POTENTIAL FLOW TURBINE AND IT'S APPLICATION

Alexander Gokhman[1]
William Holveck[2]
Geoffrey McCavitt[3]

Abstract

This paper presents a new type of hydraulic reactive turbine with radial wicket gates (gates having pivotal axes parallel to the turbine axis) designated the "Potential Flow Turbine". The runner in this turbine could be axial, as in a Kaplan turbine, or mixed flow, as in a Francis turbine. The wicket gates in the Potential Flow Turbine are capable of both regulating and closing off flow to the water passages. At the same time they have a shape providing the flow with constant whirl at the entrance to the runner for the design conditions and, therefore, the correspondingly designed runner delivers to the draft tube the flow with whirl equal to zero. The new turbine has improved efficiency and cavitation coefficient, σ.

Introduction

The radial wicket gates in the Francis and Kaplan turbines are cylindrical objects. The term"cylindrical" is used here in a strict mathematical sense to mean a three-dimensional geometric shape defined by a plurality of parallel lines. It is evident that the discharge angle at the trailing edge of these wicket gates from the top of the gate to the bottom is constant. By the discharge angle we mean the angle between trailing edge exit element and the radial direction. Due to the change in direction of the water passages, the constant discharge angle of wicket gates results in a variable value of whirl, $(V_u R)_i$, (V_u is circumferential component of absolute velocity vector, R is radius from turbine axis) in the flow coming into the runner.

---

[1] Vice President, Fluid and Power Research Institute, San Francisco, CA 94122

[2] Chief Engineer, Hydro West Group, Bellevue, WA 98005

[3] Senior Mechanical Engineer, Pacific Gas and Electric Company, CA 94105

As will be shown in following section of this paper, the whirl, $(V_u R)_i$, at the wicket gate exit decreases from the bottom to the top. This in turn results in variation of the whirl at runner exit, $(V_u R)_e$, which increases from hub/crown to periphery. The value of $(V_u R)_e$ at design mode is zero at the hub/crown in order not to have the central vortex and, therefore, $(V_u R)_e$ is positive along the blade exit with maximum at periphery. In addition, the variation of $(V_u R)_i$ along the span of the wicket gate generates a vortex wake leaving the trailing edge of each gate along streamlines of absolute flow. Due to these vortex wakes, the flow at the entrance to the runner is not axisymmetric and, therefore, the runner also can not have constant in time value of circulation, Γ, along its span. Variation of Γ in the runner generates unsteady vortex wake leaving the trailing edge of each runner blade along streamlines of relative flow.

The presence in the draft tube of these two systems of vortex wakes (along the streamlines of absolute and relative flows) and of positive whirl, $(V_u R)_e$, results in loss of efficiency and pressure pulsations. In addition, the positive value of $(V_u R)_e$ at the periphery increases the value of the cavitation coefficient, σ, for the peripheral profiles of the blade.

The fluid mechanical research in the hydroturbine industry in recent years has focused largely on the solution of analyses problem, i.e. on the computation of the flow in the turbine water passages and this resulted in improvement of performance. However, much more improvement will be achieved by eliminating the source of described above deficiencies caused by the conventional wicket gates by replacing them with wicket gates providing the constant value of $(V_u R)_i$ at the inlet to the runner, as it is done in Potential Flow Turbine invented by Dr. Alexander Gokhman (Notice of Allowance from the US Patent Office of 12/9/94). The patent rights for the Potential Flow Turbine were assigned by the inventor to Hydro West Group. The development of this new turbine began in 1992 at Fluid and Power Research Institute (FPRI) and Hydro West Group. Pacific Gas and Electric Company (PG&E) is supporting research for the theoretical development of a Potential Flow combination of wicket gates and runner. It is anticipated that this R&D work will continue in 1995 – 1996 and will result in an experimental test of the model turbine.

Hydraulic Analysis of Francis and Kaplan Turbines

In this section we will consider conventional turbines with radial intake, i.e. Francis and Kaplan turbines with cylindrical radial wicket gates. In turbines with radial intake the water flows through the wicket gates toward the turbine axis and is deflected downwardly (axially) toward the turbine discharge. Due to the curvature of the water flow, the radial component of the absolute velocity, V_r, at the trailing edge of the wicket gate decreases from the bottom of the gate to the top of the gate. Where the curvature of the water path is very sharp, there can be a sharp decrease in V_r from the bottom of the wicket gate to the top of the wicket gate.

The vector velocity of the water flow from the wicket gates follows the trailing edge exit element and has almost the same angle with respect to the radial direction, from the bottom of the wicket gate to the top of the wicket gate. Since V_r decreases from the bottom of the gate to the top of the gate, V_u also gets smaller from the bottom of the wicket gate to the top of the wicket gate. Therefore, for conventional gates the value of whirl, $(V_uR)_i$, decreases from the bottom to the top of the wicket gate (radius, R, along the discharge of the conventional wicket gate is constant).

The variable value of the whirl, $(V_uR)_i$, in the flow coming to the runner causes the following phenomena at the design mode (at optimum):

1. The incoming flow is not potential. According to Stokes theorem, variation of the whirl $(V_uR)_i$ along the wicket gate trailing edge creates a vortex wake leaving the trailing edge along the streamlines of the absolute flow [1]. Therefore, there are n_{wg} vortex wakes in the flow coming to the runner (n_{wg} is the number of the wicket gates).

2. The incoming flow is not axisymmetric, since the axisymmetry is destroyed by n_{wg} vortex wakes. Therefore, the runner also can not have constant in time value of circulation Γ, along its span. Variation of Γ in the runner generates unsteady vortex wakes leaving the trailing edges of each runner blade along streamlines of relative flow [1].

3. The flow leaving the runner has positive value of the whirl,$(V_uR)_e$, along the entire blade trailing edge excluding the point at the hub/crown where whirl is zero ($(V_uR)_e$ has maximum value at periphery).

Indeed, the change of the whirl, $\Delta(V_uR)$ in the runner for each elementary turbine is defined by Euler equation:

$$\Delta(V_uR) = \frac{g\eta_{e\ell}H}{\omega} \tag{1}$$

where:

g is the acceleration due to gravity
$\eta_{e\ell}$ is the efficiency of the elementary turbine
H is the head of the turbine
$\omega = \pi N/30$ is the angular velocity of turbine (N is the turbine rotational speed)

It is easy to see, that for properly designed turbine with $\eta_{e\ell} = \eta_{max}$, $\Delta(V_uR)$

is constant along the runner span from the hub/crown to the periphery.

The value of whirl leaving the runner:

$$(V_uR)_e = (V_uR)_i - \Delta(V_uR) \tag{2}$$

The value of $(V_uR)_e$ at the hub/crown must be equal to zero at the design mode in order to avoid the whirl along the turbine axis in the draft tube cone after the runner, since the axial whirl causes the loss of efficiency and instability of the flow in the draft tube. Thus, at the hub/crown the whirl at the runner inlet $[(V_uR)_i]_h = \Delta(V_uR)$ at design mode and since the whirl at the runner inlet along the entire leading edge (excluding the point at the hub/crown)is larger than $[(V_uR)_i]_h$ the whirl at the exit is positive and has a maximum at the periphery.

Let $(V_uR)_i = k[(V_uR)_i]_h$,where k monotonically increases from $k_h = 1$, at the hub/crown, to $k_p = k_m$, at periphery (according to the experimental data coefficient k_m varies from 1.1 to 3.0 for different water passages geometries). Then at the design mode we have the following conditions for inlet and exit of the runner:

$$(V_uR)_i = k\Delta(V_uR) \tag{3}$$

$$(V_uR)_e = (k-1)\Delta(V_uR) \tag{4}$$

The phenomena described above are strongly pronounced in Kaplan, propeller and low/middle head Francis turbines ($k_m = 2.0$–3.0). In high head Francis turbines, these phenomena are not strongly pronounced ($k_m = 1.1$–2.0), since in the high head Francis turbines the flow turns from radial to axial very gradually.

All these phenomena lead to the loss of efficiency. The energy of the vortices and the positive value of whirl cannot be restored and they dissipate in the draft tube. The absence of symmetry in the incoming flow causes instability of the flow angle along the runner blade inlet edge and, therefore, additional shock losses at the runner entrance.

The losses caused by a positive value of the whirl along trailing edge of the runner can be computed by the following formula, based on the energy conservation law:

$$\Delta\eta = \frac{\pi \int_0^{L_e} (V_{ue})^2 V_{me} R_e d\ell_e}{gHQ} \tag{5}$$

where:

V_{ue} is the value of circumferential projection of absolute velocity along the runner blade trailing edge.
V_{me} is the value of meridional projection of absolute velocity along the runner blade trailing edge.
L_e is the total length of the blade trailing edge.
$d\ell_e$ is differential of the length of the blade trailing edge.
R_e is the radius along the blade trailing edge
Q is the flow rate of the turbine

The described losses are estimated up to 2% for Kaplan and propeller turbines and up to 4% for low/middle head Francis turbines.

Additionally, in the low/middle head Francis turbines, the high positive value of the whirl at the exit of the blade near the runner periphery causes the value of cavitation coefficient, σ, at the runner periphery to be much higher than at the crown at the design mode (at optimum).

In the Kaplan and propeller turbines, this is generally not true, since σ for these turbines is often higher for the hub profiles.

Hydraulic Analysis of the Potential Flow Turbine

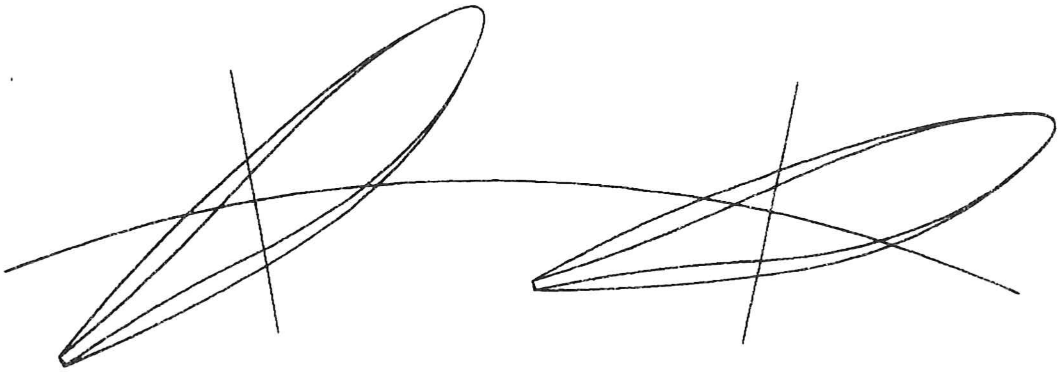
The Potential Flow Turbine is a turbine with the guide gate apparatus having a plurality of radial wicket gates with trailing edges presenting discharge angles which vary from the bottom of the gate to the top of the gate such that at the design gate angle all streamlines of the flow depart the gate with constant value of the whirl along its trailing edge. Therefore, in this turbine the radial wicket gates at the design mode deliver to the runner the flow with $(V_u R)_i = \Delta(V_u R)$ for all streamlines along the runner inlet.

There are the following constraints on the shape of the potential flow wicket gates (potential gates) in order to enable them to close the water passages. The trailing edges of the potential gates at the side facing the stay vanes are shaped as straight segments parallel to the central axis, and leading edges of the gates are shaped as straight cylinders parallel to the central axis. Figure 1 represents the potential gates designed for Spaulding #3 at design and closed positions.

The runner for the Potential Flow Turbine (either mixed-flow runner or axial-flow runner) has the blades shaped to provide $(V_u R)_e = 0$ for all streamlines along the runner exit at the design mode (optimum) when combined with potential gates.

shaped as straight segments parallel to the central axis and leading edges of the gates are shaped as straight cylinders parallel to the central axis. The Figure 1 presents the potential gates designed for Spaulding #3 at design and closed positions.

DESIGN POSITION



CLOSED POSITION

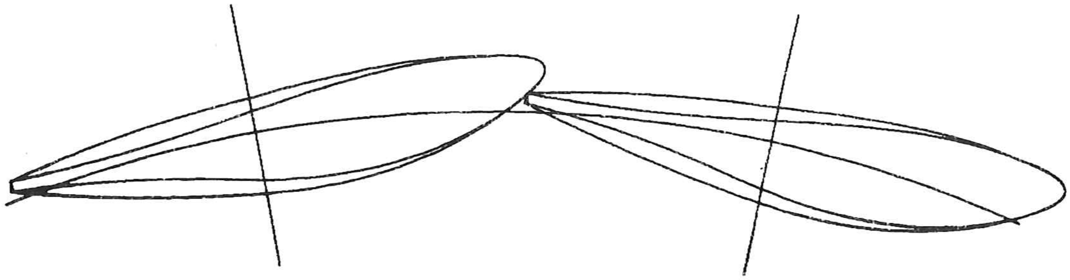


Figure 1. The Potential Flow Wicket Gates for Spaulding #3

The runner for the Potential Flow Turbine (either mixed-flow runner or axial-flow runner) has the shape of the blades which provides $(V_u R)_e = 0$ for all streamlines along the runner exit at the design mode (optimum) when combined with potential gates.

be determined as follows:

$$tan\beta = \frac{V_m R}{V_u R - \omega R^2} \tag{6}$$

Using equation (1), at the design mode for the Potential Flow Turbine for the inlet and the exit of the runner correspondingly:

$$tan\beta_i = \frac{V_m R}{\frac{g\eta H}{\omega} - \omega R^2} \tag{7}$$

$$tan\beta_e = -\frac{V_m}{\omega R} \tag{8}$$

Using equation (1) and conditions (2) and (3), at the design mode for Francis and Kaplan turbines for the inlet and the exit of the runner correspondingly:

$$tan\beta_i = \frac{V_m R}{k\frac{g\eta H}{\omega} - \omega R^2} \tag{9}$$

$$tan\beta_e = -\frac{V_m R}{(k-1)\frac{g\eta H}{\omega} - \omega R^2} \tag{10}$$

In a case of the turbine with axial-flow runner the value of the meridional projection of absolute velocity is the same at inlet and exit of the runner for each streamline and can be approximately expressed as follows:

$$V_m = \frac{4Q}{\pi(D_r^2 - d_h^2)} \tag{11}$$

where:

D_r is the diameter of the runner
d_h is the diameter of the runner hub

Therefore, for the Potential Flow Turbine in the case of axial-flow runner at the design mode for the inlet and the exit of the runner correspondingly:

$$tan\beta_i = \frac{4QR}{\pi(D_r^2 - d_h^2)(\frac{g\eta H}{\omega} - \omega R^2)} \tag{12}$$

$$tan\beta_e = -\frac{4Q}{\pi\omega R(D_r^2 - d_h^2)} \tag{13}$$

And for the Kaplan or Propeller turbine at the design mode for the inlet and the exit of the runner correspondingly:

$$tan\beta_i = \frac{4QR}{\pi(D_r^2 - d_h^2)(k\frac{g\eta H}{\omega} - \omega R^2)} \tag{14}$$

$$tan\beta_e = \frac{4QR}{\pi(D_r^2 - d_h^2)[(k-1)\frac{g\eta H}{\omega} - \omega R^2]} \tag{15}$$

Application of the Potential Flow Turbine

This section presents the numerical results of application of the Potential Flow combination of wicket gates with runner to the replacement of the wicket gates and runners at Butt Valley and Spaulding #3, two candidate powerplants, owned by Pacific Gas and Electric Company. These results were obtained using the software available at Fluid and Power Research Institute for fluid mechanical design of hydroturbine water passages. The runner blades were designed by the program INNA generalized for the case of the mixed-flow runner. The program INNA is based on the method of singularities and accurately predicts the turbine cavitation coefficient, σ_t. The values predicted by INNA have been successfully supported by experimental data [2,3].

The advantage in efficiency for the Potential Flow Turbine at optimum was predicted by the program EFFI. For this purpose the runner coupled with conventional wicket gates was designed for the same conditions as the potential flow runner and the loss of efficiency due to the positive whirl in draft tube was computed in EFFI using the formula (5) which is based on the energy conservation law.

Application of the Potential Flow wicket gates and runner to Butt Valley:

Nominal Gross Head, $H_g = 110.3376m$
Nominal Net Head, $H_n = 85.3440m$
Nominal Net Power, $P_n = 41,030.00kw$
Synchronous Speed of Rotation, $N = 200.00rpm$
Diameter of the Runner, $D = 2.82m$
Plant Cavitation Coefficient, σ_p=0.102

Wicket Gates and Runner	η	σ_t	Cavitation Status
Existing	0.900	–	Cavitation
Conventional	0.928	0.142	Cavitation
Potential Flow	0.950	0.084	Cavitation Free

Application of the Potential Flow wicket gates and runner to Spaulding #3:

Nominal Gross Head, $H_g = 97.0178m$
Nominal Net Head, $H_n = 92.4032m$
Nominal Net Power, $P_n = 7150.00kw$
Synchronous Speed of Rotation, $N = 450.00rpm$
Diameter of the Runner, $D = 1.27m$
Plant Cavitation Coefficient, σ_p=0.057

Wicket Gates and Runner	η	σ_t	Cavitation Status
Existing	0.880	–	Cavitation
Conventional	0.925	0.171	Cavitation
Potential Flow	0.944	0.055	Cavitation Free

References

1. V. Kopeetsky *Hydrodynamics of the Propeller Located in Circular Pipe* , Ship Industry Publishing, Leningrad, USSR, [1956]. (Russ.)

2. A. Gokhman and J.D. Lebrun, *The Design, Analysis and Manufacturing of Pickwick Landing Replacement Runners*, Water Power '85, ASCE, [1985].

3. J. Carson et al., *River Flow Maintenance Turbine for Milner Hydroelectric Development*, Water Power '95, ASCE, [1995].