Status and Vision of Turbine Aeration

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INTRODUCTION

Although of minor concern prior to about 1970, environmental problems stemming from turbine discharges of low dissolved oxygen (DO) continue to receive important attention as a significant issue at many hydroelectric facilities. The U.S. Department of Energy recently found improving low DO, along with providing fish passage and minimum flow, to be one of the most important environmental mitigation issues for the hydropower industry (USDOE, 1991). In the United States, attention to low DO is driven primarily by the Electric Consumers Protection Act (ECPA) of 1986. For a given project, ECPA provides a process by which the development of hydropower shall be balanced with concerns for the protection of wildlife, fish, recreation, and other environmental-related site characteristics. As a result of ECPA, and based on criteria by the U.S. Environmental Protection Agency (USEPA), specifications for monitoring and maintaining DO levels are becoming a regular part of license agreements for affected hydroplants. In these situations, utilities must provide a method to increase the DO in the turbine releases.

To provide dissolved oxygen, a variety of methods are available (e.g., see Bohac and Ruane, 1990). However, where operable, turbine aeration is often the method of choice. Such aeration can be provided by natural aspiration or forced injection. With natural aspiration, air is supplied to openings in the turbine where the pressure is subatmospheric. In some cases, subatmospheric conditions are created by adding small deflectors or baffles on flow boundaries in the turbine. Outside, the openings are vented to the atmosphere, thus providing the pressure difference to draw air into the water. A naturally aspirating turbine is also called an auto-venting turbine (AVT). With forced injection, the pressure in the turbine is above atmospheric, requiring compressors or blowers to push air into the water. In both the AVT and forced injection arrangements, the DO is increased by the transfer of oxygen from the entrained air to the water. Due to the minimal requirements for extra mechanical equipment, as well as reduced expenses for operation and maintenance, the AVT usually is the least-cost alternative for increasing DO in hydro releases.

This paper gives a brief overview of the status and vision for turbine aeration. Included is a short presentation of the DO problem, current practice for providing aeration in existing and new hydroturbines, and comments regarding the testing and analysis of aerating units. The vision focuses on aspects of turbine aeration that are presently under development, or planned for development in the near future. Examples cited in these discussions are based largely on the experience of the Tennessee Valley Authority (TVA) and Voith Hydro, Inc., in providing aerating hydroturbines for projects under TVA's comprehensive Lake Improvement Plan.

PROBLEM BACKGROUND

The root cause of low DO is well documented in the literature (e.g., see Ruane and Hauser, 1991). Briefly, in many reservoirs, solar heating creates thermal stratification in the summer, yielding a water column with a warm surface layer and a cool bottom layer. This arrangement is hydrodynamically stable, which inhibits mixing of the warm and cool layers and isolates the bottom water from atmospheric oxygen. Concurrently, the respiration of biological organisms and decomposition of organic substances, both in the water and sediments, deplete DO in the bottom layer of the reservoir. For projects with intakes located in the bottom layer, this low DO water is released during hydropower operations, often creating poor water quality in the river downstream from the reservoir.

Summaries of the potential extent of low DO in different parts of the U.S. are given by the USEPA (1989). The summaries are based on statistical analyses of DO data (e.g., STORET) and site questionnaires of dams managed by the U.S. Army Corps of Engineers (USACE), TVA, and U.S. Bureau of Reclamation (USBR). In general, projects with low DO (i.e., DO $\leq$ 5 mg/L) have been reported throughout the country, indicating that no areas are immune from the problem. Reservoirs of depth greater than 50 feet and retention time greater than 10 days, especially those in the warm, humid climates, are more likely to encounter problems with low DO. This trend is supported by data from TVA and USACE, which in some areas report as many as 50 percent of the hydro sites with concerns for low DO. Data collected by the USBR show that low DO is not as problematic in arid climates, where at most only 4 percent of reporting sites express concern. It should be noted, however, that these summaries are based on sparse data. Worldwide, hydro projects with low DO should be identifiable by the same root causes and trends recognized for projects in the United States.

STATUS

In existing units, the evolution of turbine aeration has led to a number of retrofit designs. These designs typically provide air at one of two locations, either the vacuum breaker outlet or the entrance to the draft tube. Within TVA, the former location is preferred and is currently used in 21 Francis units at 9 projects. All these arrangements provide naturally aspirating, or auto-venting, capabilities. Also, in all but one of these turbines, hub baffles are used to enhance the airflow. The baffles include two basic designs, streamlined and flat plate, and in most cases include a separate air pipe to bypass the vacuum breaker inlet valve (Carter, 1995). Although air is not needed year round, TVA experience has found that the energy loss attributable to baffles is smaller than the cost to install these devices temporarily for the low DO season, if the baffle design is optimized. Cavitation damage has not been significantly increased by the baffles, and in some cases enhanced airflow has reduced adverse surging, reduced load swings, and reduced turbine vibrations.

Examples of hydro facilities where air is provided in existing units at the entrance to the draft tube, including propeller-type runners, are given by Miller and Sheppard (1983). To offset lower velocities and higher pressures typically found at this location, such arrangements usually require a deflector of size larger than that of hub baffles. For propeller runners, furnishing air in the draft tube is at this time the only feasible option for providing AVT capabilities in existing units.

For new and replacement units, an ongoing joint development effort by TVA and Voith Hydro has made substantial improvements in the design of aerating hydroturbines. In this work, requirements for aeration are included as an integral part of the turbine design. To eliminate the need for hub baffles, locations to supply air are selected at sites that will aspirate air as a natural outcome of the turbine geometry. The first units containing this technology are the new replacement Francis turbines at TVA's Norris Dam (Figure 1). These AVT units each contain several methods to oxygenate the flow, including central, distributed, and peripheral aeration outlets at the exit of the turbines. Each method has been tested in single and combined operation for environmental (DO uptake) and hydraulic performance over a wide range of conditions. Results show that up to 5.5 mg/L of DO uptake can be obtained, with efficiency losses ranging from 0 to 4 percent, depending on the operating condition and aeration method. Compared to the original turbines, these units provide overall efficiency and capacity improvements of 3.5 and 10 percent, respectively (March and Fisher, 1996).

As part of the work for the replacement units at Norris, new procedures have been developed for the analysis and testing of aerating turbines. In general, analyses focus on the prediction of three factors (Greenplate and Cybularz, 1993): airflow; DO uptake; and performance effects. Prediction of airflow requires a balance between the computed pressure loss through the air supply passageways and the pressure at the aeration outlets found by computing the flow through the turbine. The latter computation involves the effects of a two-phase air/water mixture. Due to the complexity of these flows, the prediction of airflow at this time relies heavily on dimensionless parameters derived from model and prototype measurements of pressures at the aeration outlets.

Current procedures for predicting DO uptake are based on a scaling relationship presented by Thompson and Gulliver (1993). In the relationship, the oxygen transfer efficiency is given as a function of the concentration of entrained air, runner speed, and runner diameter. Also found is an empirical "transfer" coefficient, which, based on TVA/Voith experience, depends on a variety of factors, including the location of air entrainment and other yet to be determined site-specific turbine characteristics.

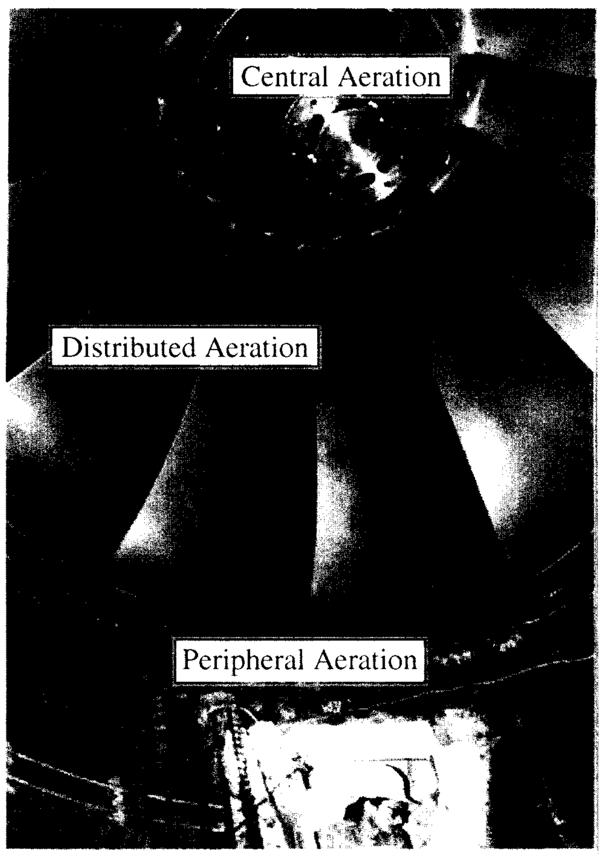

Figure 1. New Aerating Turbine for Norris Unit 2

The prediction of performance effects has been limited to an examination of the relative change in turbine efficiency derived from model tests conducted over a range of operating conditions, with and without air admitted at the various aeration locations (Greenplate and Cybularz, 1993). Results of prototype tests at Norris show that this procedure tends to overpredict the amount of efficiency loss.

Although this leads to a "conservative" estimate of the performance effect, an improved procedure is needed. This is true not only for assessing the quality of the turbine design, but also for effectively evaluating the cost of turbine aeration compared with other methods for enhancing DO.

New procedures for testing aerating turbines include the measurement of the additional parameters, in both model and prototype situations, needed to assess the environmental performance of the units (e.g., Hopping et al., 1996). These include airflow, DO upstream of the turbine, and DO and total dissolved gas (TDG) downstream of the turbine. TDG is needed to verify that aeration will not cause gas bubble disease in tailwater fish populations. In model situations the procedures specify the runner speed and NPSH required to scale DO uptake and performance effects. Procedures also include an improved method for turbine testing that uses a PC-controlled, multitasking operating system to automate and integrate data acquisition, analysis, and reporting (Wolff et al., 1995).

VISION OF FUTURE NEEDS

Based on the current status of aerating turbine technology and the anticipated trends in the hydropower industry, several aspects of turbine aeration are presently under investigation:

Problem Identification - The amount of DO data has increased substantially since the late 80's. Studies to assess the extent of low DO need to be updated using this new information and include a more worldwide view. In these studies, the data needs to be supplemented with detailed information for the physical design, environmental, watershed, and operational factors of the projects in order to develop a more reliable method to evaluate the potential for low DO at sites where water quality data is not available.

Options for Turbine Aeration - The new technology developed for Norris is being expanded to include improved options for turbine aeration. These developments are needed to enlarge the range of site conditions applicable to AVT technology and to reduce costs. New designs are to be tested for TVA's Douglas Dam, which includes Francis turbines containing a much higher tailwater submergence than those at Norris. To allow aeration at projects where discharge TDG/nitrogen levels may be too high, experiments are also being conducted with oxygen injection through the turbine aeration outlets. For propeller-type units, entrainment of the amounts of air required to obtain the desired DO uptake can substantially reduce draft tube efficiency. Studies to examine the unique aeration problems for these types of units are 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 quantities, 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 developed and implemented a machine condition monitoring system to help balance the energy, economics, and environmental requirements for hydro facilities, including DO uptake. For units with multiple aeration options, an optimization module determines which option (or options) should be operated to provide the desired DO level with the least impact on operating efficiency.

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