Air Lubrication Drag reduction on Great Lakes Ships

Final Report

Steven L. Ceccio — Department of Naval Architecture and Marine Engineering, University of Michigan, Ann Arbor

Simo A. Mäkiharju — Department of Mechanical Engineering, University of Michigan, Ann Arbor

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University of Michigan
Department of Naval Architecture and Marine Engineering
Room 215, 2600 Draper Drive,
Ann Arbor, 48109-2112

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Executive summary

Due to environmental concerns and rising fuel cost, it would be advantageous for the future of the Great Lakes shipping industry to reduce fuel consumption. One potential way to achieve this is by reducing the ships' resistance. Without major hull form changes or decrease in operational speed, the form and wave resistance of a ship are mostly fixed and only frictional drag could be reduced. As interest in drag reduction has increased over the last two decades, several research projects in the USA, Europe and Asia have investigated the possibility of reducing frictional drag by using air lubrication. Air lubrication is achieved pumping air beneath the hull and thus reducing the area of hull in direct contact with the liquid flow, or in the case of discrete bubbles by modification of momentum transport and average density in the boundary layer. If properly implemented, it is estimated that air lubrication could lead to net fuel saving between 5 and 20%, with the corresponding reduction in NO_x, SO_x, particulate and CO_2 emissions.

Air lubrication techniques can be divided into three major categories; Bubble Drag Reduction (BDR), Air Layer Drag Reduction (ALDR), and Partial Cavity Drag Reduction (PCDR). *Proposed ships utilizing PCDR are sometimes called Air Cavity Ships (ACS) in the literature.* Figure 1 illustrates the conceptual difference between these three techniques.

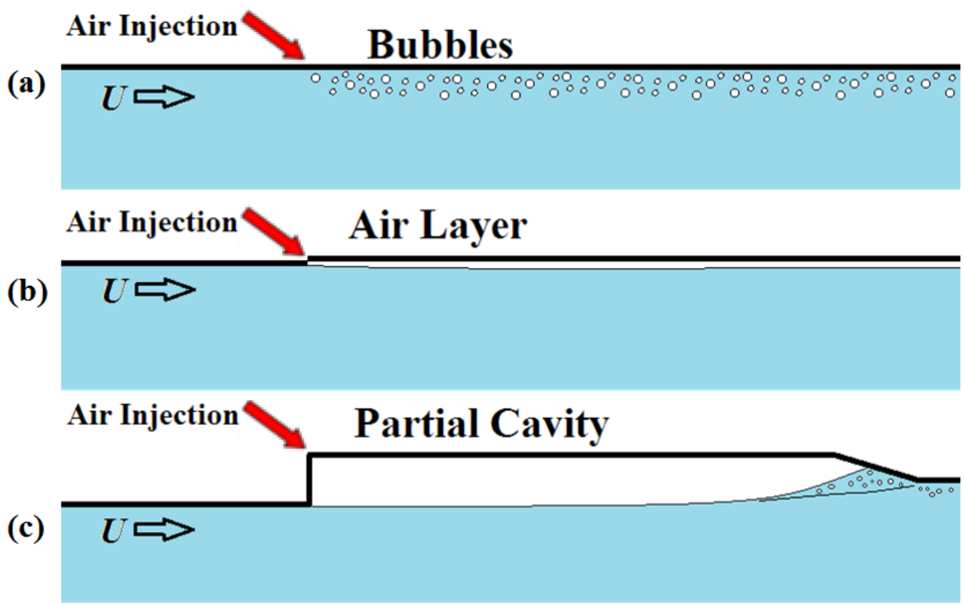

Figure 0.1 – (a) In DBR discrete air bubbles are introduced into the boundary layer on the hull and they are thought to reduce the frictional drag by reduction of bulk density and by modifying momentum transport. However, downstream from the injection site the bubbles can migrate away from the surface and their effect is reduced. (b) In ALDR a continuous film of gas separates the liquid and hull, thus reducing friction. This film has been found to persist far downstream of the gas injection site. (c) In PCDR a thick recess filled with gas separates the liquid and hull, thus reducing friction of the area of the recess. The closure of the cavity is designed to minimize loss of air.

For any air lubrication technique to be considered for implementation, the potential net energy savings must be sufficient to justify the added complexity of the air supply system and the capital, operational and maintenance costs. We performed an energy cost-benefit analysis for ALDR and PCDR, and discuss the results and some of the limitations of their validity. A more simplified cost-benefit analysis for ALDR has been previously provided by Ceccio *et al.* (2010). The current study focuses on the two air lubrication techniques that seem most viable based on current data; ALDR and PCDR.

The air layer or partial cavity will reduce the frictional drag on the area covered. It is assumed that the ship's form drag is not appreciably changed by the air injector, strakes or other appendages attached to the hull to achieve air lubrication. Assuming further that practically all of the ship's energy consumption is used for propulsion, the possible percentage net energy savings can be estimated by considering the ratio of net energy savings to total energy consumption. To estimate the energy required by the air supply system, we must first estimate gas fluxes required to achieve ALDR and PCDR. Data for these estimates was found in Elbing *et al.* (2008) and Mäkiharju *et al.* (2010).

Figure 0.2 − The *M/V American Spirit* is a cargo ship operating on the Great Lakes. L = 306 m, w = 32m and midsummer draft 8.8 m (Picture from American Steamship Company's web page).

To show the results of the energy cost-benefit analysis, we considered a specific ship type. The American Steamship Company's *M/V American Spirit*, shown in figure 0.2, was chosen for these calculations, albeit not all the technical detail on the ship was available to us and hence some additional assumptions were required.

Assumptions:

- The ship has a very large block coefficient. While the exact hull shape is not available to us, we assume that 7% of the beam has curvature and 15% of the length is bow and stern, so that ~ 50% of the wetted hull is flat and horizontal making it ideally suited for air lubrication.
- The top speed for this ship is ~7.5 m/s, leading to a maximum Froude number of 0.14, hence we assume that the frictional drag accounts for 60% of the ships total resistance.
- For both air layers and partial cavities we assume that the friction on the area covered is reduced by 80%, which is the lower bound of the frictional drag reduction observed in experiments.
- Propulsor efficiency is assumed to be high (75%), as the higher this value is, the lower the net energy savings available will be.

- Efficiency of the generator providing electricity for the compressor is assumed to be 90%.
- The air compressor efficiency was assumed to be 60%.
- Pressure drop due to piping losses was assumed to be 15 psi.
- For ALDR, the air layer is assumed to persist indefinitely once formed.
- For PCDR, a single multi-wave partial cavity is assumed to span the length of the recess.

With these assumptions the net energy saving as function of speed can be estimated, and the results are presented in figure 0.3.

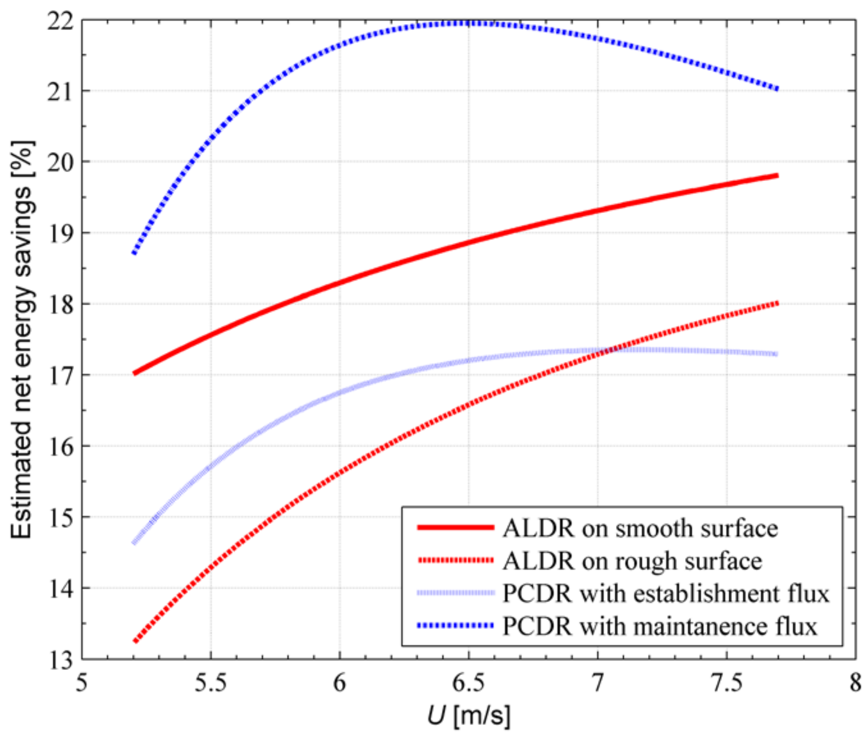

Figure 0.3 − *Estimates of the potential net energy savings for a ship similar to the M/V American Spirit.*

There have been two sea trials where the flow was likely in the BDR-transitional-ALDR region (based on flow regions as defined in Elbing *et al.* 2008). One such sea trial on the Pacific Seagull yielded 5 to 10% net energy savings according to Hoang *et al.* (2009) while a second sea trial by Mitsubishi Heavy Industries achieved 8 to 12% net energy savings (Mizokami *et al.* 2010). The potential net energy savings predicted for ALRD in figure 3 are higher than observed in these sea trials. This is likely explained by either or both of the following: the sea trials may not have had sufficient air flux supplied to achieve a true air layer (as could be assumed from the local frictional drag measurements presented by Hoang *et al.* 2009), or the area fraction of the wetted hull covered for these ships was less than what was assumed possible for ships with large block coefficients, such as those operating on the Great Lakes (or the new triple-E class cargo ships). For PCDR, a scale test by MARIN recently showed 15% net energy savings (Foeth, 2011) and a 1:12th scale test by STENA achieved resistance reduction of 20 to 25% (*Surveyor*, 2011).

In the analysis, the percentage of frictional drag reduction for the surfaces covered by air was assumed to be a conservative 80%, given that other components of drag may in fact increase. It is important to note that any effects of possibly increased form drag and all other details, such as the effect of air entrainment into the propulsor, were omitted. It is not the intent to make a strong quantitative argument, but rather to show qualitatively the trends of the energy economics of air lubrication, and thereby to determine whether the energy savings break-even point could be surpassed. The energy savings break-even point depends on three principal parameters, ship's draft, length and operating speed. The net energy savings achieved, will likely deviate from those estimated here as they depend on all the assumptions made in the analysis, and on how the experimental results would scale to conditions not tested in the experiments. There are certainly boundaries for these techniques that have not been encountered within the limited parameter ranges of the experiments on which estimates of required air flux were based. The economic cost-benefit is highly ship specific, but would easily provide a net benefit if the estimated 10-20% net energy savings are realized.

1. Introduction

Shipping is vital for global commerce, as it is generally one of the most economical and environmentally friendly transportation methods. In addition to the commercial shippers, the world's navies and innumerous cruise lovers need and want, respectively, shipping to be as economical as possible with minimal environmental harm. Since approximately 60% of a typical ship’s propulsive power is required to overcome frictional drag, any technique that could significantly reduce a ship's frictional resistance might have a substantial impact both economically and environmentally.

Frictional drag stems from the velocity of a fluid on a solid surface being the same as the velocity of the surface due to the no-slip condition. Momentum is transferred from free stream to near-wall-region by structures in the boundary layer and shear. Methods proposed for frictional drag reduction (FDR) are based on reducing the density or viscosity of fluid near the wall (air lubrication), alter the momentum transport in the boundary layer (air or polymers) or “violate” the no slip condition (can be encountered in microscopic MEMS scale devices). Throughout the last two centuries, various methods to reduce the frictional component of drag have been proposed. These include injection of polymers, the use of riblets, compliant walls, electromagnetic methods, and various air lubrication techniques (Proc. of Int. Symp. on Seawater Drag Reduction 1998, 2005).

We will consider only air lubrication. A simple test to illustrate how air lubrication works is to run a thin, but sturdy, plate through air and then through water while keeping the widest area on the sides. The resistance is mostly due to frictional drag, and you can immediately observe that the resistance in air is much less than in water. This is because the dynamic viscosity (the natural resistance to flow) and density of air are much less than those of water. In fact, at the same speed the frictional drag for a flat plate is more than 500 times greater in water than it is in air.

Successful application of air lubrication to both existing and new craft would save fuel and reduce exhaust emissions. The challenge is to efficiently deliver the air to the hull and manage its flow for the maximum reduction of friction drag. If successful, air lubrication has been estimated to lead to fuel saving between 5 and 20%. We consider the use of these methods on ships and barges operating on the Great Lakes. In the following paragraphs we will further discuss the different techniques, available data from laboratory and sea-trials, and consider the energy and economic cost-benefit for a chosen representative Great Lakes ship.

2. Different air lubrication techniques

Within the field of air lubrication there is a wide variety of techniques that have been suggested since the 19th century (Latorre 1997). Air lubrication can be divided into three main subcategories: Bubble Drag Reduction (BDR) (Kodama *et al.* 2000, Madavan *et al.* 1985); Air Layer Drag Reduction (ALDR) (Elbing *et al.* 2008); and Partial Cavity Drag Reduction (PCDR) (Butuzov 1967). While a handful of ships today benefit from any form of air lubrication for friction drag reduction, recently Mitsubishi Heavy industries (Mizokami *et al.* 2010), Stena Bulk, MARIN, and DK-group have undertaken serious commercial development and some are beginning to offer their versions of air lubrication to shipping companies. This increased investment, along with continued fundamental research, is bringing these methods closer to being mature and widely adopted techniques, from which the Great Lakes shippers can also benefit. Given the potential for a 5 to 20% net fuel savings, with an equivalent reduction in emissions, these techniques could have a notable environmental and economic impact for the great lakes region. Figure 2.1 shows the conceptual differences between the various techniques discussed in the following three chapters.

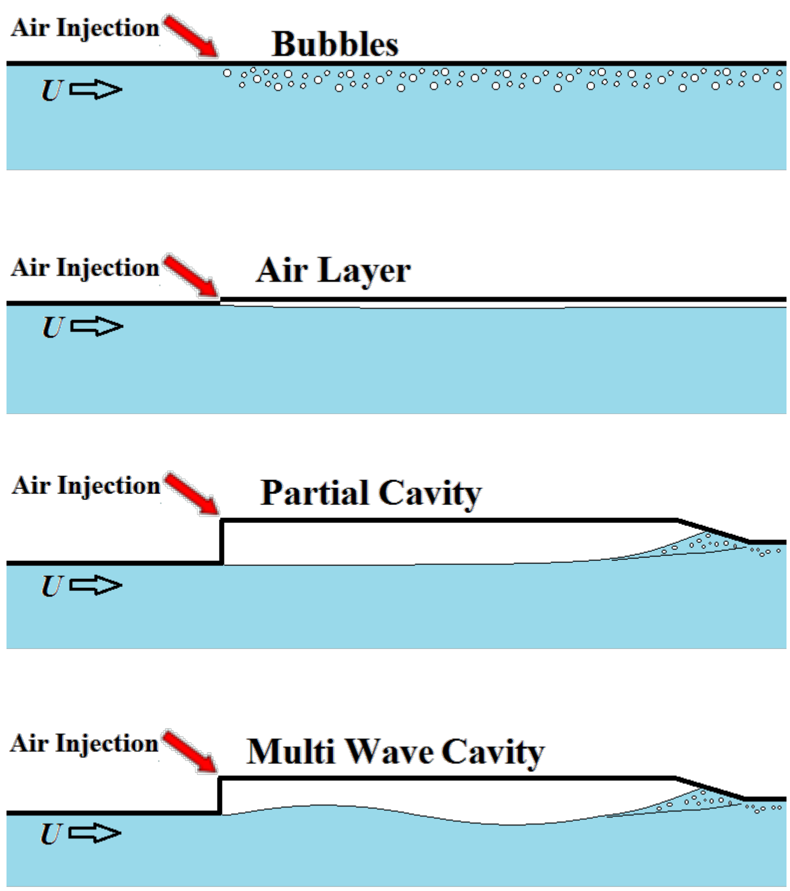

Figure 2.1 – Conceptual sketches illustrating the different air lubrication techniques. From the top: BRD, ALDR, PCDR and multi-wave PCDR.

2.1 Bubble drag reduction

In Bubble Drag Reduction (BDR) small bubbles are injected into the boundary layer as shown in the first sketch of figure 2.1. The dispersed bubbles act to reduce the bulk density and to modify turbulent momentum transport. The technique is sometimes referred to as micro bubble drag reduction, when the bubbles are very small compared to the boundary layer thickness or wall units. This technique is subject of many studies (Kodama *et al.* 2000 and Sanders *et al.* 2006) and some discuss whether the drag reduction mainly comes from modification of effective viscosity, density change, turbulence modification, or change in momentum transport. However, many of the early and most promising studies were conducted at the laboratory scale and questions remain regarding the technique's suitability to ship scale; how much gas injection is needed, what is the maximum possible FDR, how far downstream from injection site will FDR persist, how important is the bubble size, performance in salt water, what is the best injection method, etc. Figure 2.2 from Elbing *et al.* (2008) illustrates a major concern with the persistence of BDR.

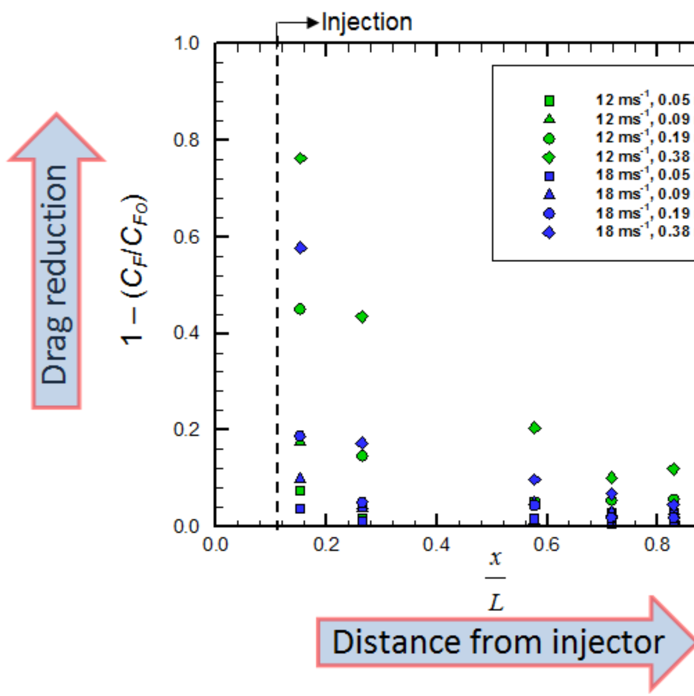

Figure 2.2 – Here *L* is ~13 meters. At higher speeds most of the FDR from bubble injection was lost 2 meters downstream of the injection site (Elbing *et al.* 2008).

2.2 Air Layer drag reduction

In Air Layer Drag Reduction (ALDR) gas creates a seemingly continuous lubricating layer between hull and liquid. Surface devices (small backward step for instance) may be used to enforce boundary layer separation upstream of the injection point to aid in the initial formation of the layer. In ALDR, as in BDR, no effort is made to re-circulate the injected gas. Air is injected beneath the hull of a ship, forms a film on the flat (horizontal) part of the hull and reduces the frictional drag on the area covered by in excess of 80%.

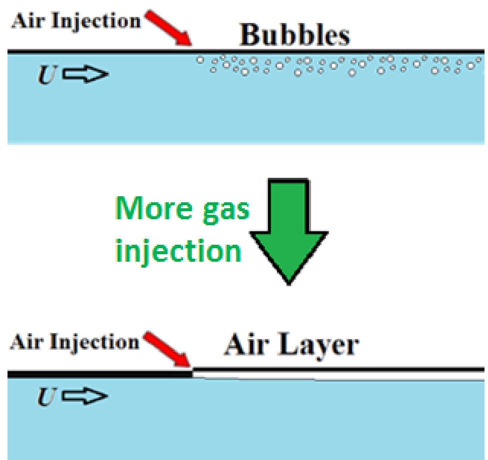

Figure 2.3 − With sufficient gas flux, the injected gas bubbles coalesce into a film. In recent experiments by our group a ½” tall backward facing step was used to help the air layer form initially at the injector.

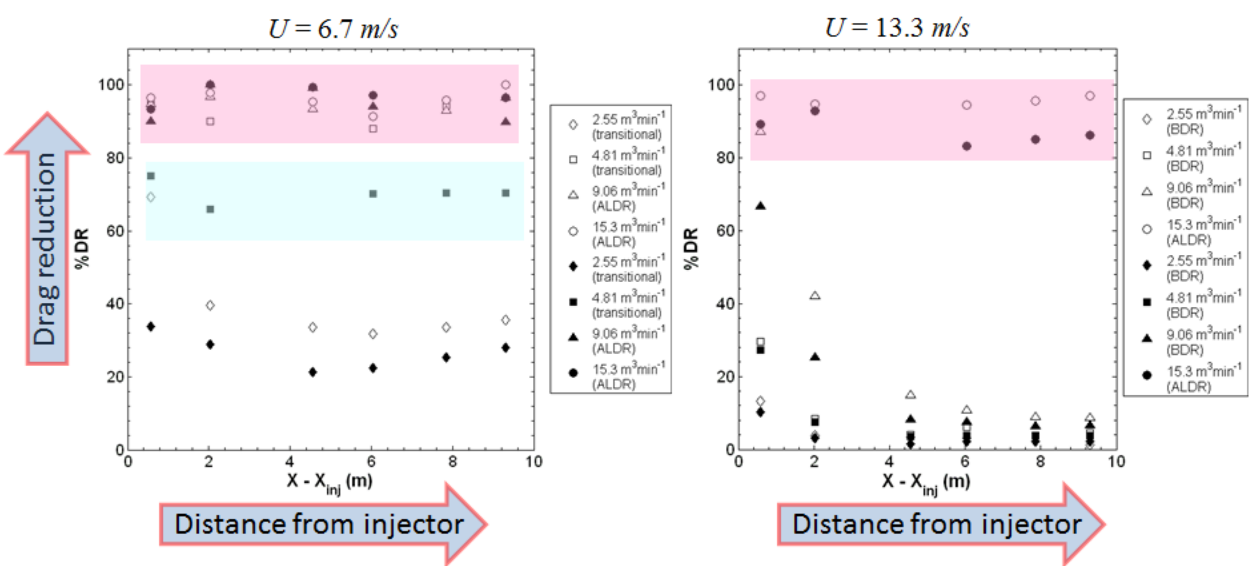

Figure 2.4 − On a 13 m long model, with injector 2 m downstream of the leading edge, the effect of ALDR was found to persist for the entire length of the model whereas the effect of BDR was seen to rapidly decay (Elbing *et al.* 2008).

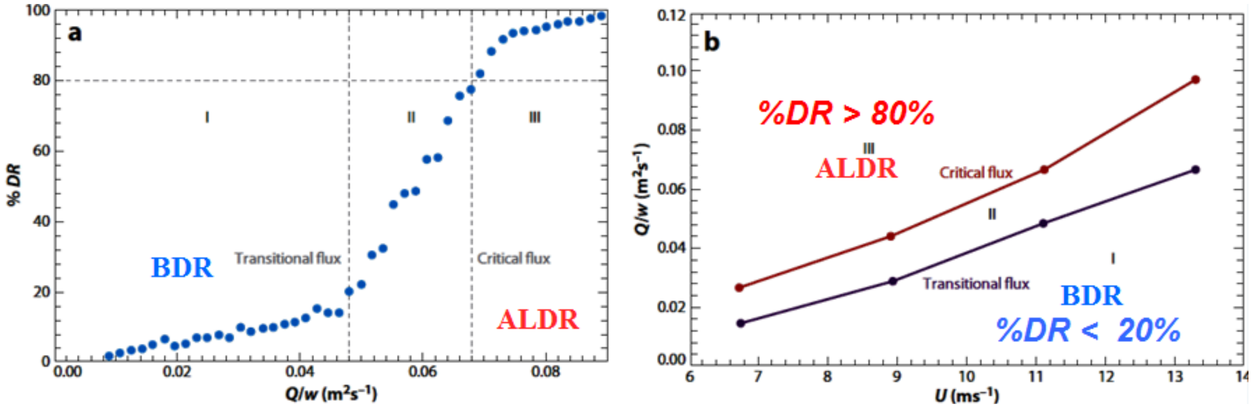

Figure 2.5 − Gas flux required to transition from bubble to air layer drag reduction. a) Percentage drag reduction *versus* air flux. The percentage of drag reduction was measured 6 m from the injector. b) Transitional ALDR and critical ALDR gas fluxes (Ceccio 2010, Elbing *et al.* 2008).

2.2.1 Sea-trial on the Pacific seagull

A recent sea-trial was reported on by Hoang *et al.* (2009) and based on the information provided we estimate that this sea-trial may have reached the transitional-to-ALDR region shown in figure 2.5. Table 2.1 provides details on the ship used. Local shear stress measurements on the hull indicated 20 to 40% reduction in frictional drag, and overall net fuel savings of 10% at ballast conditions and 5% at full-load were reported. However, the exact injected air volume fluxes were not reported.

Table 2.1. Description of the Pacific Seagull by Hoeng *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

2.2.2 Sea-trial by Mitsubishi Heavy Industries

Another sea trial, where the transitional or ALDR region may have been reached, was reported by Mizokami *et al.* (2010), who obtained 8 to 12% net energy savings on a ship characterized in table 2.2

Table 2.2. Ship used 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

2.2.3 Observations

It has been found that a clear separation line helps the air layer to form initially. Influence of moderate steady flow perturbations on ALDR is minimal in the presence of a forced separation line. However, it is not known if stronger perturbations would break the air layer, and how would an air layer behave in heavy seas. While Elbing *et al.* (2008) found 80% drag reduction persisting for the entire length of the model and there are no indications on a limit for the length of the layer, it cannot be said with certainty that an air layer would persist indefinitely without additional gas injection.

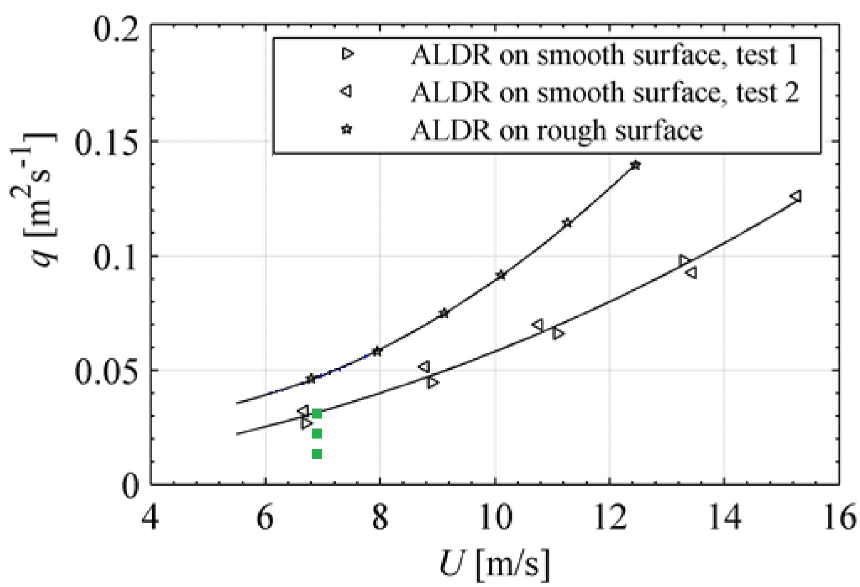

Figure 2.6 – Data from Elbing *et al.* (2008) on air fluxes required for ALDR on a model in the Large Cavitation Channel. For comparison, the green dots show the approximate air fluxes used in the sea-trial where 8 to 12% net fuel savings were reported by Mizokami *et al.* (2010).

2.3 Partial cavity drag reduction

In Partial Cavity Drag Reduction (PCDR) gas creates a lubricating layer between the hull and liquid as shown in the bottom two sketches of figure 2.1. Drag reduction is achieved by filling a recess, much thicker than the ship-hull boundary layer thickness, with gas. To apply PCDR on a ship's hull, the bottom of the hull needs to have indentations, which are to be filled with gas, usually air. A backward-facing step (BFS) on the upstream end of the recess and a gently downwards sloping closure on the downstream side normally form the recess which traps the gas, thus forming a ventilated partial cavity. Gas is injected continuously into the cavity to make up for that which is lost to entrainment, but with proper cavity design the gas loss is minimized. In addition to the single wave partial cavity discussed in Lay *et al.* (2010) and Mäkiharju *et al.* (2010), a multi wave partial cavity drag reduction may be possible, which would enable there to be multiple ideal operating speed ranges where the cavity would be closing on the beach with low air loss. With a properly designed closure and within a design speed range(s), only a minimal amount of the introduced gas is lost at the cavity closure. The gas separates the solid surface from the liquid resulting in more than a 95% decrease in frictional drag for the area covered.

Researchers in the former USSR studied PCDR for decades and developed several ships which utilize it (Butuzov 1967, Butuzov *et al.* 1999, Amromin and Mizine 2003), and these ships are sometimes called air cavity ships (ACS). In the last decade, there has been renewed interest in air lubrication and many research groups have studied PCDR through numerical modeling (Amromin *et al.* 2006, Matveev 2003), small scale experiments (Arndt *et al.* 2009, Gokcay *et al.* 2004), and large scale experiments (Lay *et al.* 2010, Mäkiharju *et al.* 2010). Also, a recent review by Ceccio (2010) discusses some of the remaining research questions relevant to PCDR. Most recently Stena (Surveyor 2011) and Marin (Foeth 2011) have presented encouraging results from sea trials on reduced-scale ship models.

Calm conditions sometimes accompany river and lake shipping, while most ocean going and great lakes ships operate in conditions where waves are omnipresent and the sea state can be severe; hence we also need to understand how PCDR performs under perturbed flow. Partial cavities in perturbed flows were studied in small scale experiments by Koprikova *et al.* (2008) and Arndt *et al.* (2009), and at Reynolds number, *Re*, based on downstream distance from air injector of over 10^6 in Mäkiharju *et al.* (2010), however *Re* for most ships is $O(10^9)$.

Gas requirements are minimized with proper cavity closure design. Figure 2.7 shows sketch of the cavity and a picture of the closure from where gas is shed. Figure 2.8 shows the air flux required to establish and maintain a cavity. PCDR may be suitability for ships and barges of the Great Lakes, as the large flat bottoms of the GL ships are ideal. However, care would have to be taken in a design to ensure the draft of the ship doesn’t exceed the limit on draft set by the Soo locks.

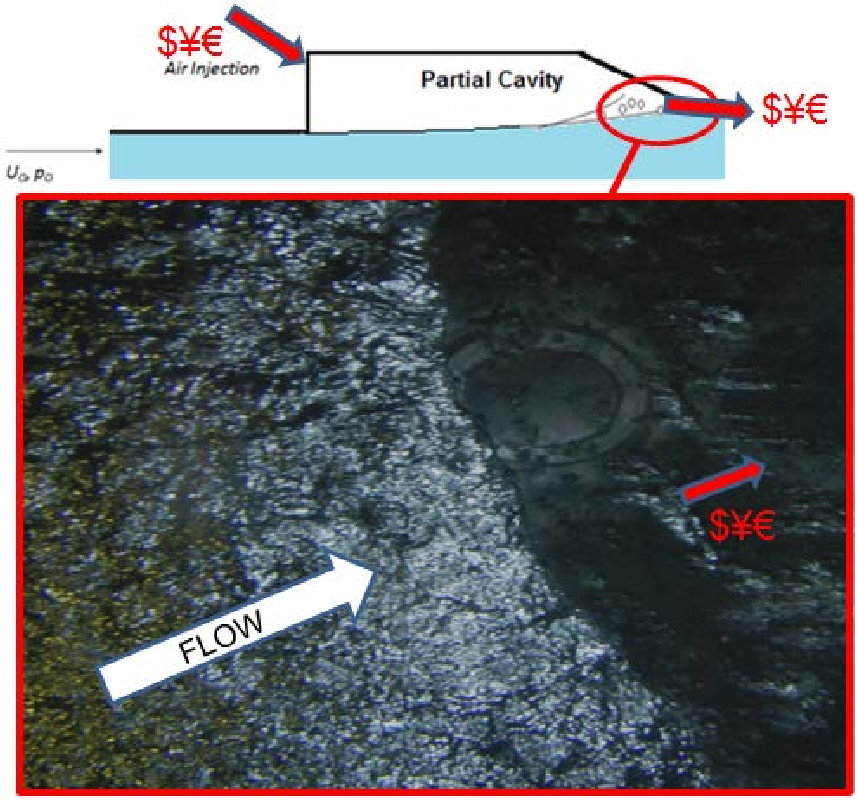

Figure 2.7 – Cavity closure at the beach as viewed from below, with arrows indicating the flow direction and gas clouds being shed from the closure.

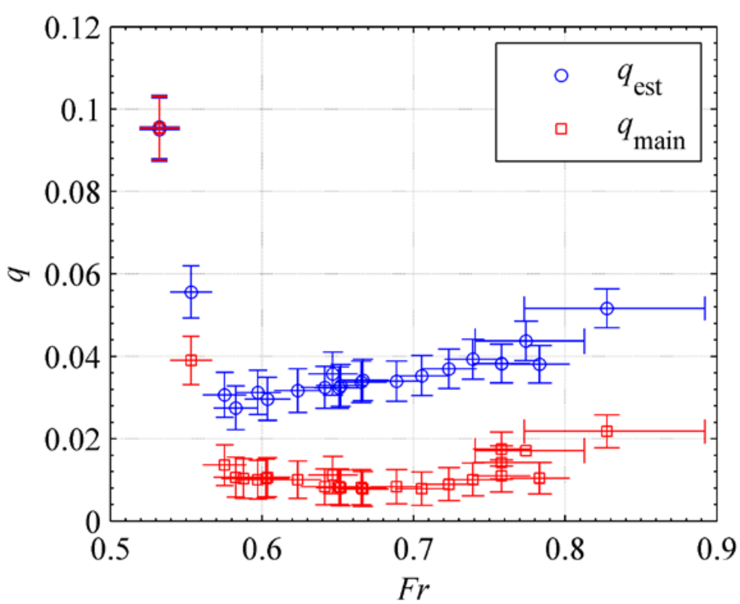

Figure 2.8 – The minimum gas flux, q, required to establish and maintain the cavity as a function of the Froude number (Mäkiharju *et al.* 2010), where we can see a region of minimal gas requirements for $0.56 < Fr < 0.75$. However, for a multi-wave cavity it might be possible to have multiple good operating regions. (Here $q = Q/UWH_{step}$ and $Fr = U/\sqrt{gL_{cavity}}$, where W is the span, U the flow speed, Q the volumetric gas flux, and H_{step} is the step height.)

The effect of ambient waves was mimicked in experiments by Mäkiharju *et al.* (2010). A gate's flap's motion created large disturbances. Pressure oscillated up to ±15% and velocity up to ±5%. This led to rapid changes in the cavity length and pressure, and increased maintenance gas flux requirements as shown in figure 2.9, however in all the conditions tested the cavity could be maintained.

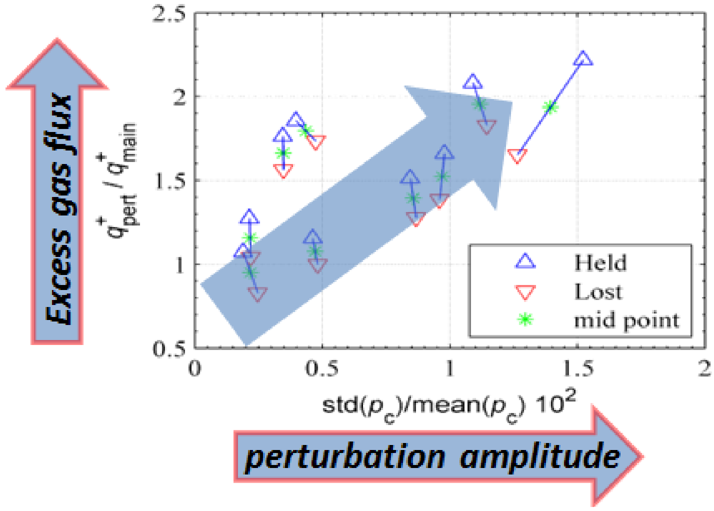

Figure 2.9 − Maintenance gas flux requirements for PCDR in perturbed flow divided by the maintenance gas flux required under steady flow conditions (Mäkiharju *et al.* 2010).

PCDR sea-trials are being conducted by Stena, DK-group and Marin, but few published results are available to date and nothing that could be used to estimate the results for a Great Lakes freighter. Mäkiharju (2012) discusses scaling of PCDR by comparing data obtained from geometrically similar experiments performed a size scale 14 apart. Figure 2.10 shows one of the most interesting results, which suggests that perhaps after a critical Reynolds number the normalized gas flux has values in the same range at different size scales. If this were the case, then results from the LCC experiments (Mäkiharju *et al.* 2010) could be used to estimate gas fluxes for a full size ship.

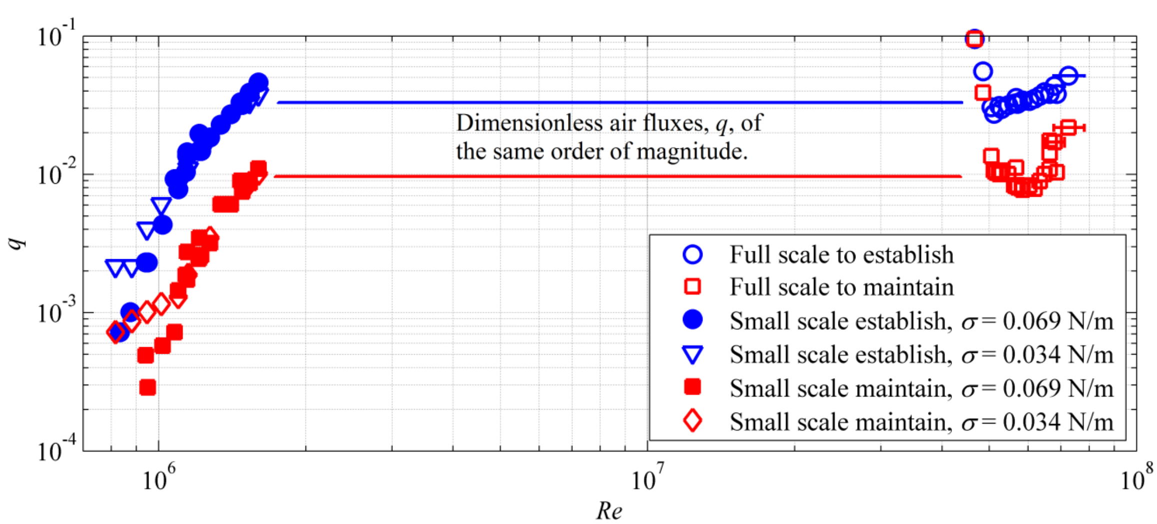

Figure 2.10 − Critical dimensionless gas fluxes as a function of Reynolds number.

3. Air Lubrication Energy Cost-Benefit Analysis

For any air lubrication technique to be considered for implementation, the potential net energy savings must be sufficient to justify the added complexity of the air supply system and the capital, operational and maintenance costs. We present an energy cost-benefit analysis for ALDR and PCDR, and discuss the results and some of the limitations of their validity. A more simplified cost-benefit analysis for ALDR has been previously provided by Ceccio *et al.* (2010). BDR is not considered, as the results available to date are dependent on bubble size distributions and BDR's frictional drag reduction effect's downstream persistence may not be sufficient to make it viable (Elbing *et al.* 2008).

The air layer or partial cavity will only reduce the frictional drag on the area covered. It is assumed that the ship's form drag is not appreciably changed by the air injector, strakes or other appendages attached to the hull to achieve air lubrication. Assuming further that practically all of the ship's energy consumption is used for propulsion, the possible percentage net energy savings, $\%E_{saved}$, can be estimated by considering the ratio of net energy savings to total energy consumption

$$\frac{\%E_{saved}}{100} \cong \frac{\Delta t \cdot P_{saved}}{\Delta t \cdot P_D / \eta_{prop}} \tag{3.1}$$

where P_{saved} is the net power savings, P_D is the power required to overcome the ship's total drag, η_{prop} is the propeller efficiency and the increments of time, Δt, cancel. The net energy savings can be estimated by considering the reduction in power required to overcome frictional drag and the power required to supply the gas, yielding

$$P_{saved} = \frac{P_D f_{FD}}{\eta_{prop}} \frac{A_{ac}}{A_{wet}} \left(\frac{\%D_R}{100} \right) - \frac{P_{comp}}{\eta_{elect}} \tag{3.2}$$

where $\%D_R$ is the percentage frictional drag reduction on the air covered by air, f_{FD} is the fraction of total drag due to friction, A_{ac} area covered by air, A_{wet} total wetted hull area, P_{comp} is the power required to run the compressor or blower, and η_{elect} is the efficiency of producing the electricity for the compressor/blower relative to the efficiency of providing power for the shaft. Hence a value of one should be used if the ship's propellers are electrically driven, as is the case for ships with Azipods or in general for a ship with integrated electric plants as proposed for Great Lakes ships by Parsons *et al.* (2011). The percentage of total drag due to friction is ship specific and depends also on speed, but here it is estimated from figure 3.1.

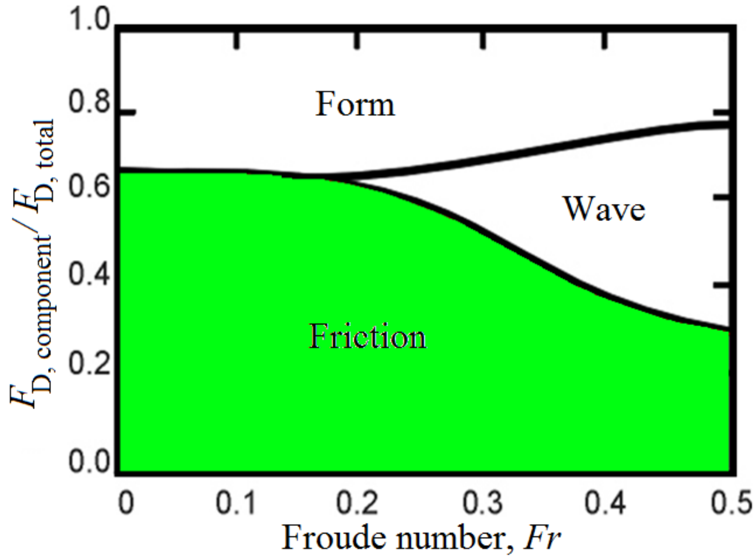

Figure 3.1 – Typical contributions of different components of ship's resistance as a function of Froude number as commonly reported in the literature.

As shown in figure 3.1, of the total drag, frictional drag accounts for approximately 60% for Froude number less than 0.2. Here the Froude number is defined as

$$Fr = U/\sqrt{gL} \tag{3.3}$$

where U is the ship's speed, g is the gravitational constant (9.81 m/s^2), and L is the overall length of the ship. The power required to overcome frictional drag, $P_{FD} = P_D\, f_{FD}$, can be approximated from the frictional drag on a flat plate, which is given by

$$P_{FD} = \frac{1}{2}\rho_w U^3 WLC_D \tag{3.4}$$

where for a turbulent flow over a flat plate with a smooth surface drag coefficient, C_D, may be taken to be $0.523/\ln^2[0.06\mathrm{Re}_L]$ (White 2006), W is the width, and L is the length of the plate. From basic thermodynamic principles (Sonntag *et al.* 2003) the power needed to compress a given mass flow rate of gas via a polytropic process (*i.e.* process where PV^n =constant) is given by

$$P_{comp} = \frac{\dot{m}_g p_1 n}{\eta_c \rho_{g,1}(n-1)}\left(\left[\frac{p_2}{p_1}\right]^{(n-1)/n} - 1\right) \tag{3.5}$$

For an isentropic process the exponent n (also called index or polytropic index) would is replaced by k, the ratio of specific heats, which is 1.40 for air. $\dot{m}_g$ is the mass flow rate of gas, p_1 is the initial pressure, assumed to be 1 atm, p_2 is the pressure to which the gas needs to be compressed, which depends on the pressure beneath the hull determined by draft and piping losses, $\rho_{g,1}$ is the density of the gas to be compressed and η_c is the compressor efficiency.

The mass flow rate needed is related to the volume flow rate requirement at pressure below the hull, and assuming that the gas is cooled to 25 °C after compression we can write

$$\dot{m}_g = Q\frac{\rho_{g,1}p_3}{p_1} \tag{3.6}$$

For a slow moving ship the pressure under the hull is assumed to be equal (or slightly less) than the hydrostatic pressure at the draft depth, $p_3 = \rho_w gD$, where D is the ship's draft. Note that $p_2 = p_3 + \Delta p_{loss}$. In eqn 4.6, Q is the volume flux of gas required to achieve ALDR or PCDR at pressure p_2 and it can be estimated by curve fitting the data provided by Elbing *et al.* (2008) and Mäkiharju *et al.* (2010), as in figure 3.2.

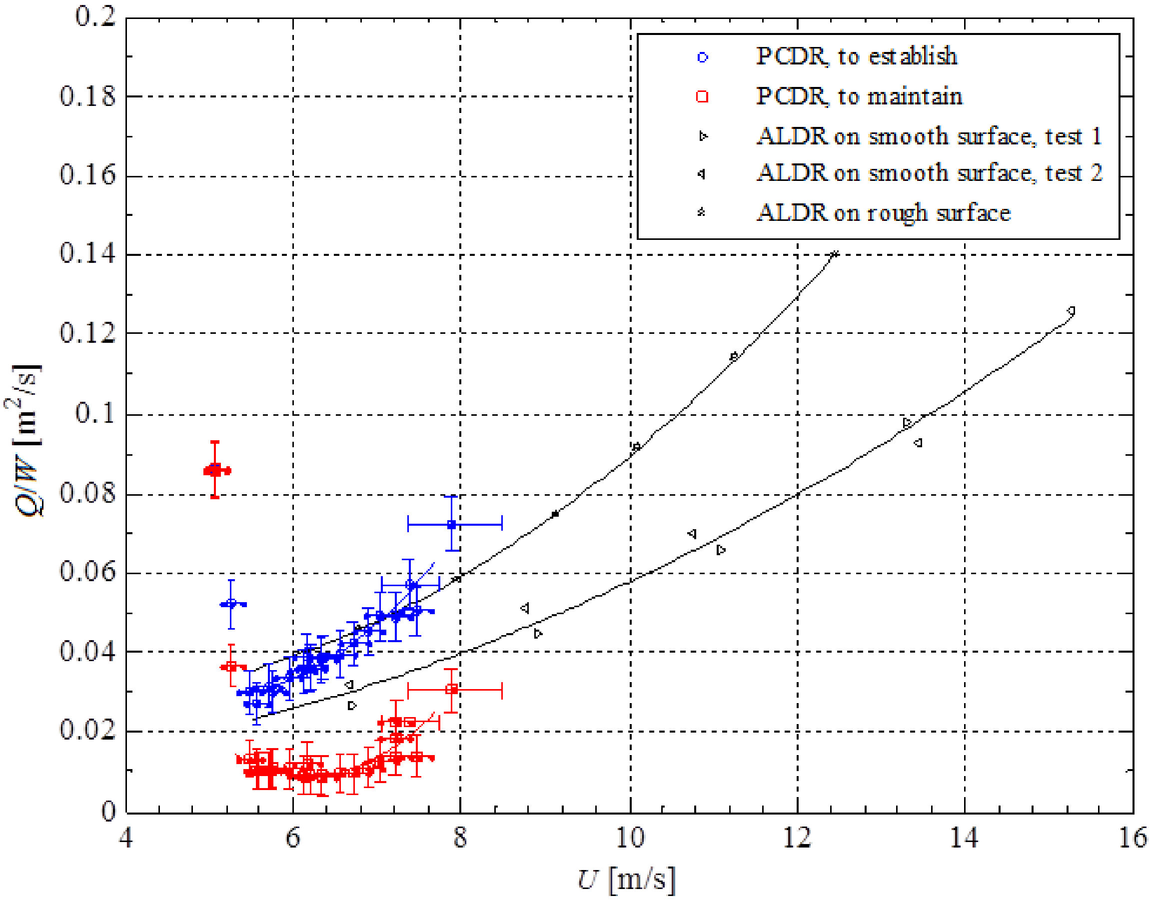

Figure 3.2 − Required volumetric flow rate per unit span to achieve an air layer on a smooth surface (▹ and ◃), on a rough surface (✩), to establish a partial cavity (o) and to maintain a partial cavity (□). Solid lines are curve fits given in equations 3.7a-d. The wide error bars at the two highest PCDR test speeds are due to variation of the free stream conditions and uncertainty of the velocity measurement performed using LDV in optically semi-opaque bubbly flow.

The experimental data and simple curve fits are shown in figure 3.2. The curve fits for volumetric air flux per unit span, Q/W, are given by

$$Q/W = 0.00126U^2 - 0.00755U + 0.0391 \tag{3.7}$$

for ALDR on a rough surface. Original data cover speed range from 6.79 to 12.45 m/s and a quadratic fit is used returning an R^2 = 1.00. On a smooth surface the original data cover a speed range from 6.67 to 15.26 m/s and a quadratic fit with R^2 = 0.99 is given by

$$Q/W = 0.000501U^2 - 2.98 \cdot 10^{-5}U + 0.00800 \tag{3.8}$$

For PCDR a linear curve fit for the data establishment flux from 5.48 to 7.46 m/s gives a quadratic fit with R^2 = 0.95

$$Q/W = 0.00476U^2 - 0.04796U + 0.150 \tag{3.9}$$

For the maintenance flux in the same range a quadratic fit with R^2 = 0.81 is given by

$$Q/W = 0.00701U^2 - 0.0866U + 0.277 \tag{3.10}$$

3.1 Example calculations

As an example, let's consider a ship similar to the American Steamship Company's *M/V American Spirit*, shown in figure 3.3. The wetted hull area is roughly approximated based on data from Miller (1979).

Figure 3.3 − The M/V American spirit is a cargo ship operating on the U.S. Great Lakes. *L*= 306 m, *w*= 32 m and midsummer draft 8.8 m (American Steamship Company).

Assumptions*:*

- This ship has a very large block coefficient. We assumed that 93% of the beam and 85% of the length is flat and suitable for a cavity or an air layer. This leads to A_{ac}/A_{wet} ~ 50%.
- The top speed for this ship is assumed to be ~7.5 m/s, leading to a maximum Froude number of 0.14, hence based on figure 3.1 we assume that the fraction of frictional drag of total resistance is always approximately 60%, f_{FD} = 0.6.
- For both air layers and partial cavities we assume that the friction on the area covered is reduced by 80%, which is the lower bound of the FDR based on Lay *et al.* (2010).
- Propulsor efficiency is conservatively assumed to be higher than usual (75%), as the higher this value is, the lower the net savings percentage will be.
- Efficiency of the generator providing electricity was assumed to be low, a mere 90%.
- The compressor efficiency was assumed to be 60%. (Based on information given by Continental Blower, the efficiency within +/- 50% of the ideal operating point for the given pressure differential is closer to 70%).
- Pressure drop due to piping losses was assumed to be 101 kPa.
- For ALDR the air layer is assumed to persist indefinitely once formed.
- For PCDR a single multi-wave partial cavity is assumed to span the length of the bottom. (It is assumed that the surface in the recess beneath the hull can have multiple wave crests and troughs along its streamwise length, but that the air entrainment rate would be same as for the shallow water partial cavities discussed in Mäkiharju 2012.)

The final expression for the net energy savings is obtained by combining eqn. 3.1 and 3.2, yielding

$$\frac{\%E_{savings}}{100} \approx f_{FD}\frac{A_{AL}}{A_{wet}}\left(\frac{\%D_R}{100}\right)-\frac{P_{comp}\eta_{prop}}{P_D\eta_{elect}} \qquad (3.11)$$

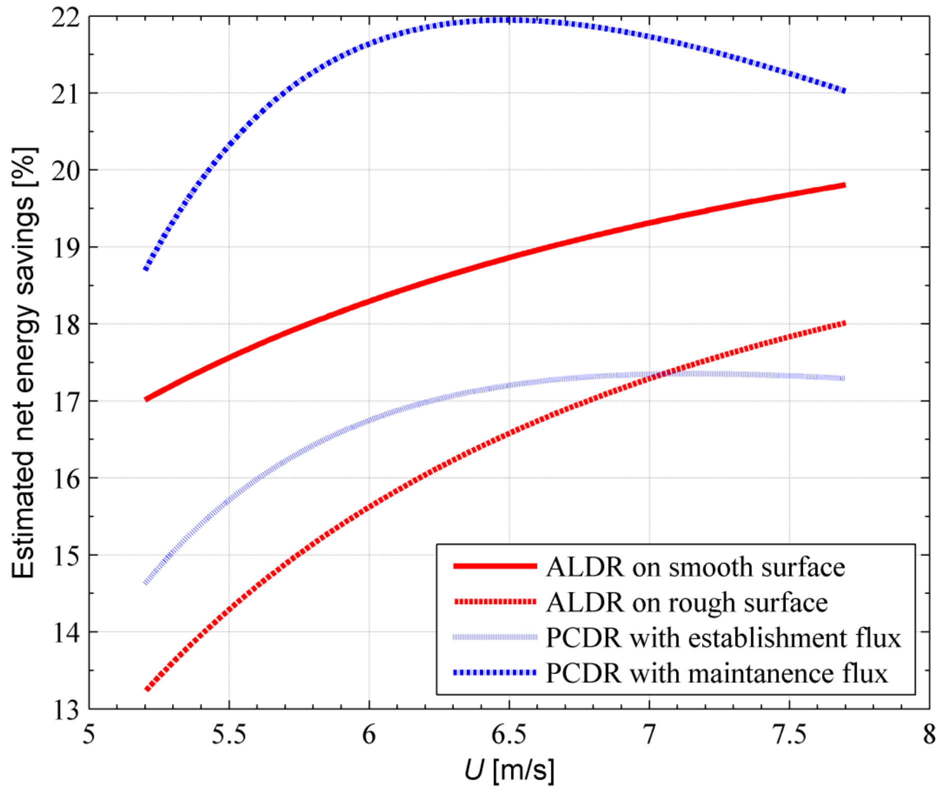

Figure 3.4 − Estimates of the potential net energy savings for a ship similar to the *M/V American Spirit*.

3.2 Discussion

There have been two sea trials where the flow was likely in the BDR-transitional-ALDR region (based on flow regions as defined in Elbing *et al.* 2008). One such sea trial on the Pacific Seagull yielded 5 to 10% net energy savings according to Hoang *et al.* (2009), while a second sea trial by Mitsubishi Heavy Industries achieved 8 to 12% net energy savings (Mizokami *et al.* 2010). As for PCDR, a scale test by MARIN recently showed 15% net energy savings (Foeth, 2011) and for a 1:12th scale test by STENA they reported resistance reduction of 20 to 25% (Surveyor 2011). The potential net energy savings predicted for ALDR in figure 3.4 are slightly higher than observed in the sea trials. This is likely explained by a combination of the following: the sea trials may not have had sufficient air flux supplied to achieve a true air layer (as could be assumed from the local frictional drag measurements presented by Hoang *et al.* 2009), air entrainment into the propulsor, presence of flow perturbations in the open ocean or the area fraction of the wetted hull covered for these ships was less than assumed in the current analysis.

For the surface covered by air, the percentage of frictional drag reduction was assumed to be 80% for both ALDR and PCDR to be conservative, and given that other components of drag may in fact increase. It is important to note that any effects of possibly increased form drag and all other details, such as the effect of air entrainment into the propulsor or that some of the energy is used for ship service loads, were omitted. It was not the intent to make a strong quantitative argument, but rather to show qualitatively the trends of the energy economics of air lubrication, and thereby to determine whether the energy savings break-even point could be surpassed for a Great Lakes ship.

The energy savings break-even point depends on three principal parameters, ship's draft, length and operating speed. The net energy savings achieved, will likely deviate from those estimated here as they depend on all the assumptions made in the analysis, and on how the data from water tunnel experiments shown in figure 3.2 would scale to conditions not tested in the experiments. There are certainly boundaries for these techniques that have not been encountered within the limited parameter ranges of the nominally two dimensional experiments on which estimates of required air flux were based.

A ship specific analysis in collaboration with the ship owner would enable more accurate estimates, and a sea-trial would provide answers to the remaining open questions.

4. Economic cost benefit

As the exact economic numbers relating to the ship operations are not a matter of public record, the shipping professionals can estimate the cost better than we, but the potential annual cost savings can be approximated from

$$\Delta C_{annual} = S_{fuel} - C_{\text{maintanence}} - C_{\text{annuity of initial cost}} \tag{4.1}$$

where the annual fuel cost savings are given by

$$S_{fuel} = C_{fuel} \frac{\%E_{savings}}{100} \left(1 + \frac{\%O_{overhead}}{100}\right) \tag{4.2}$$

and the initial cost per year spread out over the ship's lifetime is given by

$$C_{\text{annuity of initial cost}} = C_{initial} \frac{i(1+i)^n}{(1+i)^n - 1} \tag{4.3}$$

where n is the number of years and i is the interest rate.

According to US Army Corps of Engineers (2010), in 2008 a typical fuel cost for a Great Lakes 1000 footer was \$15,207/day and season had 275 days. Assuming an annual fuel price increase of 5% since 2008, current fuel cost for a season would be \$4,840,000. This is also in agreement with the fuel cost estimates from Parsons *et al.* (2011), if we assume 38 annual trips. Based on discussion from Chapter 3 we assume 18% net energy savings and neglect the associated overhead cost, leading to annual fuel savings, S_{fuel}, of \$871,000. If the air delivery system maintenance were to cost \$100,000/year and initial investment of \$2,000,000 is required for compressor and retrofit, then with 2.5% inflation/interest rate for a 20 year period $\Delta C_{annual} \approx$\$643,000. This would correspond to \$12,850,000 savings over 20 years. Even with 4.7% net energy savings the system could pay for itself, but it is also possible that the savings would be greater if *O*(18%) net energy savings were achieved and the fuel costs rise more than inflation.

These cost estimates are crude, and the shipping professionals are best capable of refining these with knowledge of the actual cost figures for a specific ship. Being energy net positive was a necessary but not a sufficient condition to justify air lubrication. One would need to analyze ship specific initial cost from labor, materials, machinery, and lost opportunity cost during retrofit, lost cargo capacity, maintenance cost of air delivery system, future fuel cost change, potential future carbon credit savings, PR value, and for a new ship there may be offsets, as a smaller engine and fuel tanks may suffice for a ship using ALDR or PCDR.

5. Summary

Currently at least four large projects investigating the various air lubrication techniques are ongoing worldwide, and air lubrication looks to be especially promising for ships with flat bottoms and with high length-to-beam ratios. Of the two sea-trial producing net energy savings, the Pacific Seagull had L/B = 5.9 (Hoeng *et al.* 2009) and Mitsubishi's ship had L/B = 4.3. A Great Lakes 1000 footer has L/B ratio of 9.6, which combined with high box coefficient and shallow draft make the 1000 footer a perfect candidate for implementing air lubrication.

PCDR requires more modifications to the bottom of the hull than BDR or ALDR, but could potentially offer larger frictional drag reduction with a lesser gas flux. Hence, the capital cost would probably be higher than for ALDR, but the operating cost may be lower. The tradeoff between upfront cost and operating cost will be a ship specific consideration. Also, air layers probably offer a more flexibility in the operating speed range, while PCDR may be significantly more economical for a narrow operating speed range(s). Hence the suitability of each of these techniques for a given ship or barge is also affected by the intended use of the vessel.

A special consideration for Great Lakes ships is that they must pass through the relatively shallow locks and hence draft is critical. For the Great Lakes ships it may be more suitable to try ALDR first as required retrofit is smaller and no significant change of draft (< 2") is perceived. In the simplified calculations the energy cost-benefit predicted was 13 to 22%, but ship specific design and benefit analysis is needed, followed by sea trials. The life time cost for implementing air lubrication should be calculated with the shipping professionals.

6. Potential Economic Impacts of the Research Results

The economic and environmental impacts of successfully implemented air lubrication could be significant, as a ship's fuel consumption may be reduced by 5 to 20%. However, the techniques have yet to be implemented on the Great Lakes and hence the potential benefits are yet to be realized.

A ship specific analysis in collaboration with the ship owner would enable a more accurate energy and cost estimates. Ultimately, retrofitting an existing ship for ALDR followed by sea-trial and years of operation would provide answers to the remaining technical and economic questions.

7. Dissemination of study result

A journal article related to this research project is currently being prepared for submission, and we anticipate it to be published in 2012-2013.

An addition to a presentation at the 2011 GLMRI affiliates fall meeting, two other presentations were given which referenced this funded research. One presentation was given at the American Physical Society's Division of Fluid Dynamics meeting in Baltimore, MD, in November 2011. Also, S. Mäkiharju's thesis defense presentation included material related to this project.

The dissertation of Simo Mäkiharju contains material related to this funded research, and accordingly includes the GLMRI in the acknowledgements. The reference to the dissertation is: *Mäkiharju, S., "The Dynamics of Ventilated Partial Cavities Over a Wide Range of Reynolds Numbers and Quantitative 2D X-ray Densitometry for Multiphase Flow," PhD thesis, University of Michigan, 2012.*

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