Renewable Energy 34 (2009) 1885–1894

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Technical Note

Radial- and mixed-flow turbines for low head microhydro systems

K.V. Alexander [a,*], E.P. Giddens [b,1], A.M. Fuller [a,2]

[a] Department of Mechanical Engineering, University of Canterbury, PB 4800, Christchurch, New Zealand
[b] Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand

ARTICLE INFO

Article history:
Received 14 September 2008
Accepted 10 December 2008
Available online 3 February 2009

Keywords:
Microhydro
Hydropower
Renewable energy
Home energy
Low head
Remote power generation

ABSTRACT

This paper describes the design of two different specific speed microhydro turbines operating at heads between 6 and 12 m, at small scale and up to heads of 50 m at larger scales. The features are specifically tailored for ease of manufacture and uniquely resistant to debris blockage. Test machines are described and test results given; hydraulic efficiencies of over 70% have been achieved in all test models despite the fact that the turbine blades are made from flat plate, specifically to simplify manufacture. Outline drawings are given with key dimensions for each reference model, along with the equations for scaling to arbitrary sizes. These turbines are the mixed- and radial-flow members of a family of turbines developed to cover the microhydro range from 2 to about 50 m of head, which is below the range where Pelton wheels are applicable.

1. Introduction

This paper is one of a group of papers describing a University of Canterbury program that sets out to provide a properly configured range of low head microhydro systems, from radial- to axial-flow designs, based on a modular concept and aimed in particular at third-world sites where regional workshops might be capable of undertaking much of the manufacture themselves. With that in mind, the scope of this paper is a subset of the microhydro program at the University of Canterbury. This paper's scope is specifically the radial- and mixed-flow members of the turbine group. A previous paper has covered the University's axial-flow designs [1]. To allow this paper to stand alone it repeats some of the introductory material from ref. [1] before focusing on the information specific to the radial- and mixed-flow turbines.

A particular goal of the whole program is to provide well-grounded but lowest-cost options for the communities who possess an adequate hydro resource and access to basic fabrication facilities, but who are confined to either no option, or less suitable options due to a lack of design knowledge of appropriate power generating technologies. Earlier papers have given an overview and justification of the modular approach of this program, in particular in ref. [2], which is summarised by Table 1 and Fig. 2. The analysis leading to the most economic choice of penstock was covered in ref. [3], and the four low head members of this project were discussed in ref. [1].

Microhydro is typically used to describe sites of output below about 25 kW, as shown in Fig. 1. Above that is considered to be minihydro, where the scale of investment is such that professional input is proportionally smaller and there is some advantage in professionals building custom-made systems. The area of particular interest for the overall program discussed here is specific speeds above those of the Pelton wheel (that is heads below those serviced by Pelton wheels). Pelton wheels extract energy from high-head, low-flow sites. Because the flow is small the penstock and machinery are relatively small. So Pelton wheels are smaller and less costly to implement than reaction turbines of a similar power output. These reaction turbines by contrast are designed by necessity for more flow so they are larger and tend to be more expensive. While a number of Pelton wheel solutions is already available [4] this overall program aims to complement these by providing efficient designs for lower head sites.

In this paper the focus of attention is the turbines with specific speeds $N_S = 61$ and $N_S = 96$, with heads just below those of Pelton wheels as noted in both Figs. 1 and 2.

2. Turbine forms and scaling

It is well known that different forms of turbine are required for different conditions; the classic range of turbine forms relevant to this project is shown in Fig. 3. The forms are classified by their specific speeds, where in this project the specific speed is defined as:

* Corresponding author. Tel.: +64 3 3667 001x7385; fax: +64 3 3642 078.
E-mail addresses: keith.alexander@canterbury.ac.nz (K.V. Alexander), amf88@student.canterbury.ac.nz (A.M. Fuller).
1 Recently deceased.
2 Tel.: +64 3 364 2987x8390.

0960-1481/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.renene.2008.12.013

Nomenclature

$_1$	subscript denoting leading edge station
$_2$	subscript denoting trailing edge station
g	gravitational acceleration (m/s^2)
$_h$	subscript denoting location on blade/hub intersection
H_R	head ratio, site/reference
H	turbine head (m)
$_i$	subscript denoting a counter
$_j$	subscript denoting a counter
L_R	length ratio, site/reference
$\dot{m}$	mass flow rate (kg/s)
N	runner rotational speed (rev/min)
N_R	RPM ratio, site/reference
N_S	specific speed
P_r	power out of the runner, assuming frictionless bearings (kW)
P_R	power ratio, site/reference
Q	flow rate (m^3/s)
Q_R	discharge ratio, site/reference
r	general radius (mm)
$_{ref}$	subscript denoting parameter of a reference machine
$_{site}$	subscript denoting parameter of machine scaled to match a real site
$_t$	subscript denoting location on blade tip (Fig. 5)
T_r	runner torque (Nm)
v	average flow velocity entering the scroll casing (m/s)
v_a	axial flow velocity (m/s)
v_c	circumferential flow velocity (m/s)
V_{1i}	absolute flow velocity at inlet to runner, at the ith radius station (m/s)
V_{2i}	absolute flow velocity at exit from runner, at the ith radius station (m/s)
V_{1ti}	component of flow velocity in a plane perpendicular to the datum radius, at the ith radius station (m/s)
α_1	projected absolute velocity flow angle in the axial plane at entry to the runner as shown in the velocity triangle (deg) (Fig. 10)
β	blade angle relative to the impeller plane (deg)
η_t	turbine hydraulic efficiency (does not include η_m)
π	3.14159…
θ	angle clockwise around runner axis from the setup point "Blade Datum" (deg)
ρ	density of water (kg/m^3)
ψ	blade setup angle for mixed-flow turbine blades (deg) (Fig. 8)
γ	cone half-angle for mixed- flow turbine hub (deg)

$$N_S = N\frac{\sqrt{\eta_t g Q}}{H^{\frac{3}{4}}} \tag{1}$$

Note that this is not a dimensionless number since for convenience it ignores water density and includes time units in both minutes and seconds.

In an alternative form:

$$N_S = N\frac{\sqrt{P_r}}{H^{\frac{5}{4}}} \tag{2}$$

Table 1
Features of the Giddens microhydro systems.

Philosophy
- Maximum cost-effectiveness; minimum cost; minimal need for consultant assistance
- Six turbine types, each scaled to 6 or 7 sizes, to cover the low head field
- Modular components used throughout – each compatible with multiple projects
- Simple fabrication of turbines achievable by regional workshops
- Runner blades designed flat for ease of fabrication
- Turbine sizes chosen to use optimum flow from available low cost PVC penstocks

Hydrodynamic design
- Turbines properly designed and configured for intended low head applications
- Turbines run continuously at full power at maximum fluid efficiency point
- Turbines drive generators directly at 1500 RPM; no belts pulleys or gears
- All six turbine types have been laboratory tested and proven (1 still in progress)
- All turbines run at 70% efficiency or over

Electrical systems
- Systems deliver AC at 230 volts, compatible with most AC appliances
- 1500 RPM AC induction or synchronous 4-pole generators used
- Systems run continuously at maximum power and best operating point
- Unused power is diverted to a dump load by a simple controller managing RPM
- No batteries

Maintenance
- Systems designed for minimal maintenance
- No flow-spanning structures or control vanes to block with leaves
- Swept leading edges on runner blades to shed leaves

where P_r is the runner output power in kW, and the exponent of H is now 5/4. Further:

$$P_r = \frac{\eta_t \rho g Q H}{1000} \tag{3}$$

For a given specific speed the geometrical form of the turbine remains the same, but the size may be scaled. This allows the design for each specific speed to be scaled to match the available penstock flows in Fig. 2, and to deliver, from the appropriate heads and discharges, the four or five power bands to cover the 0.2–25 kW range shown. When scaling from a reference machine using Eq. (1), the hydraulic efficiency η_t is needed. Efficiency changes only slightly with scale, but for accuracy it can be predicted from an empirical function of the physical size, the so-called majoration effects, in Eq. (9) below and [5, p. 765].

Of specific interest to this project is that these several sizes of the same form can be arranged to deliver at a fixed rotational speed N. This is apparent from Eq. (1) where Q and H may be increased while keeping N_s and N constant. A constant rotational speed N enables the generation of alternating current in the standard frequency using directly driven 4-pole generators, regardless of installation size. This is a design requirement of the modular project.

2.1. Scaling to full-scale from laboratory turbines

Once a survey is completed at a particular site, flow Q and head H will be known. From these the appropriate turbine can be determined using Eqs. (1)–(3). Fig. 2 shows the result of this exercise. But in order to generate Fig. 2 there has been a process of scaling geometrically similar machines. This process involves selecting the right machine form, (defined by its specific speed, N_S as in Fig. 3) and then scaling it to the appropriate size at the appropriate speed N. This process, essentially as found in ref. [6] is achieved as follows:

Suppose there is a reference turbine of known P_r, N, H, Q, N_S, and size. The task is to scale that reference machine to a different power for a site installation. The project requires that $N_{site} = 1500$ rev/min