Hydraulic and Environmental Performance of Aerating Turbine Technologies

by

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Abstract

EPRI's 2002 report, *Maintaining and Monitoring Dissolved Oxygen at Hydroelectric Projects: Status Report* (1005194) provided a comprehensive review of a wide range of techniques and technologies for improving the dissolved oxygen (DO) levels in releases from hydroelectric projects. Aerating turbine technologies have been developed and demonstrated by multiple turbine manufacturers. These technologies can provide higher generation efficiency, higher capacity, and improved environmental performance. However, aerating turbine technologies have not been widely implemented, in part due to insufficient information on, and industry understanding of, the life-cycle costs and benefits from the technologies. This paper is based on a December 2009 EPRI report, *Technology Update on Aerating Turbines* [March, 2009]. The 2009 report and this paper supplement the 2002 EPRI report and focus primarily on aerating turbine technologies for new turbine installations and turbine upgrades. Limited information on performance of retrofitted aeration systems is also presented for comparison purposes.

Turbine manufacturers, utilities, and agencies provided information and performance data for aerating turbine technologies. Specific industry examples are examined and presented as case studies, with an emphasis on hydraulic performance (turbine efficiency with and without aeration, turbine capacity increases) and environmental performance (air flows and DO increases). The paper discusses the development of aerating turbine technologies, describes some of the difficulties in assessing the performance of aerating turbines, provides detailed case studies for three aerating turbine technologies (central aeration, peripheral aeration, and distributed aeration), discusses the implications of the case study results for plant operation and optimization, and makes recommendations for additional related research.

1. INTRODUCTION

Overview of Aeration

Impoundments and flow releases from hydropower facilities can adversely impact the aquatic life upstream, downstream, and passing through the sites. In the United States, regional environmental concerns include the improvement of dissolved oxygen (DO) levels to protect aquatic habitat in tailwaters below dams.

Hydropower projects likely to experience problems with low DO include those with a reservoir depth greater than 15 m, power capacity greater than 10 MW, reservoir volume greater than 6.1×10^7 m^3, densimetric Froude number less than 7, and a retention time greater than 10 days [EPRI, 1990]. In general, these include projects with watersheds yielding moderate to heavy amounts of organic sediments and located in a climate where thermal stratification isolates bottom water from oxygen-rich surface water. At the same time, organisms and substances in the water and sediments consume and lower the DO in the bottom layer. For projects with bottom intakes, this low DO water may create problems both within and downstream from the reservoir, including possible damage to aquatic habitat.

Before about 1980, detailed studies of the potential impacts of hydropower on water quality, including low DO, generally were not required prior to licensing. In 1986, however, the Electric Consumers Protection Act (ECPA) defined a process by which the development of hydropower must be balanced with concerns for the protection of environmental site characteristics. As a result of ECPA, and based on criteria developed by the U.S. Environmental Protection Agency, requirements for monitoring and maintaining DO levels have become a regular part of license agreements for affected hydro projects. Among the largest owners of affected hydro projects, however, are federal agencies, which are exempt from the licensing protocol of the Federal Energy Regulatory Commission (FERC). These include the U. S. Bureau of Reclamation (USBR), the U. S. Army Corps of Engineers (USACE), and the Tennessee Valley Authority (TVA).

Development of Technologies for DO Enhancement

Under the self-imposed targets and deadlines of a five year, $50,000,000 Lake Improvement Program funded from power system revenues, TVA developed a variety of new technologies for increasing DO in turbine discharges and successfully resolved minimum flow and dissolved oxygen problems throughout its reservoir system. The minimum flow and water quality enhancements have been responsible for the recovery of 290 km of aquatic habitat lost due to intermittent drying of the riverbed and for DO improvements in more than 480 km of rivers below TVA dams [March and Fisher, 1999]. The technologies developed and deployed under the Lake Improvement Plan include minimum flow hydropower units, reliable line diffusers for cost-effective oxygenation of reservoirs upstream from hydro plants, effective labyrinth weirs and infuser weirs which provide minimum flows and aerated flows downstream from hydro plants, retrofit turbine aeration systems, and aerating turbines. Aerating turbines, which use the low pressures created by flows through the turbines to induce additional air flows, are typically the most cost-effective DO enhancement technology for the Francis-type turbines typical of hydroplants with DO concerns. This report focuses on aerating turbine technologies for new turbine installations and turbine upgrades.

Historical Perspective on Aerating Turbines

In the 1950s, turbine venting was introduced in Wisconsin to reduce the water quality impact of discharges from the pulp and paper industry and from municipal sewage systems [Lueders, 1956]. Research was also conducted in Europe to develop turbine designs that would boost dissolved oxygen (DO) levels in water passing through low head turbines [Wagner, 1958]. By 1961, turbine aeration systems were operating in the U. S. at eighteen hydroplants on the Flambeau, Lower Fox, and Wisconsin Rivers [Wiley et al., 1962; Wisniewski, 1965].

Aeration systems using draft tube deflectors were developed using physical model tests and installed by Alabama Power during the 1970s at ten turbines in hydroplants on the Black Warrior and Coosa Rivers, resulting in DO increases of 0.5 to 1.0 mg/L and efficiency losses up to 2% [Bohac et al., 1983]. During the late 1970s and early 1980s, the Tennessee Valley Authority (TVA) developed small, streamlined baffles, called hub baffles, which reduced energy losses while increasing air flows and operating range. The hub baffles installed at TVA's Norris Project provided DO uptakes averaging 2 to 3 mg/L with typical efficiency losses of 1 to 2% [Bohac et al., 1983].

During the mid-1980s, Voith Hydro Inc. and TVA invested in a joint research partnership to develop improved hydro turbine designs for enhancing DO concentrations in releases from Francis-type turbines. Scale models, numerical models, and full-scale field tests were used in an extensive effort to validate aeration concepts and quantify key parameters affecting aeration performance. Specially-shaped geometries for turbine components were developed and refined to enhance low pressures at appropriate locations, allowing air to be drawn into an efficiently absorbed bubble cloud as a natural consequence of the design and minimizing power losses due to the aeration. TVA's Norris Project, which was scheduled for unit upgrades, was selected as the first site to demonstrate these "auto-venting" or "self-aerating" turbine technologies. The two Norris aerating units contain options to aerate the flow through central, distributed, and peripheral air outlets, as shown in Figure 1-1.

In testing the aerating turbines, measurements were required to evaluate both the hydraulic and the environmental performance of the aeration options. The hydraulic performance is based on the performance compared to the original turbines and the amount of aeration-induced efficiency loss. The environmental performance is evaluated primarily by the amount air flow and the amount of the DO uptake. At Norris, each aeration option was then tested in single and combined operation over a wide range of turbine flow conditions.

Compared to the original Norris turbines, the innovative aerating replacement units provide overall efficiency and capacity improvements, weighted over the operating range, of 3.7 percent and 10 percent, respectively, as shown in Figure 1-2 [March and Fisher, 1999]. This corresponds to an additional annual generation, for the same amount of rainfall, of about 17,000 MWh for the Norris Project. The new turbines have also shown significant reductions in both cavitation and vibration.

For environmental performance, results show that up to 5.5 mg/L of additional DO uptake can be obtained for single unit operation, with all aeration options operating and a zero level of incoming DO. In this case, the amount of air induced into the turbine is more than twice that obtained in the original turbines, which had a retrofitted aeration system utilizing hub baffles. At the Norris Project, turbine aeration is typically initiated in July, when the DO level monitored upstream from the turbines begins to drop. Throughout the low DO season, various combinations of aeration options are used, based on the head, power, and required DO uptake. Aeration typically ends in November, when cold, dense surface water promotes enough vertical mixing to reduce the thermal stratification. Typical DO improvement through the Norris turbines is 5.5 mg/L, with an additional 0.5 mg/L of DO improvement obtained from air entrainment in the flow over a

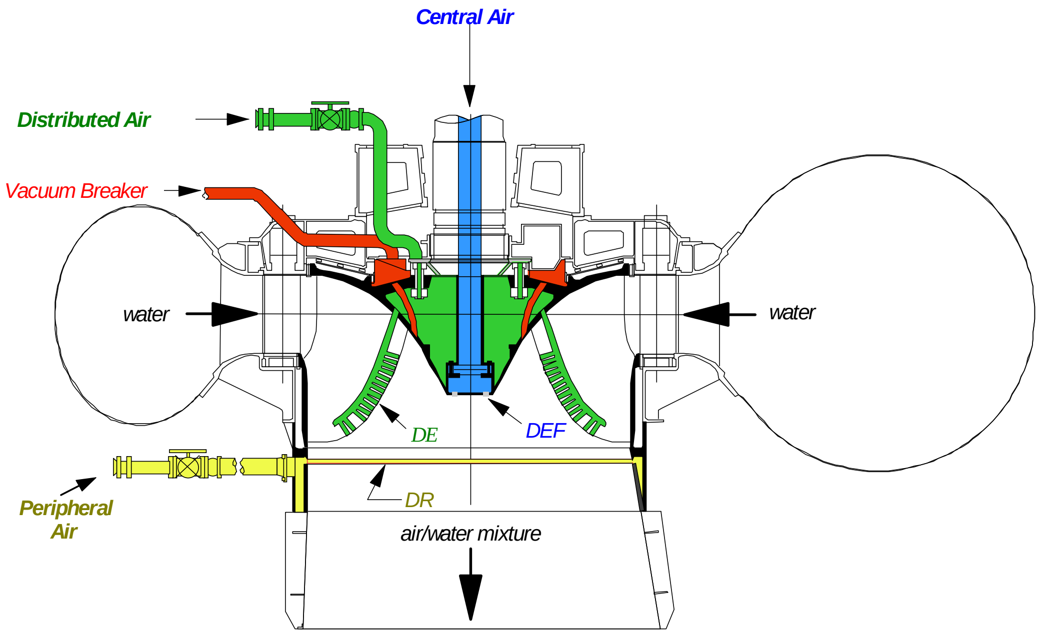

Figure 1-1
Sectional View of Norris Francis Turbine Showing Distributed Aeration (Green), Central Shaft Aeration (Blue), Central Vacuum Breaker Aeration (Red), and Peripheral Aeration (Yellow)

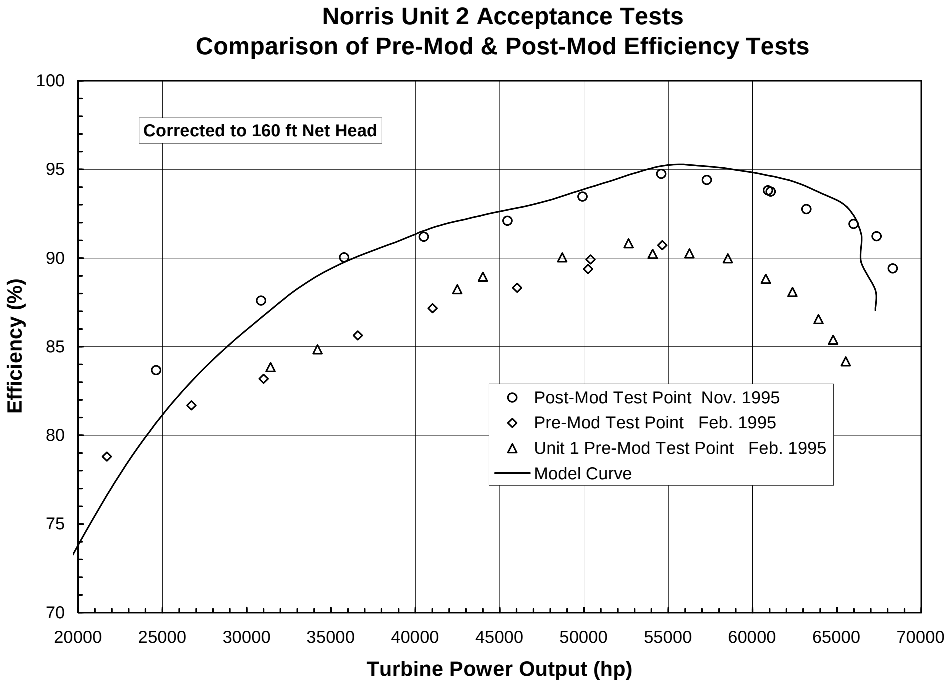
Norris Unit 2 Acceptance Tests
Comparison of Pre-Mod & Post-Mod Efficiency Tests

Figure 1-2
Hydraulic Performance Results for Norris Aerating Francis Turbine

re-regulating weir that provides minimum flows downstream from the powerhouse to meet the DO target level of 6.0 mg/L. Results from bioenergetics modeling of trout growth, calibrated and confirmed by fishery studies, indicate a 270% increase in the annual growth for a downstream DO of 6 mg/L compared to the base case without environmental improvements and a 160% increase in the annual growth compared to the previous Norris hub-baffle aeration system that maintained a downstream DO of approximately 4 mg/L.

As shown in Figure 1-3, typical efficiency losses during aeration at Norris range from -0.2 to +4 percent, depending on the operating conditions and the aeration option or options used. For the Norris aerating turbines, the central aeration option has the highest impact on efficiency, the peripheral aeration option has an intermediate impact on efficiency, and the distributed aeration option has the least impact on efficiency. The average aeration-related turbine efficiency loss during the July to November aeration period has been held to less than 2 percent at the Norris Project.

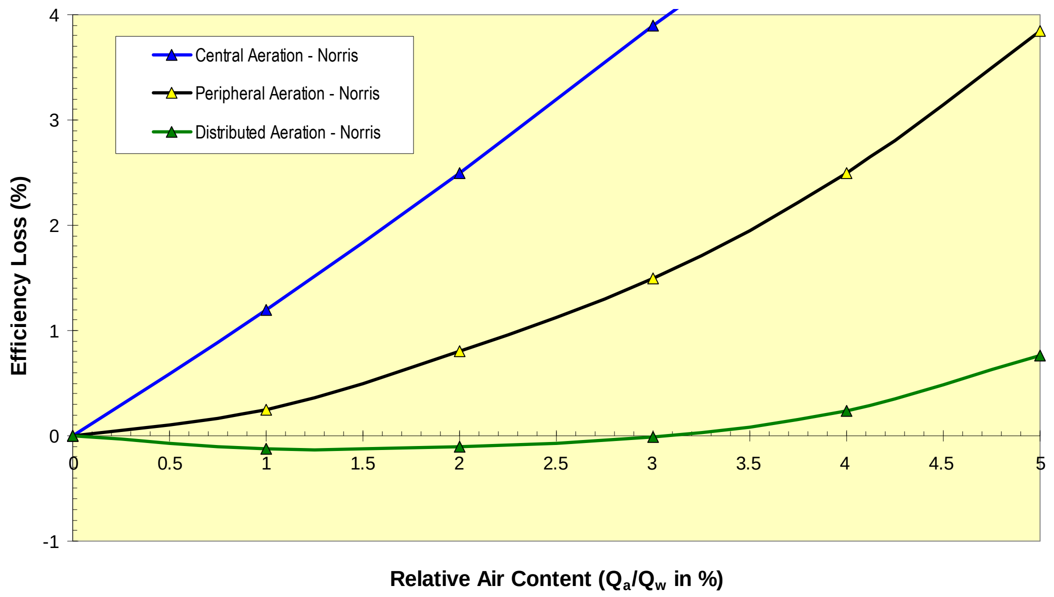

Figure 1-3
Typical Effects of Aeration on Hydraulic Performance for Norris Francis Turbine

The successful demonstration of multiple technologies for turbine aeration at TVA's Norris Project in 1995 has helped to develop market acceptance for aerating turbines. Major turbine manufacturers who currently offer aerating turbines include ALSTOM, American Hydro, Andritz, and Voith Hydro.

2. UPDATED LITERATURE REVIEW

Review of Recent Literature (1998 - 2009)

In the past, several comprehensive reviews, covering a wide range of techniques and technologies for improving the dissolved oxygen (DO) levels in releases from hydroelectric projects, were completed [Bohac et al., 1983; EPRI, 1990]. Most recently, EPRI [2002] discusses hydrological conditions contributing to low DO levels in reservoirs, describes biological effects of low DO levels, provides a comprehensive summary of techniques and technologies for improving low DO levels, and discusses DO modeling and monitoring. EPRI [2002] also includes case studies for the aerating turbines at TVA's Norris Project and the "second-generation" aerating turbines at Duke's Wateree Project.

The current paper and the related report [March, 2009] supplement EPRI [2002] by focusing primarily on aerating turbine technologies for new turbine installations and turbine upgrades. The literature review in the following portions of Section 2 describes aerating turbine technologies reported during the period from 1998 through 2009. This date range provides several years of overlap with EPRI [2002] and updates some of the EPRI [2002] references.

Overview Papers

During the 1998 - 2009 period for this review, several papers provide an overview of DO-related topics.

March and Fisher [1999] discusses technologies for turbine design and control systems to improve dissolved oxygen levels in turbine discharges and survival of fish during turbine passage. The paper describes development, testing, and test results for these technologies, with an emphasis on collaboration of stakeholders and balance between environmental stewardship and economical power production.

Čada et al. [1999a] and Čada et al. [1999b] describe the U. S. Department of Energy's Advanced Hydropower Turbine System Program and its goal of maximizing hydropower resources while minimizing adverse environmental effects. In addition to discussing fish passage issues, these papers provide a summary of DO concerns, low DO mitigation technologies, and aerating turbine progress.

Black et al. [2002] summarizes technological advances achieved between 1990 [EPRI, 1990] and 2002 [EPRI, 2002]. The paper includes results from a review of FERC documents related to low DO levels for approximately 300 projects. Over one-third of the licenses reviewed include requirements for the applicants to maintain a minimum DO level in the tailrace. The paper provides a matrix comparing technologies for mitigation of low DO levels and commenting on their general advantages and disadvantages. For aerating turbines, the listed advantages include a broad operational range, high levels of DO uptake, reduced efficiency losses compared to baffles or other air injection methods, reduced O&M costs, and minimum efficiency impact during non-aerating operations. The listed disadvantage is a high initial cost, which can be reduced by incorporating aeration capabilities into a scheduled turbine rehabilitation.

Retrofitted Turbine Aeration Systems

During the 1998 - 2009 period for this review, a variety of papers describe retrofitted turbine aeration systems. Retrofitted turbine aeration systems, typically using the existing vacuum breaker system, additional air piping through the headcover, and/or draft tube ports below the turbine, are one of the least expensive forms of aeration in terms of initial cost. However, life-cycle costs can be substantial due to efficiency losses and increased O&M costs.

Jarvis et al. [1998] describes early work with turbine venting at Ameren Missouri's Osage Project in central Missouri.

Harshbarger et al. [1999] provides a summary of results for retrofitted turbine aerations systems at the U. S. Army Corps of Engineers' eight-unit, 340 MW Bull Shoals Project, the two-unit, 80 MW Norfork Project, and the four-unit, 200 MW Table Rock Project. The retrofitted turbine aerations systems increased air flows and resulted in typical DO uptakes of 1 to 2 mg/L at Bull Shoals for eight-unit operation, 2 to 2.5 mg/L at Norfork for two-unit operation, and 2 to 3 mg/L at Table Rock for single unit operation. Little impact on efficiency or capacity was observed for Bull Shoals and Table Rock. At Norfork, the overall efficiency and capacity were relatively unchanged, but the best efficiency point shifted from 38 MW to 33 MW and the efficiency at maximum capacity dropped by about 2%, both of which have implications for optimized plant operations.

Shultz et al. [2002] reports the successful use of unsteady flow and water quality models to evaluate operating scenarios included DO improvements from the retrofitted draft tube aeration system installed at the PPL Holtwood LLC's 40 MW Lake Wallenpaupack Project.

Ware et al. [2004] discusses American Hydro's Retrofit Aeration System (RAS), which is a design methodology utilizing computational fluid dynamics (CFD) analyses, mechanical redesign of air and water passageways, and procedures for implementing the RAS with minimal outage time. The RAS methodology was applied at Ameren Missouri's Osage Project to Unit 3, an aerating replacement turbine supplied by American Hydro in 2002, and to Unit 6, an original Osage turbine supplied by Allis-Chalmers in the early 1930s. For Unit 3, DO uptakes ranged from 4 mg/L at low flows to 2.5mg/L at high flows. The corresponding Unit 3 efficiency losses ranged from -40% (i.e., an efficiency improvement) at low flows to 4% at high flows. For Unit 6, DO uptakes ranged from 3.5 mg/L at low flows to 0.4 mg/L at high flows. The corresponding Unit 3 efficiency losses ranged from -20% (i.e., an efficiency improvement) at low flows to 0% at high flows. The authors conclude that "…a refined turbine upgrade, including re-runnering, will provide the best environmental enhancement, and yet very significant improvements to water quality can be made by implementing a Retrofit Aeration System to existing turbine hardware." Information on subsequent retrofit modifications to Osage Unit 6, including additional air piping and a draft tube door vent, is provided in Ware and Sullivan [2006].

Désy et al. [2004] describes the collaboration between the U. S. Bureau of Reclamation (USBR) and G. E. Hydro (now Andritz) to evaluate alternative aeration solutions and, ultimately, to choose a retrofitted peripheral aeration system for the USBR's Canyon

Ferry Project. Canyon Ferry includes three 18 MW Francis units. DO uptakes ranging from 5.6 mg/L at low loads to 2.1 mg/L at maximum load were predicted.

Moore [2009] provides information on the retrofitted draft tube aeration systems installed on three units at Southern Company's 18 MW Lloyd Shoals Project, located in Georgia on the Ocmulgee River. These systems allowed the project to meet Georgia's DO requirement (i.e., a minimum discharge DO of 4 mg/L and an average of 5mg/L) without using the downstream aerating weir, which needed costly repairs. During aeration, additional efficiency losses of 2 to 3% are experienced at Lloyd Shoals.

Aerating Turbines

During the 1998 - 2009 period for this review, a variety of papers describe aerating turbines. Aerating turbines are designed to use the low pressures created by flows through the turbines to induce additional air flows.

Jablonski and Kirejczyk [1998] provides some information on the new, centrally aerating ALSTOM turbines installed at Unit 1 of Duke Power Company's two-unit, 36 MW Oxford Project and at Unit 3 of Duke's four-unit, 60 MW Wylie Project. Duke evaluated low DO mitigation technologies, including vacuum breaker venting, forebay oxygen diffusers, retrofitted turbine venting, and forced air venting on the basis of capital costs, maintenance costs, lost capacity due to aeration, and lost efficiency due to aeration. Because Duke was also preparing specifications for replacement turbines for Oxford and Wylie under their Upgrade and Modernization Program, the selection of new aerating turbines was a cost-effective solution. Capital costs for the aeration systems were less than 8% of the total turbine costs, with no additional efficiency losses or capacity losses when the aeration systems are not in operation.

ALSTOM's central aeration system channels air to the runner cone from an air intake located in the head cover. Performance test results for Oxford and Wylie showed that air flow can have a significant impact on loss of capacity and efficiency. For example, efficiency losses up to 2.5% at maximum gate opening and 9.6% in the vicinity of the best efficiency gate opening were experienced. Station operators use guide charts to control air valve settings based on wicket gate opening, tailwater elevation, and DO target levels and to provide the proper balance between power production and DO enhancement. Gaffney et al. [1999] summarizes Jablonski and Kirejczyk [1998] and provides additional information on Duke's Upgrade and Modernization Program.

Papillon et al. [2000a] and Papillon et al. [2000b] describe an ALSTOM central aeration system and provide rules of similitude for interpreting and scaling results from physical model test of the aeration systems. Results from model tests and prototype tests are presented as confirmation. Papillon et al. [2002] provides model test results for three variations of ALSTOM's central aeration system and a peripheral aeration system. The peripheral aeration system had a significantly lower impact on efficiency compared to the central aeration alternatives.

Sigmon et al. [2000] discusses the evaluation of four DO enhancement methods for Duke's Wateree Project, including vacuum breaker aeration, retrofitted central aeration, an aerating replacement turbine, and a forebay oxygen injection system. The alternative selected for Wateree Unit 3 was a Voith Hydro replacement turbine with distributed aeration, due to the long term environmental benefits from increased DO uptake and the operational flexibility for increased generation during the time of year when DO is low and energy values are high. Reported DO uptakes range from a low of 3.9 mg/L to a high of 4.3 mg/L as output power ranges from 9 MW to 19 MW.

Parrott and Fisher [2003] provides preliminary results from the installation of Unit 5, the first upgraded unit at the USACE's seven-unit, 364 MW Thurmond Project with a Voith Hydro distributed aeration system. The distributed aeration system draws air from three air intakes located in the head cover through hollow turbine blades to the trailing edge of each blade. Additional information is provided in Parrott and Fisher [2006] and Hobbs [2008] (see below).

Fraser et al. [2005] describes the use of physical model tests to measure and predict the effects of central and peripheral air injection on the DO levels and operating efficiencies for a GE (now Andritz) Francis turbine. The paper also includes some discussion of similitude requirements for predicting prototype aeration performance from a physical model study.

Kepler and Hager [2005] and Hager [2006] describe the runner upgrade for Unit 5 at Exelon Power's 514 MW Conowingo Hydroelectric Generating Station, located on the Susquehanna River. The upgraded runner was designed for low flow operational capability, increased efficiency, increased capacity, and DO enhancement. Voith Hydro's distributed aeration system channels air from six air intakes located in the head cover through hollow turbine blades to the trailing edge of each blade. Each air intake includes a valve operated by the control system. Performance results were not available at the time of publication.

Parrott and Fisher [2006] updates results for the USACE's Thurmond Project as more units have been upgraded with distributed aeration Voith Hydro turbines. Additional DO uptakes up to 4 mg/L are reported, as well as significant water quality improvements throughout a monitored 16-mile reach of the Savannah River downstream from the Thurmond Project.

Hobbs [2008] describes the USACE Savannah District's experience with three DO enhancement technologies, including a retrofitted turbine aeration system at the five-unit, 432 MW Hartwell Project, a forebay oxygen diffuser system at the eight-unit, 684 MW Russell Project, and distributed turbine aeration at the seven-unit, 364 MW Thurmond Project. The retrofitted turbine aeration system at Hartwell provides DO uptakes up to 3 mg/L with a corresponding efficiency loss of 0.5%. The Voith Hydro distributed aeration systems for all of the Thurmond turbines draw air from three air intakes located in the head cover of each unit through hollow turbine blades to the trailing edge of each blade. The turbine efficiency impact is 0.2% when providing 2 mg/L of DO uptake, and the turbines are capable of providing more than 4 mg/L. This paper also describes several advanced control and monitoring systems for turbine efficiency, water quality, oxygen diffuser control, and turbine aeration control.

Foust et al. [2008] provides some of the most comprehensive results for central, peripheral, and distributed aeration systems. The paper presents data on the relationships among aeration airflows, aeration injection locations, and aeration system head losses and discusses the effects of air induction on local pressures. For flow rates approximately 20% below best efficiency, central aeration provides the largest pressure differentials and air induction capability, followed by distributed aeration and peripheral aeration. For flow rates from 10% below best efficiency to maximum capacity, distributed aeration provides the largest pressure differentials. The effect of aeration on local pressures is greatest for central aeration, followed by peripheral aeration. Distributed aeration has the least effect on local pressures. Consequently, when local pressures are adjusted for the effects of aeration, distributed aeration shows the potential for inducing the largest air flows into the turbine. The paper also examines the influence of aeration technology on turbine performance. For flow rates approximately 20% below best efficiency, peripheral aeration and distributed aeration provide the lowest impact on turbine efficiency, and central aeration provides the highest impact, up to 13% for air/water flow ratios of 5%. For flow rates at best efficiency, peripheral aeration and distributed aeration provide the lowest impact on turbine efficiency, and central aeration provides the highest impact, up to 17% for air/water flow ratios of 5%. For flow rates at 20% above best efficiency, peripheral aeration and distributed aeration provide the lowest impact on turbine efficiency, and central aeration provides the highest impact, up to 25% for air/water flow ratios of 5%. In addition, for flow rates from best efficiency to 20% above best efficiency, distributed aeration is significantly more efficient than peripheral aeration. Field data is also presented to show that the DO uptake efficiency for distributed aeration is significantly greater than the DO uptake efficiency for central aeration and peripheral aeration. At best efficiency, the DO uptake efficiencies are 42%, 33%, and 23% for distributed aeration, peripheral aeration, and central aeration, respectively. Corresponding results at flows of 20% above best efficiency, typical of maximum load, show DO uptake efficiencies of 54%, 38%, and 36% for distributed aeration, peripheral aeration, and central aeration. The authors conclude that the highest DO uptakes and the lowest impacts on efficiency are achieved with a distributed aeration system, followed by a peripheral system.

Rohland and Sigmon [2008] describe a Voith Hydro aeration system designed for a replacement powerhouse at the Bridgewater Hydroelectric Station near Nebo, North Carolina. While distributed aeration would have been the preferred solution, the small size of the runner required the substitution of a combined system using both central aeration and peripheral aeration. Both central and peripheral aeration will be used during periods of low flow operation, and only the peripheral aeration will be used during periods of high flow operation requiring DO enhancement.

Foust et al. [2009] describes airflows, efficiency effects, and oxygen uptakes associated with new distributed aeration turbines installed at Ameren Missouri’s Osage Hydroelectric Project on the Osage River near Lake Osage, Missouri. This eight-unit, 240 MW plant has recently installed four new Voith Hydro turbines with distributed aeration and has conducted extensive hydraulic and environmental performance tests on the units. Air/water flow ratios ranged from 3.2% to 6.6%, depending on flow rate and tailwater elevation. At best efficiency flows, impacts on turbine efficiency ranged from 1.6% at an air/water flow ratio of 4.8% to 3.5% at an air/water flow ratio of 6.4%. At flows 10% above best efficiency, impacts on turbine efficiency ranged from 2.1% at an air/water flow ratio of 4.5% to 4.1% at an air/water flow ratio of 6.0%. During the performance testing, typical incoming DO levels ranged from 2.1 mg/L to 2.4 mg/L, and typical outflow DO levels ranged from 5.7 mg/L to 6.3 mg/L, depending on tailwater level and flow. At the lowest tailwater level, DO uptakes ranged from 4.4 mg/L to 5.1 mg/L, and at the highest tailwater level, DO uptakes ranged from 3.4 mg/L to 3.8 mg/L. At all of the tested tailwater levels, the effect of aeration on turbine efficiency was less than 1% for DO uptakes up to 3 mg/L.

Kao [1997], Kao et al. [1998], and Kao et al. [1999] describe an innovative turbine design which includes an updraft flow arrangement, a vertical flow control valve replacing the wicket gates, a divergent flow chamber replacing the draft tube, and exit flow into the tailwater free surface. Laboratory results show that this design may provide effective tailwater aeration.

Related Topics

During the 1998 to 2009 period for this review, several papers describe topics related to aerating turbines.

For example, Almquist et al. [1998] provides a draft test code for evaluating the performance of aerating turbines. This draft test code is also included as an appendix to a final report under the U. S. Department of Energy’s Advanced Hydropower Turbine System Program [Franke et al., 1997].

Hopping et al. [1999] reports “lessons learned” from the Norris experience with multiple aeration technologies. The paper provides industry guidelines on economic justification for turbine aeration systems, preparation of appropriate procurement specifications for turbine aeration systems, and verification of the hydraulic and environmental performance of turbine aeration systems.

Faulkner [2000] describes applications for environmental monitoring at hydroplants, including DO and other water quality monitoring. The article provides information on the environmental monitoring and optimization system used by TVA for the aerating turbines at the Norris Project.

Peterson et al. [2001] addresses multiple approaches to DO improvements at hydropower facilities. These include structural approaches (e.g., aerating turbines, aerating weirs, oxygen diffuser systems), operational approaches (e.g., modified timing and duration of flow releases), and regulatory approaches (e.g., site-specific DO standards, standards based on biocriteria, watershed-based trading). The authors conclude, “A combination of mitigation techniques, including structural, operational, and regulatory approaches, may be the most effective way to address DO problems at hydropower projects.”

Kühlert and Ware [2004] discusses the development of a computational fluid dynamics (CFD) model to understand and predict performance of retrofitted aeration systems for Ameren Missouri’s Osage Project. The model was used to analyze effects on turbine performance, pressure losses in air flow passageways, air flow rates, and DO uptake for potential design modifications to the retrofitted aeration system.

Bevelheimer and Coutant [2006] describes a modeling study to predict downstream environmental benefits which can be achieved due to low DO mitigation techniques, such as aerating turbines. A suite of models simulated hydrodynamics, water quality, and fish growth as affected by DO, water temperature, and food availability for a 26-mile portion of the Caney Fork River downstream from Center Hill Dam. The study assessed the effects of alternative mitigation techniques and levels of improvement on the water quality and fish growth throughout the modeled portion of the river. The authors note that results from the study demonstrate the value of the modeling techniques for evaluating tradeoffs among hydropower operations, power generation, and environmental quality.

March [2006] discusses modern systems for plant optimization, unit commitment, and control that combine environmental constraints associated with increased dissolved oxygen levels, the effects of the environmental operations on unit performance, and periodic optimization at the system level and the plant level, including real-time plant optimization for the constantly varying loads associated with automatic generation control (AGC). The paper provides several examples, including aerating turbines at the USACE's Thurmond Project and Ameren Missouri's Osage Project, to show that periodic and real-time environmental optimization can lead to improved environmental performance, improved operating efficiencies, and improved profitability. Smith et al. [2007] extends the discussion of environmental optimization to include the challenges of selecting environmental objectives considering ecosystem complexity and the differing uncertainty, time scales, and hierarchy between conventional hydro system optimization and emerging concepts of environmental optimization.

McGinnis and Ruane [2007] describes the development of a discrete-bubble model (DBM) for two hydropower projects, Duke's Wylie Project and South Carolina Electric & Gas Company's Saluda Project. The DBM predicts the rate of oxygen transfer from a single bubble traveling through a draft tube and tailrace as a function of flow rate, air/water ratio, and bubble size. The model was used successfully to predict the discharge DO for the Saluda Project and the Wylie Project to within 10% of the observed values. Ruane and McGinnis [2007] details the application of the discrete-bubble model at the Saluda Project for a variety of operating policy scenarios, resulting in a cost-effective, site-specific DO standard for the Lower Saluda River.

3. HYDRAULIC AND ENVIRONMENTAL PERFORMANCE

Introductory Remarks

Performance testing is typically conducted to verify conformance with environmental and hydraulic goals or guarantees for aerating turbines [Hopping et al., 1999]. As shown in Figure 3-1, testing of aerating turbines can be broadly divided into two categories, aeration and non-aeration performance testing. Non-aeration testing is conducted with all aeration systems off, and essentially identical to the performance testing of conventional hydroturbines. Typical parameters include turbine efficiency, maximum power, cavitation level, vibration, shaft runout, and thrust load. Testing of an aerating turbine encompasses additional evaluations for both environmental performance and hydraulic performance. Environmental performance is typically measured by the DO uptake and sometimes the level of total dissolved gases (TDG). Air flow is needed to verify gas transfer characteristics of individual aeration options. The hydraulic performance is measured by the aeration-induced efficiency change, $\Delta\eta$. In computing $\Delta\eta$, both η_a (with aeration) and η_0 (without aeration) are found using the procedures of PTC-18 or IEC 41. Airflow and pressures at the aeration outlets are desirable to verify hydraulic characteristics of individual aeration options. Aeration can affect other mechanical aspects of turbine operation, so measurements for cavitation and vibration can also be a part of aeration performance testing.

To help the hydro industry standardize the proper procedures by which ΔDO, $\Delta\eta$, and other parameters should be measured and evaluated, TVA engineers used the Norris aerating turbine testing as the bases for developing a draft test code for aerating turbines [Almquist et al., 1998]. The draft test code gives guiding principles for determining the environmental and hydraulic performance of aerating turbines. Included are recommendations for methods of measurement, instrumentation, test procedures, and analysis of data. The draft test code is also included in a final USDOE Advanced Hydro Turbine Project report [Franke et al., 1997].

Hydraulic Performance

For this paper, the terminology in Figure 3-1 is simplified. Environmental performance is unchanged, but hydraulic performance combines mechanical performance and hydraulic performance from Figure 3-1. Test codes, such as PTC-18 [ASME, 2002] and IEC 41-1991 [IEC, 1991], apply and include procedures to measure flow rate, head, and power output to calculate the turbine efficiency. Because changes in performance, rather than absolute performance, are of primary interest, index testing is often utilized for aeration performance tests.

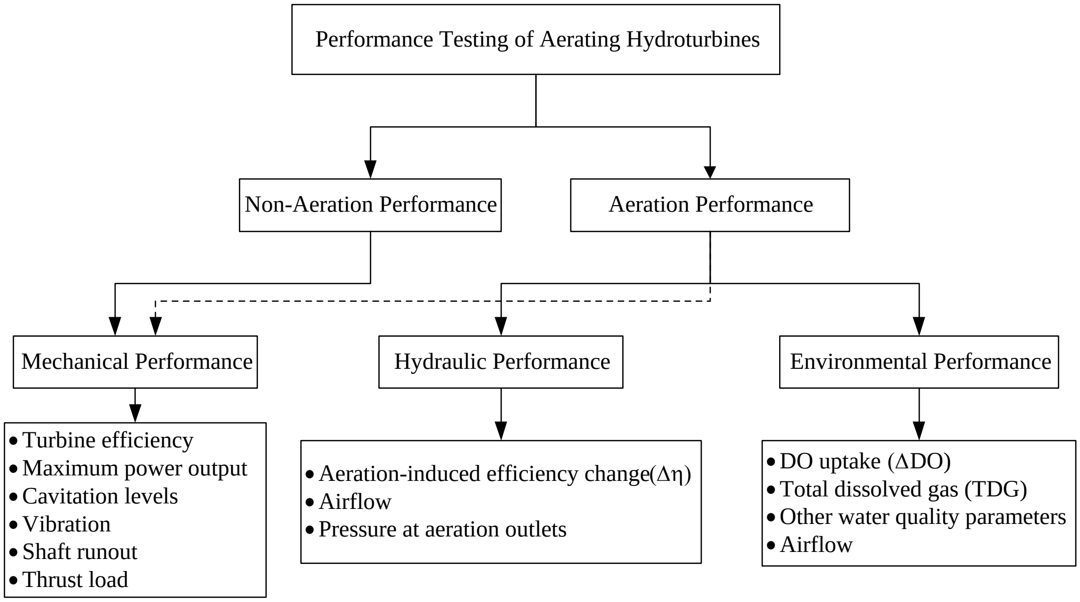

Figure 3-1
Flowchart for Testing Aerating Hydroturbines, from Hopping et al. [1999]

Environmental Performance

Difficulties in evaluating environmental performance are graphically illustrated in Figure 3-2. Errors in the measurement of dissolved oxygen contribute significant to the uncertainty associated with determining the environmental performance (i.e., DO uptake) [Hopping et al., 1999]. This is primarily due to spatial variations of DO in the turbine penstock and in the tailwater. Variations in the penstock result from DO stratification in the reservoir and withdrawal flow patterns, while variations in the tailwater are due to incomplete mixing of air in the turbine discharge and an uneven distribution of flow in the tailrace.

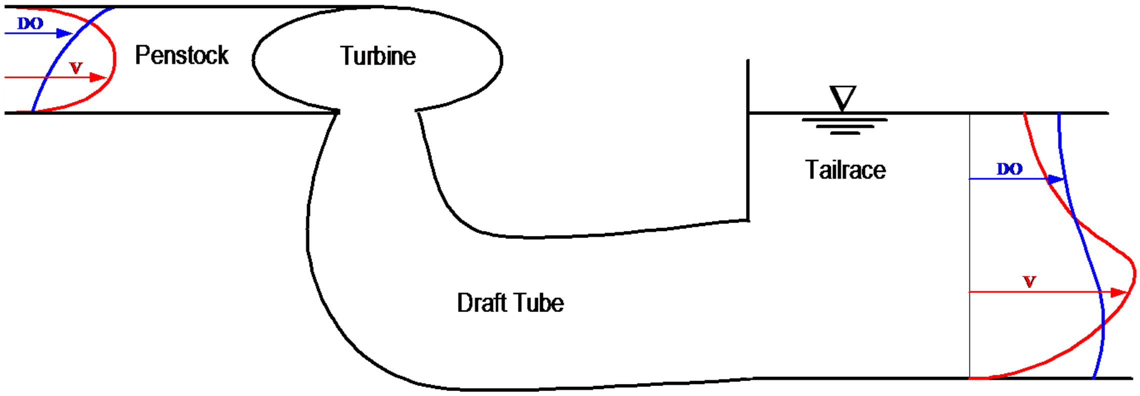

Figure 3-2
Sectional Diagram Illustrating Difficulties in Testing Aerating Hydroturbines

Due to these variations, the estimated confidence interval for measured values of DO can easily vary between 0.5 mg/L and 1.0 mg/L, which can creates large uncertainty in the computed DO uptake. The effect of large uncertainty in DO uptake can be costly, not only in determining conformance to environmental performance guarantees, but also in terms of supplying and operating DO enhancement systems. With a large uncertainty, a conservative approach must be taken in selecting and operating these environmental systems.

To increase accuracy in the measurement of turbine environmental performance, the draft test code for aerating turbines recommends multiple DO readings in the turbine penstock and tailwater. Uncertainty in the incoming DO can be reduced by obtaining independent, continuous DO measurements from multiple taps upstream from the turbine. In the tailwater, multiple, continuous DO measurements at several points across the turbine discharge are recommended. The optimum number of tailwater sensors depends on the magnitude of DO spatial variations and the size of the tailrace. Due to the high cost of deploying multiple sensors, it is beneficial to perform a pre-test evaluation of velocity and DO patterns in the tailrace. This will allow DO sensors to be strategically located to avoid redundant measurements in areas of flow stagnation or recirculation. Pre-test, midtest, and post-test calibrations of DO sensors in a common bath to a common standard also should be performed to reduce uncertainty.

4. CASE STUDIES

Overview

The three case studies in this section describe examples where utilities have, to varying degrees, assessed the hydraulic and environmental performance of aerating turbine technologies and provided results for incorporation into this paper. The case studies describe the available hydraulic and environmental performance information for aerating turbines using peripheral, central, and distributed aeration.

Case Study, Aerating Turbine with Peripheral Aeration

Description of Plant

This four-unit, 119 MW hydroplant is owned and operated by an industrial utility. In 2001, Unit 4 was upgraded with a Voith Hydro Inc. aerating turbine using peripheral aeration supplied through two air inlets. This case study is based on results for Unit 4. Subsequently, two additional units at this plant have been upgraded with similar aerating turbines using peripheral aeration.

In preparation for turbine upgrades and modernization, index tests were conducted on Unit 4 in 1999. After the Unit 4 runner upgrade in 2001, additional index tests were conducted to evaluate the new unit. Air flows into the peripheral aeration system were also measured, using differential pressures measured at the throats of the bellmouth intakes for the air supply piping. For the Unit 4 upgrade, a complete physical model study, including the draft tube, was conducted. The best efficiency results from the model study were used as the index reference for the test results reported in this case study.

Hydraulic Performance

Physical model test results and index test results for Unit 4 are shown in Figure 4-1. The peak efficiency from the physical model results has been used to “index” and normalize both the upgraded turbine results and the original turbine results. The shape of the efficiency curve for the prototype turbine agrees closely with the model results. Without aeration, the upgraded turbine achieves a best efficiency increase of about 2% and a capacity increase of 4 MW, about 14%, compared to the original turbine. With maximum aeration, the upgraded turbine achieves a best efficiency increase of about 1% and a capacity increase of 2.7 MW, about 9.5%, compared to the original turbine. With maximum aeration, the best efficiency point remains at 24 MW, similar to the original unit. With no aeration, the best efficiency point is at 27 MW. Actual efficiency losses during operation are lower than these values when DO and TDG targets can be met with reduced air flows.

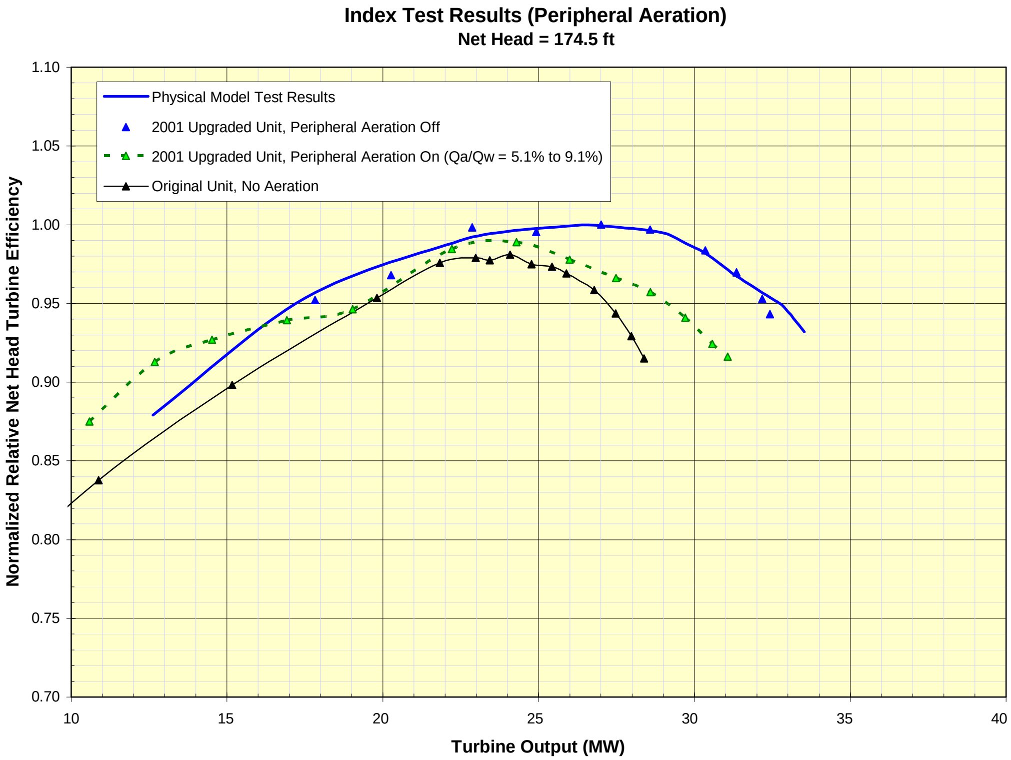

Figure 4-1
Hydraulic Performance for Aerating Turbine with Peripheral Aeration (Net Head 174.5 ft)

Environmental Performance

Only limited environmental performance data is available for this unit. Figure 4-2 shows air flow results as the percentage ratio of volumetric air flow to volumetric water flow, Q_a/Q_w, also called φ, versus turbine output expressed in megawatts (MW). Q_a/Q_w values between 8% and 9% are achieved in the range of 10 MW to 17 MW. When the vacuum breaker closes above 17 MW, the Q_a/Q_w value drops to 7%. At 22 MW, the Q_a/Q_w values begin to drop gradually throughout the remaining power range, with a low of 5% at the maximum load of 31 MW. Based on previous experience with other installations, these values of Q_a/Q_w should be able to provide DO uptakes of about 4 mg/L to 6 mg/L.

Additional Information

Additional, more comprehensive information on environmental performance could be obtained from this site through detailed analyses of plant operational data and environmental monitoring data.

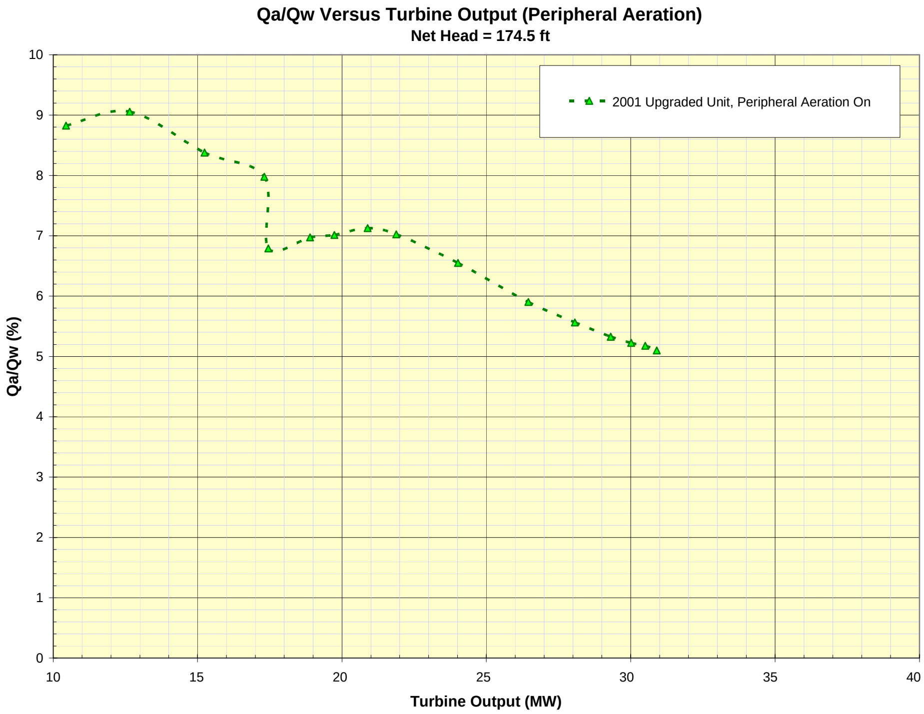

Figure 4-2
Q_a/Q_w Versus Turbine Output for Aerating Turbine with Peripheral Aeration
(Net Head 174.5 ft)

Case Study, Aerating Turbine with Central Aeration

Description of Plant

This eight-unit, 240 MW hydroplant is owned and operated by an investor-owned utility. In 2002, Units 3 and 5 were upgraded with aerating turbines using central aeration, supplied by American Hydro Company. The original units, supplied by Allis-Chalmers, were also retrofitted with central aeration. This case study is based on test results for Unit 3.

In preparation for additional turbine upgrades and modernization, efficiency tests were conducted on Unit 3 and Unit 6 in 2005. Efficiency test procedures followed ASME Performance Test Code 18-2002 [ASME, 2002]. The pressure-time method was used for water flow measurements. Air flows into the central aeration systems were also measured, using differential pressures measured at the throats of the bellmouth intakes for the air supply piping.

The plant's original design also included two small station service units, manufactured by Allis-Chalmers. Each of the station service units was designed to operate at 170 cfs and approximately 60% efficiency. The station service units were replaced in 2010 with American Hydro units including peripheral aeration, rated for 3.6 MW and 450 cfs at 90 ft of head and operating at approximately 90% efficiency.

Hydraulic Performance

Numerical model predictions for Unit 3 performance and results from the 2005 efficiency tests for Unit 3 and Unit 6 are shown in Figure 4-3. The peak efficiency from the numerical model results has been used to normalize both the upgraded Unit 3 turbine results and the original Unit 6 turbine results. Without aeration, the upgraded Unit 3 turbine achieves approximately equal efficiency and a capacity increase of 6.3 MW, about 21%, compared to the Unit 6 original turbine. With maximum aeration, the upgraded turbine achieves approximately equal efficiency at maximum capacity and a capacity increase of 3.2 MW, about 11%, compared to the Unit 6 original turbine. Actual efficiency losses during operation are lower than these values when DO and TDG targets can be met with reduced air flows.

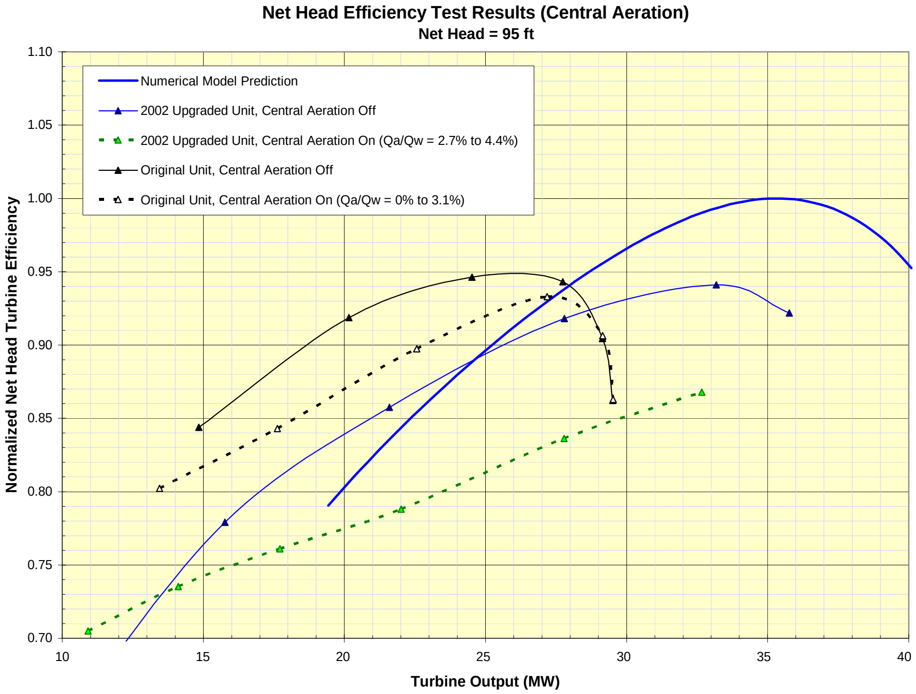

Figure 4-3
Hydraulic Performance for Aerating Turbine with Central Aeration (Net Head 95 ft)

Environmental Performance

Figure 4-4 shows air flow results as Q_a/Q_w versus turbine output expressed in megawatts (MW). Q_a/Q_w values between 4.4% and 2.7% are achieved in the range of 10 MW to 33 MW, with Q_a/Q_w gradually dropping with increased turbine output. The upgraded Unit 3 turbine provides significantly higher Q_a/Q_w values across the operating range.

Limited DO uptake information, provided for this unit in Ware and Sullivan [2006], is shown for multiple tailwater elevations in Figure 4-5. Incoming DO was measured with instrumentation installed in the penstock, and tailrace DO was measured from a boat in the tailrace. The data for a tailwater elevation of 560 ft corresponds to the performance data reported in this case study. The reported DO uptakes ranged from 4.4 mg/L at a turbine flow of 1,700 cfs to 4.3 mg/L at a turbine flow of 3,900 cfs.

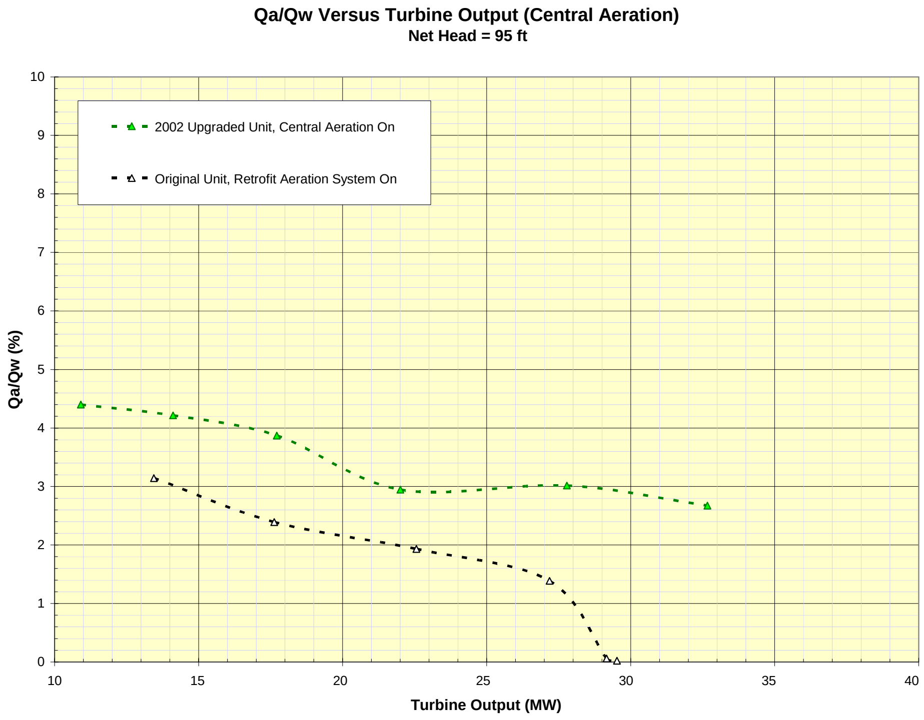

Figure 4-4
Q_a/Q_w versus Turbine Output for Aerating Turbine with Central Aeration (Net Head 95 ft)

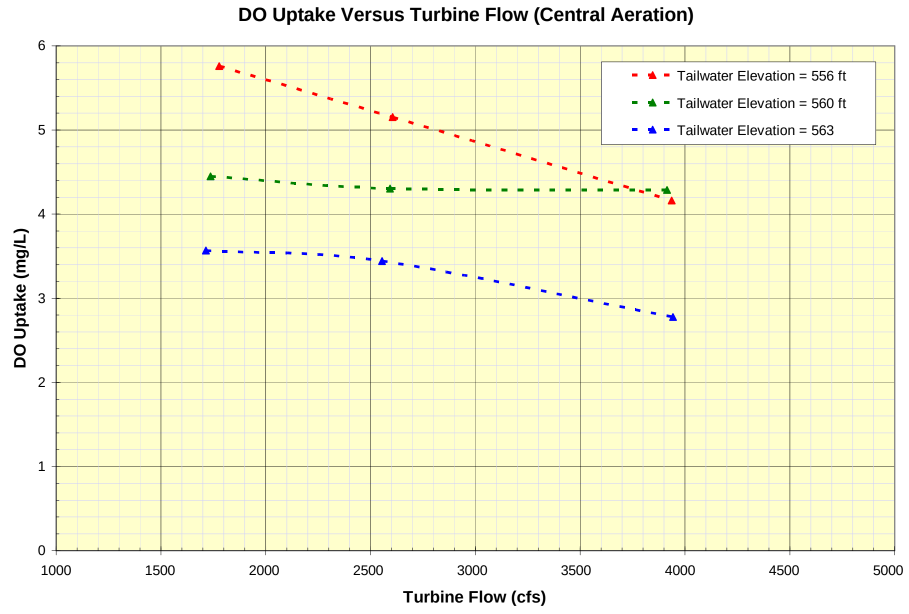

Figure 4-5
DO Uptake Versus Turbine Flow for Aerating Turbine with Central Aeration, from Ware and Sullivan [2006]

Additional Information

Additional, more comprehensive information on environmental performance could be obtained from this site through detailed analyses of plant operational data and environmental monitoring data.

The project's new FERC license, issued in 2007, raises the minimum flow from 450 cfs to 900 cfs. The two station service units were upgraded in 2010 to supply the increased minimum flow as well as 7.2 MW of combined power production. In addition, the new station service units have aeration capabilities, which can provide increased environmental benefits compared to flow alone [March and Fisher, 1999]. The additional annual generation benefit from the upgrade to the station service units, certified by FERC for a production tax credit, is 10,575 MWh [FERC, 2011].

Case Study, Aerating Turbine with Distributed Aeration

Description of Plant

This eight-unit, 240 MW hydroplant is owned and operated by an investor-owned utility. In 2008, Units 1 and 7 were upgraded with aerating turbines using distributed aeration, supplied by Voith Hydro Inc. This case study is based on test results for Unit 1.

For the Unit 1 and Unit 7 upgrades, a complete physical model study, including the draft tube, was conducted. After the Unit 1 and Unit 7 upgrades, efficiency tests were conducted on Unit 3 and Unit 6 in 2008. Efficiency test procedures followed ASME Performance Test Code 18-2002 [ASME, 2002]. The pressure-time method was used for water flow measurements. Air flows into the central aeration systems were also measured, using differential pressures measured at the throats of the bellmouth intakes for the air supply piping.

Hydraulic Performance

Model test results and efficiency test results for Unit 1 are shown in Figure 4-6. The peak efficiency from the physical model results has been used to normalize both the upgraded Unit 1 turbine results and the original Unit 6 turbine results. Within the test uncertainty, the peak efficiency from the model tests corresponds to the measured efficiency. The shape of the efficiency curve for the prototype turbine agrees closely with the model results. Without aeration, the upgraded turbine achieves the best efficiency at turbine output of 32.6 MW, which is an efficiency increase of about 3.4% compared to the original turbine, and a maximum capacity of 36.9 MW, which is an increase of 7.4 MW, about 14%, compared to the original turbine. With maximum aeration, the upgraded turbine achieves the best efficiency at a turbine output of 31 MW, which is an efficiency increase of about 1% compared to the original turbine, and a maximum capacity of 35.8 MW, which is an increase of 6.3 MW, about 21%, compared to the original turbine. With maximum aeration, the efficiency at maximum capacity is 3.8% higher than the efficiency at maximum capacity for the original turbine. Maximum aeration at best efficiency for Unit 1 reduces the efficiency by 2.4% and reduces the best efficiency turbine output from 32.6 MW to 31 MW. Actual efficiency losses during operation are lower than these values when DO and TDG targets can be met with reduced air flows.

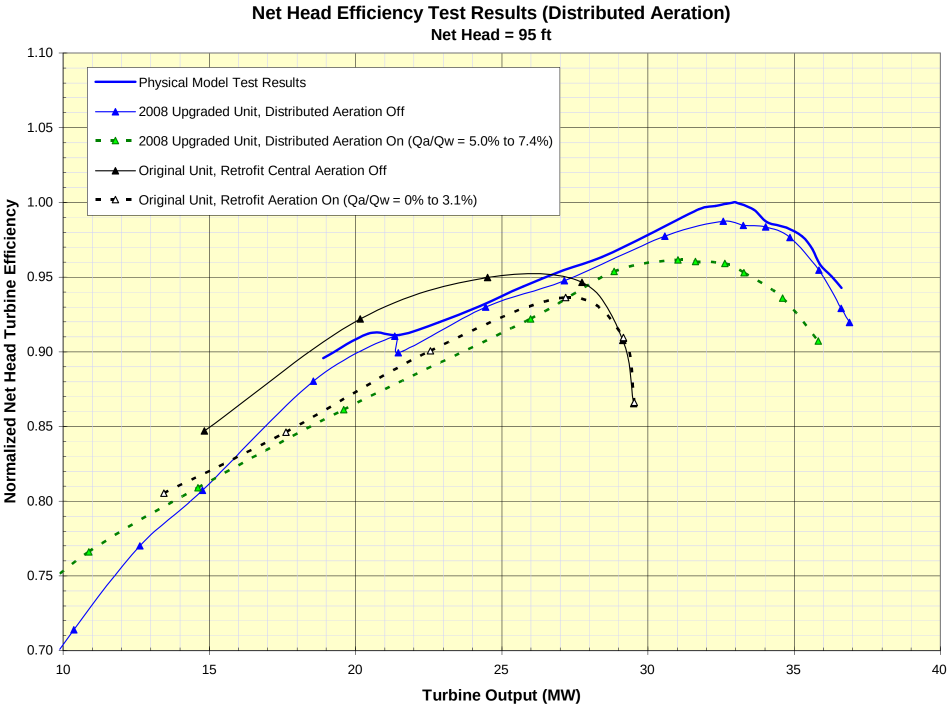

Figure 4-6
Hydraulic Performance for Aerating Turbine with Distributed Aeration (Net Head 95 ft)

Environmental Performance

Figure 4-7 shows air flow results as Q_a/Q_w versus turbine output expressed in megawatts (MW). Q_a/Q_w values between 7.4% and 5.0% are achieved in the range of 10 MW to 36 MW, with Q_a/Q_w gradually dropping with increased turbine output between 10 MW and 15 MW, leveling off between 15 MW and 26 MW, then rising gradually between 15 MW and 26 MW. The upgraded Unit 1 turbine provides significantly higher Q_a/Q_w values across the operating range compared to the Unit 6 original turbine.

Limited DO uptake information, provided for this unit in Foust et al. [2009], is shown for multiple tailwater elevations in Figure 4-8. Incoming DO was measured with instrumentation installed in the penstock, and tailrace DO was measured from a boat in the tailrace. The data for a tailwater elevation of 562 ft corresponds to the performance data reported in this case study. The reported DO uptakes ranged from 3.4 mg/L to 3.8 mg/L for turbine flows from 3,100 cfs to 4,850 cfs.

Additional Information

Additional information on hydraulic and environmental performance at other heads is provided in Foust et al. [2009]. More comprehensive information on environmental performance could be obtained from this site through detailed analyses of plant operational data and environmental monitoring data.

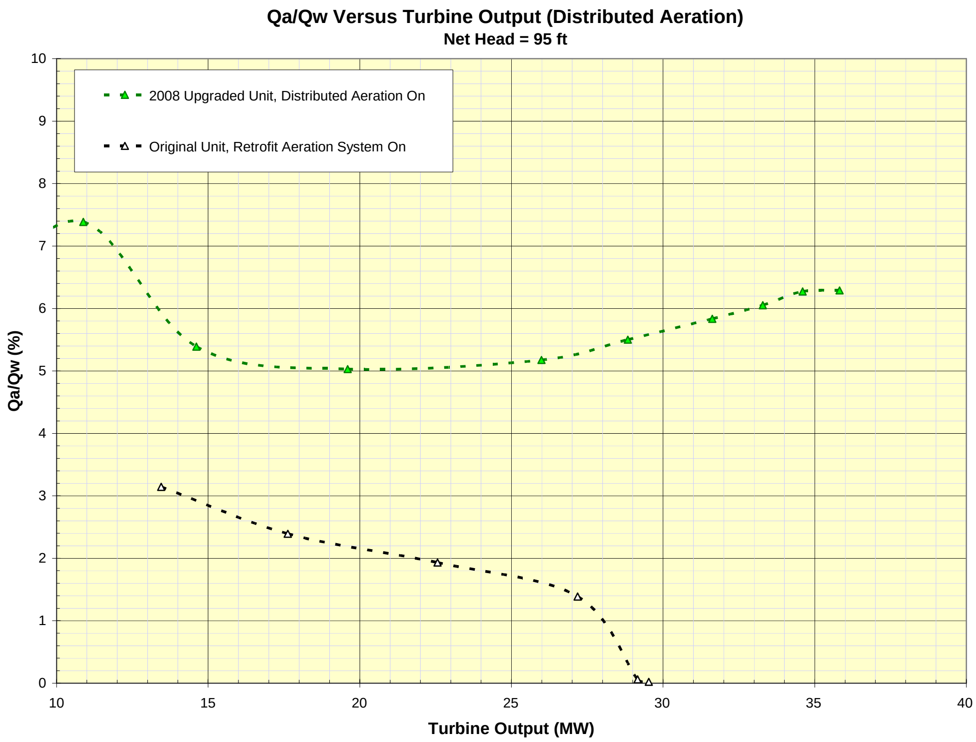

Figure 4-7
Q_a/Q_w Versus Turbine Output for Aerating Turbine with Distributed Aeration (Net Head 95 ft)

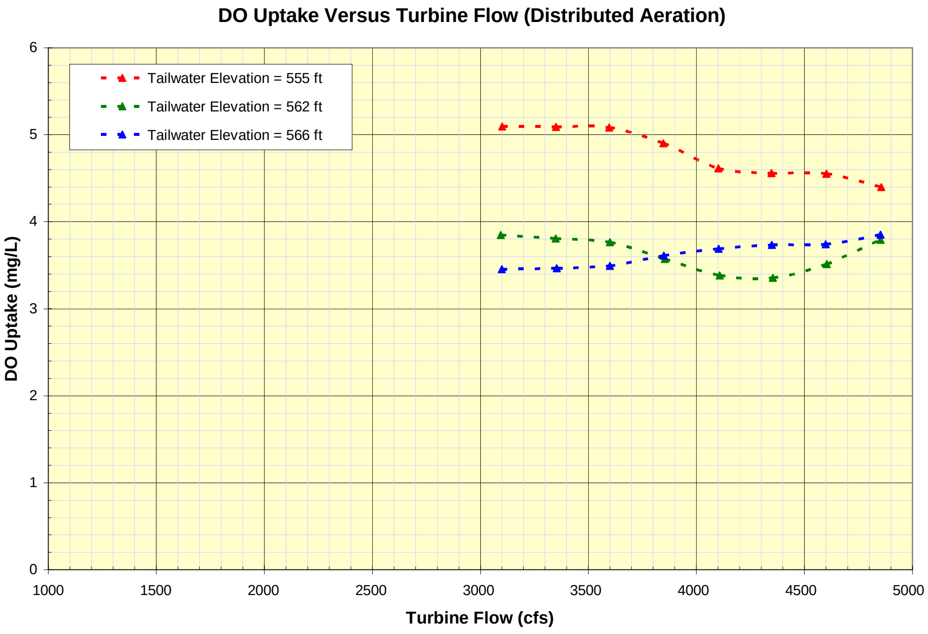

Figure 4-8
DO Uptake Versus Turbine Flow for Aerating Turbine with Distributed Aeration, from Foust et al. [2009]

5. DISCUSSION OF RESULTS FROM CASE STUDIES

Aeration Effects on Turbine Efficiency

Typical effects of air flows on turbine efficiency for peripheral, central, and distributed aeration are provided in Foust et al. [2008]. Figures from Foust et al. [2008] are re-plotted and extended to higher values of Q_a/Q_w (i.e., the volumetric air flow rate divided by the volumetric water flow rate, expressed as a percentage) in Figures 5-1, 5-2, and 5-3. The original guidelines from Foust et al. [2008] are shown as solid lines, and linear extrapolations are shown as dotted lines. Data points corresponding to test results for the three case studies are provided in these three figures.

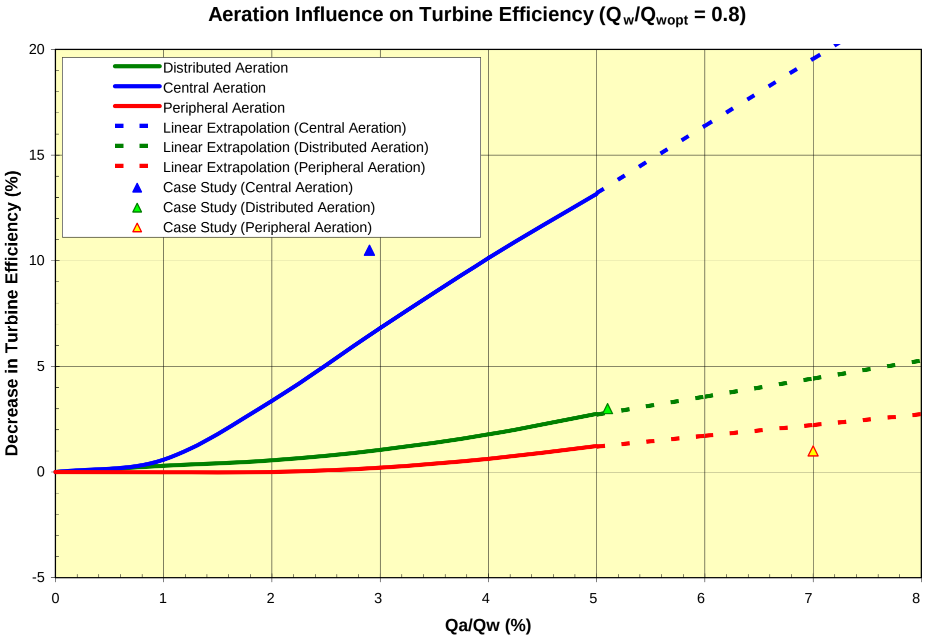

Figure 5-1
Decreases in Turbine Efficiency for Peripheral (Red), Central (Blue), and Distributed (Green) Aeration at Q_w/Q_{wopt} of 0.8, adapted from Foust et al. [2008]

Figure 5-1 shows typical decreases in turbine efficiency with peripheral aeration (red line), central aeration (blue line), and distributed aeration (green line) for a Q_w/Q_{wopt} of 0.8 (i.e., a water flow rate which is 80% of the water flow rate at the maximum turbine efficiency without aeration). A Q_w/Q_{wopt} of 0.8 corresponds to a flow range that is typical of the lower limit for a normal operational range. In this flow range, the decrease in efficiency from the peripheral aeration case study is lower than expected, the decrease in efficiency from the central aeration case study is higher than expected, and the decrease in efficiency from the distributed aeration case study is close to the expected value.

Figure 5-2 shows typical decreases in turbine efficiency with peripheral aeration (red line), central aeration (blue line), and distributed aeration (green line) for a Q_w/Q_{wopt} of 1.0 (i.e., a water flow rate which equal to the water flow rate at the maximum turbine efficiency without aeration). A Q_w/Q_{wopt} of 1.0 corresponds to the flow range for the

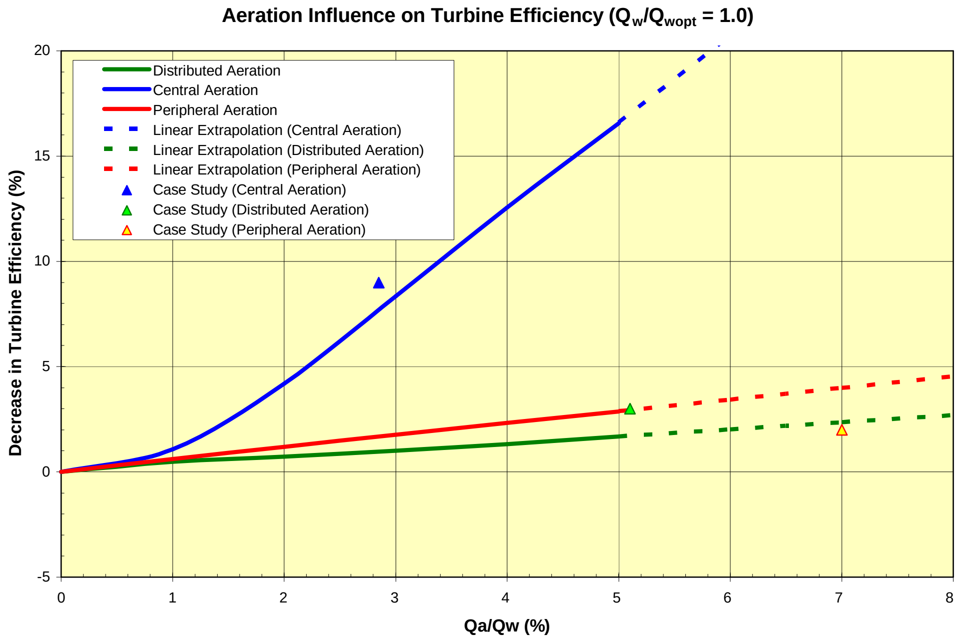

Figure 5-2
Decreases in Turbine Efficiency for Peripheral (Red), Central (Blue), and Distributed (Green) Aeration at Q_w/Q_{wopt} of 1.0, adapted from Foust et al. [2008]

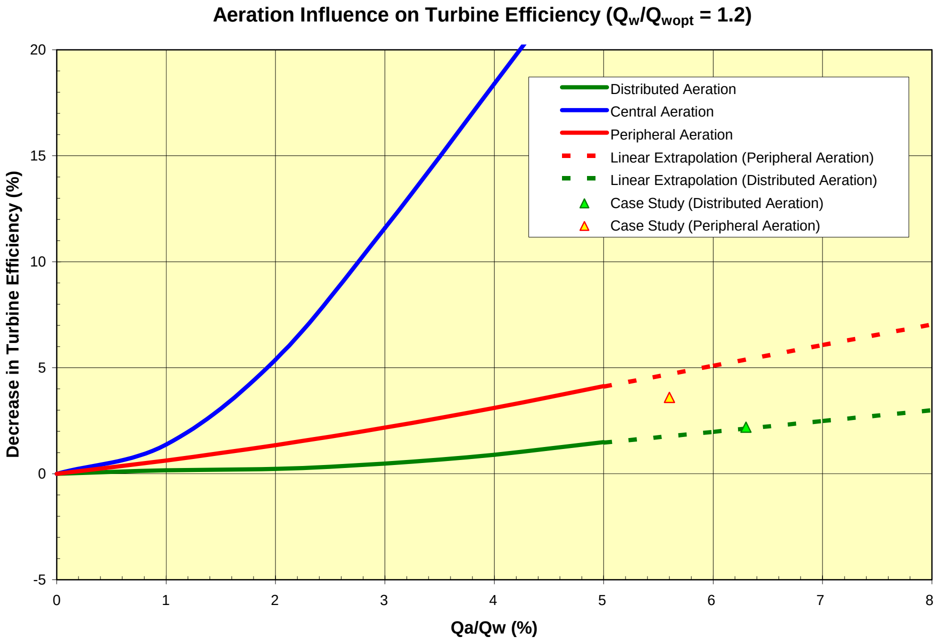

Figure 5-3
Decreases in Turbine Efficiency for Peripheral (Red), Central (Blue), and Distributed (Green) Aeration at Q_w/Q_{wopt} of 1.2, adapted from Foust et al. [2008]

most efficient turbine operation. In this flow range, the decrease in efficiency from the peripheral aeration case study is lower than expected, the decrease in efficiency from the central aeration case study is somewhat higher than expected, and the decrease in efficiency from the distributed aeration case study is somewhat higher than expected.

Figure 5-2 shows typical decreases in turbine efficiency with peripheral aeration (red line), central aeration (blue line), and distributed aeration (green line) for a Q_w/Q_{wopt} of 1.2 (i.e., a water flow rate which is 20% higher than the water flow rate at the maximum turbine efficiency without aeration).

A Q_w/Q_{wopt} of 1.2 corresponds to a flow range that is typical of the upper limit for a normal operational range. In this flow range, the decrease in efficiency from the peripheral aeration case study is lower than expected, and the decrease in efficiency from the distributed aeration case study is close to the expected value. No results are available from the central aeration case study for a Q_w/Q_{wopt} of 1.2.

This comparison of the effects of aeration on turbine efficiency from the case study results with the typical expected values from Foust et al. [2008] underscores the scatter inherent in the data behind the three lines in each graph. Presumably, site-specific details such as draft tube design contribute significantly to the observed variation.

Efficient Operation and Environmental Optimization

The central aeration case study and the distributed aeration case study describe units located at the same hydroplant. Figure 5-4 shows turbine efficiencies versus turbine outputs for the three unit types at this plant, operating at a net head of 95 ft. The turbine efficiencies have been normalized to the maximum measured efficiency of the most efficient unit. The plant has two original units with retrofitted central aeration, two 2002 upgraded units with central aeration, and four 2008 upgraded units with distributed aeration. The challenges for efficient operation of the plant's eight units under non-aerating and aerating conditions, over a range of heads, and with rapid load swings are apparent.

To improve the overall efficiency at this plant, a SCADA (Supervisory Control and Data Acquisition) system upgrade called the "Advanced Features Control System" (AFCS) was implemented. The goal of the AFCS was to optimize overall plant efficiency while ensuring that overriding constraints, such as license compliance and environmental compliance, were also met. The AFCS includes unit (i.e., turbine and generator) performance information for non-aerating and aerating operation over the anticipated head range of the plant. The control algorithm receives a plant load setting from the Independent Transmission System Operator (ISO), calculates the optimum method to dispatch each of the eight main units, then every few seconds automatically adjusts the power on each unit to meet the time-varying load setting. As the head changes, the AFCS maintains each operating unit within a narrow band of its most efficient operating point and automatically brings units from condensing operation or reduced load to generating operation or from generating operation to condensing operation or reduced load as required to meet the total plant load demand.

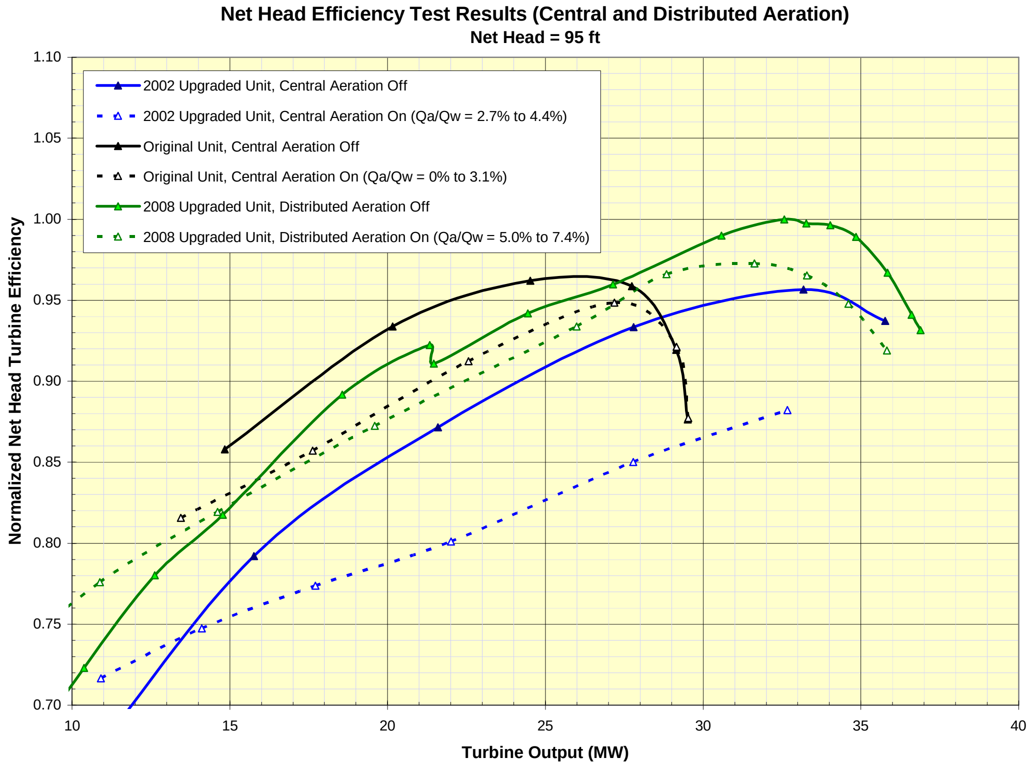

Figure 5-4
Normalized Turbine Efficiencies versus Turbine Output for Three Unit Types

For operations under aerating conditions, an Air Order Model (AOM) has been implemented to control and optimize the airflows supplied to the eight units. A Discrete Bubble Model (DBM) is incorporated into the AOM. The DBM predicts the rate of oxygen transfer from a single bubble traveling through the draft tube and tailrace as a function of flow rate, air/water ratio, and other factors. The DBM, which was calibrated based on DO uptake tests at the plant, uses real-time data to determine the amount of air that is needed to attain DO targets in the tailrace. The input data includes inflow DO, unit flow rates, tailrace elevation, temperature, and total dissolved gases (TDG). Using the DBM results, the AOM balances airflows among unit, utilizing the most efficient units first, and controls valves on the air intake piping for each unit to ensure that DO and TDG targets are attained and that excess aeration does not occur. The AOM and DBM self-adjust based on feedback data from the tailrace DO and TDG monitor , which is located about 1 mile downstream, and the travel time between the powerhouse discharge and the downstream water quality monitor.

This combination of the Advanced Features Control System and the Air Order Model provides an advanced form of environmental optimization that has not been achieved elsewhere. Additional evaluations and improvements to the AFCS and the AOM are ongoing.

6. SUMMARY AND RECOMMENDATIONS

Summary

This paper uses a review of the technical literature from 1998 through 2009 and contacts with personnel from turbine manufacturers, utilities, and agencies to provide information and performance data on aerating turbine technologies. Hydraulic and environmental performance results are analyzed and presented as case studies for three aerating turbine technologies (central aeration, peripheral aeration, and distributed aeration). The paper describes some of the difficulties in assessing the performance of aerating turbines, discusses the implications of the case study results for plant operation and optimization, and provides recommendations for additional related research.

Recommendations

To further assist turbine manufacturers, agencies, and utilities in their efforts to evaluate and improve the hydraulic and environmental performance of aerating turbines, the following recommendations are provided:

- Turbine manufacturers, agencies, and utilities should be encouraged to assist the hydropower industry by providing access to existing hydraulic and environmental performance information for aerating turbines.
- The hydropower industry should establish a national database of hydraulic and environmental performance data for aerating turbines. The national database could be funded by EPRI, DOE, USACE, or another appropriate sponsor and maintained by a national laboratory with related experience, such as Oak Ridge National Laboratory.
- Additional performance information should be solicited for the smaller “minimum flow” turbine installations which include DO enhancement.
- Additional performance information should be solicited from European and Asian utilities and agencies as aerating turbine solutions are applied in those areas.
- ASME PTC-18’s continuing efforts for the development and standardization of a comprehensive test code for aerating turbines should be encouraged and financially supported by the hydropower industry.
- Long term monitoring and data analyses for various aerating turbine technologies should be conducted to provide hydraulic and environmental performance results over a much wider range of conditions.
- As a collaborative R&D study and a contribution to the hydropower industry, EPRI should survey turbine manufacturers and utilities and compile incremental cost information for various aerating turbine technologies.
- A wide variety of related research activities should be encouraged and supported. Some of these research topics include:
    1. Improving the aeration-related scaling relationships between physical models and prototypes;

2. Improving numerical models for predicting draft tube effects on decreases in turbine efficiency under non-aerating and aerating conditions;
3. Improving numerical models for predicting gas transfer and resulting DO and TDG levels;
4. Developing cost-effective DO enhancement options for Kaplan and bulb turbine units;
5. Developing and improving environmental optimization tools; and
6. Developing new, more cost-effective methods to measure DO in reservoir releases.

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