THE BIGGEST BANG: FIXING WATER HAMMER IN A DAF

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ABSTRACT

The Stromlo Water Treatment Plant (WTP) has a rarely used dissolved air flotation and filtration (DAFF) system. Despite multiple attempts to fix the problem, the dissolved air flotation (DAF) bubble production system suffered from persistent water hammer events since its construction in 2003/4.

When bringing the system online for an "operate-to-maintain" campaign in February 2018, operator error resulted in a severe and highly destructive water hammer incident. Icon Water responded by implementing physical and automated changes to prevent recurrence.

This paper describes:

- the root causes of the incident
- the changes made, including the considerations made for intermittent operation
- the benefits realised from these changes.

This work highlighted an often-overlooked hazard in dissolved air flotation (DAF) systems: the amplification of water hammer effects by two-phase flow. By sharing this information, operators of DAF systems can assess their vulnerability to this hazard and, if necessary, take preventive measures to avoid severe safety and business outcomes.

1.0 INTRODUCTION

Built in 2003/04 and owned by Icon Water, Stromlo WTP uses dual-media filtration to supply up to 250 ML/d of drinking water to the ACT and Queanbeyan. It includes a DAF function that is a critical control point in our Drinking Water Quality Management Plan. DAFF is required when: raw water turbidity exceeds 15 NTU, when coagulation performance is poor (pre-filter turbidity >5 NTU), or when abstracting water from the Murrumbidgee River (which was essential for Canberra and Queanbeyan's water security between 2007 and 2012).

However, such conditions have been rare over the past decade, making DAF use economically unjustified. Aside from the noted period, the system has remained idle except for infrequent "operate-to-maintain" campaigns for functional testing and operator training.

The original DAF liquid system consisted of six (6) fixed-speed recycle pumps (90 kW motors, direct started), five (5) saturation vessels (each supplying two filters), and pneumatically actuated rubber-seated butterfly valves. The liquid level in each vessel was controlled by modulating its water inlet valve. Recycled water is delivered via a 500 m pipeline and enters each vessel above the liquid level with a static head of approximately 130 kPa (13 m). The DAF saturation vessels operated at around 550-580 kPa and could only be depressurised by opening their outlet valves. System start-up and shutdown were manual processes.

The DAF system has experienced persistent water hammer, particularly when reactivating offline saturation vessels, since the plant was commissioned in 2003/2004. Multiple attempts have been made to remedy the situation; however, these changes were largely reactive, poorly documented, and had questionable effectiveness. Operators had observed that these water hammer effects, especially when opening the saturation vessel outlet valves, were worsening over time. The system's pneumatic control valves were also becoming "stickier" and often faulted when the system was brought online. The business had normalised to this abnormal system operation

In February 2018, during the start-up phase of an "operate-to-maintain" campaign, a communication breakdown during a shift change led to a series of system valves being operated in the incorrect sequence. This ultimately caused a water column separation within the recycle water pipework, resulting in a severe and explosive water hammer event that caused extensive damage to multiple components of the DAF system. The system was rendered inoperable. Photographs of the damage can be found in Appendix A. Fortunately; no personnel were harmed. The operator on duty at the time had no prior experience operating the system.

2.0 DISCUSSION

2.1 Initial investigations and concepts

Icon Water initially engaged a consultant to assist in determining the root cause of the 2018 explosion and to develop a concept for a system redesign to prevent a recurrence. Their work, completed in 2019:

- Could not determine the actual failure mechanism. Conventional water hammer modelling indicated that pressure transients exceeded the pressure rating of the pipework. However, this alone could not account for the damage experienced during the event.
- Proposed solutions that focused almost exclusively on modifying the water side of the DAF saturation vessels (renewing saturator inlet valves and installing variable-speed drives on all recycle water pumps) and significantly reinforcing pipe supports (a "survival upgrade").
- Did not propose any changes to address the ongoing, although less severe, in-service water hammer when opening the outlet valves of the Saturation Vessels.
- Did not consider automating the start-up and shutdown, which would eliminate operator error in a system that typically has minimal operation.
- Did not propose simplifying how the system worked.

When moving into the next stage of the project in 2020, Icon Water concluded that a different approach was needed—one that placed the operator at the centre of the design by:

1. Automating system functions, particularly start-up and shutdown, to eliminate operator error.
2. Selecting equipment and control strategies that support infrequent operation.
3. Simplifying system operation as much as possible to increase confidence when starting up, operating or shutting down a system that operators may have little experience with.

2.2 Designing for intermittent operation

After making repairs to restore system functionality, the system was observed in operation during an operate-to-maintain campaign in January 2021.

At this time, the stickiness of the DAF saturation vessel outlet valves was determined to be the primary cause of the less severe in-service water hammer in the system. These valves opened suddenly between 20 and 30 seconds after compressed air was applied to the pneumatic actuators. These actuators were initially fitted with speed controllers but had been removed many years prior, again with little documentary evidence. The natural rubber seats in the valves had swollen when they dried out while the DAF system was offline. The valve operation was also hindered by the significant pressure differential across the valve, as the DAF Saturation Vessels at Stromlo WTP operate at pressures of around 550-580 kPa.

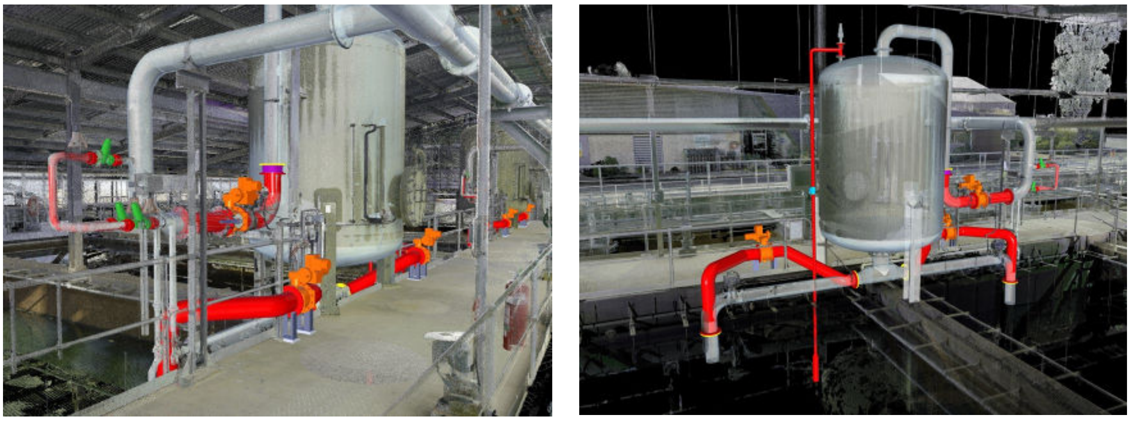
These observations validated the need to carefully select equipment suited to both the process duties and intermittent operation.

2.1 Ultimate project scope and delivery

This project delivered a range of improvements to enhance the safety, efficiency, and reliability of the DAF Recycle Pump system and Saturation Vessels. Key elements included:

- *Full automation of system start-up and shutdown:* This eliminates the human error that caused the event. Dedicated pipework was also installed to depressurise the DAF Saturation Vessels when taking them offline or during power failure.
- *Pumping manifold improvements:* The single non-return valve in the DAF Recycle Pumping delivery pipe manifold was replaced, and a new pressure relief valve was installed on the discharge manifold of the DAF Recycle Pump system.
- *Improved water hammer transient protection:* Non-return valves were added to the water inlets of each DAF Saturation Vessel to prevent pressure transients from travelling into the DAF Recycle Pumping delivery main and back to the pump system.
- *Pump motor control changes:* Four (4) of the six (6) DAF Recycle Pumps were fitted with soft-starters, while the remaining two were upgraded with variable speed drives (VSDs), which now regulate water pressure in the system.
- *Valve and actuator replacements:* The existing pneumatically actuated rubber-seated butterfly valves at the inlet and outlet of the Saturation Vessels were changed for electrically actuated, metal-seated double eccentric butterfly valves. The electric actuators have variable speed drives to initially open the valve more slowly from the closed position.
- *New liquid level control philosophy:* The previous water-throttling approach was replaced by instead intermittently applying the compressed air to that maintain the water levels between defined thresholds. This method enhances the consistency of bubble formation consistency and minimising premature air precipitation (Haarhoff and van Vurren 1993) and provides for potential energy savings in the water pumping system by eliminating losses across a control valve.

Figure 1 contains a visual summary of the changes to the Saturation Vessels.



(a) (b)

<u>Figure 1:</u> ***Visual summaries of the system changes to the Saturation Vessels (a) to the Saturation Vessels, looking southwest; (b) to the Saturation Vessels, looking northeast.***

Construction and commissioning occurred during 2022, with project commissioning and handover occurring between July and September 2023.

2.2 Benefits realised and learnings

Benefits realised:

- The modifications to the Stromlo WTP DAF system have eliminated all observable water hammer, even under the most severe conditions. This is an outstanding result, considering the length and elevation change within the DAF recycle water pipeline.
- DAF system start-up (functional testing of equipment and the filling of each saturation vessel) and shutdown is fully automated via SCADA, including depressurising each saturation vessel when taken out of service. Eliminating human error will prevent a repeat of the 2018 explosion.
- Modifying the saturation vessel level control approach and eliminating hydraulic losses has created an opportunity to save energy in the DAF recycle water pumping system through relatively simple modifications, such as trimming pump impellers.

Learnings:

- Project commissioning and business integration need to consider the system's intermittent operation and the shift patterns of water treatment plant operators more carefully. Intermittently operated systems will typically be started up and shut down more frequently than those that run continuously. Despite a 28-day proving period in 2023, some operators have yet to start up and shut down the system. Infrequent operation also emphasises the importance of proven work instructions and operational procedures.

2.3 Hidden hazards found

While testing the system's response to a "crash stop" of the DAFF Recycle Pumps (simulated as an immediate loss of power), we observed that the newly installed non-return valves on the inlets to the Saturation Vessels closed rapidly and remained closed longer than expected. This behaviour was expected from the redesigned system in response to a pressure transient in the water pumping system, but it also ultimately identified the missing piece of the February 2018 failure puzzle.

The new non-return valves on the inlets to each Saturation Vessel were also preventing compressed air from entering the DAF Recycle Pump system's discharge line. During the February 2018 incident, the energy stored inside the Saturation Vessels—assuming isentropic expansion of the compressed air—was equivalent to approximately 1 kg of gunpowder (Lindeburg, 2001). Only when this stored energy was combined with the pressure transients caused by water hammer could the extent of system damage be fully explained.

Conventional water hammer modelling packages do not consider multiphase flows, and the backflow of compressed air into the DAF recycle water pipeline was a pivotal factor in the February 2018 explosion within the Stromlo WTP DAF system.

3.0 CONCLUSIONS

- DAF saturation systems operate at sufficient pressures to present significant safety hazards. Reliance on contemporary single-phase transient pressure analysis models will underestimate the multi-phase transient pressures that can lead to catastrophic equipment failure. Abnormal operation of such a system cannot become familiar or normalised. Robust management of engineering changes is also essential.
- Intermittently operated systems demand a greater attention on managing human factors and more care is often needed in equipment selection. Standardised design, integration and optimisation approaches may need to be challenged, and change management for intermittently operated systems is even more critical than for those that operate continuously.
- DAF saturation vessels without fully submerged water inlets are prone to backflow of compressed air when the water recycle pumps are not running. This could lead to a sudden release of energy (by isentropic expansion) with potentially severe safety and business implications. By sharing this information, the authors hope that the owners and operators of DAF systems will evaluate their vulnerability to this hazard and, if necessary, take preventive measures.
- It is possible to design water hammer and misdirected multiphase flows out of existing DAF systems.

4.0 ACKNOWLEDGEMENTS

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5.0 REFERENCES

Haarhoff J and van Vuuren L (1993) *A South African Design Guide for Dissolved Air Flotation*, report number TT 60/93, Water Research Commission, Pretoria, South Africa.

Lindeburg MR (2001) *Mechanical engineering reference manual for the PE exam*, 11th edn, Professional Publications, Belmont, California.

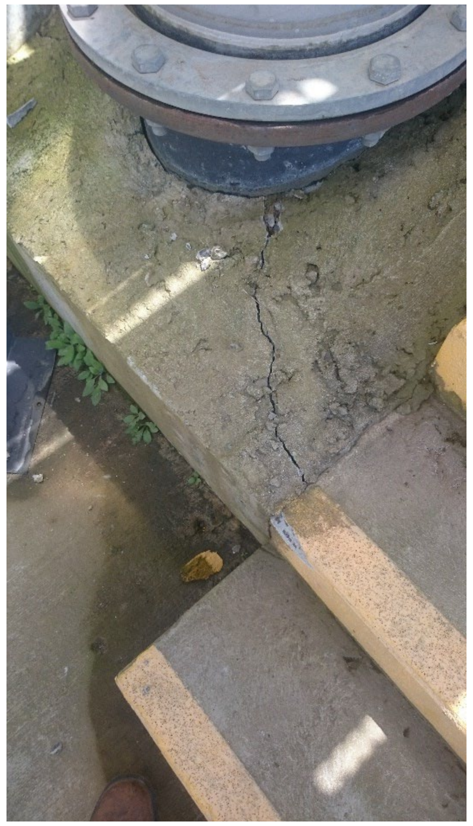
APPENDIX A: DAMAGE CAUSED IN 2018 STROMLO WTP DAF WATER HAMMER INCIDENT

(a)

(b)

(c)

(d)



(e)

(f)

(g)

(h)

(a) Rubber gasket that was blown out between flanges in the DAF recycle water pipeline approximately 350 m from the DAF recycle water pumps; (b) Damage to pressure regulating valves and PN16-rated pipework for DAFF water spray lines–valve has yet to be recovered or located; (d) Damage to a separate pressure regulating valve and PN16-rated pipework on Saturation Vessel 4 for DAFF water spray lines–fragments found 250 m away; (d) Pressure regulating valve recovered from Saturation Vessel 4, cracks also extend to the base of the valve; (e) Cracking in the concrete plinth adjacent to a rising section of the DAF recycle water pipeline caused by its movement during the event; (f) Vertical movement of DN450 mm spiral stainless steel DAF recycle water pipeline support during the event, being temporarily supported with bricks; (g) Damage caused to the filter building cladding by movement of the DN450 mm DAF recycle water pipeline during the water hammer event; (g) Buckling of a grating caused by lateral movement in the DAF recycle water pipeline during the event.