Using Minimum-flow Low-head Impulse Turbines to Increase Dissolved Oxygen

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Abstract. Tennessee Valley Authority (TVA), like many other power producers in the south, faces two major environmental hurdles at its hydroelectric dams: one is maintaining water quality suitable for aquatic life; another is maintaining minimum flows for habitat and navigation. TVA contracted with Oak Ridge National Laboratory (ORNL) to leverage their research on Small Modular Hydro (SMH) to develop a way to meet environmental criteria with new minimum-flow hydropower systems that would operate when the flow required at a dam is too small for the existing turbines. These SMH systems have the potential to reduce the wear and tear of pulsing the large turbines, while still producing electricity and meeting environmental criteria during minimum-flow periods. This paper summarizes the research performed on the potential of low-head crossflow turbines operating during minimum flow periods to increase dissolved oxygen levels downstream of hydroelectric dams.

Introduction

Tennessee Valley Authority (TVA) faces two major environmental hurdles at its hydroelectric dams: one is maintaining water quality suitable for aquatic life; another is maintaining minimum flows for habitat and navigation. Since the early 90s, TVA has spent more than $60 million to remedy these two areas of trouble, pulsing releases through the dams to prevent dry beds and employing several different methods of introducing dissolved oxygen into waters upstream of the dam, flowing through the powerhouse, and downstream of the dam

Minimum Flow

Since the minimum flows required by environmental criteria at TVA's dams are generally less than the safe minimum operating flows of the main generating units, average minimum flow rates are maintained by spilling or by pulsing the turbines on and off. In the latter case, downstream regulating weirs attenuate the flow to provide a more regular flow pattern and prevent dry stream beds when the units are off. How to quantify the value of avoided wear and tear from frequent starts and stops on hydroelectric equipment is an ongoing research question (ORNL, 2018). The frequent operation of units outside of safe operating ranges has been attributed to past turbine equipment failures (Leyland, 2010).

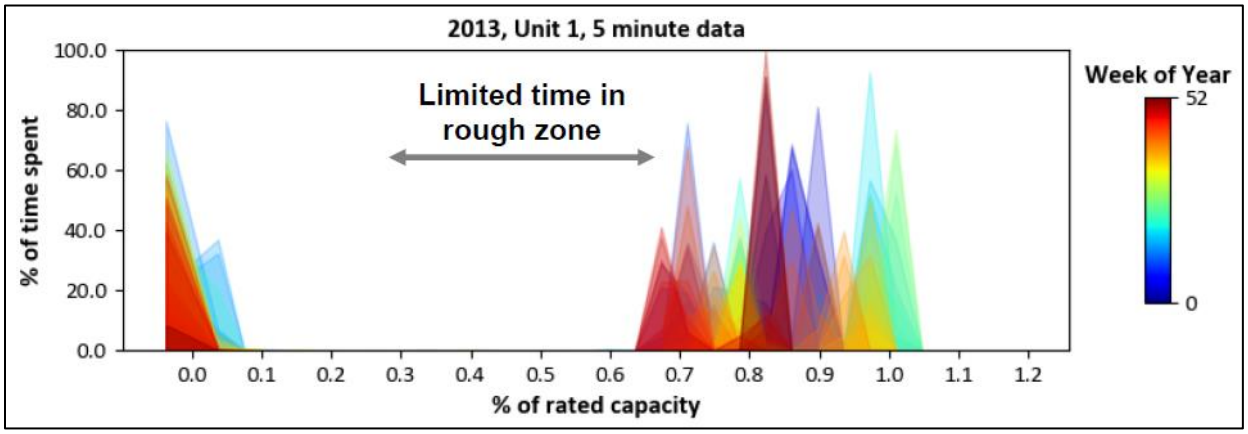

Figure 1: Historical data of TVA's Norris units avoiding the rough zone (ORNL, 2018). Operation at +/-0.5% of rated capacity indicates condensing mode.

While normal operating procedures recommend limiting the start/stop of a unit, if a facility cannot pass a minimum flow over a spillway or through a low-level outlet, a decision may be made to pulse a unit for a brief period of time to pass a minimum flow. This start/stop stresses the unit and also causes the unit to pass through an undesirable rough zone. Small hydropower turbines sized to pass the required minimum flow rates have the potential to generate power and reduce the pulsing frequency of large turbines, limiting stresses from start/stops and time spent operating in the rough zone

Dissolved Oxygen

Although water molecules contain an oxygen atom, this oxygen is not used by aquatic organisms living in natural waters. A small amount of free oxygen molecules (O_2) are dissolved in water, similar to the carbon dioxide dissolved in carbonated beverages. This dissolved oxygen (DO) is breathed by aquatic organisms. Oxygen enters streams from the atmosphere mainly through diffusion across the air-water interface and through entrainment of air pockets into turbulent flow. Rapidly moving water, such as a cascading mountain stream or turbulent large river, tends to entrain more atmospheric air into the flow and thus contains more DO than stagnant water (USGS, 2019).

Low dissolved oxygen (DO) is a common problem in reservoirs in the southern U.S. During the warmer months of late summer, these reservoirs can experience thermal stratification, or separation into distinct layers of varying temperature and oxygen content. The uppermost layer is characterized by high temperature, low density, and high levels of DO. This upper layer sits atop a denser, colder, subsurface layer of water. In summer these two layers do not mix due to density differences. While the upper layer can exchange oxygen with the atmosphere across the free surface, the lower layer is isolated and can experience oxygen depletion due to chemical and biological demands. For example, the cold deep layer of water is too dark for plants to grow and produce oxygen through photosynthesis while the oxygen in this deep layer is consumed by bacteria and other bottom-dwelling organisms.

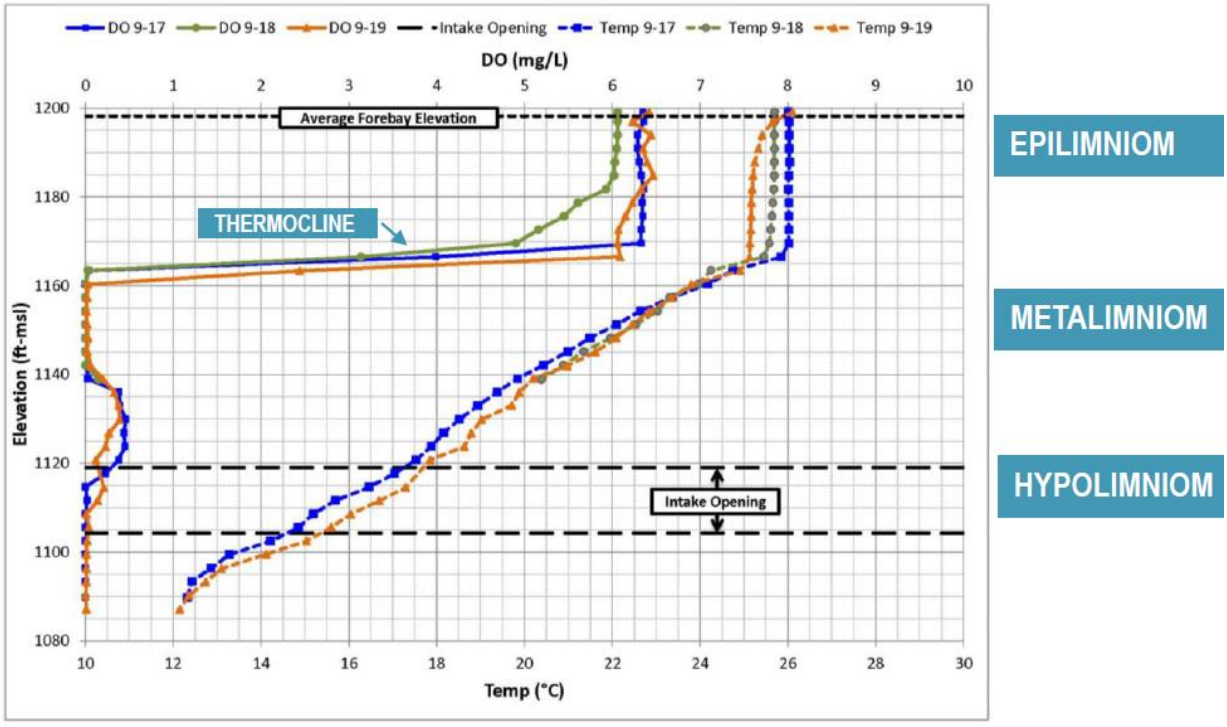

Figure 2: Typical thermal stratification in a hydroelectric reservoir (Sigmon, 2019).

As the depth increases from upper layer to lower layer, DO concentrations quickly decline, potentially reaching levels as low as 1 milligram per liter near the reservoir bottom at some sites (Rohland & Sigmon, 2008). Since turbine intakes are typically located at the bottom of the reservoir, the oxygen-deficient water flows downstream as hydroelectricity is produced. The release of water with DO concentrations of 1 milligram per liter into the tailrace is problematic because aquatic ecosystems generally require a minimum DO concentration of four to six milligrams per liter. TVA currently uses four methods to help meet downstream DO goals: surface-water pumps, oxygen injection, aerating turbines (either auto-venting type or using air compressors), and/or aerating weirs (TVA, 2018).

Surface-Water Pumps

Surface-water pumps are rail mounted on the upstream face of a dam and push oxygen-rich surface water downward toward the intakes of the dam. From there, the water flows through turbine to the downstream channel.

Figure 3: Typical surface pump installation (Foust & Coulson, 2011)

Oxygen-Injection System

Oxygen-injection systems convert liquid oxygen to a gaseous form which is then injected into perforated piping suspended just above the reservoir floor upstream of a dam. Just like the surface-water pumps, the flow carries oxygen-rich water through the dam during generation and then downstream.

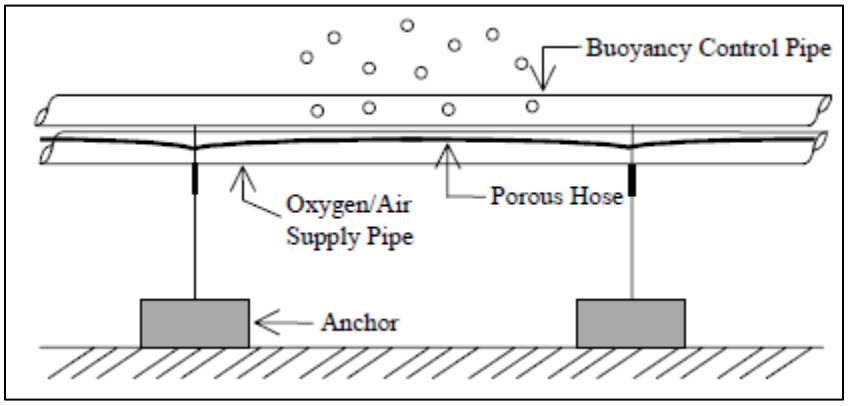

Figure 4: Schematic of porous hose diffuser (McGinnis, 2002)

Aerating turbines

Auto-venting turbines (AVT) draw air into the water at low-pressure zones near the turbine runner during hydroelectric power generation, increasing the concentration of dissolved oxygen in the tailwater before it continues downstream. Air compressors or low-pressure blowers are also used to increase the concentration of dissolved oxygen in hydropower releases by mixing pressurized air with water passing by the turbine runner.

TVA has been at the forefront of turbine aeration technologies. Turbine venting in the U. S. began in the 1950s, typically through vacuum breaker systems. TVA developed hub baffles in the late 1970s, which reduced energy losses and increased air flows. Modern auto-venting turbines were developed in the 1980s and 1990s through joint research by TVA and Voith Hydro Inc (ORNL, 2011). Figure 5 shows a cross section of auto-venting turbine aeration locations.

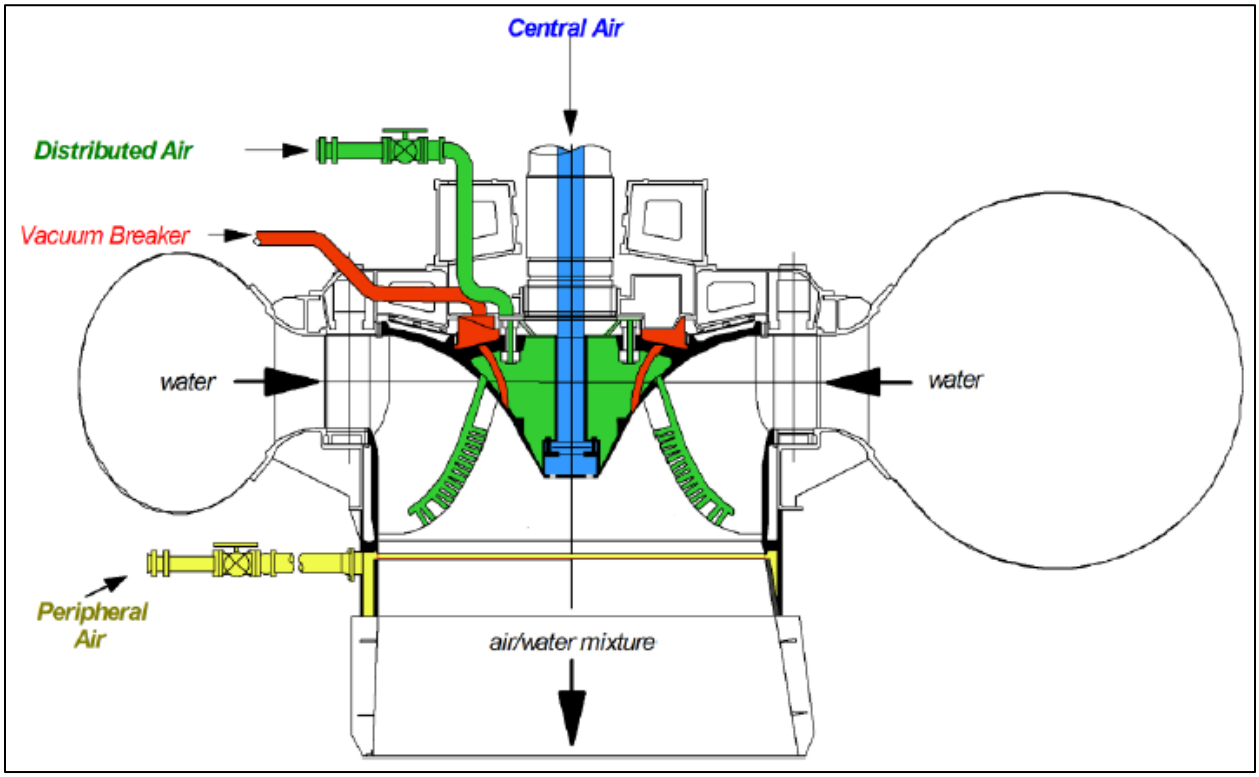

Figure 5: Overview of auto-venting turbine (AVT) aeration techniques (ORNL, 2011)

Each of these aeration techniques results in decreased efficiencies. Typical efficiency decreases are at least 10%, 7%, and 3% for central, peripheral, and Voith Hydro's "distributed aeration" respectively.

Aerating Weirs

Aerating weirs are small dams located downstream of a larger dam to maintain a minimum tailwater flow when the larger upstream dam is not generating hydroelectric power and to aerate the water as it flows over the weir.

Bevelhimer and Coutant (2006) provided further information about these techniques.

DO Uptake Potential in Crossflow Turbines

Significant research has gone into characterizing DO increases downstream of aerating reaction turbines like the Francis. Unlike Francis or Kaplan turbines, however, which require expensive modifications to provide aeration, impulse turbines provide natural aeration through jets that discharge flow at atmospheric pressure. The creation of highly turbulent spray from impulse turbines results in substantial water surface area that helps improve air-water interfacial gas transfer. Few studies characterize the DO improvement potential of impulse turbines because these turbines generally require more head than most dams in the south provide for acceptable efficiency. Crossflow turbines however have a range of applicable flows and heads that overlaps Kaplan and Francis turbines. As shown in Figure 6, most of the minimum flow requirements at TVA dams could be met with single-unit crossflow turbines.

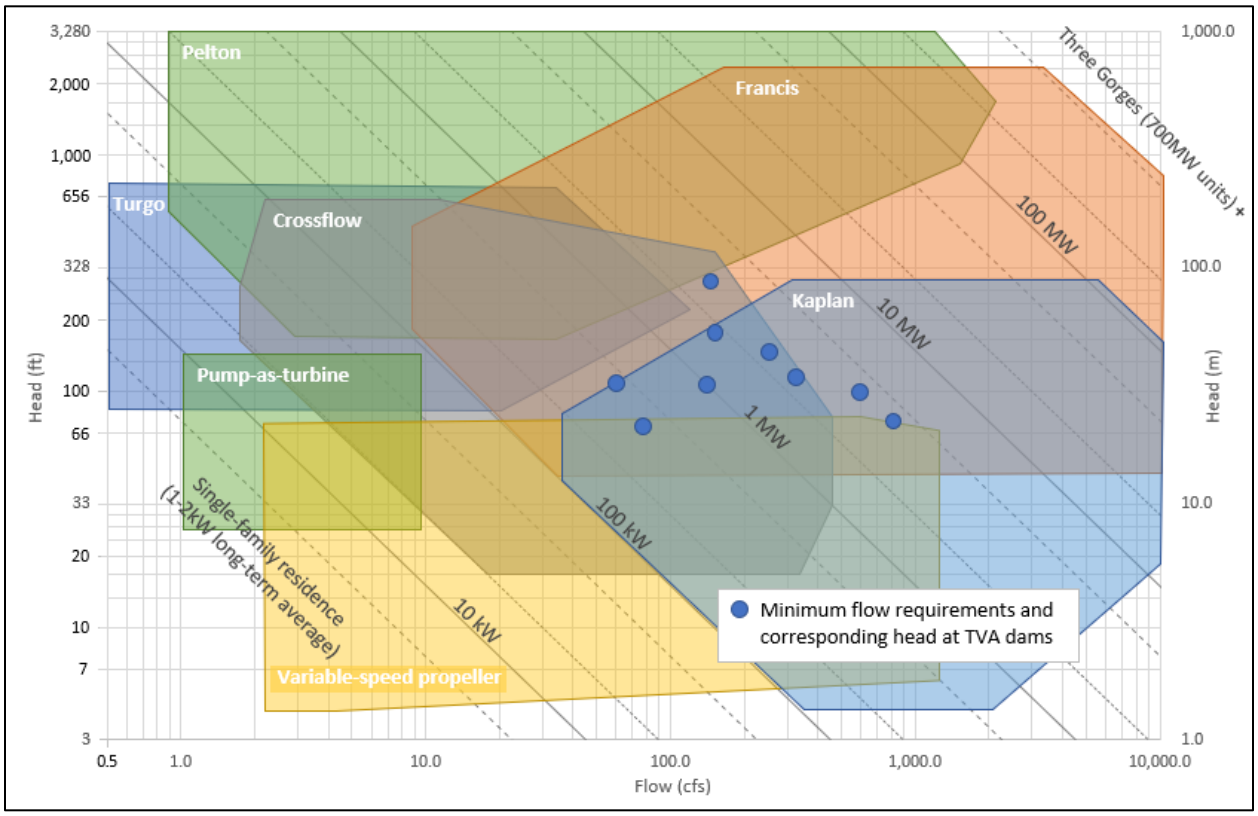

Figure 6: Typical turbine application ranges, and minimum flow requirements at TVA dams.

The authors applied the discrete bubble model (DBM) to a typical crossflow installation to determine the potential DO *uptake*, or the amount of increase in DO from the turbine intake to the end of the tailrace. The DBM was successfully used to predict output DO from aerating Francis turbines at Duke Energy's Wylie and Saluda hydropower projects to within 10%, and was determined to be a useful tool to predict the effectiveness of turbine upgrades, for assessment studies used to attain DO objectives in turbine discharge, and for predicting air flows required to attain DO objectives (McGinnis, 2007).

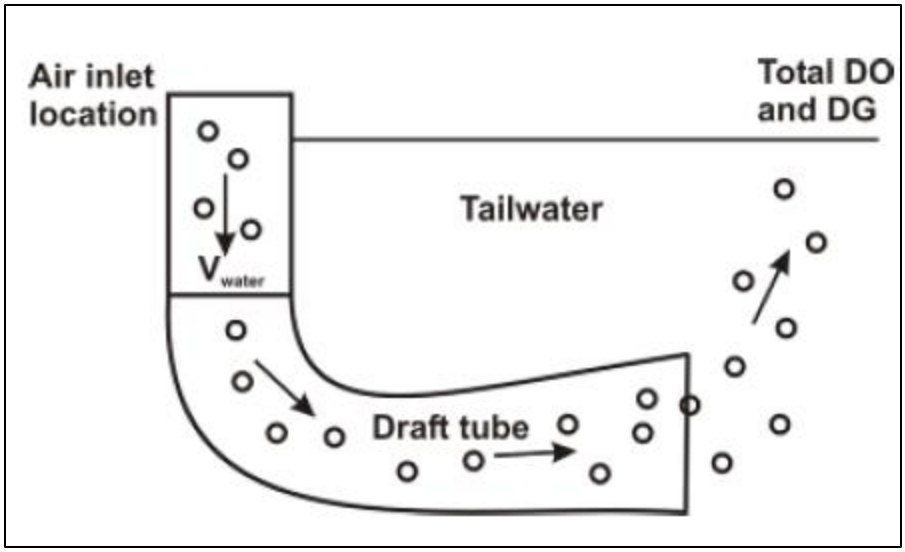

Figure 7: Schematic of air flow through a traditional AVT (Foust & Coulson, 2011)

The DBM calculates the theoretical rate of oxygen transfer from individual bubbles as they travel through the draft-tube system and tailrace. In the case of a crossflow turbine, rather than entering a turbine near the runner and passing through a draft tube before entering the tailrace, the bubbles plunge into the tailrace and then rise vertically at a predictable velocity as the water flow travels more or less horizontally along the tailrace.

For a given volume of gas, the rate of transfer is a function of (Sigmon, 2019):

- Bubble surface area – the smaller in diameter the bubble the greater the number of bubbles for a given volume of air, hence greater surface area;
- Pressure – the greater the pressure, the greater the transfer;
- Dwell time at pressure – the longer the bubble is at pressure, the greater the transfer;
- Temperature – the colder the water, the more oxygen may be absorbed;
- Inlet DO Level – the lower the inlet DO level, the more oxygen may be absorbed.

The formula for the molar transfer rate of gas from the bubble plume into the water per unit height of the tailrace channel as the bubbles plunge and then rise within the channel is:

$$\frac{\mathrm{d}M}{\mathrm{d}z} = -K_{\mathrm{L}}(HP_i - C)\frac{4\pi r^2 N}{v_{\mathrm{b}}}\ (\mathrm{mol\ m^{-1}\ s^{-1}}) \qquad (1)$$

where:

$\mathrm{d}M$	=	mass flux of gas (mol/s)
$\mathrm{d}z$	=	change in depth (m)
K_L	=	liquid-side mass-transfer coefficient, m/s
H	=	Henry's constant (mol/m^3/bar)
P_i	=	partial pressure for gas i (bar)
C	=	aqueous-phase concentration (mol/m^3)
r	=	bubble radius (m)
N	=	number of bubbles per second
v_b	=	bubble velocity (m/s)

The model was developed using a time-stepped Microsoft Excel spreadsheet, allowing the gas flux to be recalculated at each time step. The model accounts for changes in the volume of individual bubbles due to transfer of oxygen and nitrogen (and hence changing partial pressure) and for variation in hydrostatic pressure.

Key model inputs for the DBM include the water flow rate through the turbine, the airflow rate, and the initial bubble size. An airflow rate of 5% of the water flow rate (by volume) was used based on previous measurements of air entrainment in the discharge of crossflow turbines (Erdmannsdoerfer & Patzig, 1991), which was found to be a constant proportion regardless of water flow rate. The initial bubble diameter was assumed to be 0.5 mm. The authors plan to calibrate this value by measuring DO uptake at Duke Energy's Cedar Cliffs minimum flow crossflow unit.

The bubble-rise velocity and mass transfer coefficient, both known functions of the bubble diameter, are adjusted at every time step. The following correlation equations were used (McGinnis, 2002):

Correlation equations for Henry's constant ($mol\,m^{-3}\,bar^{-1}$), mass transfer coefficient ($m\,s^{-1}$), and bubble-rise velocity ($m\,s^{-1}$)

Correlation equation	Range
$H_O = 2.125 - 5.021 \times 10^{-2} T + 5.77 \times 10^{-4} T^2$ (T in °C) $H_N = 1.042 - 2.450 \times 10^{-2} T + 3.171 \times 10^{-4} T^2$ (T in °C)	
$K_L = 0.6r$ $K_L = 4 \times 10^{-4}$	$r < 6.67 \times 10^{-4}$ m $r \geqslant 6.67 \times 10^{-4}$ m
$v_b = 4474 r^{1.357}$ $v_b = 0.23$ $v_b = 4.202 r^{0.547}$	$r < 7 \times 10^{-4}$ m $7 \times 10^{-4} \leqslant r < 5.1 \times 10^{-3}$ m $r \geqslant 5.1 \times 10^{-3}$ m

Preliminary estimates predict a DO uptake of approximately 0.8 mg/L through the turbine discharge and tailrace channel for a standard crossflow installation. By constructing a 1.0-meter-deep baffle wall that the flow must pass under immediately after being discharged from the turbine, thereby increasing the pressure on the bubbles and the dwell time at pressure, the DO uptake is estimated to increase to approximately 1.4 mg/L. These predictions have yet to be tested with actual site measurements. Calibration of the average initial bubble diameter is expected to result in this model being able to provide accurate DO uptake predictions at potential minimum-flow crossflow turbine installations. It is also important to note that these predicted DO uptakes are for standard installations, with no effect to typical efficiencies, unlike aeration of Francis turbines which decrease typical efficiencies as noted previously.

Comparison to Other Oxygenation Techniques

While the estimated DO uptake at a crossflow turbine is not as high as distributed aeration, it is comparable to that of some of the simpler central or peripheral aeration techniques, as shown in Table 1. It should also be considered that distributed aeration becomes infeasible below a certain size runner, since the air is pulled into the flow through hollow passages fabricated into the runner blades.

Table 1. Examples of improvement in tailwater dissolved oxygen by several techniques (adapted from EPRI 2002)

Technique	DO uptake (mg/L)	Measurement Location
Oxygen injection	4 to 5	Richard B. Russell Dam (USACE) Savannah River, GA/SC
Surface water pump	1.3	J. Percy Priest Dam (USACE) Stones River, TN
	2.0	Douglas Dam (TVA) Holston River, TN
	2.3	Bagnell Dam (Union Electric Co.) Lake of the Ozarks, MO
Turbine venting – Central or peripheral	0.5 to 3	Logan Martin Dam (Alabama Power Co.) Coosa River, AL
	0.5 to 3	Wylie Dam (Duke Power Co.) Catawba River, SC
	1.1 (single unit*)	Fontana (TVA) Little Tennessee River, NC
	1.6 (single unit*)	Apalachia (TVA) Hiwassee River, NC
	2 to 3 (single unit*) 0.5 to 2 (multiple*)	Bulls Shoals, Table Rock, and Norfolk Dams (Southwestern Power Administration) White River, AR
Turbine venting – Distributed aeration	5 to 6.5	Norris Dam (TVA) Clinch River, TN
	Up to 5.5	Wateree Dam (Duke Power Co.) Wateree River, NC
Downstream weir	2.4	Lloyd Shoals Project (Georgia Power Co.) Okmulgee River, GA
	3.0	Canyon Dam (Guadelupe-Blanco River Authority) Guadelupe River, TX
	4.2	South Holston Dam (TVA) South Fork Holston River, TN
	6.6	Chatuge Dam (TVA) Hiawassee River, NC

*At projects with multiple turbines, the realized benefit per unit decreases as more units are brought online since higher tailwater elevation reduces the suction head available for inducing air.

Comparison to Other Minimum-Flow Turbine Options

The authors compared the initial capital costs (ICC) and long-term cost of electricity (LCOE) of several different conceptual minimum-flow hydropower options, including two modular approaches (Options 4 and 5) that would minimize the amount of excavation and construction time required. The costs were estimated using an existing TVA dam with a minimum flow requirement as the reference site. Table 2 below provides preliminary comparison data from the conceptual design cost estimates.

Table 2. Cost estimates from minimum-flow hydropower conceptual designs at a TVA dam reference site.

	Option 1: Francis	Option 2: Cross-flow	Option 3: Kaplan	Option 4: Pump-As-Turbine (PAT)	Option 5: Semi-Kaplan with Rim Generator
Number of turbine units	2	1	1	5	2
Unit flow, q (cfs)	120	240	240	48	120
Max setting above TW (ft)	13.7	0.0	0.0	6.7	6.7
Net head (ft)	142.6	127.6	142.6	142.6	126.3
Approx. avg T/G efficiency	90%	84%	90%	80%	80%
Power rating (kW)	2610	2179	2610	2320	2054
Capacity Factor	40%	40%	40%	40%	40%
Energy (kWh/yr)	9,144,415	7,636,813	9,144,415	8,128,369	7,198,838
Total Initial Capital Cost	**$ 6,680,000**	**$ 5,798,000**	**$ 8,354,000**	**$ 6,169,000**	**$ 6,233,000**
Unit cost per kW	**$ 2,560**	**$ 2,660**	**$ 3,201**	**$ 2,659**	**$ 2,687**
LCOE (/MWh)	$ 29.22	$ 30.37	$ 36.54	$ 30.36	$ 34.63

Supplemental measures for increasing dissolved oxygen

Where a new intake and penstock is required, adding minimum-flow units presents the opportunity to also provide selective withdrawal; the intake can be placed to draw water from higher in the reservoir where the dissolved oxygen concentration is higher. Selective withdrawal can provide a cost-effective mitigation solution for small hydropower facilities because of the low capital investment required (Daniil & Gulliver, 1991).

The Roanoke Rapids hydro development, completed in 1955 on the Roanoke River in eastern North Carolina, was a test case for the U.S. hydropower industry in the issue of water quality downstream of hydropower dams (Peters, 1958). A submerged weir was installed around the turbine intakes in 1958 to draw water from the epilimnion, acting as a high-level intake but at a lower construction cost. The Gaston hydropower project, completed in 1963 and now owned by Dominion Energy, was later constructed with an underwater dam around the intakes, based on the results of studying the effects of the submerged weir at Roanoke. Unfortunately, most of TVA's dams were constructed prior to the 1950s, and the construction of such an underwater dam "in the wet" would be a much more expensive option than if it were constructed at the start like at Gaston.

In the TVA conceptual design case study used to develop the data presented in Table 2, selective withdrawal using a new high-level intake was modeled in combination with pulling water from the existing low-level intake in order to provide target temperatures downstream for species with varying water temperature needs. The colder low-level water would keep the temperatures low enough for the downstream Trout population, while the upper-level water would keep the temperatures high enough for the Boulder Darter population and at the same time improve the dissolved oxygen concentrations downstream.

Conclusion

Preliminary estimates predict a DO uptake of approximately 0.8 mg/L through the turbine discharge and tailrace channel for a standard crossflow installation. By constructing a 1.0-meter-deep baffle wall that the flow must pass under immediately after being discharged from the turbine, thereby increasing the

pressure on the bubbles and the dwell time at pressure, the DO uptake is estimated to increase to approximately 1.4 mg/L. These predictions have yet to be tested with actual site measurements. Calibration of the average initial bubble diameter is expected to result in this model being able to provide accurate DO uptake predictions at potential minimum-flow crossflow turbine installations. It should be noted that the DO uptake predicted herein would only be adequate to affect the downstream DO concentration during times of minimum flow. The effect on downstream DO would be much less if existing non-aerating hydropower units were operating alongside a crossflow minimum-flow turbine, or if low DO water were otherwise bypassing the crossflow turbine. It is also important to note that these predicted DO uptakes are for standard installations, with no effect to typical efficiencies, unlike aeration of Francis turbines which decrease typical efficiencies. Crossflow minimum-flow turbines have the potential to reduce the wear and tear of pulsing large turbines, while still producing electricity and addressing environmental criteria during minimum-flow periods.

About the Authors

Jeremy Wells, PE is a civil engineer who has always been fascinated with the millennia-old practice of harnessing power from water. His focus is on designing innovative civil works structures for small hydro projects. He has consulted on both new and existing projects, including Ames Hydro, the world's first commercial AC hydropower plant. Mr. Wells can be reached at jeremy@wellsengineering.*net* or by phone at 719-588-0926.

Lindsay George, PhD, PE founded Small Hydro Consulting (SHC) in 2016 to provide engineering and project management services to the small hydropower community. SHC specializes in small hydro projects constructed on existing infrastructure including irrigation canals, municipal water supply pipelines and the rehabilitation of non-operational small hydro systems.

Adam Witt, PhD was previously a hydropower systems research engineer at Oak Ridge National Lab, where his research focused on evaluating, developing, and deploying innovative hydropower software and technologies. He is now a water resources engineer at Stantec in Sacramento, CA. He has a BA in Physics from Carleton College in Northfield, MN and received a Masters and PhD in Civil Engineering from the St. Anthony Falls Laboratory at the University of Minnesota under a fellowship from the Hydro Research Foundation.

Curt Jawdy, PE is a civil engineer that has worked primarily in the water resources sector. Previous to working at TVA, Curt performed studies of groundwater and stormwater flows for several consulting firms. He is now serving as a hydrologist at TVA, helping to build robust decision systems in the realtime and planning horizons.

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