Options for Fuel Saving for Ships

Karsten Hochkirch, FutureShip GmbH, karsten.hochkirch@GL-group.com
Volker Bertram, FutureShip GmbH, volker.bertram@GL-group.com

1. Introduction

Mid-term and long-term fuel prices are expected to range from 500 to 1000 $/t including expected future surcharges for CO_2 (carbon-dioxide) emissions. Therefore ship operators will put higher pressure on ship owners to obtain fuel efficient ships. These in turn will put pressure on ship yards to supply fuel efficient ships. As a result, we expect to see a paradigm shift in designs and refits to improve the fuel consumption of ships.

There are any many ways to reduce fuel consumption.
- reduce required power for propulsion
- reduce required power for equipment on board
- use fuel energy more efficiently for propulsion and on-board equipment
- substitute fuel power (partially) by renewable energies like wind and solar energy

Surveys on partial aspects of fuel saving options have been published before. Several HSVA (Hamburg Ship Model Basin publications, *Hollenbach et al. (2007), Mewis and Hollenbach (2007), Hollenbach and Friesch (2007),* give rather comprehensive overviews of hydrodynamic options in design and operation of ships. *Hochhaus (2007)* discusses various approaches to recuperate energy losses from the main engine to use them for on-board equipment. New hull form features are developed to improve the fuel consumption for given payload, *Harries et. Al (2007)*. We will discuss more comprehensively the available options in the following, but recommend them nevertheless for further studies.

2. Reduce required power for propulsion

We may use traditional hydrodynamic approaches to decompose the power requirements into resistance and propulsion aspects. While propulsor and ship hull should be regarded as systems, the structure may help to understand where savings may be (largely) cumulative and where different devices work on the same energy loss and are thus mutually excluding alternative.

2.1. Reduce resistance

There are many ways to reduce the resistance of a ship. On the most global level, there are two (almost trivial) options:

- *Reduce ship size:* The lightship weight may be reduced for example by (expensive) lightweight materials, more sophisticated structural design involving possibly formal optimization and reducing the ship length. None of these options is straightforward. The ship length should consider hydrodynamic aspect as well as production and weight aspects. However, reducing the required power during the design stage by the assorted measures discussed below will reduce in turn the weight of engines, power trains and fuel tanks and yield considerable secondary savings due to smaller ship size.
- *Reduce speed:* Speed reduction is a very effective way to reduce fuel consumption and emission. HSVA reports fuel savings of typically 13% for bulkers or tankers, 16-19% for containerships, for a speed reduction by 5%, *Mewis and Hollenbach (2007)*. Slow steaming reduces in itself fuel consumption significantly. However, the ship is then operated in off-design, thus sub-optimal condition. This offers assorted potential improvements to reduce the fuel consumption further:

electronically controlled main engines allowed better efficiencies at slow steaming and reduce also lubrication oil consumption; controllable pitch propellers allow better propeller efficiency over a wider range of rpm; adapted new bulbous bows may reduce wave resistance considerably. On the other hand, waste heat from exhausts and cooling water is considerably reduced and may require reconfiguration of auxiliary engine systems for slow steaming. In sum, a supporting engineering analysis is recommended when deciding on slow steaming for a longer time.

The largest levers in ship design lie in the proper selection of main dimensions and the ship lines. Ship model basins should be consulted to assess the impact of main dimensions based on their experience and data bases. On a more detailed level, for a given speed and ship weight, all components of the ship resistance, *Bertram (2000a),* may offer fuel saving potential:

- *Frictional resistance of bare hull:* The frictional resistance (for given speed) depends mainly on the wetted surface (main dimensions and trim) and the surface roughness of the hull (average hull roughness of coating, added roughness due to fouling). Ships with severe fouling may require twice the power as with a smooth surface. The battle against marine fouling is as old as seafaring, *Bertram (2000b).* Silicone-based coatings create non-stick surfaces similar to those known in Teflon coated pans. In addition to preventing marine fouling effectively, these smooth surfaces may result in additional fuel savings. Figures of up to 6% are quoted by shipping companies. An average hull roughness (AHR) of 65 μm is very good, AHR = 150 μm standard, and AHR > 200 μm sub-standard, *Hollenbach and Friesch (2007).* As a rule of thumb, every 25 μm of hull roughness corresponds to 0.7-1% of propulsion power, *N.N. (2008c).* As a more exotic approach, a film of air on part of the hull reduces friction and in turn fuel consumption. The air cavity ship uses compressors to constantly pump air under the ship. However, the technical effort is considerable. Researchers work on fuzzy acrylic paints that will contain thin air films. The air film may even inhibit bio-fouling, preventing barnacles and other organisms from attaching themselves.

- *Wave resistance of bare hull*: For given main dimensions, wave resistance offers large design potential. Moderate changes in lines can result in considerable changes of wave resistance. As the length of the created waves depends quadratically on speed, the interaction of bulbous bow and forebody of the ship changes with speed. Thus a bulbous bow changes effectiveness with speed. Bulbous bows should be designed based on CFD (computational fluid dynamics), but in most cases fast codes based on simplified potential flow models suffice, *Bertram (2000a).* A formal optimization is recommended as this may offer substantial savings on typical designs, *Hutchison and Hochkirch (2007),* typically 4-5% can easily be gained and 1-2% improvement are feasible even on hulls that are deemed already highly ‘optimized’ in limited form variations with CFD and model tests in model basins, Fig.1, *Abt and Harries (2007).* Optimization of the aftbody lines requires considerably higher computer resources due to the dominant effects of viscosity and turbulence. However, pilot applications show the feasibility of the approach and formal optimization of aftbody lines is expected to appear soon as a standard option in ship design. Hull optimization, whether based on potential flow models or viscous flow models, is particularly attractive for new designs where the ship owner can and should specify that such an optimization is performed. For existing ships, refits of bulbous bows may have payback times of less than a year, *Hochkirch and Bertram (2009),* but it is frequently problematic to obtain original hull descriptions. Service providers (classification societies, model basins, consultants) cannot divulge proprietary lines of one client (shipyard) to another (ship owner).

- *Residual resistance of bare hull (mainly due to flow separation)*: Flow separation occurs when the velocity gradients become too large in a flow. Large curvature in flow direction should then be avoided. Flow separation in the aftbody is delayed by the flow acceleration due to the propeller and different in model scale and full scale. CFD simulations may help in finding suitable compromises between hydrodynamic and other design aspects.

- *Resistance of appendages*: Appendages contribute disproportionately to the resistance of a ship. CFD simulations can determine proper alignment of appendages.
- *Rudder resistance*: Rudders offer an often underestimated potential for fuel savings. Improving the profile or changing to a highly efficient flap rudder allows reducing rudder size, thus weight and resistance. Due to the rotational component of the propeller, conventional straight rudders at zero rudder angle encounter oblique flow angles to one side at the upper part and to the other side in the lower part. This creates opposing lift forces which cancel each other, but the associated induced drag forces add. By twisting the rudder these unnecessary drag forces can be reduced. Compared to a conventional semi-balanced rudder, a twisted rudder with Costa bulb may have 4% lower power consumption, Fig.2, *Hollenbach and Friesch (2007).* High-efficiency rudders combine various approaches to save fuel: twisted rudders are combined with a bulb on the rudder as a streamlined continuation of the propeller hub, e.g. *Beek (2004), Lehmann (2007).* In theory, the gap between the hubcap and the forward part of the bulb should be as small as possible. In practice there has to be gap sufficient to allow for structural deflection under load and propeller aperture and rudder and also tolerances that can be realistically achieved under real shipbuilding conditions. Savings of 2-8% are claimed by the manufacturers.
- *Added resistance due to seaway:* Intelligent routing (i.e. optimization of a ship's course and speed) may reduce the average added resistance in seaways. For example, the Ship Routing Assistance system, *Rathje and Beiersdorf (2005),* was originally developed to avoid problems with slamming and parametric roll, but may also be used for fuel-optimal routing. However, GL experts estimate the saving potential to less than 1% for most realistic scenarios. In any case, routing systems for fuel optimization should not only consider the added resistance to motions in waves, but also the higher rudder resistance due compensation of drift forces.
- *Added resistance due to shallow water:* Routing systems may also consider shallow water and the associated increased resistance, *Friedhoff (2006).*
- *Added resistance due to wind*: Wind adds power requirements in two ways: (a) direct aerodynamic resistance on the ship and (b) indirect power demand due to drift in side winds. The effect can be evaluated in wind tunnel tests and CFD simulations. Proposals for wind resistance reductions include frontal spoilers, optimized container stowage and awnings. Savings of 1-1.5% on the overall power demand have been estimated, *Hollenbach et al. (2007).* However, operational constraints hinder practical applications so far.

For each draft and speed, there is a fuel-optimum trim. For ships with large transom sterns and bulbous bows, the power requirements for the best and worst trim may differ by more than 10%, *Mewis and Hollenbach (2007).* Systematic CFD simulations are recommended to assess the best trim and the effect of different trim conditions. Decision support systems for fuel-optimum trim based on such simulations have been proven to result in considerable fuel savings (typically 5% as compared to even keel) for relatively low investment, *Hansen and Freund (2010)*. They are expected to become a standard feature on larger cargo ships within the next decade.

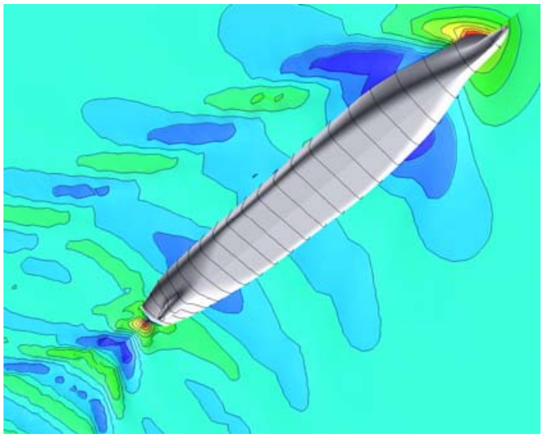

Fig.1: Bulb optimization by CFD, source: www.futureship.net

Fig.2: Twisted rudder with Costa bulb, source: www.hsva.de

2.2. Improve propulsion

The propeller transforms the power delivered from the main engine via the shaft into a thrust power to propel the ship. Typically, only 2/3 of the delivered power is converted into thrust power. A special committee of the *ITTC (1999)* discussed extensively assorted unconventional options to improve propulsion of ships and the associated problems in model tests. In short, model tests for these devices suffer from scaling errors, making quantification of savings for the full-scale ship at least doubtful.

- *Operate propeller in optimum efficiency point:* The propeller efficiency depends among others on rpm and pitch. Fixed pitch propellers are cheaper and have for a given operating point a better efficiency than controllable pitch propellers (CPPs). They may be replaced if the operator decides to operate the ship long-term at lower speeds. CPPs can adapt its pitch and thus offer advantages for ships operating over wider ranges of operational points. Several refit projects have been reported, with savings up to 17% quoted due to new blades on CPPs, *N.N. (2008a).*

- *Reduce rotational losses:* For most ships, there is substantial rotation energy lost in the propeller slipstream. Many devices have been proposed to recover some of this energy. These can be categorized into pre-swirl (upstream of the propeller) and post-swirl (downstream of the propeller) devices. Pre-swirl devices are generally easier to integrate with the hull structure. Rudders behind the propeller recover automatically some of the rotational energy. Therefore potential gains should always be considered with rudder behind the propeller to avoid overly optimistic estimates. Pre-swirl devices include the SVA Potsdam (Potsdam model basin) pre-swirl fin, pre-swirl stator blades, *Liljenberg (2006),* and asymmetric aftbodies, *Schneekluth and Bertram (1998).* Probably the best known post-swirl device is the Grim vane wheel, *Schneekluth and Bertram (1998).* The original Grim vane wheel is located immediately behind the propeller generating extra thrust. The vane wheel is composed of a turbine section inside the propeller slipstream and a propeller section (vane tips) outside the propeller slipstream. The vane wheel became unpopular after several reports of mechanical failures, most notably for the 'Queen Elizabeth 2'. IHI and Lips BV developed a modified vane wheel supported on the rudder, overcoming the mechanical problems of the original Grim vane wheel, Fig.3, *N.N. (1992).* Other post-swirl devices are stator fins and rudder thrust fins. Stator fins are fixed on the rudder and intended for slender, high-speed ships like car carriers, *Hoshino et al. (2004).* Rudder thrust fins are single foils attached at the rudder, proposed by Hyundai H.I.
  Typically 4% fuel savings are claimed for all these devices by manufacturers. As all these devices target at the same energy loss, only one of them should be considered. Gains are certainly not

cumulative. CFD simulations are the suitable tool to evaluate effects of these devices at full scale and aid their detailed design. Contra-rotating propellers are a traditional device to recover the rotational energy losses, *Schneekluth and Bertram (1998)*. More recently, podded drives and conventional propellers have been combined to hybrid CRP-POD propulsion, *Ueda and Numaguchi (2006)*, claiming 13% fuel savings.

- *Reduce frictional losses:* Smaller blades with higher blade loading decrease frictional losses, albeit at the expense of increased cavitation problems. A suitable tradeoff should be found using experienced propeller designers and numerical analyses.
- *Reduce tip vortex losses:* The pressure difference between suction side and pressure side of the propeller blade induces a vortex at the tip of the propeller. This vortex (and the associated energy losses) can be suppressed (at least partially) by tip fins similar to those often seen on aircraft wings. The general idea has resulted in various implementations, differing in the actual geometric form of the tip fin, ITTC (1999), namely contracted and loaded tip (CLT) propellers (with blade tips bent sharply towards the rudder), Fig.3, Sparenberg-DeJong propellers (with two-sided shifted end plates), or Kappel propellers (with integrated fins in the tip region).
- *Reduce hub vortex losses:* Devices added to the propeller hub may offer cost effective fuel savings. Propeller boss cap fins (PBCF) were developed in Japan, Fig.3, *ITTC (1999)*, *N.N. (1991)*. Publications of the patent holders report 3-7% gains in propeller efficiency in model test and 4% for the power output of a full-scale vessel. Reported gains have to be considered with caution, *Junglewitz (1996)*. “The presence of the rudder significantly reduces the strength of the hub vortex and hence the gain in propeller efficiency due to PBCF can be reduced by 10-30%”, *ITTC (1999)*. The Hub Vortex Vane (HVV), jointly developed by SVA Potsdam and Schottel, offers an alternative to PBCF. The HVV is a small vane propeller fixed to the tip of a cone shaped boss cap. It may have more blades than the propeller. The vendors claim increases of 3% in propeller efficiency.
- *Operate propeller in better wake:* The propeller operates in an inhomogeneous wake behind the ship. This induces pressure fluctuations on the propeller and the ship hull above the propeller, which in turn excite vibrations. The magnitude of these vibrations poses more or less restrictive constraints for the propeller design. A more homogeneous wake translates then into potentially better propeller efficiency, for example by a larger propeller diameter or larger blade loading on the outer radii. For new designs, wake equalizing devices like Schneekluth nozzles (a.k.a. wake equalizing ducts (WED)), Grothues spoilers, vortex generators, *Schneekluth and Bertram (1998)*, may therefore improve propulsion and save fuel. For existing ships, despite several refits more recent independent analyses shed doubts concerning the effectiveness of WEDs, *Ok (2005)*. “In conclusion, partial ducts [like WED] may result in energy saving at full scale, but this was not, and probably cannot be proven by model tests […]”, *ITTC (1999)*.

Fig.3: Improving propulsion: CLT propeller (left), PBCF (center), Grim vane wheel (right)

2.3. Other aspects

Resistance and propulsion and main engine interact. Partial improvements of individual components as possible as discussed so far, but the system analyses considering the interaction of the components offers additional saving potential.

Ships are frequently hydrodynamically tuned for a design speed, but later operated most of the time at lower speeds, even when they are not “slow-steaming”. If designed for a more realistic mix of operational speeds, ships are estimated to exploit further fuel saving potential. Similarly, an even speed profile in operation saves fuel. This is largely a question of awareness. Fuel monitoring systems have proven to be effective in instigating more balanced ship operation with fuel (and emission) savings of up to 2%.

3. Reduce required power for equipment on board

There are various options to save power in the assorted energy consuming equipment onboard ships. The saving potential depends on the ship type. Examples are in more efficient electronically controlled pumps, HVAC (heat, ventilation and air conditioning) ventilation systems, and energy saving lighting. Energy-saving lamps not only reduce the energy requirements for lighting, they also reduce the waste heat from the lamps and thus the energy needed by air conditioning systems to cool lighting rooms down again.

Ship engines convert only up to 50% of the fuel energy into propulsive power. Approximately 25% of the fuel energy is lost in the exhaust heat and another 25% in the cooling water. There are various approaches to recuperate some of these energy losses, *Hochhaus (2007)*. Exhaust heat may be used for steam generation or to fuel deep-freeze absorption chillers. Hot coolant may be used to produce fresh water from sea water.

Avoid oversized main engines. Sea margins should be adapted to ship type, ship size and intended operational trade. For example, 7-8% sea margin may suffice for large containerships. The sea margin may be selected based on standard seakeeping analyses or in standard cases also based on experience. The frequently added engine margin may be omitted altogether. Ships are often operated at considerably lower speeds than the design speed, but operators want to keep the capability for occasional high speed. The required margins for such occasional high-speed operator are expensive and may be better covered by falling back on the auxiliary engine power (power take-in (PTI) via shaft generator) on the rare occasion when high speed is needed. Detailed engineering analyses can be used to assess feasibility and cost aspects of alternative configurations, Fig.5. For slow-steaming ships with controllable pitch propeller, it is better to reduce the brake mean effective pressure than the rpm. If the ship shall be operated at lower speeds for a longer period the engine may be adapted to the mean effective pressure by changing the fuel injection system or installing an exhaust turbocharger. Intelligent monitoring and simulation software can combine engine supplier data and standard onboard monitoring data for a given operational profile to determine optimum combinations of propeller pitch and rpm.

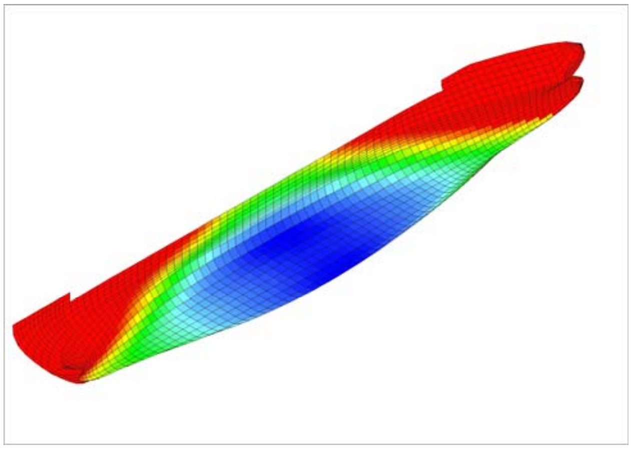

Fig.4: Added resistance in seaway can be assessed by potential flow codes

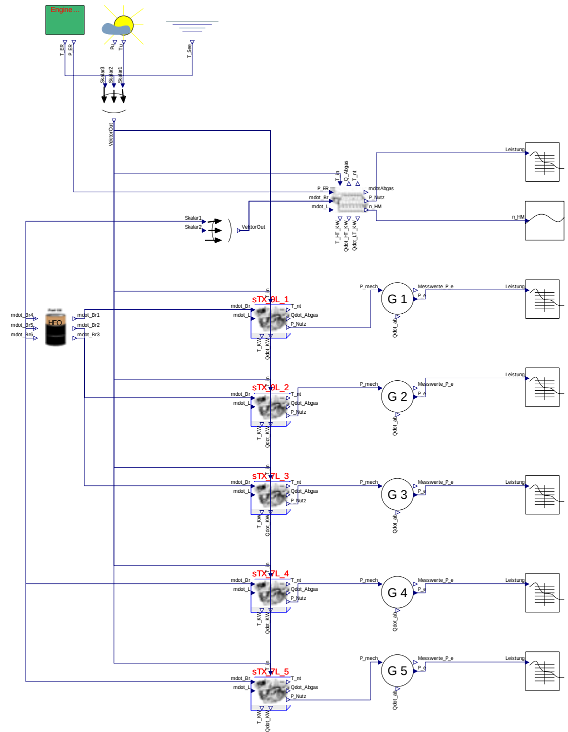

Fig.5: Simulation model of engine configuration to assess fuel consumption based on operational profile

Avoid oversized auxiliary engines. Better overall energy management systems may balance the energy demand of the consumers on board reducing peak demands allowing in turn a reduction of the generator capacity. This in turn reduces the weight of the ship. Simulations of the overall machinery system are able to predict fuel consumptions for provided energy consumer profile, *Freund et al. (2009)*, *Hansen and Freund (2010)*. These simulations allow assessment of alternatives and ultimately better balanced energy profiles.

4. Increase use of renewable energies

Wind has been the predominant power source for ships until the late 19th century. Wind-assistance has enjoyed a recent renaissance. Wind-assisted ships use predominantly other means of power (typically diesel engines) and wind power plays only a secondary role. With increasing ship speed, wind assistance makes less sense as increasingly efficient sails are needed. Constraints are initial investment, space requirements, stability and required man-power for operation and maintenance. Despite these constraints, several industrial projects have been realized in the past decade. Wind kites have been brought to commercial maturity by the company Skysails, Fig.6, drawing also on expert advice from Germanischer Lloyd. Kites harness wind power at larger heights without the stability penalties of high masts. The development has enjoyed large media attention, and in 2007 the first prototype was tested successfully on the MS “Beluga Skysails” and the “Michael A”, *N.N. (2008b)*. Fuel savings in excess of 10% quoted by the manufacturer apply for slower ships. Flettner rotors are another technology harnessing wind energy for ship propulsion. After 80 years of obscurity, they have resurfaced in 2008 when Lindenau shipyards delivered a GL-class freighter equipped with Flettner rotors. These four cylinders, each 27 m tall and 4 m in diameter, are predicted to save nearly half of the conventional fuel needed by the ship.

Fig.6: Towing kite harnessing wind energy, source: www.skysails.de

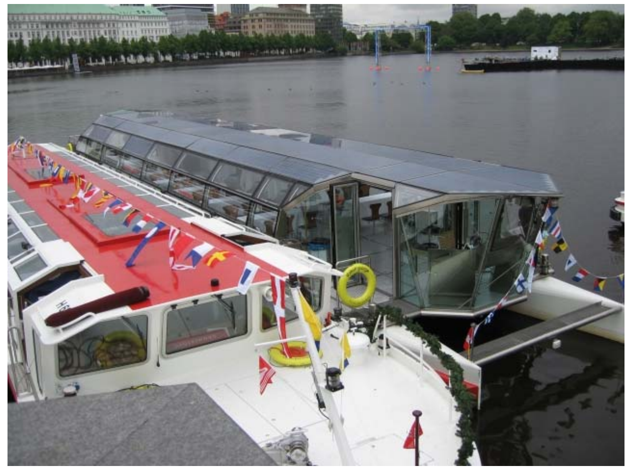

Fig.7: Solar catamaran "Alstersonne", source: www.kopf-solarschiff.de

Solar energy may supply an environmentally friendly part to the total energy balance of a ship. For inland ferries, solar power and fuel cells are an attractive option to have zero-emission ships, Fig.7. For other ships, diesel and solar energy may be combined. Diesel-electric drive systems are already quite common. Future ships may combine then diesel generators for 50% of the total power consumed, fuel cells providing 30% and a solar generator accounting for the remaining 20%. Solar-power and wind-power can be combined, using fixed sails equipped with solar panels. This option is employed successfully on the SolarSailor ferries operated in Sydney and San Francisco.

5. Conclusion

There are many technical levers to save fuel and thus emissions for ships. Unfortunately, there is large scatter in saving potential and quoted saving potential is unreliable. Manufacturers frequently quote best cases and sometimes extrapolate erroneously results from model tests to full scale ships. Despite these uncertainties, the compiled information may serve for a first assessment on a case by case basis and identification of most promising options. This requires interdisciplinary team work of clients and consulting experts. For a more quantitative assessment, dedicated analyses often based on simulations are required.

Despite these words of caution, there is wide consensus that significant potential for fuel saving exists and dedicated consultancy companies can support ship owners and operators in tapping into these potentials.

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