Air Lubrication Drag Reduction on Great Lakes Ships

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Outline

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2. Air Lubrication Techniques
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    2. ALDR
    3. PCDR (& MWCDR)
3. Energy Cost Benefit
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5. Summary

Background

- The use of “air lubrication” has been the goal of naval architects for many years (patents from the 1800’s).
- “Stepped Hulls” have been employed on planing craft and amphibious aircraft since the 1920’s.
- But, gas injection for drag reduction has found practical application on ***high-speed underwater objects***.
- And, its use on ***surface ships*** is under active development.

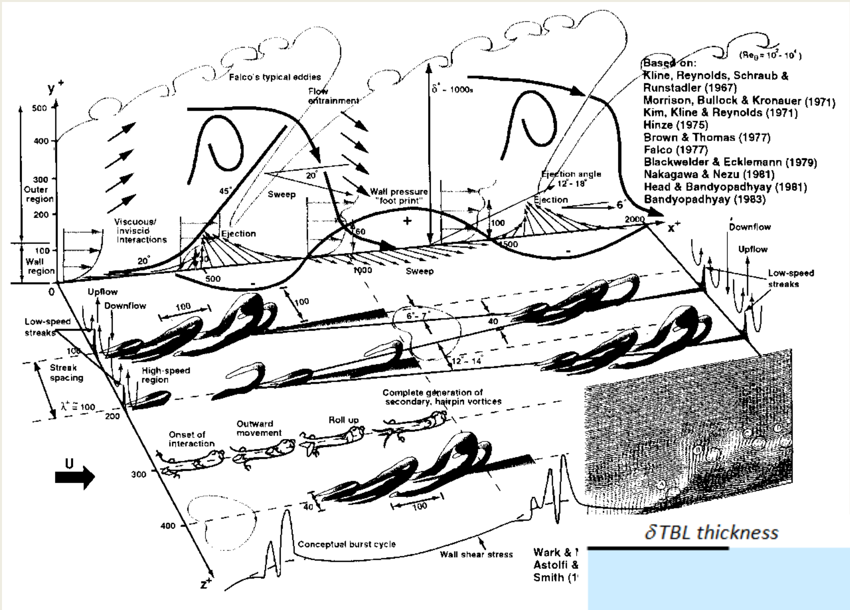
Potential Drag Reduction Benefits

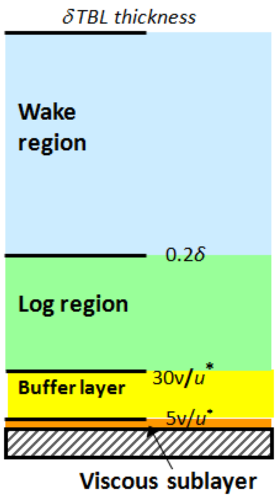
- *Reduced fuel usage & cost*
- *Increase ship performance*
- *Reduce CO_2 and other emissions (particulates, NO_X and SO_X).*

1 Frictional Drag – A Brief Review

- Velocity of the fluid on the surface is same as the velocity of the surface due to no-slip condition
- Momentum transferred from free stream to near-wall-region by structures in the boundary layer and shear

- Proven ways to reduce frictional drag:
  - **Reduce density or viscosity of fluid (air)**
  - Alter the momentum transport in the boundary layer (air or polymers)
  - “violate” the no slip condition (encountered in MEMS scale devices)





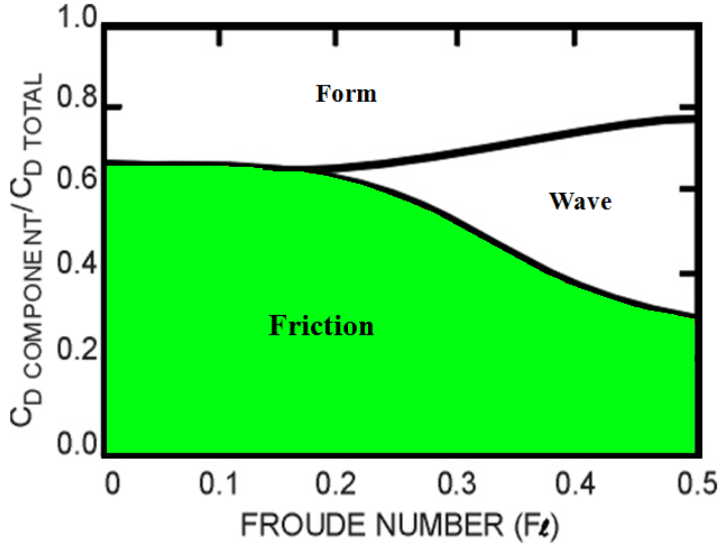
Viscous lengths of order 2 to 5 microns

1.1 Frictional Drag Reduction (FDR)

- For a ship, frictional drag accounts for ~60% of the resistance when $Fr < 0.2$

For a ship of a given length $Fr = 0.2$ corresponds to:

L [ft]	*U* [knots]
330	12
660	17
1000	21



Components of ship resistance.

Froude number is based on the ship's length, $Fr_L = U/(gL)^{1/2}$

- To achieve FDR, various techniques have been proposed
  - hydrophobic and compliant coatings, polymer injection, wall oscillations, **air lubrication**, etc.

Air Lubrication Drag Reduction

Various air lubrication drag reduction techniques:

- Bubble Drag Reduction (BDR)
- Air Layer Drag Reduction (ALDR)
- Partial Cavity Drag Reduction (PCDR)

- **Ongoing research in USA, EU*, Japan* and South Korea** *also sea-trials

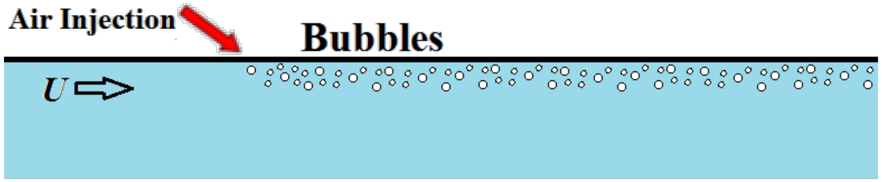
- **Ship could save between 5% and 20% of its overall fuel expenditure**

(Others have estimated up to 30% savings potential)

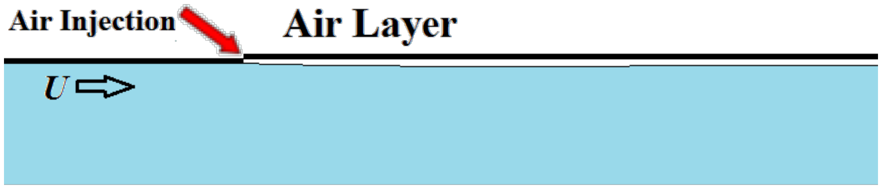
Stena AirMAX prototype.

2. Air Lubrication FDR Techniques

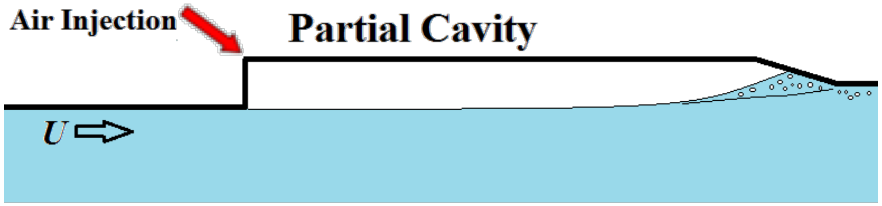
- Bubble Drag Reduction (**BDR**)
  - Small bubbles injected into the boundary layer
  - Dispersed bubbles act to reduce the bulk density and to modify turbulent momentum transport.



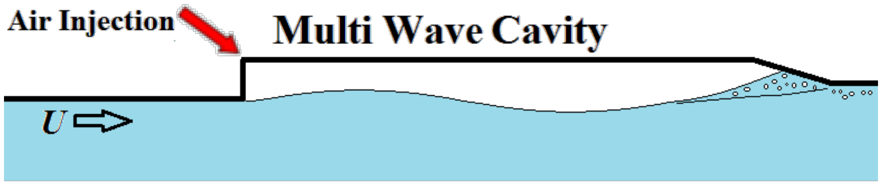
- Air Layer Drag Reduction (**ALDR**)
  - Gas creates a lubricating layer between hull & liquid
  - Surface devices may be used to create TBL flow separation upstream of the cavity.
  - No effort is made to re-circulate the injected gas



- Partial Cavity Drag Reduction (**PCDR**)
  - Gas creates a lubricating layer between hull & liquid
  - The cavities do not extend beyond the ship hull
  - Gas is injected into the partial cavity to make up for that which is lost to entrainment
  - with proper cavity design, the gas loss is minimized.



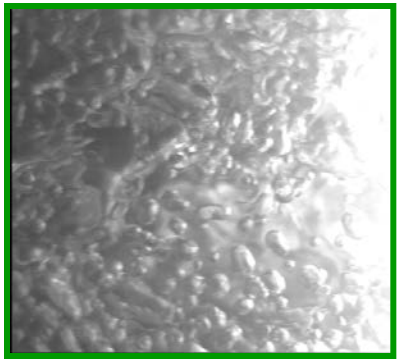
  - **Multi Wave Cavity Drag Reduction (MWCDR)**
  - Similar to PCDR, except one cavity accommodates multiple wave lenghts

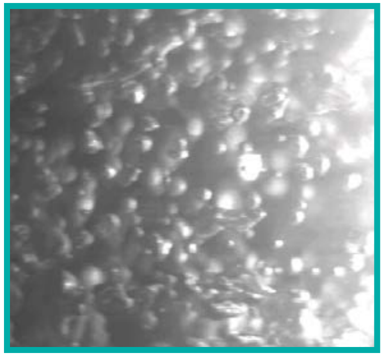


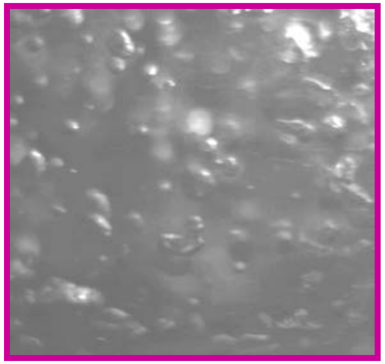
2.1 Bubble Drag Reduction (BDR)

- Sometimes referred to as **micro bubble drag reduction**, when the bubbles are very small compared to the boundary layer thickness/wall units

- Injection of small gas bubbles into the TBL.
- FDR results from
  - Modification of effective viscosity?
  - Density changes?
  - Turbulence modification?
  - Bubble splitting?
- **Studied primarily at the laboratory scale.**







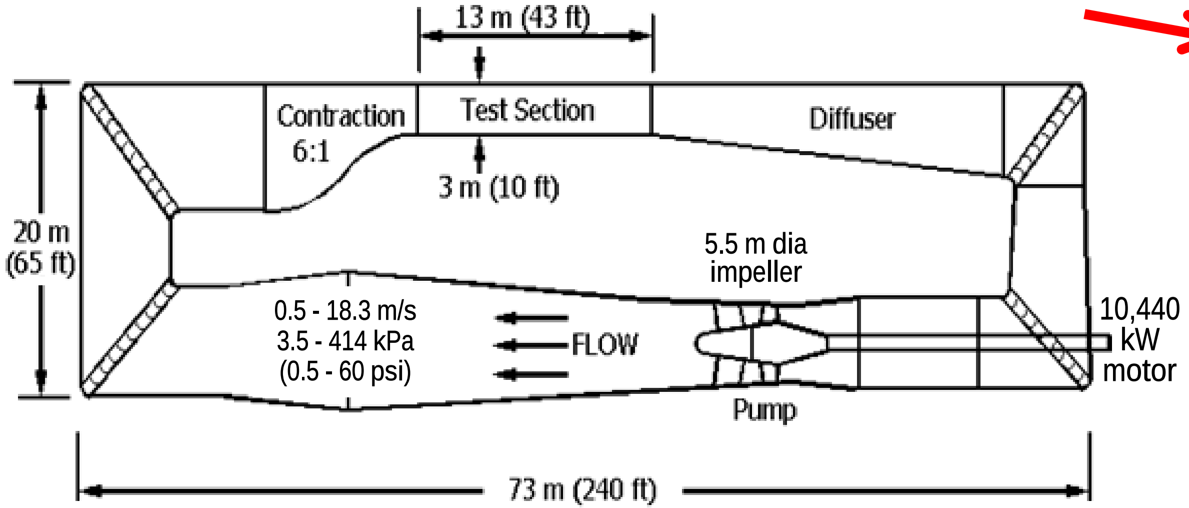
- How much gas injection is needed?
- What is the maximum possible FDR?
- How long will it persist?
- How important is the bubble size? Salt water? Injection method?

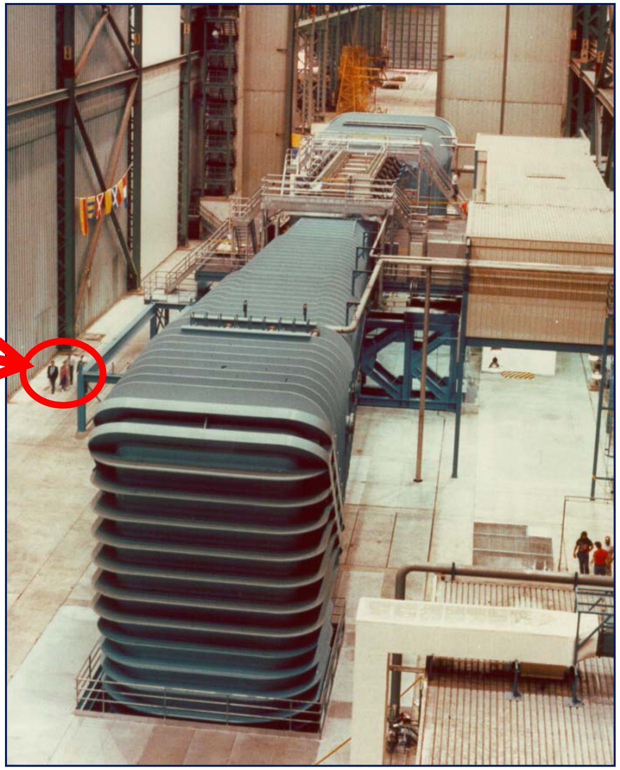
Facility Used in Previous Experiments - The Large Cavitation Channel (LCC)

US Navy's W. B. Morgan Large Cavitation Channel, Naval Surface Warfare Center, Carderock Division – Memphis Detachment

LCC is the world's largest water tunnel.

=> Experiments at near real-world scales while remaining in controlled laboratory conditions.



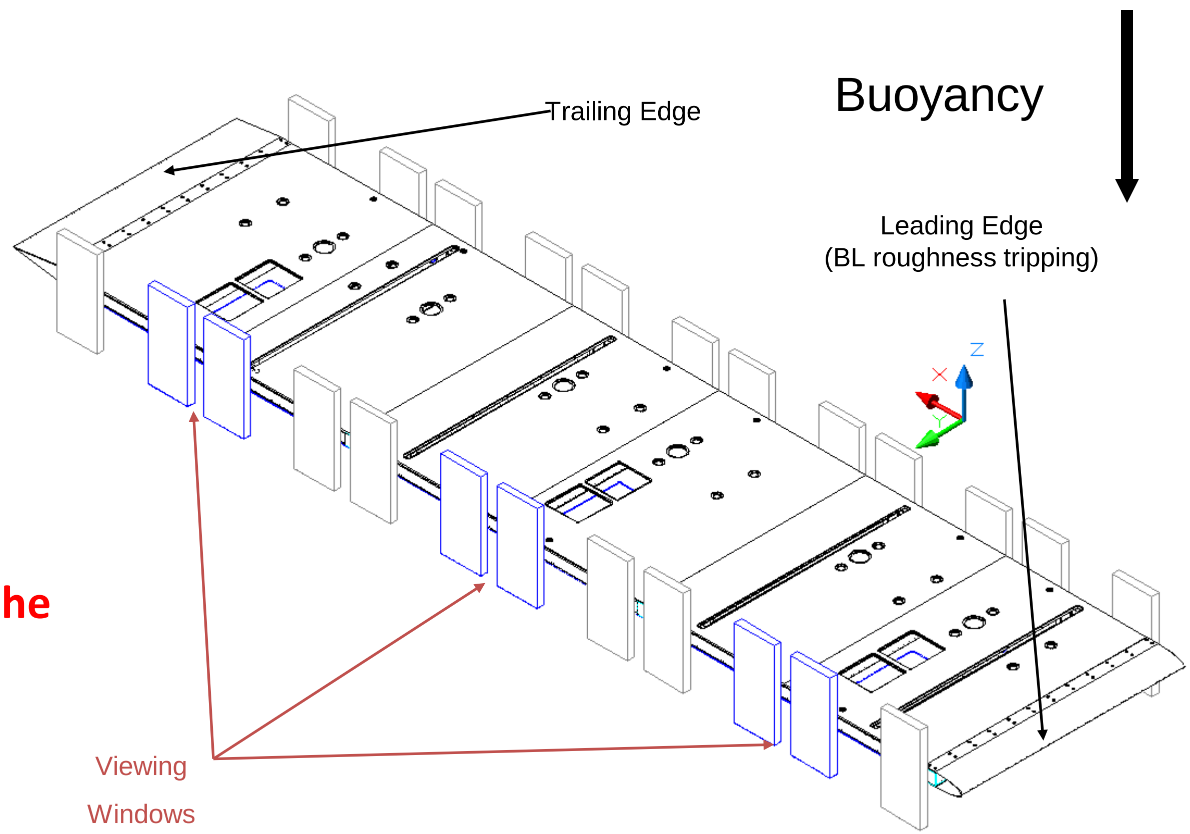


UM's Bubble Drag Reduction Experiments

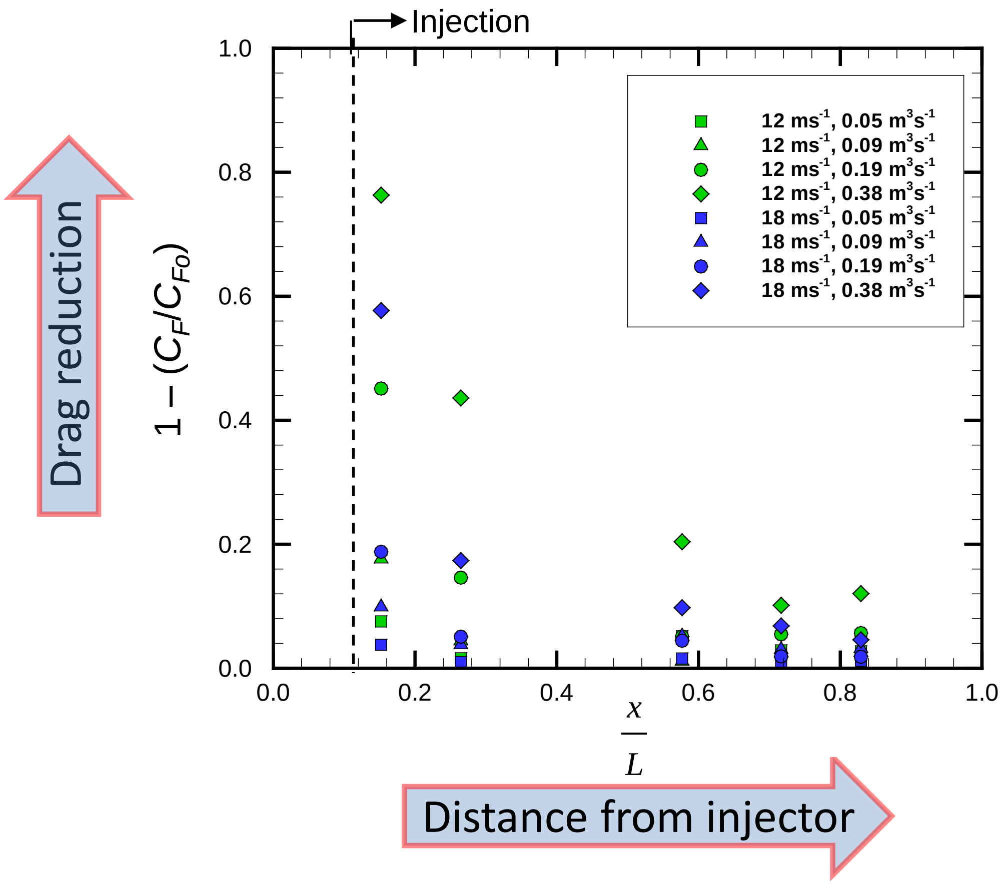
- Large flat plate
- Leading edge: 4:1 ellipse
- Trailing edge: truncated wedge
- Dimensions
  - 10 ft (3.05 m) wide
  - 42.25 ft (12.9 m) long
  - 7.25 in (18.4 cm) thick

- **Bubbles injected below the plate ("plate down")**

DARPA and ONR Support



Persistence of Drag Reduction



FDR was mostly lost in 1 to 2 meters at higher speeds.

Bubbles Move Away From the Wall

A Sample Image from a bumped-out prism: The image shows a “liquid layer” at X = 5.94 m at 12 m/s 200 SCFM injected from slot 1 at X = 1.32 m) where roughly 10% drag reduction was observed.

Note a nearly bubble free region within a few hundred microns of the wall where there are no air-water interfaces to scatter the light.

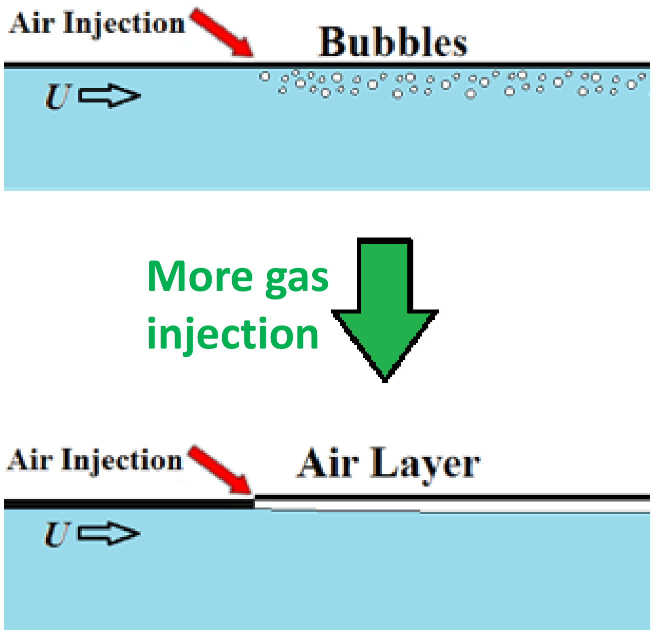
Sea-Trial on the *Olivia Maersk*

- BDR was attempted on the Olivia Maersk
- <u>No significant</u> net energy savings
- Besides the potential BDR persistence issues, it is critical to supply enough gas to get an effect.
- In this particular trial, the more passive "Winged Air Induction Pipe " air injection did not produce the expected outcome >20 knot speed
- **<u>It cost energy to save energy with BDR/ALDR</u>**
- The design of the FRD must be good to yield a positive outcome
- Also, air lubrication techniques are more ideally suited for ships with large flat bottoms …high length-to-beam ratio also beneficial

The Olivia Maersk (*L* = 238 m) was equipped with an air lubrication system based on "WAIP" technology developed in Japan.

2.2 Air Layer Drag Reduction (ALDR)

- The test model was a 12.9 m long and 3.05 m wide flat plate
- A ½” tall backward facing step was used to help the air layer form initially at the injector
- Air or gas create a high void fraction gas layer between the hull and the free-stream liquid flow.
- No effort made to re-circulate the injected gas



Air Layer Drag Reduction

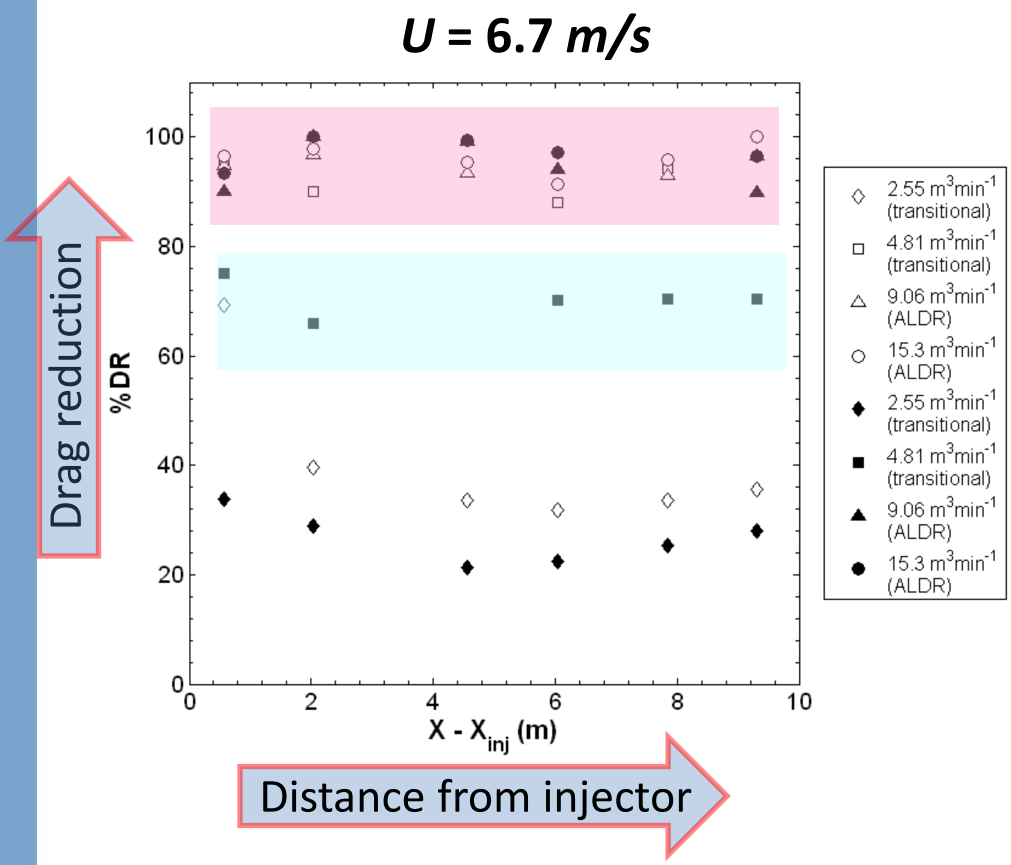
With enough gas flux, the injected gas bubbles coalesce into a film:

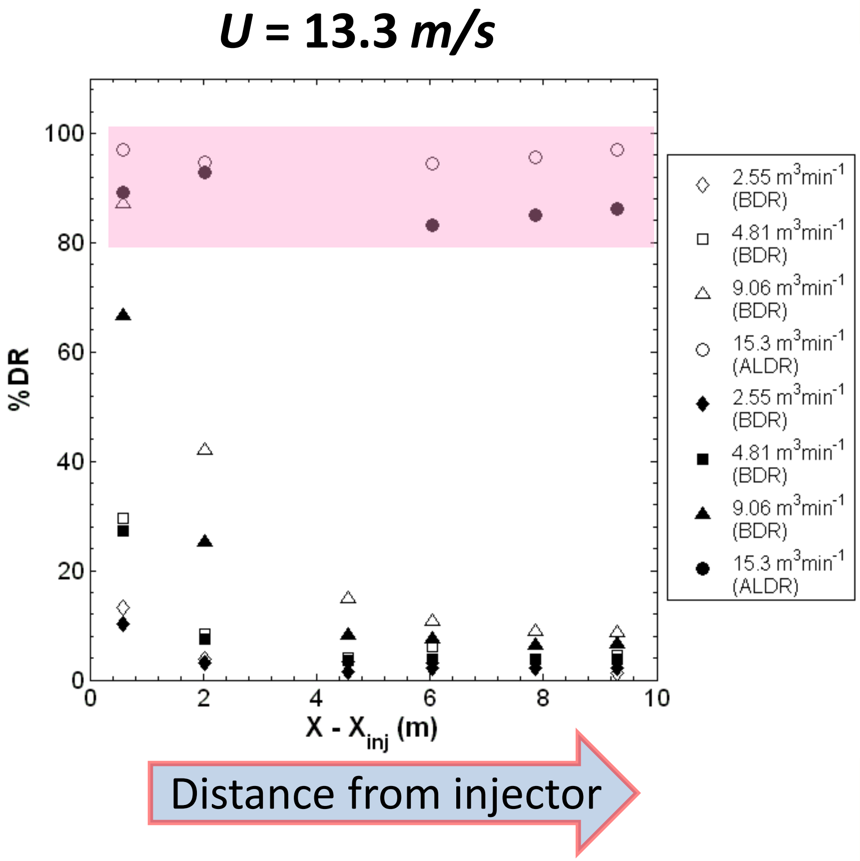
View before air injection. Start of air injection. Continuous air layer.

Movie available in a separate file.

Persistence of ALDR

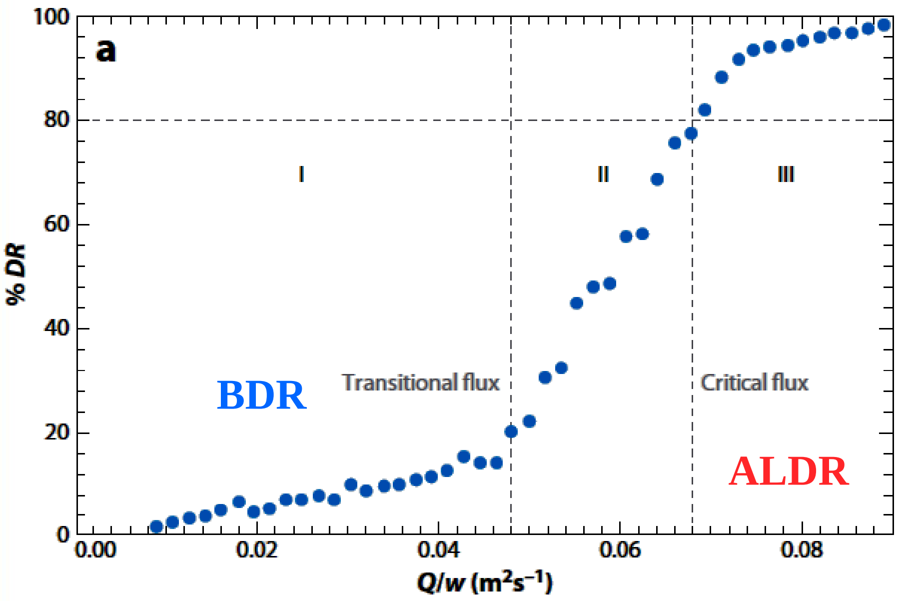
Percentage drag reduction vs. distance from injector





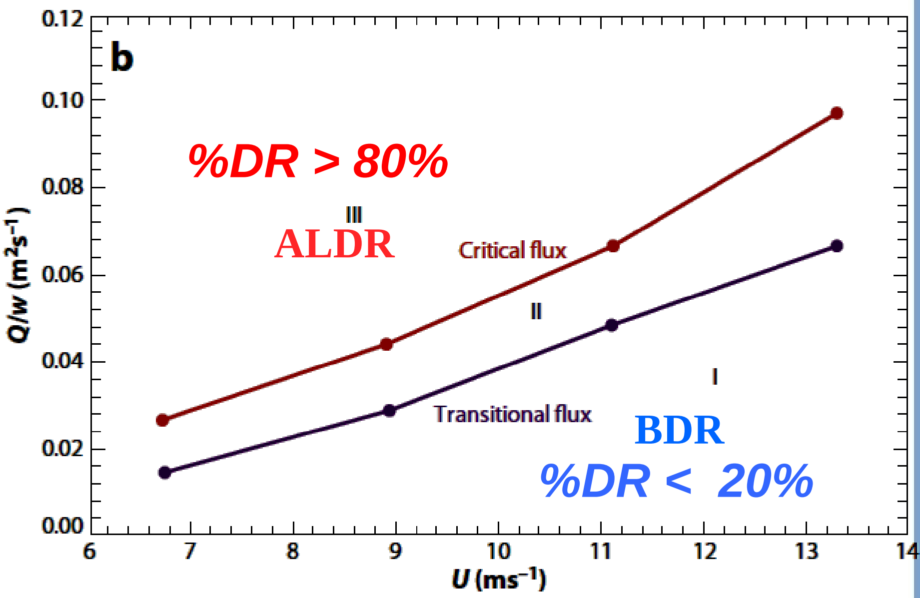
Required Air Fluxes for ALDR

Drag reduction vs. air flux



The gas flux required to transition from bubble to air layer drag reduction

"Critical" flux vs. speed



Transitional and critical air fluxes.

(The percentage of drag reduction was measured 6 m from the injector)

Sea-Trial on the *Pacific Seagull*

Reported by Hoang et al. (2009)

Length over all	126.6 m
Length between perpendiculars	120.0 m
Breadth	21.4 m
Depth	9.9 m
Draft (designed full)	7.1m
Draft (Full)	7.0 m even
Draft (Ballast)	4.0 m (trim by stern 1.5 m)
Speed (service)	12.4 kt
Main engine	3883 kW x1
Propeller	4 blades CPP
Diameter of propeller	3.6 m

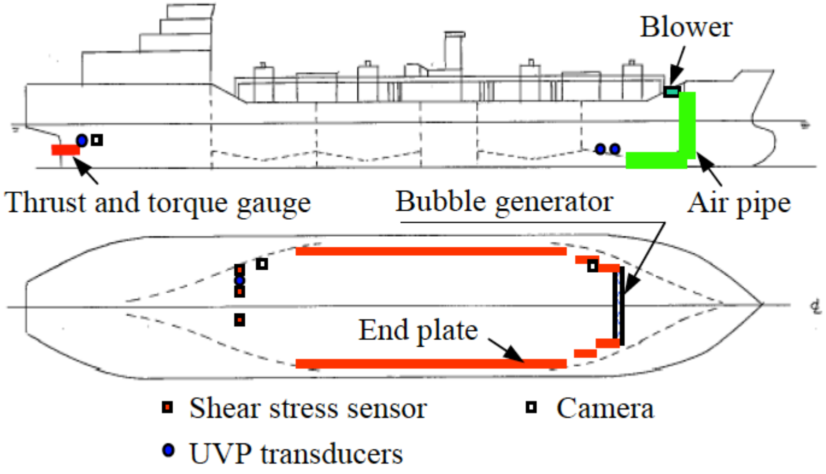
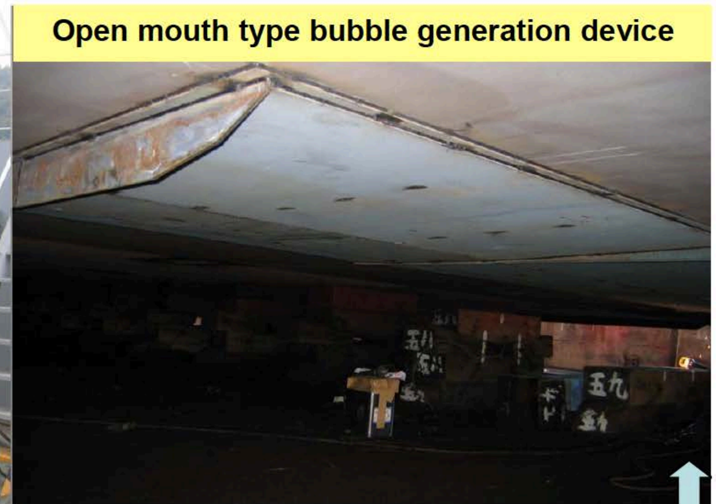
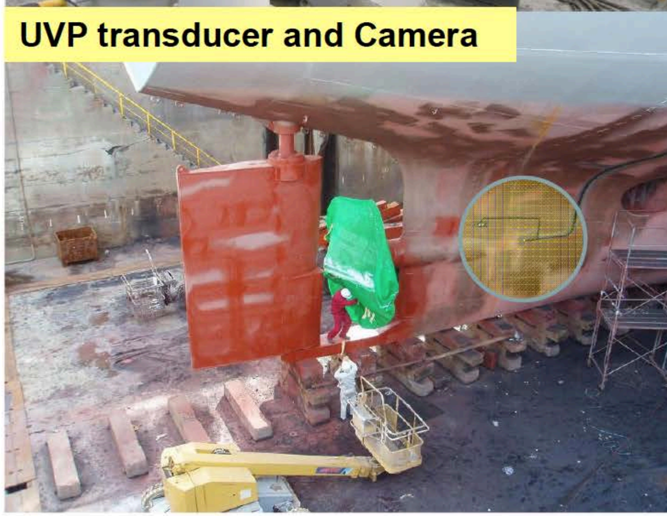
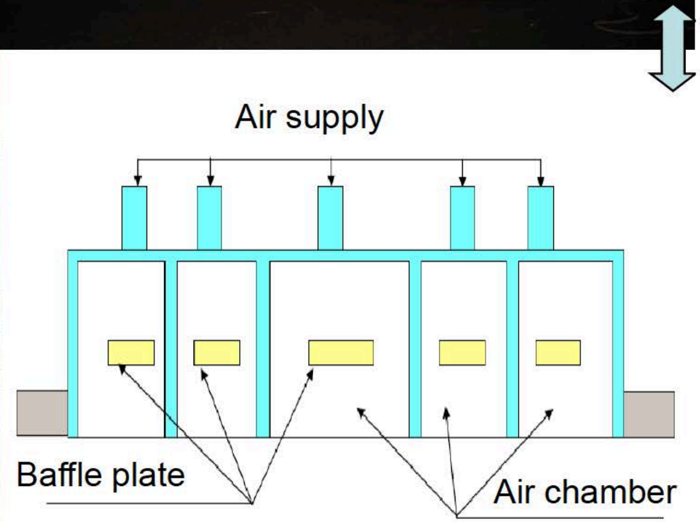


Fig. 1 General arrangement of equipment

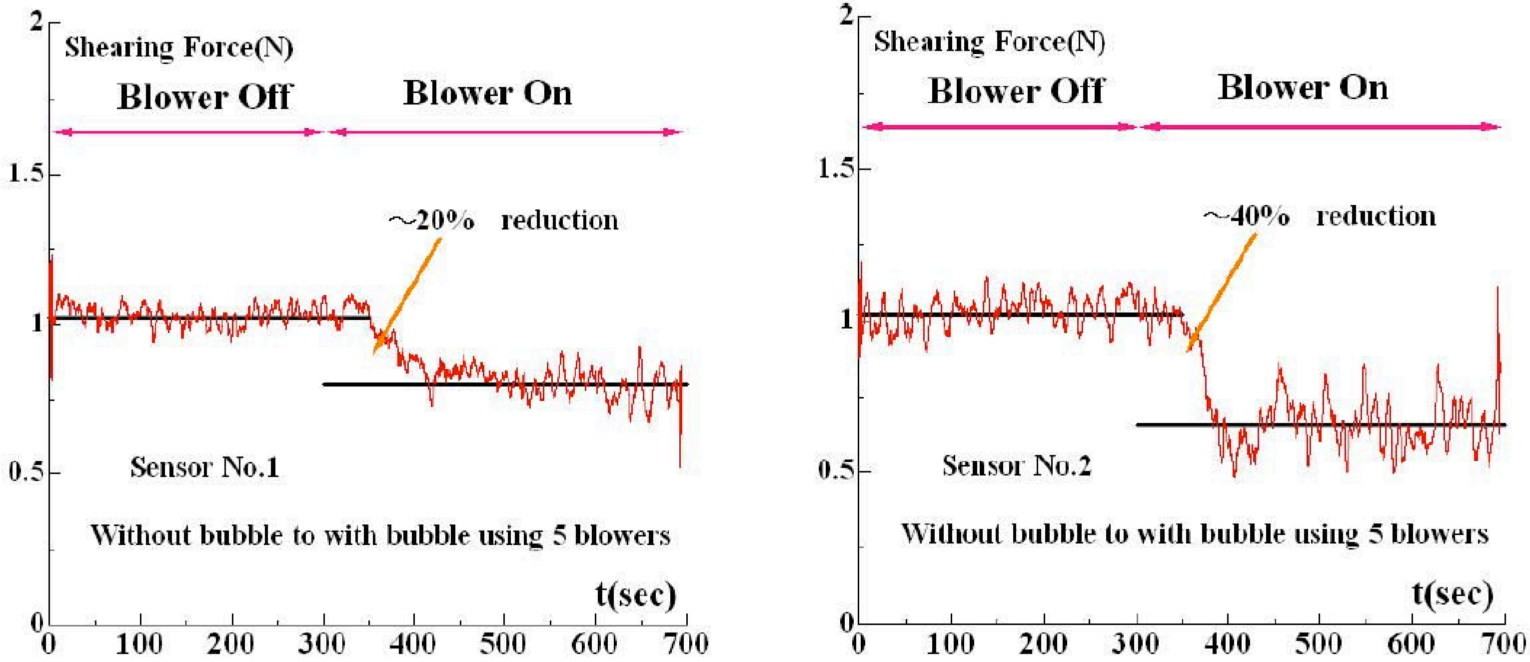

Blower


Open mouth type bubble generation device


UVP transducer and Camera


Air supply
Baffle plate
Air chamber

Local Shear Stress Measurements on the Hull



- **Net fuel savings of 10% (ballast) and 5% full-load reported**

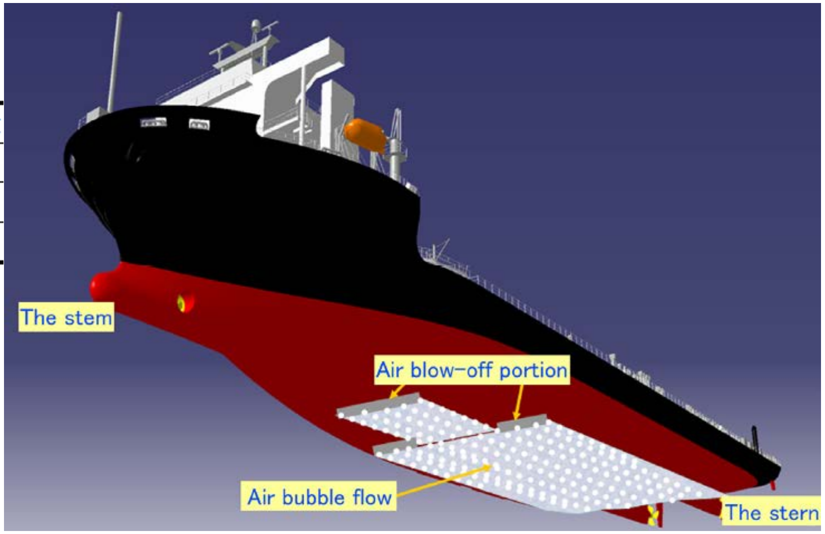
Note: Air volume fluxes not reported.

Sea-Trial by Mitsubishi Heavy Industries

Reported by Mizokami et al. (2010)

Length over all	162 m
Width	38 m
Depth	9.0 m
Draft	4.5 m / 6.37 m
Design speed	13.25 kt
Main engine	3,218 kW x 2
Propeller	CPP

q^+	Horsepower reduction	Blower power consumption	Net energy-saving effect
7 mm	680 kW	211 kW	469 kW (12%)
5 mm	530 kW	143 kW	387 kW (10%)
3 mm	380 kW	72 kW	308 kW (8%)

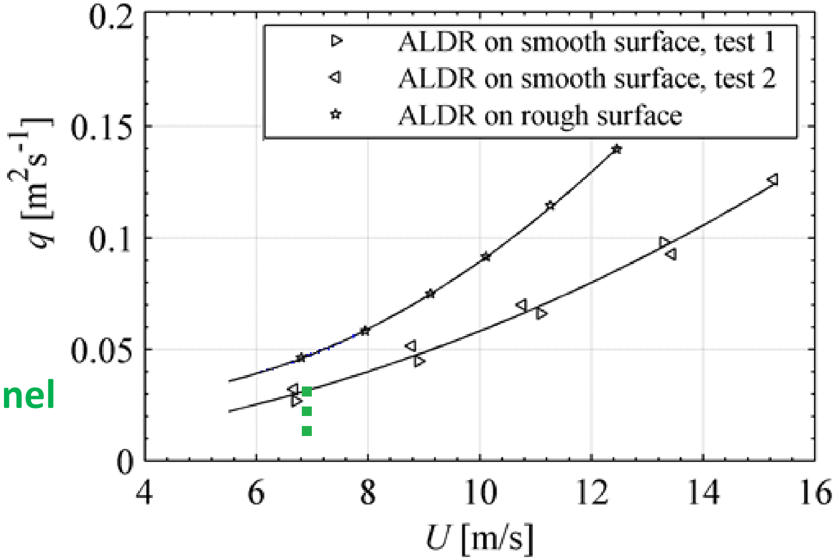


- **Obtained 8-12% net energy savings**

ALDR Observations

- ~80% drag reduction persisting for the entire length of the model
  Would the layer persist indefinitely without additional gas?
- A clear separation line helps the AL for initially
- Influence of moderate steady flow perturbations was minimal, with forced separation line. Would a stronger perturbations break the air layer?
  How would an air layer behave in heavy seas?

- **5 to 10% and 8 to 12% net fuel savings reported from sea-trials**
  - **Figure on the right shows the approximate air fluxes from to Mitsubishi trial compared to our results from the Large Cavitation Channel**



2.3 Partial Cavity Drag Reduction (PCDR)

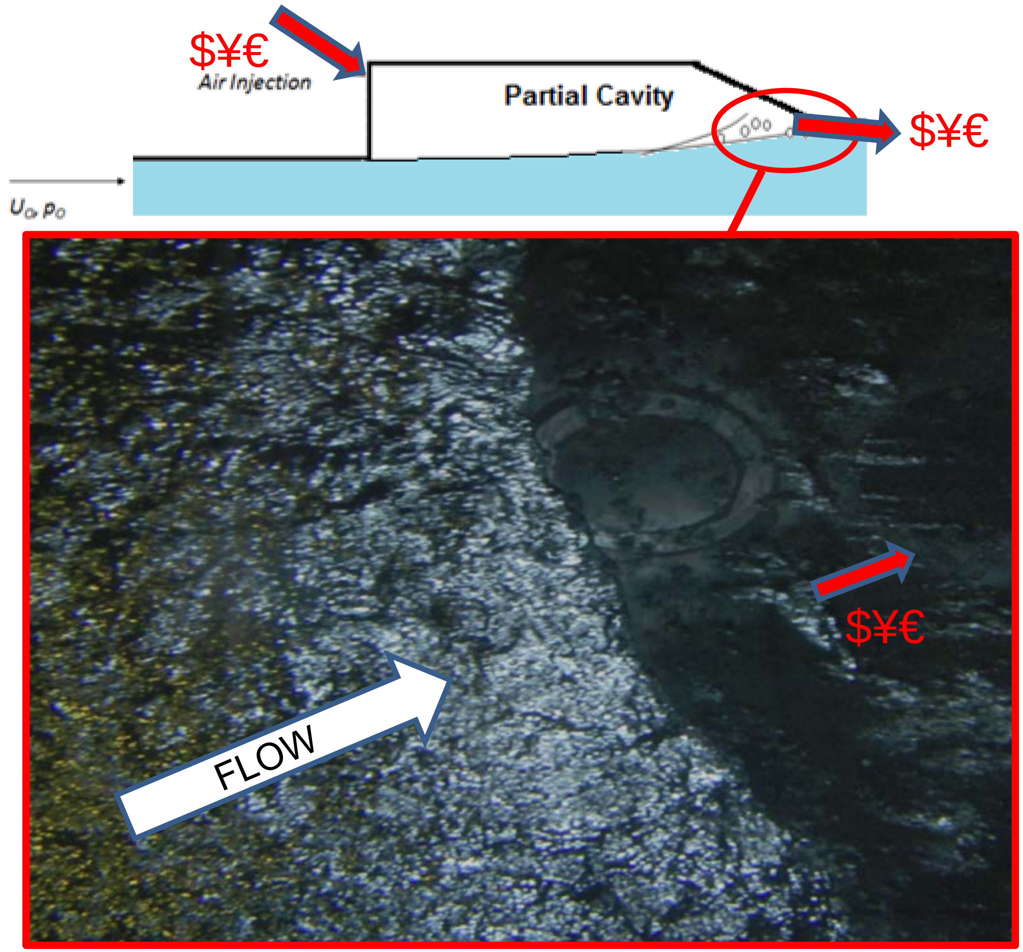
- Gas creates a lubricating layer between hull & liquid
- Gas is injected into the partial cavity to make up for that which is lost to entrainment
- With proper cavity design, the gas loss is minimized.

The 15-m long ship prototype Stena Airmax – a prototype that is part of a project in which an "air cushion" is being tested to investigate to what extent it reduces the friction between the hull and the water.

Research Objectives *Specific to PCDR*

- **Minimize gas requirements with proper cavity closure**
  - **Ideal length of cavity vs. speed**
  - **Shape of the closure surface**

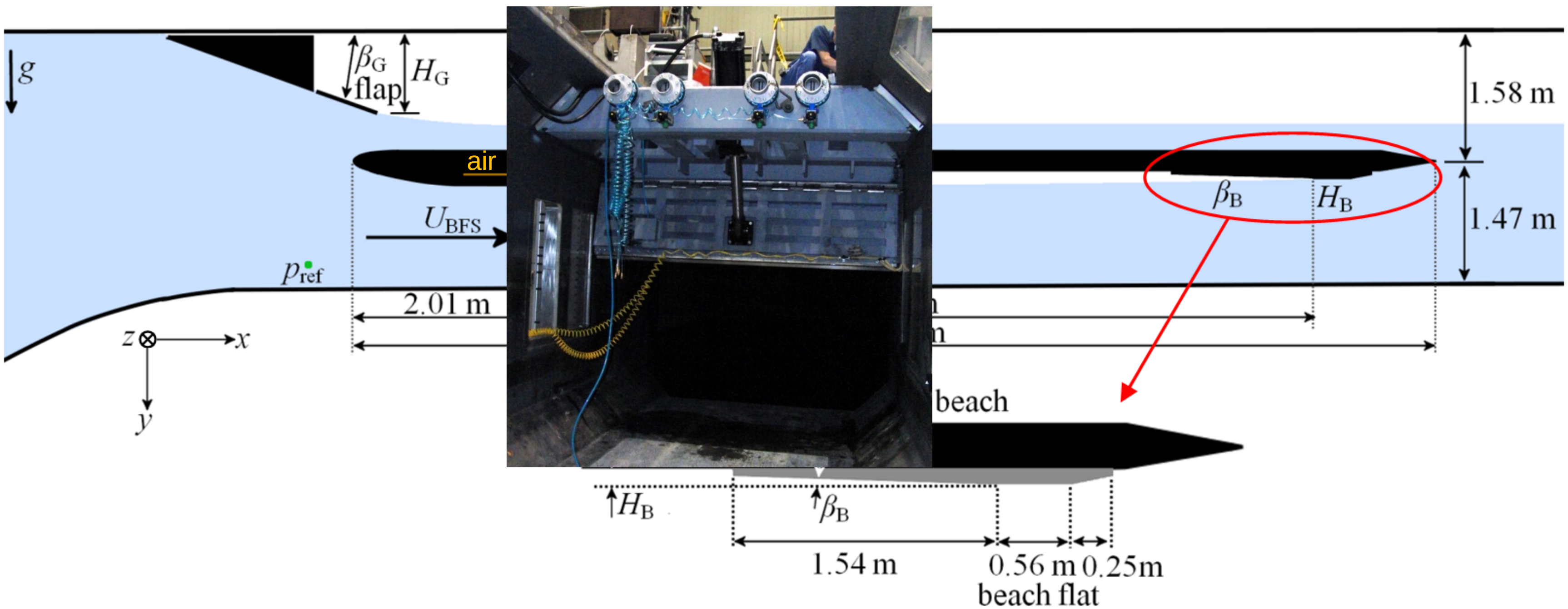
- **Suitability for ships and barges of the Great Lakes?**
  - **Flat bottoms**
  - **Operating speeds in range testes**
  - **Soo locks limit draft**



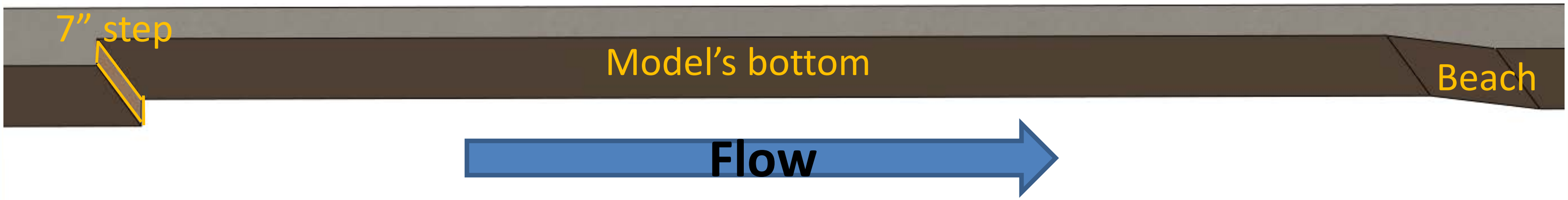
Cavity closure at the beach as viewed from below.

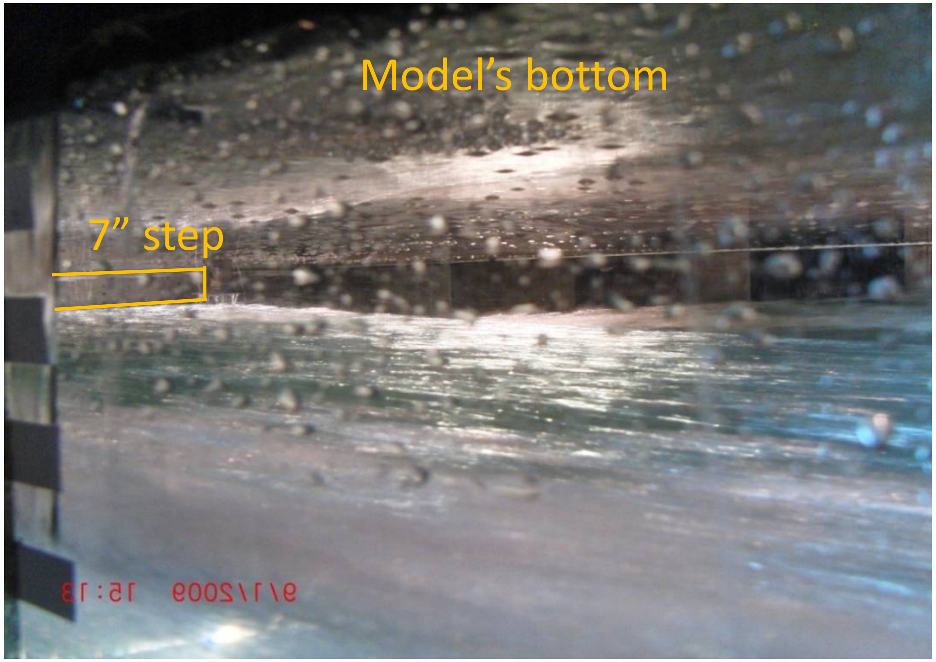
The Test Model

- 12.9 m long and 3.05 m wide flat plate with
- 17.8 cm (7 in) tall backwards facing step, BFS, 2 m from the leading edge
- A "*beach*" to close the cavity near the trailing edge

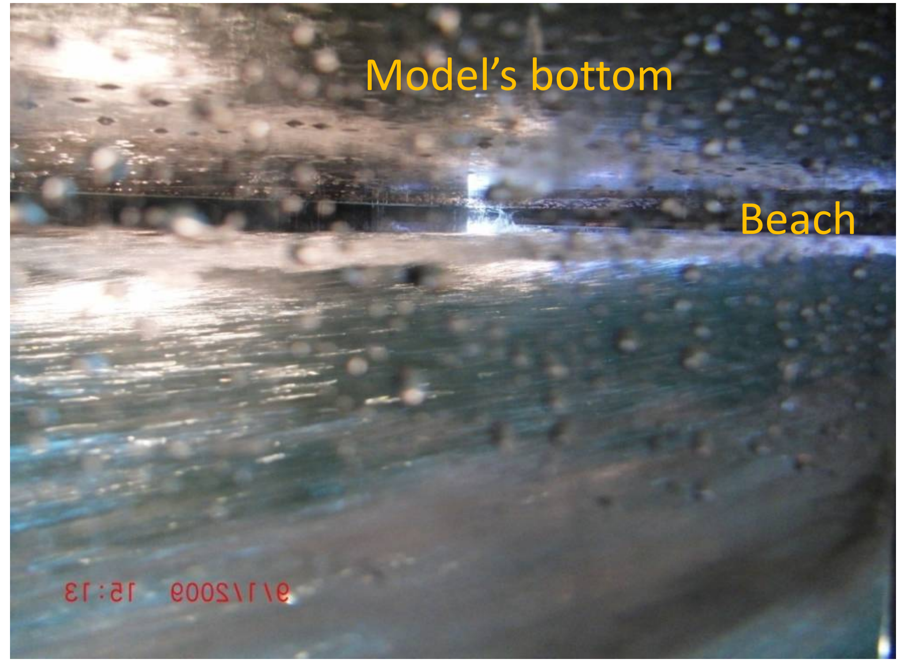


Side View Into the Cavity





Looking upstream



Looking downstream

Air Flux Requirements – PCDR in Steady Flow

The minimum gas flux, q, required to establish and maintain the cavity as a function of the Froude number.

Maybe possible to have multiple good operating regions => multi wave cavity.

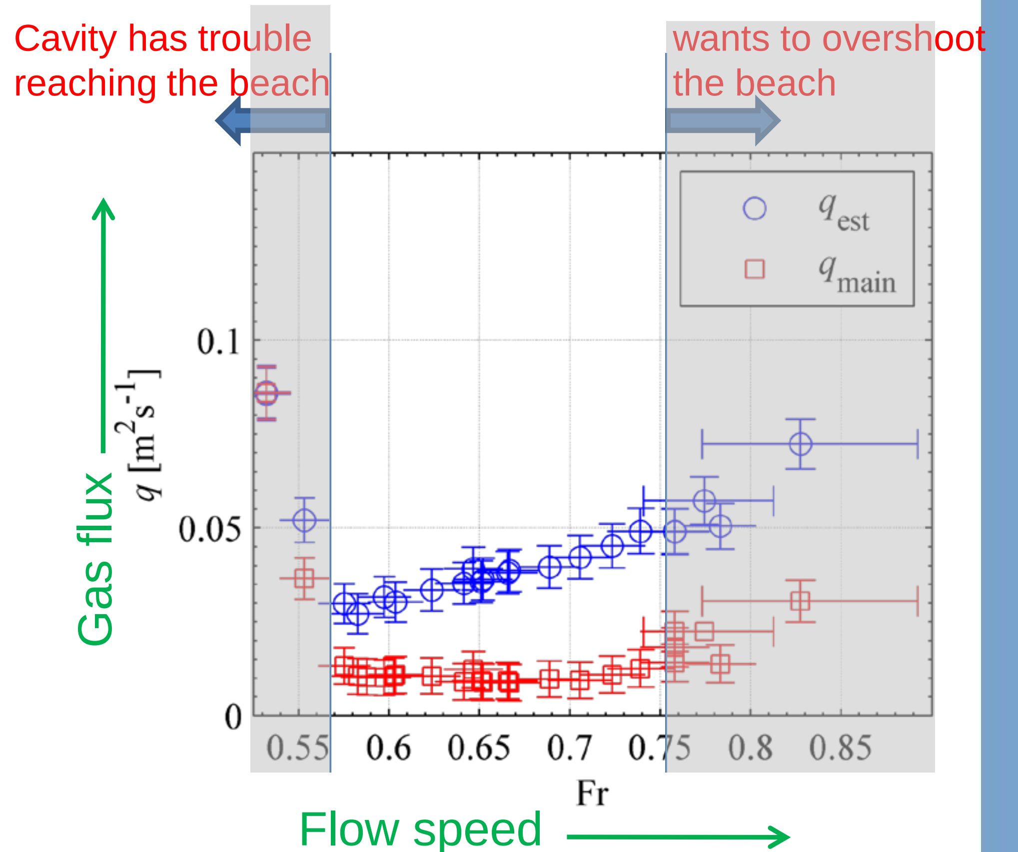
$$q = \frac{Q_c}{W} \qquad Fr = \frac{U}{\sqrt{gL_c}}$$

Q_c - gas volume flow rate at the cavity pressure (m³/s)

W - width of the model (3.05 m)

U - flow speed at BFS (m/s)

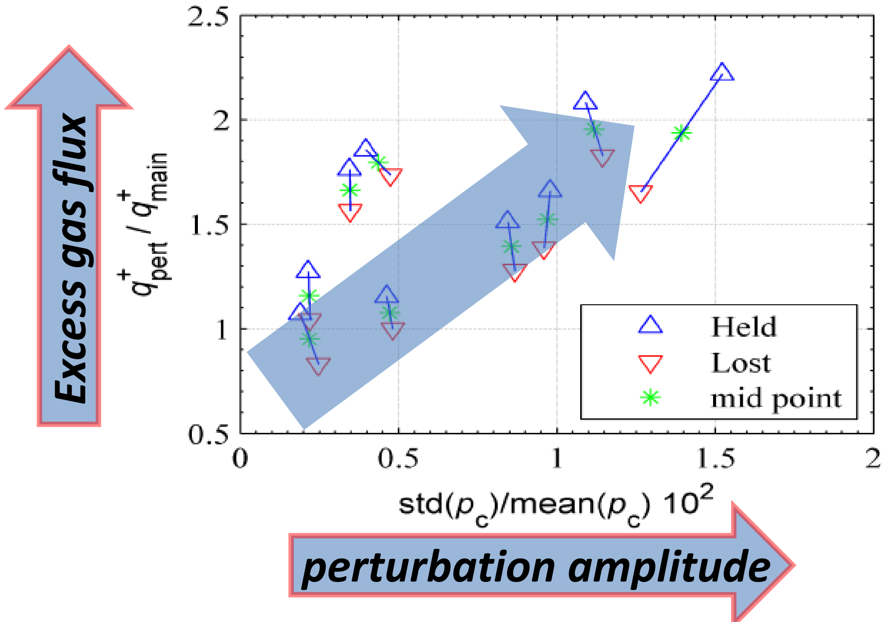
L_c – cavity length (9.25 m)



Perturbed PCDR Flow

- The gate motion created large disturbances.
- Pressure oscillated up to ±15% and velocity up to ±5%.
- Led to rapid changes in the cavity length and pressure.

Excess gas flux to maintain cavity vs. perturbation amplitude

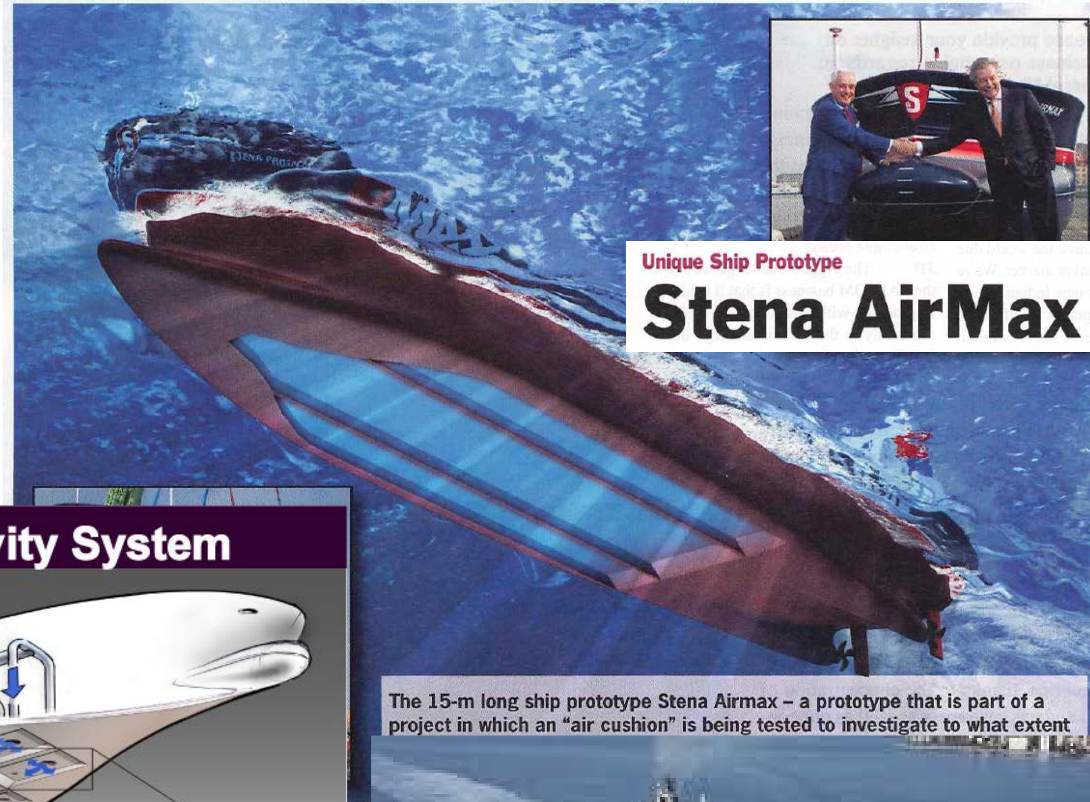


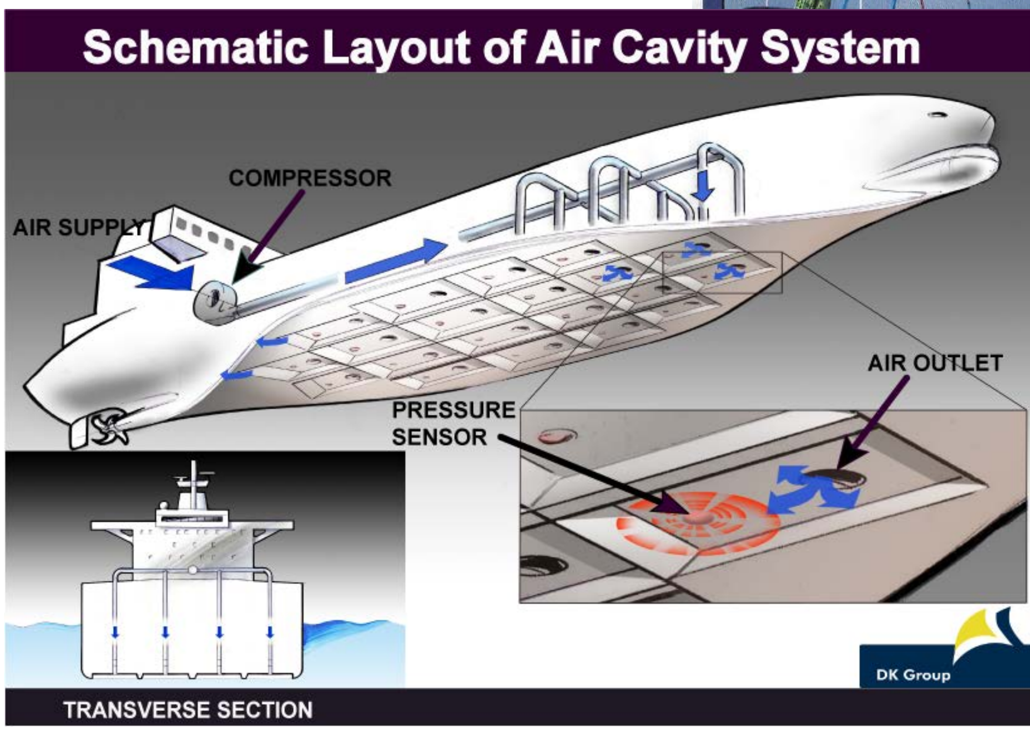
Larger the perturbation, larger the excess gas flux required. ***(Was less than Q_{est})***

PCDR Sea-Trials

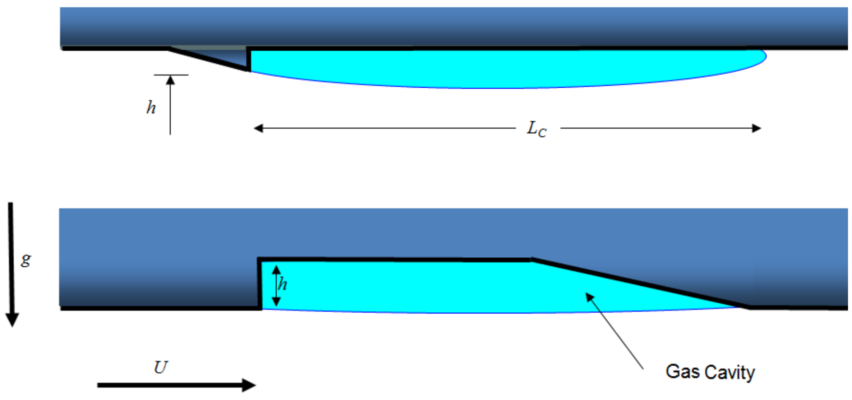
Both DK Group and Stena are conducting sea-trials.

To date, few published results.

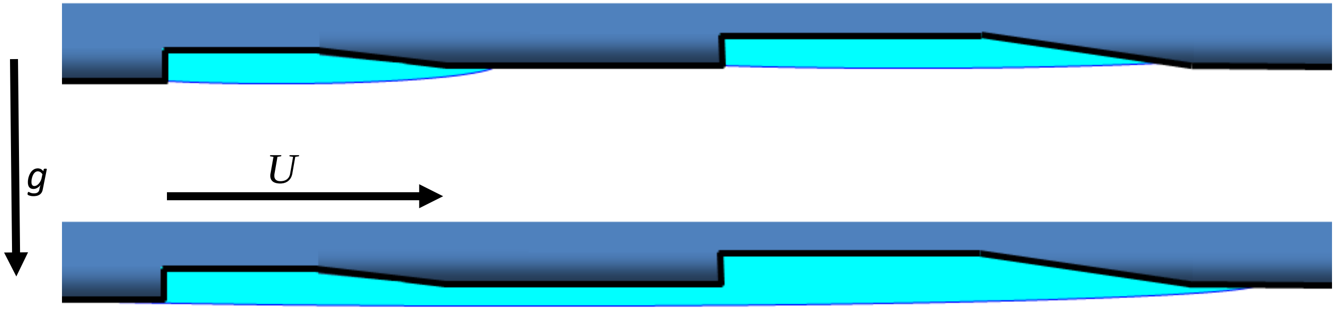




Single Wave vs. Multi Wave "Partial" Cavity



Or, cavity could be "multi-wave" and have several ranges.



Many of the PCDR concepts are based on work done in the USSR.

3. Energy Cost Benefit

- **We need to consider:**
  - **Fraction of the total resistance caused by frictional drag**
  - **Fraction of the wetted hull area that would be covered**
  - **Potential increase in form drag***
  - **Potential loss of propulsor efficiency due to air***
  - **Energy required to supply the air**

  *Highly ship specific and outside the scope of current work

- **The energy savings break-even point depends mainly on three parameters:**
  1. **draft, *d***
  2. **Air layer/cavity length, L_c**
  3. **and flow speed, *U***

Net Energy Savings

- Assuming *practically* all of the ship's energy consumption used for propulsion,
- the net energy savings possible can be estimated by considering the fraction by which drag could be reduced and the energy required to supply the compressed air

$$\frac{\%E_{savings}}{100} \approx \frac{\cancel{\Delta t} \cdot P_{saved}}{\cancel{\Delta t} \cdot P_D / \eta_{prop}} = \left[\frac{P_D f_{FD}}{\eta_{prop}} \frac{A_{AL}}{A_{wet}} \left(\frac{\%D_R}{100} \right) - \frac{P_{comp}}{\eta_{elect}} \right] \Big/ \left(\frac{P_D}{\eta_{prop}} \right)$$

P_D	Propulsive power required to overcome drag
f_{FD}	Fraction of resistance due to frictional drag
P_{comp}	Power required by the compressor to supply the air
η_{prop}	Propulsor efficiency
η_{elect}	Additional efficiency of producing electricity to compressor
A_{wet}	Wetted area of the hull
A_{AL}	Area covered by the air layer
$\%D_R$	Percentage drag reduction on the area covered by the air layer

Net Energy Savings

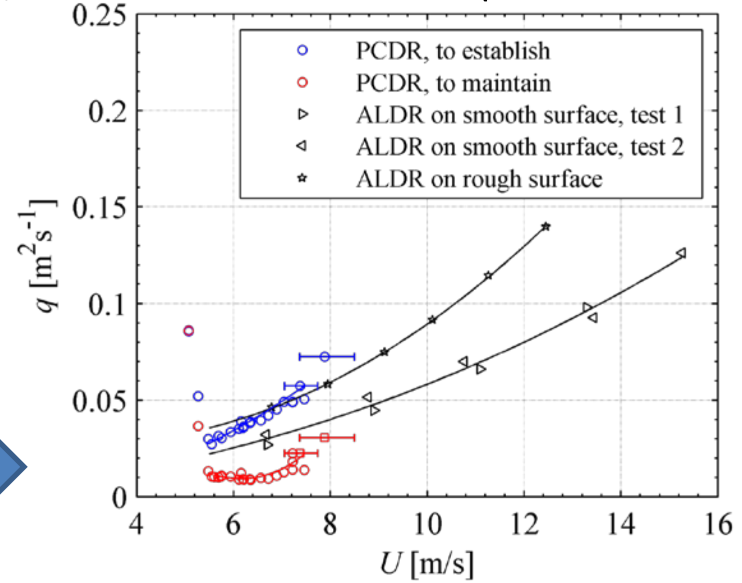
- From basic thermodynamic principles the power needed to compress a given mass flow of gas via a polytropic process is given by

$$P_{comp} = \frac{\dot{m}_g p_1 n}{\eta_c \rho_{g,1}(n-1)}\left(\left[\frac{p_2}{p_1}\right]^{(n-1)/n} - 1\right)$$

- Here the pressure p_2 depends of the ship's draft and piping losses
- The mass flow rate depends on the speed, draft, width of area covered (and specific air lubrication technique used)

$$\dot{m}_g = qW\frac{\rho_{g,1}p_2}{p_1}$$

- Where ***q* can be estimated from results of experiments presented earlier**

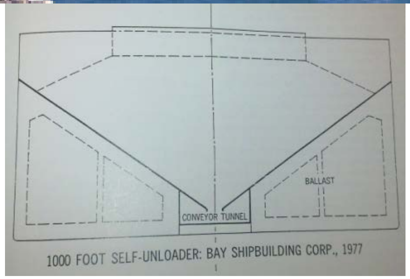


The solid lines are simple curve fits for $q^+(U)$ used in the calculations.

Example Calculations

Take a ship like the M/V American Spirit

L = 306 m, w = 32m at midsummer draft 8.8 m

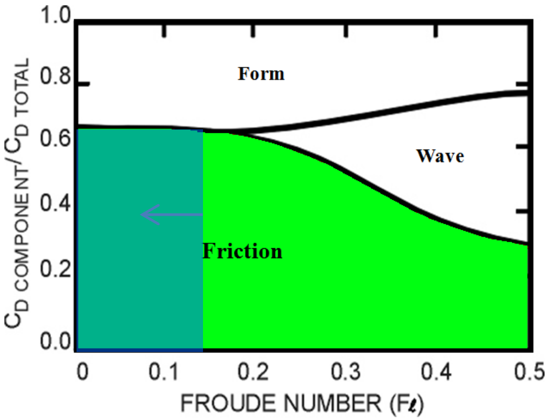


Assumptions:

- 7% of beam has curvature and 15% of length (bow to stern)
- 79% of the bottom is flat
- bottom is 62.6% of the wetted hull
- **49.5% of the wetted hull could be covered by AL**

- Top speed 7.5 m/s (~14.5 knots)
- $Fr_L = U/(gL)^{1/2} < 7.5 / (9.81 * 306)^{1/2} < 0.14$
- **Frictional drag ~ 60% of total drag**

- **For both ALDR and PCDR η_{FRD} > 80%**



Example Calculations

- Dividing the net power savings by power required without air lubrication yields percentage energy savings

$$\frac{\%E_{savings}}{100} \approx f_{FD}\frac{A_{AL}}{A_{wet}}\left(\frac{\%D_R}{100}\right) - \frac{P_{comp}\eta_{prop}}{P_D\eta_{elect}}$$

Where based on the approximate values from the previous slide

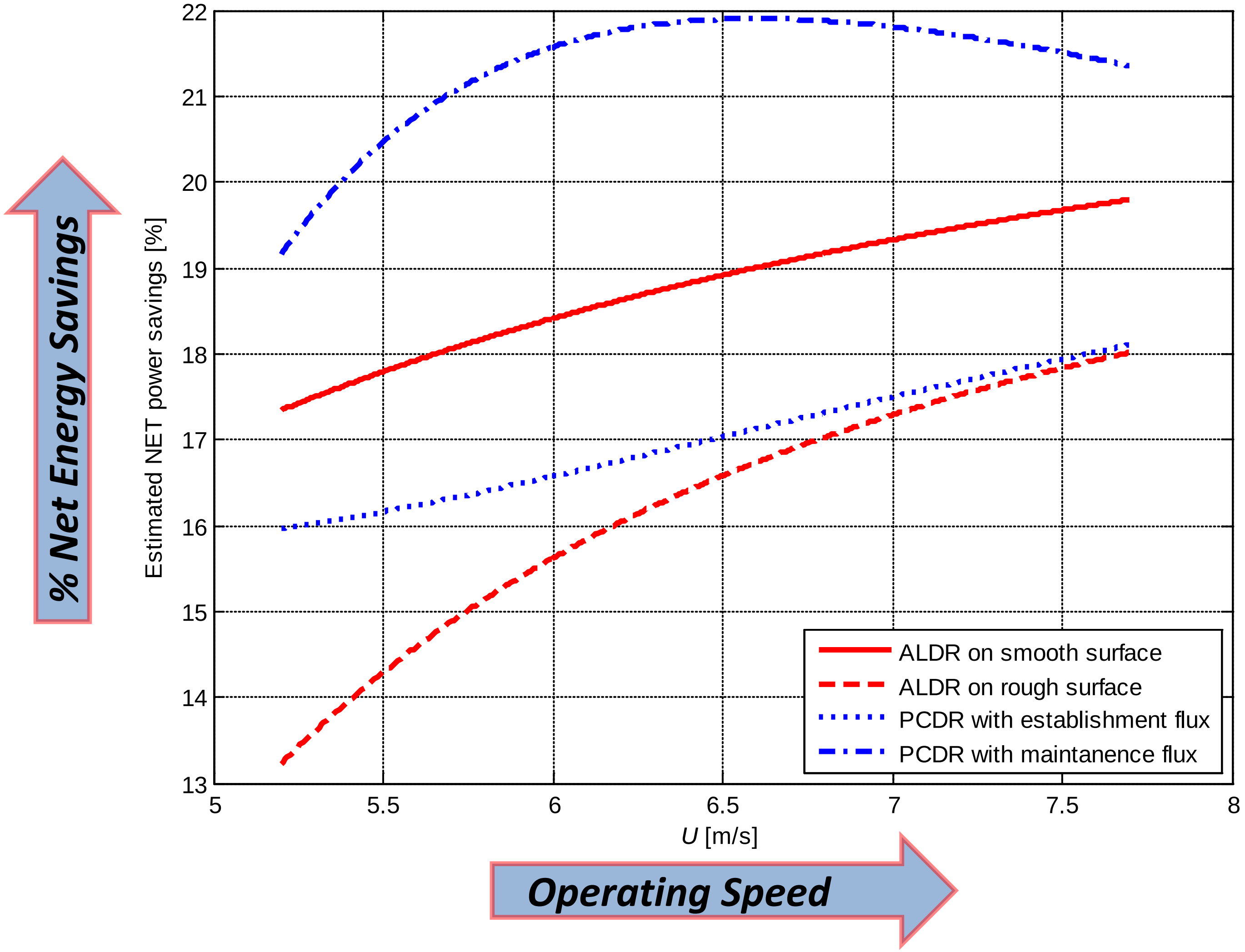
f_{FD}	Fraction of resistance due to frictional drag	**~0.6**
η_{prop}	Propulsor efficiency	**~0.75**
η_{elect}	Additional efficiency of producing electricity to compressor	**~0.9**
A_{AL}/A_{wet}	Fraction of wetted hull area covered by the air layer	**~0.49**
$\%D_R$	Percentage drag reduction on the area covered by the air layer	**~0.8**

P_{comp} Power required by the compressor to supply the air

P_D Propulsive power required to overcome drag

Also, let's conservatively use 60% compressor efficiency* and assume 15 psi losses in piping

*Based on information given by Continental Blower, efficiency within ~50% of ideal operating point for the given *dp* is ~70%



Potential net energy saving from 13 to 22%

…AND equivalent reduction in emissions!

Resistance and Propulsion Open Questions

- Air's effect on propulsor efficiency
  - ➢ Model tests and simulations needed
- Additional drag from strakes and other appendices on the hull
  - ➢ More detailed calculations, model tests and simulations needed
- Effect of sea state (perturbations) of air lubrication?
  - ➢ Some experiments performed, but more needed
- ALDR: Air layer persistence?
  - ➢ Answer from sea-trial*
- PCDR: Is one multi-wave partial cavity enough?
  - ➢ Answers needed from a sea-trials*

*longer model needed than fits in the world's largest cavitation tunnel

4. Economic Cost Benefit Estimate: **ALDR**

The shipping professionals can estimate the cost better than we, but approximately:

- The potential annual cost savings can be approximated from:
  $\Delta C_{annual} = S_{fuel} - C_{\text{maintanence}} - C_{\text{annuity of initial cost}}$
- Where the annual fuel cost savings
  $$S_{fuel} = C_{fuel} \frac{\%E_{savings}}{100}\left(1 + \frac{\%O_{overhead}}{100}\right)$$
- and the initial cost per year spread out over the ship's lifetime is given by
  $$C_{\text{annuity of initial cost}} = C_{initial} \frac{i(1+i)^n}{(1+i)^n - 1}$$
- where n is the number of years and i is the interest rate
- **Assuming :**
  - **Ship like the M/V American Spirit**
  - **air delivery system maintenance cost \$100,000/year,**
  - **initial investment of \$2,000,000 for compressor and retrofit,**
  - **annual fuel cost 4.8M\$/year and 20% overhead,**
  - **2.5% inflation/interest rate, and *n*=20 years of ship life after retrofit**

Life Cycle Cost Estimate: ALDR

- In 2008 a "typical" fuel cost for a 1000 footer $15,207/day* and season had 275 days

  ***US Army Corps of Engineers, SUPPLEMENTAL RECONNAISSANCE REPORT, GREAT LAKES NAVIGATION SYSTEM REVIEW, February 2010*

- Assuming fuel price increase of 5%/a since 2008, current fuel cost for a season would be $4,840,000, and hence for 13% energy savings the annual cost savings in present value

$$\Delta C_{annual} = 642{,}000\$ - 100{,}000\$ - 128{,}000\$ = 414{,}000\$$$

educated guess

- If we assume 20% energy savings, $759,000 per year

➢ Potentially saving could be 8.3…15.2 million dollars over a 20 year period

These cost estimates are crude, the shipping professionals are best capable of refining these by using real cost figures.

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Life Cycle Cost Open Questions

Being energy net positive: necessary but not sufficient condition.

Need to analyze:

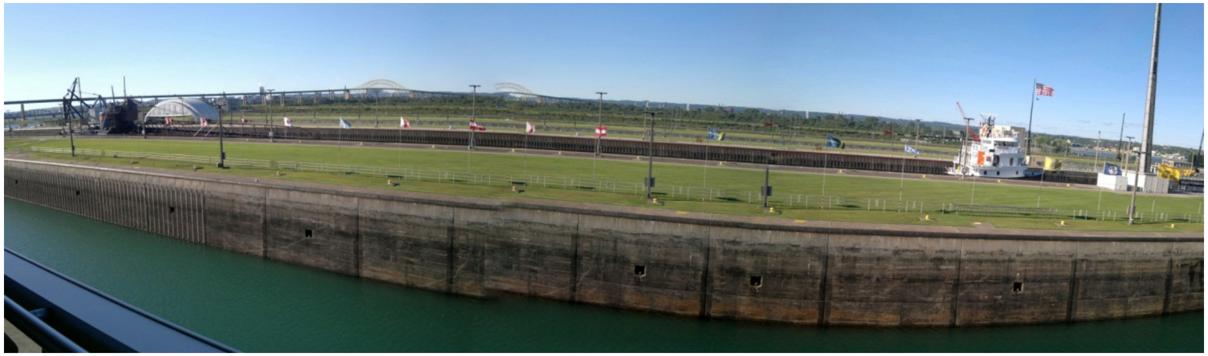
- Initial cost?
  - labor, materials, machinery, and lost opportunity cost during retrofit
- Lost cargo capacity?
  - For compressor and pipes
- Maintenance cost of air delivery system?
- Future fuel cost change?
- Carbon credit cost savings and possible “subsidies for being green”?
- PR value?
- For a new ship, there may be offsets as a smaller engine and fuel tanks may be sufficient?

Summary

- Currently at least four other large projects ongoing world wide.
- Air lubrication looks promising for ships with flat bottoms
- Especially for high Length-to-Beam ratio
  - Pacific seagull had L/B = 5.9, but a GL 1000 footer has L/B ratio of 9.6!
  - Shallow draft leads to a lower air flux requirement (ideal gas law)

- **Energy cost benefit is promising, but shipping professionals are needed to calculate more accurately life time cost**
- **<u>Ship specific</u> design and benefit analysis needed, followed by sea trials**

Picture of: Soo Locks



One special consideration for GL ships is the locks => draft is critical. Most suitable to try ALDR?