{P}{0.5\rho A_{Turbine} U^3},\; \lambda = \frac{R\omega}{U} \tag{5-6}$$

in which P is the mechanical power produced by the turbine, ρ the water density, R the turbine radius, and ω the turbine rotation rate. The relation between U_T and U_F depends on the correction employed and is a function of ε [4,6] or ε and the thrust coefficient ($C_T = T/0.5\rho A_{Turbine}U^2$) [5]. A critical assumption for the latter is the tunnel disc flow speed, rpm and thrust are the same as in the unconfined case [5].

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Results

Blockage corrections by Werle, Pope & Harper, and Bahaj et al. are applied to experimental measurements shown in Figure 1. Without correction, performance depends on inflow velocity and blockage, with increases in either parameter shifting peak performance towards higher C_P and greater λ. All corrections somewhat reduce the absolute scatter between curves for the constant blockage case. The Werle correction appears to significantly reduce scatter for the constant velocity case (Fig. 1*e*), while the other two reduce scatter, but to a lesser degree.

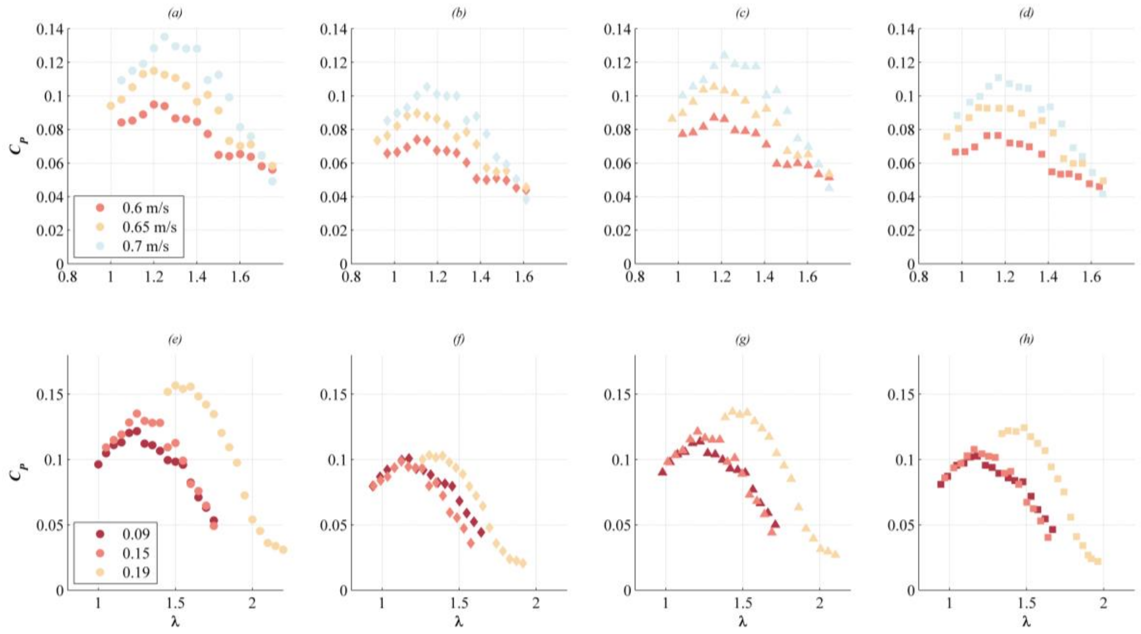

Fig. 1: Performance at same blockage (ε = 15%) varying speed (top). Uncorrected (*a*) and with Werle, Pope & Harper, and Bahaj et al. corrections *(b)-(d),* respectively. Performance at same speed (0.7 m/s) varying blockage (bottom). Uncorrected (*e*) and with Werle, Pope & Harper, and Bahaj et al. corrections *(f)-(h),* respectively.

Conclusions

Corrections are shown to reduce variation in performance curves at different levels of blockage. None of them are universally effective, likely because none of these corrections account for the full physics present in the confined flow problem. For this reason, care should be taken when choosing or applying a blockage correction. At transitional Reynolds number, the effect of blockage is likely to be convolved with the Reynolds number dependence of unsteady lift and drag. Both of these effects highlight the challenge of estimating full-scale, unconfined performance from small-scale testing.

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