Using Dissolved Oxygen Prediction Methodologies in the Selection of Turbine Aeration Equipment

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Turbine Aeration for Water Quality Enhancement

• Motivation
• Overview of Aeration Techniques
  Bubble Distributions and Performance Impacts
• Dissolved Oxygen Prediction Methodology (DBM)
• Aeration Case Study
  Central, Peripheral, Distributed for Francis Turbine Application
• Discussion
Turbine Aeration for Water Quality Enhancement: Motivation

• Hydro power very reliable with equipment lasting several decades

• Turbine Rehabilitation:
  ➢ Changes to design technology (increased power and efficiency)
  ➢ Lifecycle extension
  ➢ Hydrology changes

• Turbine Rehabilitation also provides excellent opportunity to improve environmental compatibility:
  ➢ Fish Passage
  ➢ Water Quality

  Low dissolved oxygen levels in turbine discharges can harm fish and other aquatic life.
Turbine Aeration for Water Quality Enhancement: Motivation (continued)

- Warmer temperatures can cause thermal stratification
- Reservoir separates into layers, preventing natural mixing
Turbine Aeration for Water Quality Enhancement: Motivation (continued)

• Generally recommended to keep tailrace dissolved oxygen levels above 4 to 5 mg/l

• New regulations (federal and state) are requiring minimum tailrace DO levels
  (i) instantaneous minimums
  (ii) daily average
  (ii) 30 day average

• In order to improve tailrace dissolved oxygen levels, air or oxygen gas can be introduced into the water passing through turbine.
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Turbine Aeration for Water Quality Enhancement: Overview of Aeration Techniques (AVT)

- Auto-Venting Turbines

3 primary AVT methods:
- Central aeration (blue) – air injected through deflector
- Peripheral (yellow) – air injected through continuous slot in discharge ring
- Distributed aeration (green) – air injected through hollow blade
Turbine Aeration for Water Quality Enhancement: Overview of Aeration Techniques (Bubble Distribution)

• Aeration technique has a large influence of mixing characteristics

Inefficient bubble distribution  Well disbursed bubble distribution  Uniformly distributed bubble cloud

Aeration technique influences bubble distribution ($Q/Q_{opt} = 1.4$)
Distributed aeration produces a fine bubble cloud within draft tube cone

Smaller bubbles lead to a more efficient oxygen transfer
Turbine Aeration for Water Quality Enhancement: Overview of Aeration Techniques (Peripheral Aeration)

- Laboratory investigation of peripheral point source injection vs. continuous slot
- Two separate draft tube cones manufactured
Turbine Aeration for Water Quality Enhancement:
Overview of Aeration Techniques (Peripheral Aeration)

- Void Faction = 1%
  \[ \varphi = \frac{Q_{\text{air}}}{Q_{\text{air}} + Q_{\text{water}}} \]
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Turbine Aeration for Water Quality Enhancement: Aeration Predictions

- Discrete Bubble Model (DBM)
  - Solves equations of mass transfer between two phase mixtures
  - McGinnis and Little successfully applied to airlift aerator, Speece cone, and bubble diffusers
  - Model accounts for individual site characteristics, turbine geometry and operating condition
  - Voith Hydro has implemented DMB to aeration field data, providing unique set of correlations for central, peripheral and distributed.
Turbine Aeration for Water Quality Enhancement: Aeration Predictions (DBM)

**Input:** Air quantity, turbine discharge, incoming DO+ DN, initial bubble size, temperature, pressure & draft tube geometry.

Calculation starts at bubble inlet location, continues through the draft tube, and finishes when the bubble rises to the tailwater elevation.

Accounts for changes in pressure, bubble radius, buoyancy and dissolved gas along path.

**Output:** Outgoing dissolved oxygen & total dissolved gas levels.
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Turbine Aeration for Water Quality Enhancement: Case Study

• Dissolved oxygen at many sites are well below 1 mg/l during low dissolved oxygen seasons

• During investigation, aeration performance (air flows, tailrace dissolved oxygen levels, efficiency and power impacts) evaluated for three methods of auto-venting turbine aeration.

<table>
<thead>
<tr>
<th>H/H_{opt} [-]</th>
<th>Q/Q_{opt} [-]</th>
</tr>
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<tbody>
<tr>
<td>1.0</td>
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<tr>
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<td>1.0</td>
</tr>
<tr>
<td>1.0</td>
<td>1.2</td>
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</tbody>
</table>

Table 1: Flow range corresponding to typical operation of a Francis turbine.

• Unit centerline set 5.0 ft above TWE
Turbine Aeration for Water Quality Enhancement: Case Study

- Air flow predictions

Static pressures predicted within the water passage

<table>
<thead>
<tr>
<th>H/H_{opt} [-]</th>
<th>Q/Q_{opt} [-]</th>
<th>Central $\phi$ [%]</th>
<th>Peripheral $\phi$ [%]</th>
<th>Distributed $\phi$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2.4</td>
<td>3.5</td>
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<td>1.0</td>
<td>1.6</td>
<td>2.6</td>
<td>6.5</td>
</tr>
<tr>
<td>1.0</td>
<td>1.2</td>
<td>1.6</td>
<td>2.8</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Table 2: Air flow prediction summary for natural aspiration.
Turbine Aeration for Water Quality Enhancement: Case Study

- Tailrace dissolved oxygen levels

<table>
<thead>
<tr>
<th>H/H&lt;sub&gt;opt&lt;/sub&gt; [-]</th>
<th>Q/Q&lt;sub&gt;opt&lt;/sub&gt; [-]</th>
<th>Central Tailrace Dissolved Oxygen [mg/l]</th>
<th>Peripheral Tailrace Dissolved Oxygen [mg/l]</th>
<th>Distributed Tailrace Dissolved Oxygen [mg/l]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.8</td>
<td>3.0</td>
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<td>3.8</td>
<td>6.1</td>
</tr>
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</table>

**Table 3**: Predicted tailrace dissolved oxygen levels.

- Distributed aeration only method that can provide desired tailrace dissolved oxygen levels across the operating range.
Turbine Aeration for Water Quality Enhancement: Case Study

- Impact of aeration on turbine efficiency

**NOTE**: Compressor is required for central and peripheral aeration methods.

*Air flows requirements vary for each method.
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Turbine Aeration for Water Quality Enhancement: Conclusions

- Distributed aeration is most effective for $0.8 \leq Q/Q_{opt} \leq 1.2$
  - largest potential for air flow and DO uptake
  - lowest impact on turbine efficiency

- If distributed not available, peripheral next alternative
  - for $Q/Q_{opt} \geq 0.8$, air flows, DO uptakes and efficiency impacts more favorable than central

- Central aeration third choice
  - effective below $Q/Q_{opt} = 0.8$

- AVT combinations can be used to maximize uptake while minimizing performance impacts
Turbine Aeration for Water Quality Enhancement: Conclusions

- New direction:
  - Recently Voith designed and installed a peripheral aeration system on a Kaplan turbine
    - No water quality requirements, but discharge ring being replaced
    - Air flow predictions and DBM modeling performed to evaluate effectiveness
Aeration Performance

Aeration Influence on Turbine Performance (Q/Q_{opt})

Aeration Influence on Turbine Performance (Generator Output)
Turbine Aeration for Water Quality Enhancement: Overview of Aeration Techniques (Influence of Aeration on Turbine Performance)
Turbine Aeration for Water Quality Enhancement: Conclusions

- Cost of aeration

- Important to optimize dissolved oxygen needs with efficiency impacts.
2008 Aeration Field Data (Air Flow Concentration)

Osage Units 1 and 7 Average Aerating Runner Air Concentrations (2008)

\[
\phi = \frac{Q_{\text{air}}}{Q_{\text{air}} + Q_{\text{water}}}
\]

Unit Discharge [cfs]
2008 Aeration Field Data (Dissolved Oxygen Uptakes)

Osage Measured Dissolved Oxygen Concentrations (2008)

- Tailrace
- Intake

Unit Discharge [cfs]

DO Concentration (mg/l)

TWE = 566 ft
TWE = 562 ft
TWE = 555 ft
2008 Aeration Field Data (Aeration Influence on Performance)

Aeration Influence on Unit 1 and 7 Performance ($Q/Q_{opt} = 0.8$)

- Predicted
- TWE = 565 ft
- TWE = 560 ft
- TWE = 555 ft

Aeration Influence on Unit 1 and 7 Performance ($Q/Q_{opt} = 1.0$)

Aeration Influence on Unit 1 and 7 Performance ($Q/Q_{opt} = 1.1$)

Uniformly distributed bubble cloud

Aerating Runner
Recently, the Discrete Bubble Model was developed by several investigators to predict mass transfer between different phases in an air/water mixture.

McGinnis and Little successfully applied to airlift aerator, Speece cone, and bubble diffusers.

**Governing equations:**

\[
\frac{dM_{Gi}}{dt} = K_L (HP_i - C_i) \cdot 4\pi r^2 N
\]  
(1)

- Change in moles of gas per time
- Subscript \( i \) indicates gas type (oxygen, nitrogen)
- \( C_{saturation} \)
- \( K_L \)
- \( HP_i \)
- \( C_i \)
- \( V_b \)
DO Uptake: Dissolved Oxygen Prediction Methodology

\[ \frac{dM_{Di}}{dt} = K_L (H_i P_i - C_i) \cdot 4\pi r^2 N \]

Expressions for \( K_L \) and \( H_i \)

\[ K_L = 0.6r \quad \text{[m/s]} \quad r < 0.667 \text{ mm} \]

\[ K_L = 0.0004 \quad \text{[m/s]} \quad r \geq 0.667 \text{ mm} \quad (r = \text{radius}) \]

\[ H_O = 2.125 - 0.05021T + 0.000577T^2 \quad \text{[mole/m}^3\text{bar]} \]

\[ H_N = 1.042 - 0.02450T + 0.0003171T^2 \quad \text{[mole/m}^3\text{bar]} \quad (T = \text{temperature}) \]

Equation (1) divided into \( j \) time steps \((\Delta t)\) and solved using Euler’s method:

\[ M_{Di}^{(j)} = M_{Di}^{(j-1)} + \Delta t \left( K_L \sum_{i} H_i P_i - C_i \sum_{i} 4\pi r^2 N \right)_{j} \quad (3) \]
Aeration Performance

- Air flows into the turbine (continued)

- Static pressures adjusted for amount of air present

\[
\varphi = \frac{Q_{air}}{Q_{air} + Q_{water}}
\]
Aeration Performance

- Air flows into the turbine (continued)

Drawing Pressures Under Aerating and Non–Aerating Conditions

Dashed lines: non-aerating \((\psi/\psi_{ref} = 0)\)
Solid lines: aerating \((\psi/\psi_{ref} = 1)\)