Update on Development of Auto-Venting Turbine Technology

Paul Hopping[1], Patrick March[2], Thomas Brice[3], and Joseph Cybularz[4]

Abstract

Since the 1970s, the Tennessee Valley Authority (TVA) has been active in development of technology for the auto-venting turbine. Auto-venting turbines increase the concentration of dissolved oxygen in hydropower releases by aspirating and mixing air with the water passing through the runner. Prior to 1990, much of the emphasis for auto-venting turbine (AVT) technology focused on the development of methods to retrofit existing units by adding hub baffles, installing headcover ventilation pipes, and enhancing airflow through the vacuum breaker systems. Now, TVA is focusing on the development of aerating turbines for upgrades containing new runners. These new units include aeration objectives as an integral part of the turbine design, thus improving efficiency not only for hydraulic performance but also for environmental performance. At TVA's Norris Dam, new upgrade turbines installed in 1995 and 1996 represent the first of these new type of units in the world. This paper gives a brief summary of the performance obtained by the Norris auto-venting turbines. Each of these units contain several options to aerate the flow. The fundamental site-specific conditions needed to implement AVT technology are provided. The range of applicability is illustrated in terms of plans for new auto-venting turbines in TVA's Hydro Modernization Program. Ongoing investigations for turbine aeration are summarized, as well as comments concerning basic criteria that should be included in specifications for new AVT units.

[1] Technical Specialist, Tennessee Valley Authority, Engineering Laboratory, Norris, TN 37828
[2] Manager, Tennessee Valley Authority, Engineering Laboratory, Norris, TN 37828
[3] Mechanical Engineer, Tennessee Valley Authority, Fossil and Hydro Power, Chattanooga, TN 37402
[4] Manager, Hydraulic Technology, Voith Hydro, Inc., York, PA 17405

Background

Environmental problems resulting from reservoir releases with low dissolved oxygen (DO) are a concern at many hydroelectric facilities. This fact is emphasized by a U.S. Department of Energy study which found that improving low DO, along with providing fish passage and minimum flow, is one of the most important environmental mitigation issues for the hydropower industry (USDOE, 1991). The cause of low DO is well documented in the literature (e.g., see Ruane and Hauser, 1991). In many reservoirs, solar heating creates a water column with a warm surface layer and a cool bottom layer. This arrangement is hydrodynamically stable, which inhibits mixing between the layers and isolates the bottom water from atmospheric oxygen. Concurrently, the respiration of biological organisms and decomposition of organic substances in the water and sediments deplete DO in the bottom layer. For hydro projects with intakes located deep in the reservoir, this low DO water is released to the river downstream. These conditions subsequently damage aquatic habitat in the river and contribute to other water quality problems, such as the dissolution of trace metals, release of nutrients, formation of hydrogen sulfide, and depression of pH. Due to the low cost for installation, operation, and maintenance, the auto-venting turbine is usually the optimal method to increase DO at sites containing Francis runners.

Early development of the auto-venting turbine, which began in the late 1950s, is summarized by March et al. (1992) and Bohac et al. (1983). At TVA's Norris Dam, which contains two Francis turbines (original units 60 MW each), formal testing of AVT technology began in the late 1970s. The first tests sought to provide continuous airflow in the turbines during the low DO season by blocking open the vacuum breaker. Subsequent tests examined a number of methods to enhance the airflow, including: (1) a variety of hub baffle designs to increase the subatmospheric pressure at the vacuum breaker outlets, (2) a draft tube baffle ring to provide aeration at the exit of the runner, and (3) a vacuum breaker bypass conduit to enhance ventilation of the headcover. The optimal retrofit design emerging from these tests provide an airflow of between 1.4 and 2.3 Nm^3/s (50 and 80 scfs) and a DO uptake of between 2.5 and 3.0 mg/L, depending on the turbine operating conditions. Based on the experience at Norris and other projects, retrofit arrangements can be developed to provide airflow for a variety of Francis installations (e.g., see Carter, 1995).

Performance of New Auto-Venting Turbines

For upgrades and new construction, a joint development effort by TVA and Voith Hydro has made substantial improvements in the design of the auto-venting turbine. To eliminate hub baffles, locations for aeration outlets are selected at sites that aspirate air as a natural consequence of the turbine geometry. Due to the success with hub baffles, Norris Dam was selected as the first site to demonstrate this technology. These AVT units, shown in Figure 1, contain options to aerate the flow through central, distributed, and peripheral outlets at the exit of the turbines.

In testing new auto-venting turbines, measurements are required to determine the environmental and hydraulic performance of the aeration options. The environmental performance is evaluated primarily by the amount of DO uptake, while the hydraulic performance is based on the amount of aeration-induced efficiency loss. At Norris, each aeration option has been tested in single and combined operation over a wide range of turbine flow conditions. For environmental performance, results show that up to 5.5 mg/L of DO uptake can be obtained for single unit operation with all aeration options operating. In this case, the amount of air aspirated by the turbine is more than twice that obtained in the original turbines with hub baffles. The resulting tailwater bubble plume is shown in Figure 2. To meet the 6.0 mg/L target that has been established for this project, an additional 0.5 mg/L of DO improvement is obtained by the flow over a re-regulation weir downstream from the powerhouse. For hydraulic performance, efficiency losses ranging from 0 to 4 percent are obtained, depending on the operating condition and the aeration options. Compared to the original turbines, these units provide overall efficiency and capacity improvements of 3.5 and 10 percent, respectively (March and Fisher, 1996). The new runners also have shown significant reductions in both cavitation and vibration.

Figure 1. New Auto-Venting Turbine for Norris Dam Unit 2

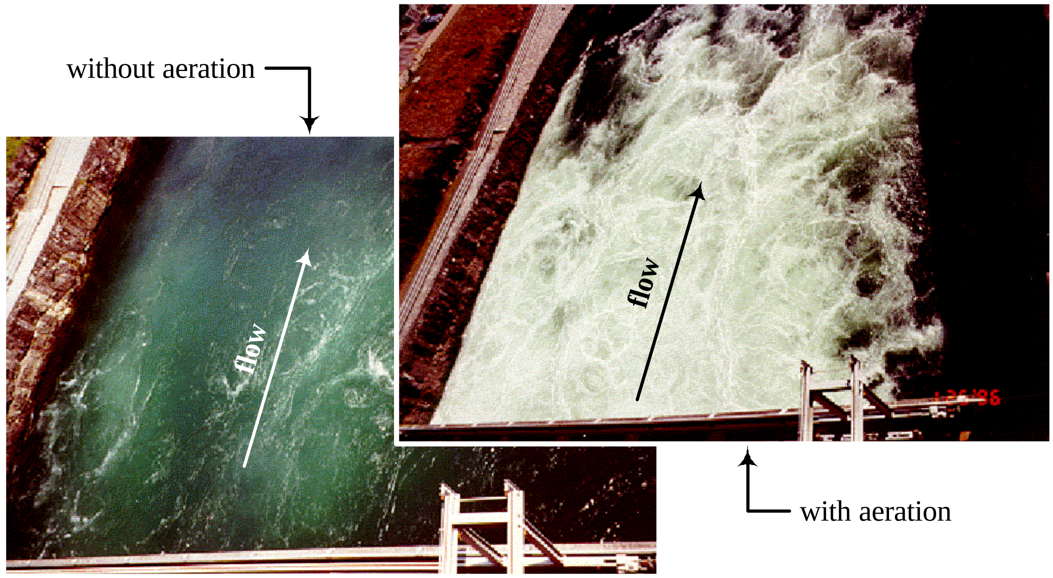

Figure 2. Bubble Plume in Tailwater at Norris Dam

In general, the environmental and hydraulic performance of a given option varies with the head and power output. Under these conditions, the options used to meet a target DO can be strategically chosen to minimize the aeration-induced efficiency loss. As an example, consider the 1996 DO data for the new units at Norris, shown in Figure 3. Turbine aeration was initiated in July when the scrollcase DO began to decrease. Throughout the low DO season, a mix of aeration options was used, based on the head, power output, and required DO uptake. Aeration was discontinued in November following reservoir turnover. On the average, the DO downstream of the project was maintained near the 6.0 mg/L target (except for a period when aeration was disrupted for an extreme series of performance tests on the new units). During the same period, the average aeration-induced turbine efficiency loss was about 1.9 percent.

Testing and Analysis

The work to provide turbine upgrades at Norris Dam has led to the development of new procedures for the testing and analysis of aerating turbines. In general, these include methods to measure and predict the environmental and hydraulic performance of auto-venting turbines, in both model and prototype situations (Greenplate and Cybularz, 1993). The parameters of interest for environmental performance include airflow, DO uptake, and total dissolved gas (TDG). The latter is needed to verify that aeration will not cause gas bubble disease in resident fish populations. For hydraulic performance, the parameter of interest is the turbine efficiency, as defined by test codes PTC-18 (ASME, 1992) or IEC 41 (IEC, 1991), with and without aeration.

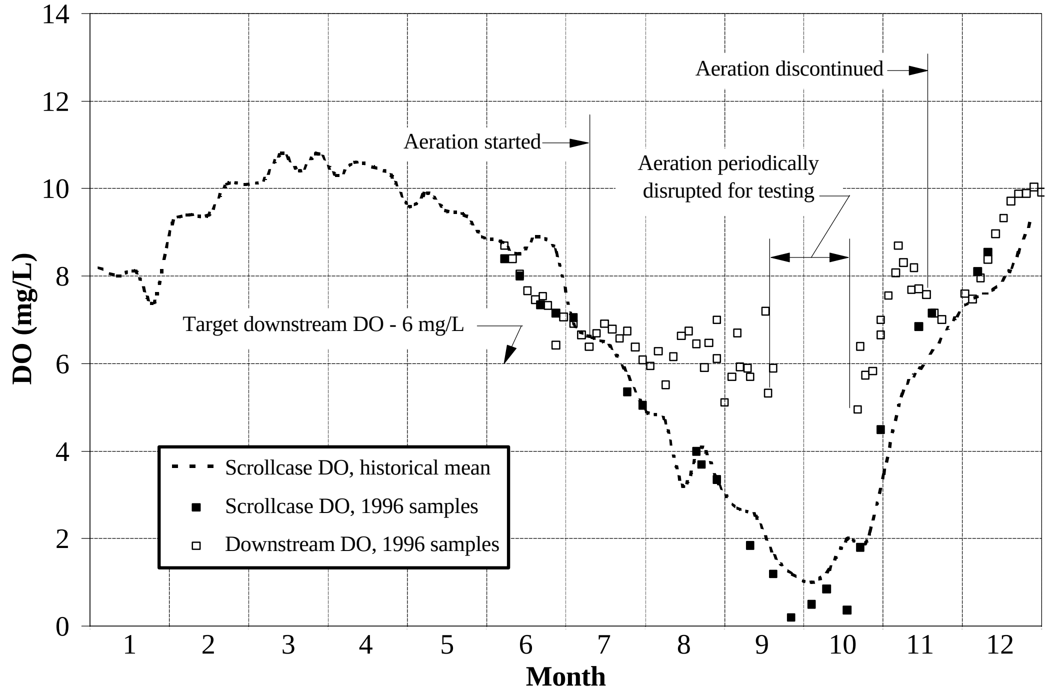

Figure 3. Dissolved Oxygen Improvement for Norris Dam, 1996

As in traditional performance testing of hydroturbines, measurements for airflow, DO uptake, and TDG need to be performed with extreme care, especially if environmental guarantees are required by the owner. Of particular importance is the dissolved oxygen. Due to significant spatial variations, measurements upstream and downstream of the turbine need to be strategically located to obtain accurate average values for the incoming and discharge DO concentrations. The current test procedure includes methods to locate DO probes and to correct for errors due to instrument calibration, offset, and drift. Depending on probe locations, corrections also may be required for DO uptake by other gas transfer processes in the tailwater. The sequence and duration of experiments also are important factors that are considered in the procedure. To facilitate these and other requirements for DO testing, a PC-controlled, multitasking testing system has been developed by TVA to obtain real-time results from performance tests and to automate the data acquisition, analysis, and reporting functions (Wolff et al., 1995).

Procedures for analysis of auto-venting turbines includes computations for the flow through the air supply conduits, the flow through the turbine, and gas transfer between air and water. Discussion of these procedures is beyond the scope of this presentation. It is emphasized, however, that these flows are extremely complex. Although the analysis allows meaningful estimates of the environmental and hydraulic performance of auto-venting turbines, there is a significant need for ongoing improvements in these procedures.

Applicability of Auto-Venting Technology

In general, auto-venting technology is applicable only for projects where subatmospheric pressures can be found or created at convenient locations in the turbines. Turbine venting is optimal for improving the DO of reservoir releases at projects where the aeration-induced head loss is small compared to the overall turbine head. Such projects tend to include Francis units. Although AVT technology has been used for propeller-type units (e.g., see Miller and Sheppard, 1983), computations show that the amount of air required to obtain the desired DO uptake can substantially reduce draft tube efficiency.

Project	Turbines: No. Units	Turbines: Head (m)	Turbines: Power (MW)	Target DO in Reservoir Release (mg/L)	Median DO Improvement Required (mg/L)	DO Improvement by Turbine Aeration (mg/L)	DO Improvement by Turbine Aeration: % of Median DO Required
Apalachia	2	110	40	6.0	0.8	2.0	100%
Blue Ridge 1	1	45	22	6.0	2.6	3.0	100%
Blue Ridge 2 (1)	1	45	1.5				
Boone	3	27	26	4.0	0.0	2.0	100%
Chatuge	1	30	10	4.0	2.9	1.0	34%
Cherokee	4	30	31	4.0	3.8	2.5	65%
Douglas 1&3	2	30	31	4.0	3.3	2.0	60%
Douglas 2&4	2	24	26				
Fontana	3	100	68	6.0	1.5	2.5	100%
Hiwassee 1	1	58	60	6.0	2.1	1.0	47%
Norris (2)	2	58	65	6.0	5.3	5.5	100%
Nottely	1	38	16	4.0	2.9	1.0	34%
South Holston	1	55	36	6.0	4.2	2.0	47%
Tims Ford (3)	1	41	41	6.0	5.6	4.0	71%
Watauga	2	66	26	6.0	2.0	2.0	100%

Notes: (1) New small turbine for minimum flow requirements.
(2) Upgrade with new turbines complete.
(3) Upgrade with new diagonal flow turbine complete. Aeration provided by forced air system.

Table 1. TVA Plans for New Auto-Venting Turbines

In TVA's Hydro Modernization Program, plans call for the use of twenty-seven new aerating turbines at thirteen projects that experience low DO. A summary of these is given in Table 1. Except for Tims Ford, all of the projects contain Francis turbines. (Tims Ford is a diagonal flow unit and includes a forced air system.) Overall, turbine aeration is expected to supply roughly 75 percent of the total required median DO uptake at these sites, including 100 percent at six of the projects. In supplying AVT technology for new turbines, a wide range of design factors and, consequently, potential air supply arrangements exist. At a given installation, careful, detailed hydraulic analysis is required to find workable alternatives for the aeration options.

Conclusions, Recommendations, and Future Directions

Experience at TVA's Norris Dam has demonstrated the feasibility of integrating objectives for DO improvement in the design of new turbines. In projects containing Francis units, turbine aeration is usually the optimal method to improve low DO in hydropower releases. At projects containing low DO where upgrades or new construction of Francis units are planned, turbine specifications should include requirements for the combined environmental and hydraulic performance of the units. These specifications also should include the methods and conditions by which the performance guarantees are to be measured and evaluated.

Procedures for testing and analysis of auto-venting turbines have been developed. However, the need for continued development of AVT technology is recognized. Initiatives that are presently underway at TVA include the following:

- Options for Turbine Aeration - This technology is being expanded to include improved options for turbine aeration. These are needed to enlarge the range of AVT applicability and to reduce costs. To allow aeration at projects where discharge TDG/nitrogen may be too high, experiments are being conducted to reduce these levels. Studies to examine the unique aeration problems of propeller-type units are also in progress.
- Testing of Aerating Turbines - To address issues regarding the combined hydraulic and environmental performance of aerating turbines, efforts are underway to establish appropriate methods of testing through the test code committee PTC-18 of the American Society of Mechanical Engineers. These issues should be addressed by TC-41 of the International Electrotechnical Commission, as well.
- Technical Evaluation - Work currently is underway to improve methods to predict airflow, DO uptake, and performance effects. In part, these improvements will involve a more detailed examination of the exact mechanisms for the transport and distribution of air in the turbine draft tube and tailwater using state-of-the-art numerical algorithms for turbulent, two-phase flow and gas transfer.
- Operational Support - TVA and Voith Hydro have jointly developed and implemented a machine condition monitoring system to help balance the energy, economics, and environmental requirements for hydro facilities. With the monitoring system, airflow, DO, and turbine efficiency can be viewed simultaneously to help operators comply with water quality requirements and achieve the desired level of power generation.

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