Testing Turbine Aeration for Dissolved Oxygen Enhancement

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Abstract

During August of 1993 the Bureau of Reclamation tested turbine aeration for dissolved oxygen (DO) enhancement at Deer Creek Powerplant near Provo, Utah. This test required a variety of instrumentation and equipment, assembled during a short time period prior to the tests. Objectives of the testing included determining the effectiveness of aeration, evaluating the impact on power output and mechanical behavior of the turbines, and obtaining data needed to design a permanent turbine aeration system. Variables of interest included standard powerplant parameters (head, discharge and power output), airflow parameters (pressure, temperature, and flowrate), water quality parameters (DO concentration and temperature), and mechanical parameters (shaft runout and bearing temperature). This paper will discuss the design of the tests and the instrumentation involved, as well as plans for additional testing during the implementation of turbine aeration at the site in the summer of 1994.

Introduction

Deer Creek Reservoir is located about 24 km (15 miles) upstream of the city of Provo, Utah and receives inflow from a watershed with extensive agricultural development and increasing commercial and urban development. During late summer months (July-October), the releases from the

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reservoir are made entirely through the powerplant and often have DO concentrations ranging from 0-2 mg/L. Past studies indicate that this has impacted about 3-5 km (2-3 miles) of heavily used blue ribbon trout fishery downstream of the dam.

The powerplant, constructed in 1958, contains a pair of Francis-type turbines and air-cooled generators, rated at 2475 kW each. The two units each discharge about 8.5 m^3/s (300 ft^3/s) at full load. The rated head on the powerplant is 36.6 m (120 ft) and the maximum head is 42.7 m (140 ft). Water levels in the tailrace below the powerplant are controlled by a 3-bay gate structure. The draft tubes on both units are simple conical diffusers discharging into prismatic chambers leading to the tailrace. Figure 1 shows a cross-section through the powerhouse and tailrace pool.

To mitigate a low-flow event on the Provo River during the winter of 1992-93, Reclamation proposed using turbine aeration to raise dissolved oxygen concentrations in the river downstream of the powerplant. Air would be injected into the turbine draft tube through existing passages to produce a mixed air-water flow that would raise DO concentrations. This concept has been tested in both model and prototype situations by many researchers, and in particular by the Tennessee Valley Authority (March, Cybularz and Ragsdale, 1991; Jones and March, 1991; Bohac and Ruane, 1990). However, substantial differences between this site and those tested in the body of past research (especially in the draft tube configuration) made it difficult to predict the effectiveness of the concept for this site. We concluded that a field test was necessary.

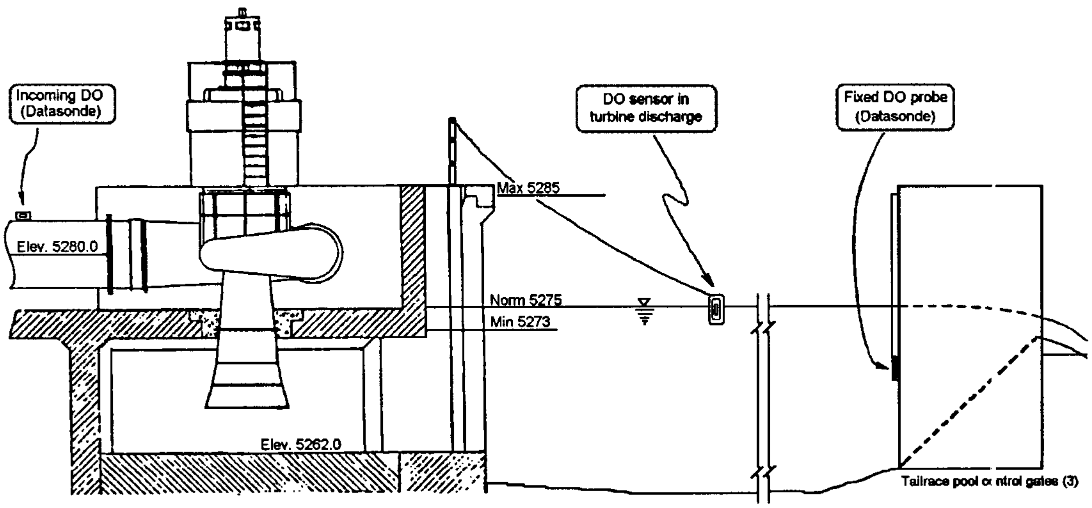

Figure 1. - Deer Creek Powerplant. The turbines installed in 1958 have simple conical diffuser draft tubes rather than formed elbow-type draft tubes for which most turbine aeration research has been done. DO measurements were taken upstream and downstream of the turbines, at the downstream end of the tailrace pool (about 200 ft downstream of the powerplant), and at several downriver locations.

Experimental Design

The test was initially planned for September of 1993, but on short notice was moved forward to August to avoid impacting planned switchyard maintenance. This also ensured that the test could be conducted during the low-DO season, since 1993 was a wet water year with a shorter and less severe low-DO season than normal. The acceleration of the test schedule required that several compromises be made in the instrumentation package for the test. Objectives of the test were to:

- Determine the effectiveness of turbine aeration for DO enhancement;
- Determine impacts of aeration on power output and mechanical behavior of the turbines;
- Collect data necessary for the design of a permanent aeration system for the powerplant;
- Determine effectiveness of aeration obtained by creating a drop across the control gates at the downstream end of the tailrace pool.

Air was supplied to the vacuum breaker systems and snorkel tubes of the two turbines using two diesel-engine-powered air compressors. Dissolved oxygen measurements were made upstream and downstream of the turbines and at the downstream end of the tailrace pool, about 200 ft downstream of the powerplant. Data collected in the powerplant were used to determine the effect of aeration on turbine performance.

The primary test was planned for the vacuum breaker system because air passages were much larger than in the snorkel tube system. Although preliminary estimates showed that axial blowers could supply the necessary flowrates through the vacuum breaker system, we were restricted to equipment that was available in the local area. The two compressors were rated to deliver 0.434 kg/s (0.957 lb/s) of air at pressures as high as 551 kPa (80 lb/in^2). This is equivalent to a volumetric flowrate of 0.354 m^3/s (750 ft^3/min) at standard temperature and pressure (101.3 kPa, 15°C [14.7 lb/in^2, 59°F]). These compressors could supply a 5-6 percent airflow rate (volumetric airflow at standard temperature and pressure compared to volumetric waterflow through the turbines).

Figure 2 shows a schematic diagram of one turbine unit with the two paths of airflow indicated. Air entering the vacuum breaker system travels between the headcover and the runner crown and enters the draft tube through seven holes in the crown of the turbine runner. Air supplied to the snorkel tube system travels through the turbine shaft and then enters the draft tube through the snorkel tube below the turbine runner.

The air supply to each unit was initially adjusted with regulators supplied on the air compressors. Flowrates were measured with two different flowmeters, described in detail in the instrumentation section. Airflow was further controlled by gate valves installed downstream of the flow mea-

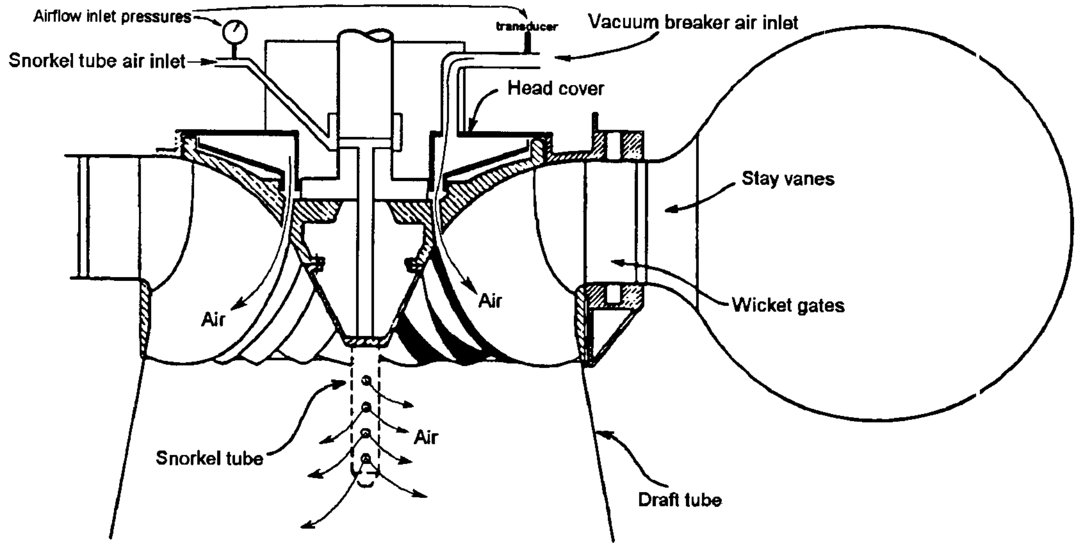

Figure 2. - Air was supplied to the draft tube through the vacuum breaker system (air flows under the headcover and through existing holes in the runner crown) and through the snorkel tube (air flows through a passageway in the shaft).

surement equipment. A check valve was installed on each line between the gate valve and the turbine to prevent possible backflow of water into the airflow meters or into the compressors.

We conducted the testing in two phases. Following installation and shakedown tests on the equipment and instrumentation, we began the balanced load portion of the tests. The two turbines were operated nearly identically, with wicket gate openings of 55-60 percent, and power outputs of about 1700 kW each. We tested aeration rates of 0 to 5.8 percent. Aeration on unit 1 was through the snorkel tube (we found the vacuum breaker system to be partially clogged for unknown reasons), and through the vacuum breaker system on unit 2. The second phase of testing was performed with unbalanced operation of the two turbines to study turbine aeration at high loads and low loads. Unit 1 was operated at a wicket gate opening of 35 percent and power output of 600 kW, and unit 2 was run at 77 percent wicket gate opening and 2750 kW power output. During two days of testing we recorded data for about 15 different combinations of operating conditions and airflow rates.

Instrumentation

Powerplant Performance Data. — Several parameters were required to calculate the combined efficiency of the turbines and generators. Discharge through the turbines was measured by ultrasonic flowmeters permanently installed on the two 1.83-m (6-ft) diameter penstocks. These meters were installed downstream of about 180 m (600 ft) of straight pipe. Head across the turbine was determined from reservoir and tailrace water surface measurements, so friction losses in the penstocks were charged against the turbines in efficiency calculations. Reservoir elevation was determined from the water level recorder in the powerhouse. Tailwater elevations were determined by direct measurement from the downstream deck of the powerhouse.

Power output from the generators was recorded from the analog gages in the powerplant control room. Analyzing the data after the tests showed that these gages were somewhat erratic and lacked precision necessary for this application. This led to significant scatter in the calculated efficiencies, although we were still able to identify significant trends in power output. With better foresight the scatter could have been reduced by making repetitive observations to obtain average readings. With more time before the test, we would have installed a watt transducer.

Vibration and Bearing Temperature Monitoring. — To ensure that turbine aeration would not create future maintenance problems, we monitored shaft runout and bearing temperatures during the tests. Shaft runouts were measured using two proximity probes located just above the turbine guide bearing, oriented at right angles to one another. Outputs from these sensors were recorded with a portable spectrum analyzer and data recorder. We recorded data at several operating conditions with and without aeration.

Both units had a prior history of cooling problems for the turbine guide bearings. This had been corrected with the addition of a cooling system using water withdrawn from the penstocks upstream of the powerhouse. Still, we were wary that any increase in vibration caused by aeration could cause problems. We monitored bearing temperatures throughout the tests, and saw no significant changes in temperature due to aeration.

Airflow and Air Pressure Measurements. — To measure the driving pressure required to inject air into the turbines, we installed a 172 kPa (25 lb/in^2) absolute pressure transducer on the air piping just upstream of our connection to the vacuum breaker system on unit 2. On unit 1, where we were forced to supply air through the snorkel tube due to the partially clogged vacuum breaker system, we installed a 689 kPa (100 lb/in^2) bourdon tube pressure gage (fig. 2). Subatmospheric pressures were not a problem on this unit during aeration due to the small size of the air piping leading to the snorkel tube. We also measured the static vacuum at the vacuum breaker and snorkel tube injection locations under each different turbine operating condition tested. Over the range tested (35 to 77 percent wicket gate setting) we found the static vacuum to be essentially constant and identical at both locations on both turbine units.

Airflow measurements were made with two different instruments. For unit 2 we rented a Hedland variable area pneumatic flowmeter rated for 0.47 m^3/s (1000 ft^3/min). On unit 1 we used a 2.54-cm (1-inch) diameter orifice plate installed in a 4.09-cm (1.61-inch) diameter pipe. This device was a last-minute substitution when our efforts to obtain a second Hedland flowmeter failed just before the test. Both of these meters were installed in-line, between the air compressor hoses and the gate valve we used to control the airflow.

Variable Area Flowmeter. — Airflow through the Hedland meter moves a magnetized, spring-loaded piston to increase the size of an annular orifice formed between the piston and a tapered metering cone in the center of the meter. An external flow indicator magnetically coupled with the piston indicates the flowrate on a pressure-compensated scale. Temperature corrections were made based on temperature measurements made on the piping near the meter with an RTD temperature sensor. The flowmeter can be operated in any orientation and does not require flow straighteners or special piping arrangements upstream of the meter. This meter is advertised to have an accuracy of ±4 percent of full-scale and repeatability within 1 percent. No exhaustive tests of accuracy or precision were performed, but we did find the meter to be easy to use and readings were quite stable. At one point in the test we swapped this meter with the orifice plate meter described below and found that for similar inlet pressures to the turbines we measured essentially the same airflows with both meters.

Orifice Plate Flowmeter. — The orifice plate flowmeter used on unit 1 required measuring several parameters to calculate the flowrate. We measured the pressure differential across the orifice plate with a 172 kPa (25 lb/in^2) Pace differential transducer, and the upstream pressure with a bourdon-tube pressure gage. The barometric pressure was also measured to convert the upstream pressure reading to absolute pressure. Finally, after allowing time for equilibrium to be established, we measured the pipe wall temperature with the RTD temperature sensor. With these measurements, the Reynolds number, discharge coefficient, and flowrate could be determined through an iterative calculation (Fluid Meters, 1959). This arrangement was effective, but more complex and time-consuming than the flowmeter used on unit 2. We found it more difficult to set desired flowrates due to the number of parameters varying as we adjusted the flow.

Dissolved Oxygen Measurements. — DO measurements were made with Hydrolab Datasondes and multi-parameter probes. These probes determine the DO concentration using an electrode assembly and a selective membrane separating the electrodes from the test sample. The electrodes consume oxygen, which depletes the DO at the interface between the sample and the membrane. Thus, to obtain accurate readings, continuous flow must be maintained past the membrane. Use of the membrane electrode probes permitted continuous (timed interval) monitoring, and avoided potential field problems with iodometric methods in which unsaturated samples are exposed to air during the sampling and handling process.

The Datasonde continuous recording probes were installed in the powerhouse to sample inflow to the powerplant prior to aeration, and at the downstream end of the tailrace pool (fig. 1). These units have internal memory, and were preset to record DO and temperature at 15 minute intervals. The instruments were checked and the data downloaded to a portable computer 1-2 times daily. Portable multi-parameter probes were used to make measurements immediately downstream of the powerplant in the flow discharging from each turbine unit (fig. 1), and at several downriver stations. The portable probes were also used as a check for the continuous probe installed at the end of the tailrace.

The probes were calibrated daily or twice daily during the tests according to manufacturer's instructions. This required recording the barometric pressure with a field meter, allowing the probe to come to equilibrium temperature, and then creating a saturated, non-pressurized air pocket above the membrane. A thin film of oxygen-saturated water remains on the probe long enough for equilibrium to be established and the probe is then calibrated against the saturation concentration at the known temperature and barometric pressure.

DO Probe Installations. — It was important to maintain flow past the membranes at the two continuous recording locations. The probe in the powerhouse sampled water drawn from the penstock for cooling of the generator bearings. A line was plumbed from the cooling water supply line to the bottom of a cylindrical well and the DO probe was installed at the bottom of the well, near the point of inflow. Flow from the cooling water line entered the bottom of the well and flowed upwards to an overflow. Although the surface of the well is exposed to air, the overflow continuously discharges the aerated water at the surface. Thus, no aeration exposure occurs at the bottom of the chamber and equilibrium measurement is possible. To confirm the measurements made at this station, the portable probes were used to measure DO in the flow exiting the powerhouse without turbine aeration. These measurements were in close agreement.

The Datasonde at the downstream end of the tailrace was installed at the bottom of a PVC pipe attached to the wall of the gate structure. The pipe was perforated at the bottom around the sensor location. Continuous downstream flow was observed past this location, but separation of the flow from the pipe created a recirculating eddy in the wake of the pipe. This eddy may have increased the exchange time required to reach equilibrium at the probe. To check the validity of data recorded at this station, measurements were made periodically at mid-channel (the middle gate opening) with the portable probes. The readings from the Datasonde in the PVC pipe did lag the mid-channel conditions and were generally lower. This indicated that the installation in the pipe may have limited the flow past the membrane and allowed the instrument to deplete the DO at the membrane interface.

DO Measurements in Bubble Plume. — Turbine aeration created a large bubble plume in the tailrace, so DO measurements made with the multi-parameter probes in the flow exiting each turbine were necessarily made in a portion of the bubble plume. There was some concern that this would produce inflated DO measurements and thus cause some error. This was checked by taking additional manual measurements with the same instrument at the downstream end of the tailrace pool, adjacent to the PVC pipe used for the Datasonde installation. After sufficient exchange time had been allowed in the tailrace, the measurements at this location were in close agreement with the measurements taken in the bubble plume. This indicated that the bubble plume had little or no influence on the DO measurements (assuming DO did not change appreciably between the two stations), or that the additional gas transfer between the two locations was about the same as any distortion of the measurements made in the bubble plume. In addition, the measurements in the bubble plume seemed as stable as those made outside of the bubble plume.

Results

Turbine aeration was very effective, and we achieved DO improvements of up to 3.5 mg/L from an initial deficit from saturation (at the water surface) of about 7 mg/L. For each test an aeration efficiency was calculated from equation 1 as follows:

$$E = \frac{C_d - C_o}{C_s - C_o} \tag{1}$$

where: C_o = incoming DO concentration
C_s = saturation DO concentration at water surface
C_d = downstream DO concentration after aeration

Figure 3 shows the aeration efficiencies plotted against the airflow expressed in percent. The majority of testing was performed with airflow rates of 4 percent or less, and in this range aeration efficiency increased about 10 percent for each 1 percent additional airflow.

In the range of 55-77 percent wicket gate setting, power losses due to aeration were about 0.5 percent for each 1 percent airflow. For the tests at 35 percent wicket gate setting there was an increase in power output of about 1-3 percent. This increase was due to the aeration alleviating draft tube surging at this gate setting.

The vibration monitoring revealed no adverse effects of aeration. The tests also confirmed that axial blowers with a maximum supply pressure of 70-100 kPa (10-15 lb/in^2) would be suitable for a permanent installation. In addition, the natural vacuum in the draft tube was sufficient to draw significant quantities of air into the turbines without blowers. Such a passive aeration system would be most effective with the turbines operating at low discharges when airflow rates could be as high as 2-3 percent.

Testing of the overflow gates at the downstream end of the tailrace pool also showed that approximately 20 percent aeration efficiency (about 1.5 mg/L increase) could be obtained by raising the gates to create a 3 ft drop, although power losses would be about 2.5-3 percent due to reduced head on the powerplant.

Implementation and Further Testing

Based on the results of the 1993 test, passive turbine aeration and manipulation of the tailrace gate will be used throughout the summer of 1994. Active aeration has been shelved indefinitely due to the high cost of

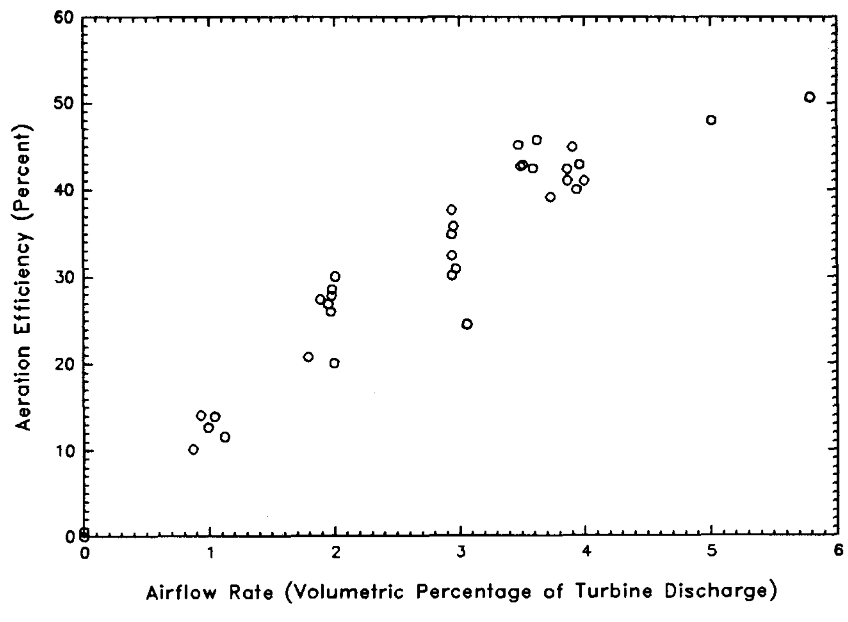

Figure 3. - Aeration efficiency achieved by turbine aeration as a function of airflow rate. This figure includes data collected in the outflow from each turbine, and in the combined powerplant flow at the downstream end of the tailrace pool (recorded with the roving multi-parameter probes). It does not include data from the Datasonde installed in the pipe at the end of the tailrace pool.

upgrading electrical equipment in the plant to provide power to the blower motors. Reclamation's Salt Lake City, Provo, and Denver Offices are now working with the Provo River Water Users Association, the Utah Division of Wildlife Resources, and the National Biological Survey to design monitoring programs for fish and aquatic invertebrates that will evaluate the biological benefits of the improved water quality. Additional hydraulic measurements will be made to measure static vacuum pressures and determine aeration-caused power losses at operating points not tested in 1993.

Acknowledgments

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