Air inlet adequacy assessment for hydro power conduits

Rationale of the study
Air inlets in power conduits are located downstream of shut-off devices, i.e. intake gate (air vents) or penstock inlet valve (air valves). They are meant to mitigate significant sub-atmospheric pressure when draining power conduits by admitting air from the atmosphere into the system. Therefore, design of these air inlets is a critical aspect for safe operation and air demand, i.e. the peak value of required air, is the key variable to base the design on. Field measurements (incidents/tests) showed deficiency of air inlets at existing facilities as conduit pressure dropped near vapor pressure. Design criteria and numerical tools exist: deploying them to existing systems is helpful to check their performance in assessing adequacy of air inlets for existing facilities so to identify relevant tools for future design.

Objectives
- Investigation of current state of the art about design methods and numerical assessment tools.
- Identification of key mechanisms generating “air demand”, i.e. the amount of air to admit into the system to mitigate the sub-atmospheric pressure.
- Implementation of numerical tools to existing facilities (for air vents and air valves).
- Evaluation of performance and validity using limited field data available for some facilities: establishment of guidance for future works.

1. Theoretical background and traditional design criteria
- Hydraulic transients induced by the closure of a shut-off device cause pressure drop: turbulence and acoustic waves are of central importance.
- Turbulent transients are characterized by an inertia-induced net flow imbalance: discharge entering the conduit reduce faster than that leaving it.
- Turbulent flow patterns can be formed downstream of intake gate (hydraulic jump) or penstock inlet valve (high velocity jets) when closing.
- Air velocity is to be limited (noise, limited pressure drop), and sonic conditions must be avoided for air inlets (ineffective, pressure drop < 48Pa).
- Air inlets were traditionally designed based on rules of thumbs (empirical relations based on rated operation or fraction of conduit area).
- Design criteria: air demand induced by air entrainment from turbulence patterns OR net flow imbalance and for normal OR rupture conditions.

Wide dispersion in reviewed design criteria & no proper hydraulic considerations i.e. (geometry, operation, closure scenario).

2. 1-D hydraulic transient model approximation
- Hydraulic model in WHAMO® (finite difference, implicit scheme): reservoirs, conduits, valves, turbines, removed air inlets (airflow not modeled).
- Simulation is trustworthy until pressure in conduits drop below atmospheric: from then, inflow is kept, outflow is modeled from reconstructed head.
- Airflow is obtained from shear net flow imbalance (volume replacement): \( Q_{\text{air}} = Q_{\text{water, out}} - Q_{\text{water, in}} \)
- Pressure drop as a function of airflow: orifice equation (air vent) or available valve characteristics (air valve).

* Water Hammer and Mass Oscillation computer program was developed by US Army Corps of Engineers for waterhammer solving.

3. Flow solving algorithms

\[
\begin{align*}
H(t + \Delta t) &= C^+ - BQ_0(t + \Delta t) = C^- + BQ_{\text{out}}(t + \Delta t) \\
pV_\alpha &= mR(TV_\alpha + mR \text{ from net storage over } \Delta t) \\
Q_{\text{air}} &= f(C_{\text{air, in}}, A_{\text{net}}, \Delta) \\
Q_{\text{water, out}} &= Q_{\text{water, in}} - Q_{\text{air}} \\
\end{align*}
\]

- Water flow: waves combination & head-discharge relation
- Airflow: volume replacement with isothermal expansion
- Turbulent flow patterns not modeled & unaccounted air entrainment

Inputs: flow in (from 1D model), geometry & hydraulic parameters

Wylie & Streeter\(^7\): intake and PIV

\[ H(t + \Delta t) = C^+ - BQ_0(t + \Delta t) = C^- + BQ_{\text{out}}(t + \Delta t) \]

\[ pV_\alpha = mR(TV_\alpha + mR \text{ from net storage over } \Delta t) \]

\[ m_a = f(C_{\text{air, in}}, A_{\text{net}}, \Delta) \]

Results
Intake gate closure: air velocity through air vent at Lake Bunten 1

\[ \text{Closure in 600s} \]

Poor performance of design criteria
Slight overestimation by USDI algorithm
1D transient model and Wylie & Streeter algorithm in good agreement with data

PIV closure: pressure downstream of air valve at Bridge River 1

\[ \text{Closure in 21s} \]

Fair agreement between 1D transient model, Wylie & Streeter algorithm and data at full closure
Strong early-stage pressure drop absolutely NOT CAPTURED for all numerical tools

Conclusions
- Design methods show significant dispersion in assumptions and results: actual geometry & operation should be considered to estimate air demand.
- 1D transient model and algorithms are fairly reliable to predict air demand (from limited validation data) based on net volume replacement.
- These prediction tools completely neglect air entrainment which might lead to significant air demand underestimation in some cases.
- None of the presented tools capture the strong pressure drop observed as soon as air is introduced to the conduit for PIV closure: local turbulent flow, patterns (water jets, spray) potentially hinder air inlets performance and further analysis should be performed (CFD modelling or laboratory testing).

Author: Hugo Charrette\(^1\)
EPFL supervisor: Dr. Farhat\(^2\)
UBC supervisor: Dr. Shawwash\(^3\)
BC Hydro coordinator: Mr. Sadeque\(^4\)

\(^1\) Section Génie Mécanique, EPFL – Laboratoire de Machines Hydrauliques, EPFL
\(^2\) Department of Civil Engineering, UBC – 4 Hydrotechnical Engineering, BC Hydro

\(^2\) Charrette, Hugo, B.E. and Streeter, V.L., Hydraulic Transients (1978)