Developments of High Rate Dissolved Air Flotation for Drinking Water Treatment

James K. Edzwald
Professor Emeritus, University of Massachusetts
Amherst, MA 01003 USA
edzwald@ecs.umass.edu

Presentation at the
7th International Symposium on Water Supply Technology
Yokohama, Japan

22 November 2006
PRESENTATION OUTLINE

• Background on DAF

• Framework and DAF Models

• Rise Velocities of Free Bubbles and Floc-Bubble Aggregates

• High Rate Processes
  – Developments
    • New York City Case
    • High Rate Technologies
  – Stratified Flow in DAF Tanks
  – Separation Zone Performance

• Concluding Statements
Dissolved Air Flotation (DAF) in Drinking Water Treatment

- First use of DAF for drinking water: Sweden in the mid-60s
  - 50 DAF plants over next 30 years in Scandinavia
- South Africa: 1st plant in 1969
- UK: widely used beginning in the 1970s
- Europe, Australia, Asia, South America: since 1980s, increasing use
- Estimate of some 100+ plants in USA & Canada

- Better clarification process than Sedimentation for treating
  - Reservoir supplies
  - Supplies with natural color

- Particularly effective in removing low density particles
  - Either initially in the water supply or those produced through precipitation

- Effective removal process for protozoa pathogens.
  - Demonstrated that DAF achieves 2-3 log removals of Cryptosporidium compared to ½ -2 log removal by sedimentation.
DAF PLANT DESIGN: Prior to the 1990’s

• Status
  – Plants Designed and Operated on an Empirical Basis
    • No Integrated Models for Pretreatment and DAF
    • No Design Models for the Contact Zone
    • Tank Size Based on Simple Analysis of Bubble Rise Velocities and Floc-Bubble Aggregate Rise Velocities

• Designs
  – Flocculation Tanks
    • 20-30 min Detention Times (Idea to Produce Flocs of 100 μm and Larger)
    • G for Mixing of 30-100 sec⁻¹ (Often, Tapered Flocculation)
  – DAF Tank Size Set through Hydraulic Loading
    • 5-10 m/hr
DEVELOPMENTS: 1990s to the Present

• In practice we have seen DAF plants with shorter pretreatment flocculation times (5 to 10 min) and higher DAF tank hydraulic loading rates (20 to 40 m/h)

• Developments due to
  – Improved understanding of DAF through models describing the process
  – Considerable body of pilot plant data demonstrating that shorter flocculation times and higher rates can be used
  – Full-scale design and experience
  – Improved tank designs from consulting engineers and equipment companies

• DAF Models
  – Edzwald and co-workers: early 1990s
  – Tambo, Fukushi, and Matsui: late 1980s and 1990s
  – Leppinen (2000) and Han (2002)
  – Haarhoff and Edzwald (2001)
  – Review of modeling
FLOTATION PLANT
FRAMEWORK

• Pretreatment
  – Coagulation chemistry
    • Essential for good DAF performance
    • Dosing and pH conditions to produce
      – particles that can form flocs and
      – flocs that can attach to bubbles in the contact zone
  – Flocculation
    • How much flocculation is required?

• Contact Zone
  – Zone of the tank in which floc particles and air bubbles are contacted

• Separation Zone
  – Free bubbles and floc-bubble aggregates are separated by rising to the surface

Question: What is the effect of particle size on Contact Zone and on Separation Zone Performance?
EFFECT OF PARTICLE SIZE ON CONTACT ZONE PERFORMANCE

- **Reservoir Supplies**
  - Particles in Raw Water are small
    - Considerable evidence for many reservoirs that particles are less than 20 µm. Most are about 1 µm
  - Coagulants
    - Form precipitated particles that start out small

- **Flocculation**
  - Particles entering the flocculation tank are small
  - Question: How much flocculation should be provided?
    - Extensive to produce large floc sizes or a smaller extent of flocculation time to produce “pin point” size flocs
CONTACT ZONE EFFICIENCY

- Flocs greater ~ 1 µm, efficiency depends on $d_f^2$
  - Larger floc; better efficiency
  - However, efficiencies of 99% are achieved for floc sizes of 20-30 µm

Conditions: detention time 3 min, floc density 1100 kg/m³, Bubble Size 60 µm, $\alpha_p$ 0.5, Bubble Volume 8000 ppm, Temp. 20 ºC
RISE VELOCITIES

- Bubbles and Floc-Bubble Aggregates are removed in the Separation Zone of DAF tanks

- Principles
  - Stokes Law

![Diagram of water treatment process](image-url)
• Bubbles of about 100 µm have been observed in the Separation Zone.

✓ For 100 µm bubbles, rise velocities are ~ 10 to 20 m/h

• Next, consider rise velocity of floc-bubble aggregates

\[ v_b = \frac{g(\rho_w - \rho_b) d_b^2}{18 \mu_w} \]
FLOC-BUBBLE AGGREGATE RISE VELOCITY

- Calculation requires determination of
  - Particle-Bubble Density ($\rho_{pb}$)
  - $N$ is the number of air bubbles attached to one floc particle
  - Equivalent Diameter of the Particle-Bubble ($d_{pb}$)

\[
\rho_{fb} = \frac{(\rho_f d_f^3) + N(\rho_b d_b^3)}{d_f^3 + N(d_b^3)}
\]

\[
d_{fb} = \left[(d_f^3) + N(d_b^3)\right]^{1/3}
\]

\[
N_{max} = \pi \left(\frac{d_f}{d_b}\right)^2 \quad \text{(from Tambo et al. (1986))}
\]

\[
v_{fb} = \frac{4g(\rho_w - \rho_{fb})d_{fb}^2}{3K\mu_w}
\]

(K : see Tambo and Watanabe (1979))
Aggregate Rise Velocity for 1 Bubble and Multiple Bubble Attachment
(100 µm bubbles, initial floc density 1100 kg/m³, 20 °C)

- Aggregate rise velocities are about their maximum value of 20 m/h for flocs of 50 µm or less.
- Flocs exceeding 100 µm can achieve high rise velocities with multiple bubble attachment.

Floc Size:
- Contact Zone: 20-30 µm
- Separation Zone: < 50 µm
- Overall: optimum sizes 20-50 µm
DAF TANK SEPARATION ZONE PERFORMANCE

• Removal of Bubbles and Floc-Bubble Aggregates

\[ v_b \geq v_{sz-hl} = \frac{Q + Q_r}{A_{sz}} \]

\[ v_{fb} \geq v_{sz-hl} = \frac{Q + Q_r}{A_{sz}} \]

• Bubble and aggregate rise velocity calculations (prior slides) of 20 m/h or less
  – Early designs at 5-10 m/hr
  – Increasing to 15 m/hr in the 1990s

• Practice: Has been found can design at higher hydraulic loadings without air bubble carryover

• Must consider hydraulic flow pattern through the separation zone – will revisit
HIGH RATE DAF PLANTS

• DAF PLANTS
  – Short Pretreatment Flocculation Times of 5 to 10 min: Small flocculation tanks
  – High Hydraulic Loadings of 20 to 40 m/h for DAF Tank: Small DAF tanks

• UMass Research in 1990s Demonstrated High Rate DAF
  – Pilot Plant Research on Pretreatment in Gothenburg (Sweden)
    • UMass and Chalmers Univ. (Purac AB & Purac UK)
    • Found good performance with short flocculation detention times
      *JAWWA, Valade, Edzwald, et al., 1996*
  – Pilot Plant Research of High Loading Rates with Short Flocculation Time
    • USA Locations: Newport News, VA & Fairfield, CT
      *JAWWA, Edzwald, et al., 1999*
  – Summary: found good DAF performance
    • Flocculation times of 5 min
    • DAF hydraulic loadings of 20-40 m/hr
New York City Case: Short Flocculation Time and Flotation over Filtration

- Croton Supply
  - Unfiltered
  - DAF Plant Under Construction

- Water quality: mean (max)
  - Turbidity: 1.1 ntu (17 ntu)
  - Apparent Color: 20 (70 CU)
  - TOC: 2.9 mg/L (12.8 mg/L)

- Plant capacity
  - $1.1 \times 10^6$ cubic meters/day

Slide from William Becker, Hazen & Sawyer

22 November 2006    James K. I.
Plant Capacity: \(1.1 \times 10^6 \text{ m}^3/\text{d}\)

Plant Footprint \((\sim 3 \text{ hectares})\)

Coagulants

Mixing \rightarrow Flocculation \rightarrow Dissolved Air Flotation \rightarrow Filtration \rightarrow UV

Backwash

\(\text{Cl}_2, \text{F}^-, \text{PO}_4^{3-}, \text{NaOH}\)

Flocculation Design: 2 stages, total detention time of 5 min

Nominal Loading of 15 m/h

Slide from William Becker, Hazen & Sawyer
HIGH RATE DAF

• Various Companies have developed high rate DAF processes
  – Purac Ltd. Based on UMass Research and other Research in Sweden
  • Developed DAFRapide®
    – Short Floc Times
    – High Flotation Rates
      » System comes without tubes or plates or has been used with plates in some industrial high rate DAF applications
      » Plates and tubes: increase clarification area; same concept as in plate settling

Photo and schematic from Purac
HIGH HYDRAULIC LOADING DAF PROCESSES

- Leopold (new in 2005): Clari DAF™
  - Numerous Pilot Studies have been done and are underway
- Rictor Oy – Finland. Developed high rate DAF. (INFILCO-DEGREMONT – Licensed from Rictor as AquaDAF™)
  - Available through Degremont in USA and Canada as AquaDaf™
  - Plants in Tampere (Finland), elsewhere in Europe, and USA (e.g., West Nyack, NY)

Tampere, Finland (30-40 m/hr)
HIGH RATE DAF PLANT

West Nyack, New York, USA (30 m/hr)

(Courtesy of Bob Raczko, United Water)

Empty DAF tank. Orifice Plate Floor for uniform flow discharge at bottom.
SEPARATION ZONE HYDRAULICS

• One cannot simply compare rise velocities of bubbles and aggregates to the hydraulic loading (vertical velocity) in the separation zone
  – Recall rise velocities of 20 m/h versus hydraulic loadings of 20 to 40 m/h

• Must consider the hydraulic flow patterns through the Separation Zone
  – Evidence of stratified flow patterns
MODIFICATION OF SEPARATION ZONE THEORY

\[ v_{fb} \geq v_{sz-hl} = \frac{Q + Q_r}{A_{sz}} \]

\[ v_{fb} \geq v_{\text{clar}-sz} = \frac{Q + Q_r}{3(A_{sz})} \]

For example:

- If the hydraulic loading (based on footprint) is 40 m/h
- What we want is the clarification loading that considers the increased separation area from stratified flow. Here, for example, it would be 3 times the footprint area. This yields a clarification loading of 13.3 m/h.
- Thus, can separate free bubbles and floc-bubble aggregates with rise velocities of 13.3 m/h or greater.

- Analogous to plates in sedimentation tanks
CONCLUDING STATEMENTS (1)

1. High rate DAF plants have been developed in the last 10-15 years. A common feature of these plants is high hydraulic loading rates of 20 to 40 m/h. Some systems also make use of short pretreatment flocculation times. Both of these developments have reduced the footprint and construction costs of DAF facilities.

2. Contact zone models predict the collisions and attachment of flocs to bubbles. The models predict greater efficiency with increasing floc size. However, efficiencies of nearly 99% are achieved with flocs of 20-30 µm.

3. For reservoir supplies which typically contain particles smaller than 20 µm, most particles are less than a few micrometers, a good strategy is to design flocculation tanks with short detention times with the goal of producing *pin point* sized floc.

4. There are considerable pilot data to support the use of short flocculation times. Several full-scale plants have been built in the last 10 years with detention times of 10 min or less. The New York City plant is under construction with a total detention time of 5 min.

5. Rise velocities of free bubbles of 100 µm are about 20 m/h; lower for cold waters. Floc-bubble aggregates rise rates are about 20 m/h for single bubble attachment to flocs of 50 µm or less.
CONCLUDING STATEMENTS (2)

6. As flocs increase in size, the aggregate rise rate decreases unless there is multiple bubble attachment. Multiple bubble attachment is required for flocs > 100 µm to achieve rise velocities of 10 to 20 m/h.

7. The flow in high rate systems can achieve a stratified flow structure effectively increasing the clarification area. This can explain how DAF tanks with loading rates of 20 to 40 m/h can perform well and remove free bubbles and aggregates with lower rise rates.

8. This consideration of stratified flow increases the clarification area while maintaining a small footprint.

9. Most high rate systems rely on the improved flow structure, improved supernatant withdrawal, and slightly deeper tanks. One system can have plates installed to increase the clarification area; it has been used in some industrial applications.
My Home Town: Deerfield, MA USA