Table of Contents

1 Introduction

1.1 Fuel costs

The price of bunker medium fuel oil (MFO) has not only changed from…

1973	30 $/t		1991	80 $/t
1974	70 $/t		1996	100 $/t
1979	150 $/t		2000	150 $/t
1981	200 $/t		2003	175 $/t
			2008	850 $/t

Table 1: Development of the price of bunker for MFO

… but further price increases caused by restricting delivery volumes by OPEC are probable. Together with a concern about fuel availability, this has caused shipping companies to prioritise all plans of reducing fuel consumption and to consider the future development of fuel supply. Fuel costs have again become the biggest single position in costing. A quick adaptation to fuel prices and charterers' requests is difficult due to the long-term investments in the shipping business. The majority of ships being used in the next 10 to 15 years have already been built and are in operation. Technical developments can only absorb a minor part of the charging of costs.

With crude oil derivatives as a primary energy source, diesel engines will still be the main propulsing engine in the medium term.

Increasing fuel prices demand special efforts. These cannot be limited to just a reduction in fuel consumption of the main engine. They are classified into three main areas:

1. methods of improving vessel movement through the water
2. methods of a better energy conversion and an improved energy transport
3. better management of the ship

The 1st method includes:

- ship design with the main components bow and stern
- coating the underwater hull
- reducing resistances

The 2nd method includes:

- consumption reduction on the main engine
- consumption reduction in auxiliary power mode
- heat recovery systems
- switching to other fuel grades
- improving propeller efficiency

The 3rd method includes:

- fleet management
- transport management
- weather routing
- optimum vessel speed
- electricity generation
- shore connection for on-shore power supply

Due to the price difference between MFO and MDO almost all shipping companies use the cheaper MFO and therefore use the worst fuel quality. Numerous engines respond with increased repair and maintenance requirements or breakdowns. In a few years time, not only the IMO directive on exhaust emissions will limit additional toxic gases, which will cause an avoidance of the cheap sulphurous MFO. Furthermore, national directives will have an impact on harbour dues and other costs. This might cause a worldwide need for burning MFO and MDO containing only a minimum of sulphur.

Using an appropriate ship design only reduces energy to a certain extent. For all future ships, design parameters have to be thought over again in order to reach a maximised economical solution regarding the new cost aspects.

Vessel size and speed have to be reconsidered. The bigger the ship the higher the decrease of specific fuel consumption at the same speed; at a higher speed it remains constant.

- Is it economically viable to operate a tanker with a speed of 17 knots? Or is this just an argument supporting competition?
- Could 12, 15, 18 or 20 knots be more appropriate considering future aspects?
- Is it adequate to transport bulk goods with 10 knots?
- How can the resistance be minimised? Main dimensions and the shape of the ship vastly influence fuel consumption.
- Is there a way to improve propulsion? Can a propeller efficiency factor of 0.6 still be increased?
- Lighter steal constructions can have a positive effect on fuel consumption.
- Can efficiency factors of main engines still be raised?

In a lot of cases, a 10 – 20% reduced output with equal vessel speed can be achieved, if the shipping companies are ready to accept higher building costs in order to get an overall more cost effective ship – that is taking capital charges and operating expenses into account.

	max. possible savings
optimising the underwater hull	7 – 20 %
bow construction	3 – 20 %
stern construction	3 – 8 %
propeller design	3 – 8 %

Table 2: Possible savings of fuel consumption, dependent on the shape of the ship and propeller

Example:

M.T. "Admiral" with P = 7850 kW MCR sails with 15.2 knots. Using 83% MCR at the engine coupling and operating the shaft generator with 400kVA results in a daily fuel consumption (with the engine manufacturer's guaranteed value of be = 0.18 kg/kWh) of: $\dot{m}_{krst_d} = P \cdot 0{,}83 \cdot be \cdot t$

$$\dot{m}_{krst_d} = 7850kW \cdot 0{,}83 \cdot 0{,}18\frac{kg}{kWh} \cdot 24\frac{h}{d} \cdot \frac{1t}{1000kg}$$

$$\dot{m}_{krst_d} = 28{,}147\frac{t}{d}$$

At a price of 850 $/t (price basis 7/2008) the daily fuel consumption costs would add up to:

$$K_{krst_d} = \dot{m}_{krst_d} \cdot K$$

$$K_{krst_d} = 28{,}147\frac{t}{d} \cdot 850\frac{\$}{t} = 23925\frac{\$}{d}$$

1.2 Lubricating oil costs

The costs for lubricating oil depend on the price of crude oil, the demands on it and its consumption. It will be calculated with 2.7 $/kg (price basis 7/2008):

$$\dot{m}_{Öl_d} = P \cdot 0{,}83 \cdot be_{Öl} \cdot t$$

$$\dot{m}_{Öl_d} = 7850kW \cdot 0{,}83 \cdot 0{,}0015\frac{kg}{kWh} \cdot 24\frac{h}{d}$$

$$\dot{m}_{Öl_d} = 235\frac{kg}{d}$$

The daily lubricating oil costs of the main engine with shaft generator amount to:

$$K_{Öl_d} = \dot{m}_{Öl_d} \cdot K$$

$$K_{Öl_d} = 235\frac{kg}{d} \cdot 2{,}7\frac{\$}{kg} = 633\frac{\$}{d}$$

The overall daily costs for fuel and lubricating oil add up to:

MFO	23925$/d
lubricating oil	633 $/d
total	24558 $/d

2 Describing and determination of consumption

2.1 Determination of possible specific consumptions

In the field of commercial freight transportation it was recognised a long time ago that the energy costs make up the main proportion of the overall costs. Therefore it has been tried to reduce them. The different routes of transport – water, road, rail, and air – have always shown a tendency to specialise in fields in which the competitive advantage is highest. Hence, the possibility of energy reduction by moving freight transportation from one means of transport to another one is very limited. Ships are compared regarding their cost effectiveness by looking at specific consumptions.

For the illustration of the propeller graph of the M.T. "Admiral" the following base values are assumed: P = 7850 kW MCR, and the on-board power network (driven by the shaft generator) with 320 kW which equals 400 kVA with cos φ = 0.8. The ship exponent which adds the relation between output and speed to the equation is a constant of 3.3.

$$\frac{P_1}{P_2} = \left(\frac{V_1}{V_2}\right)^{3,3}$$

The load on the on-board network was assumed as constant. The ship exponent which does not remain constant throughout a speed variation, can be calculated with the following equation:

$$\textit{ship exponent } x = \frac{\ell n P_1 - \ell n P_2}{\ell n \upsilon_1 - \ell n \upsilon_2}$$

v [kts]	15.1	15	14	13	12	11	10	9	8
$P_{propeller}$ [kW]	7450	7280	5800	4550	3490	2620	1910	1350	920
$P_{on\text{-}board\ network}$ [kVA]	400	400	400	400	400	400	400	400	400
P_{engine} [kW]	7850	7680	6200	4950	3890	3020	2310	1750	1320

Table 3: Power requirement at different speeds

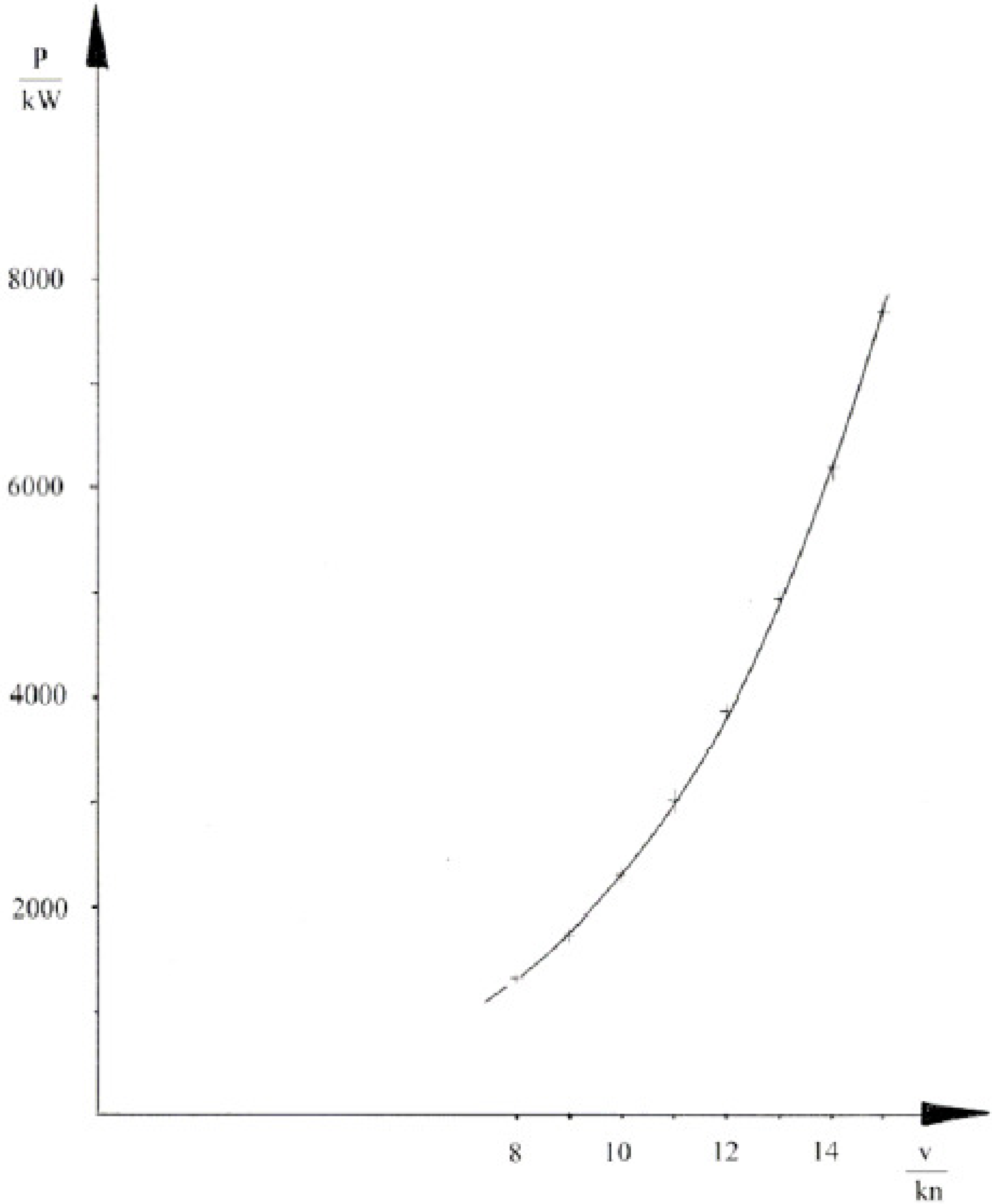


Illustration 1: Propeller graph M.T. "Admiral" including shaft generator

2.2 Guaranteed consumption

The main engine manufacturer's guaranteed specific fuel consumption is measured according to ISO standard.

General Definition of Diesel Engine Ratings (according to ISO 3046- 1:1995)

P = Continuous rating

ISO reference conditions

- Air temperature: .... 298 K (25° C)
- Air pressure:... 1 bar
- Cooling water temperature upstream of change-air cooler: ... 298 K (25° C)

The fuel consumption rates are based on ISO reference conditions and a lower calorific value of the fuel of 42,707 kJ/kg without engine driven pumps.

Main Marine Engines

MCR = Maximum Continuous Rating (fuel stop power)

Blocking of the output for engines, driving a generator, at 110% of the rated output. Overload > 100% may only be operated for a short time for recovery and prevent a frequency drop in case of load application.

Reference conditions

- Air temperature: .... 318 K (45° C)
- Air pressure:... 1 bar
- Cooling water temperature upstream of change-air cooler: ... 305 K (32° C)

Marine Auxiliary Engines

P = Continuous rating

Blocking of the output, at 110% of the rated output. Overload > 100% may only be operated for a short time for recovery and prevent a frequency drop in case of load application.

Reference conditions

- Air temperature: .... 318 K (45° C)
- Air pressure:.. 1 bar
- Cooling water temperature upstream of change-air cooler: ... 305 K (32° C)

These are optimum conditions that usually fall short during normal sea operations. Consequently, this increases the specific fuel consumption for the same main engine output.

The specific fuel consumption b_e in $\frac{kg}{kWh}$, which is guaranteed by the manufacturer, can be easily transferred into a daily consumption in tons:

$$\dot{m}_{krst\,d} = P \cdot b_e \cdot 24 \frac{h}{d} \cdot \frac{1 \cdot t}{1000 kg} \qquad \text{in} \qquad \frac{t}{d}$$

Nevertheless, the necessary considered allowance (Sea Margin, usually 15%) for effective conditions at sea should not be forgotten.

2.3 Actual consumption

The decisive factor for the actual consumption however, is the lower heat value[1] H_u of the fuel, which can only be determined in a laboratory. This can either be done by actual combustion and calculation of released heat energy with the help of a calorimeter or by combustion equations.[2]

$$H_u = c \frac{kgC}{kgKrst} \cdot 33900 \frac{kJ}{kgC} + \left(h - \frac{0}{8} \right) \frac{kgH}{kgKrst} \cdot 121500 \frac{kJ}{kgH} + s \frac{kgS}{kgKrst} \cdot 10500 \frac{kJ}{kgS} -$$

$$w \frac{kgWasser}{kgKrst} \cdot 2520 \frac{kJ}{kgWasser}$$

The standardised heat value is measured in *kJ/kg* and is defined at the value of 42707 *kJ/kg*. However, the MFO delivered by oil companies only has a heat value of 90 – 95% of the

[1] The term *heat value* was preferred instead of *caloric value* as the variable *H* in the equation shows a closer proximity to this term.
[2] Krst = fuel, Wasser = water

standard heat value. The following equations show that with a lower heat value H_u the specific fuel consumption increases and the efficiency decreases.

specific fuel consumption $$b_e = \frac{\dot{m}_{krst}}{P} = \frac{3600}{H_u \cdot \eta_e}$$

power $$P = \frac{\dot{m}_{krst} \cdot H_u \cdot \eta_e}{3600}$$

efficiency $$\eta_e = \frac{3600}{b_e \cdot H_u}$$

With the same engine power and a decreased lower heat value the daily MFO-consumption increases.

2.4 Sludge

It has to be taken into account, that the MFOs that are delivered by oil companies contain a significant amount of water (up to 1%) and other components that have to be separated in fuel processing plants because they would destroy the injection systems of Diesel engines. Amongst these are substances with a density of >1000kg/m^3 plus metallic oxides that remain as residues in the MFO after the catalytic refinement process, as well as other dirt (sand, soot, ash) in the fuel. Experience has shown that due to the separation process up to 3% of the delivered bunker consist of sludge and water. These are collected in the sludge tank but are not suitable for combustion in diesel engines.

Standardised specifications for fuels have been defined since 1987. They constitute that delivered fuels are only allowed to consist of blends of refined crude oil. This excludes the possibility of optimising the viscosity with solvents for instance, or the possibility of disposing used hydraulic oil by mixing it with MFO. These standards define maximum percentages for water, sulphur, vanadium, and metallic oxides.

2.5 Tolerance indications

The manufacturers' guarantee under test facility conditions (air and water temperature, air pressure, air humidity and heat value) a specific fuel consumption with a tolerance of ± 3% or ± 5%. It has to be assumed that the engine manufacturers exhaust this tolerance to the limit.

2.6 Quantities of gas release

The MFO is heated in bunker tanks, the settling tank and day tanks. Highly volatile hydrocarbon is emitted and evaporates into the atmosphere via vent pipes. Only very few motor vessels have a closed fuel system from the mixing tube onwards. Most vessels still operate with open systems from which fuel masses are passed off as gases and therefore get lost. The loss of MFO due to gas release depend on the

- time period
- fuel composition
- fuel temperature

2.7 Types of consumption illustrations

In order to compare fuel consumption between ships of different size, graphs have been proven to be valuable. These are specific graphs of a specific or absolute consumption in relation to vessel speed in % of nominal speed.[3]

$$\frac{t}{d};\quad \frac{kg}{h};\quad \frac{kg}{sm};\quad \frac{sm}{kg};\quad \frac{kg}{kWh};\quad \frac{g}{tdw \cdot sm};$$

The calculated values result from the following preconditions:

- $b_e = 0{,}193 \frac{kg}{kWh}$
- no influences due to abnormal weather, current or sea disturbance
- no change in draught

[3] sm stands for the German word “Seemeile” which is the “Nautical Mile/nm” in English

The possible specific consumptions are calculated as follows:

$$\dot{m}_{krst\,d} = P \cdot b_e \quad \text{in} \quad \frac{kg}{d} \quad \text{bzw.} \quad \frac{t}{d}$$

$$\dot{m}_{spez\,1} = \frac{\dot{m}_{krst}}{v} \quad \text{in} \quad \frac{kg}{sm}$$

$$\dot{m}_{spez\,2} = \frac{v}{\dot{m}_{krst}} \quad \text{in} \quad \frac{sm}{t}$$

$$\dot{m}_{spez\,3} = \frac{\dot{m}_{krst}}{tdw \cdot sm} \quad \text{in} \quad \frac{g}{tdw \cdot sm}$$

v [kts]	**15**	**14**	**13**	**12**	**11**	**10**	**9**	**8**
$P_{Motor}\,[kW]$	7680	6200	4950	3890	3020	2310	1750	1320
$\dot{m}_{krst\,d}\left[\frac{t}{d}\right]$	33.178	26.784	21.384	16.804	13.046	9.979	7.56	5.702
$\dot{m}_{spez\,1}\left[\frac{kg}{sm}\right]$	92.2	79.7	68.5	58.3	49.4	41.6	35	29.7
$\dot{m}_{spez\,2}\left[\frac{sm}{t}\right]$	10.9	12.5	14.6	17.1	20.2	24.1	28.6	33.7
$m_{spez\,3}\left[\frac{g}{tdw \cdot sm}\right]$	3.84	3.32	2.86	2.4	2.06	1.73	1.46	1.24

Table 4: Various specific consumptions in dependency on vessel speed with a shaft generator load of 400 kVA of the MT "Admiral"

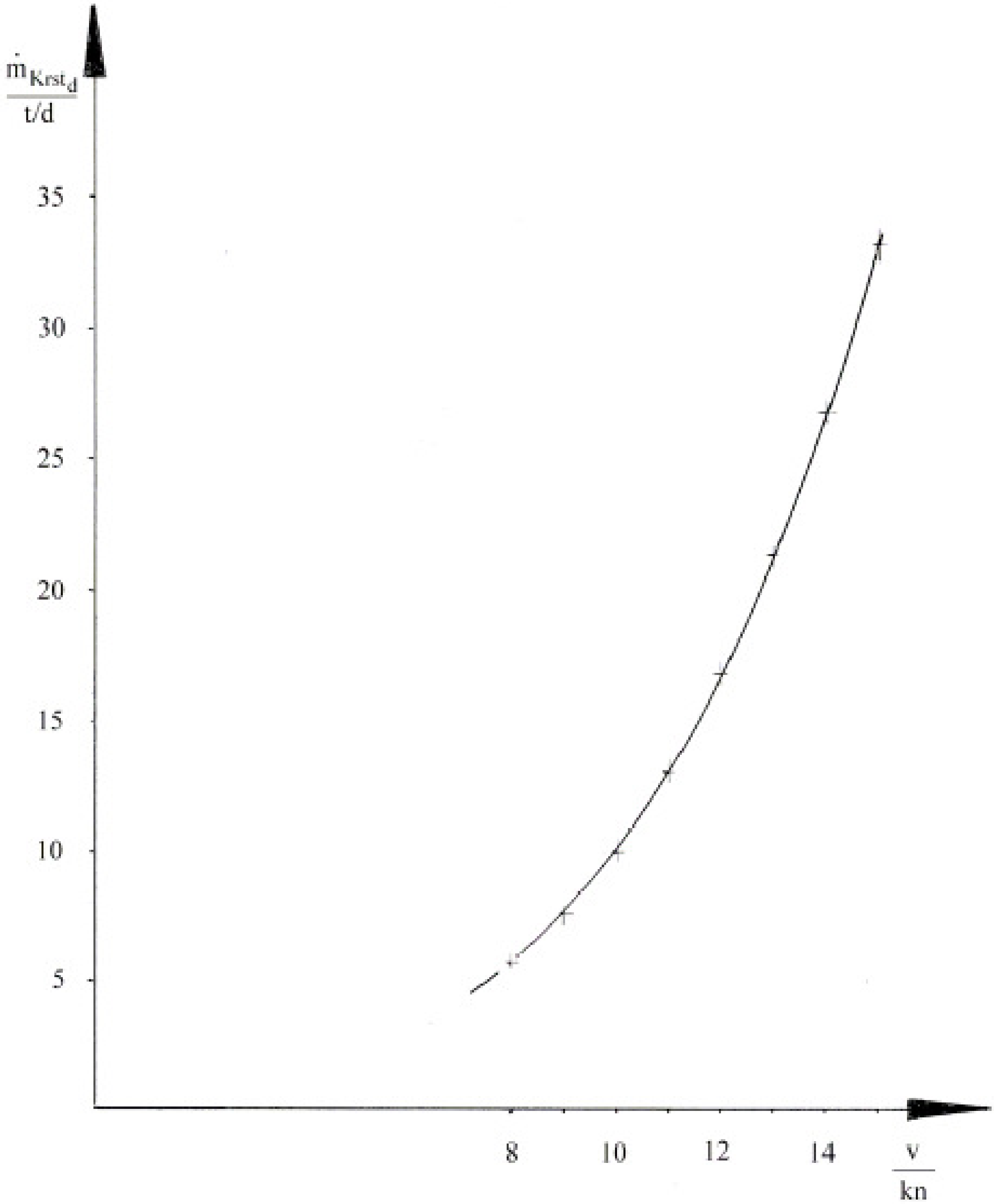


Illustration 2: Daily fuel consumption

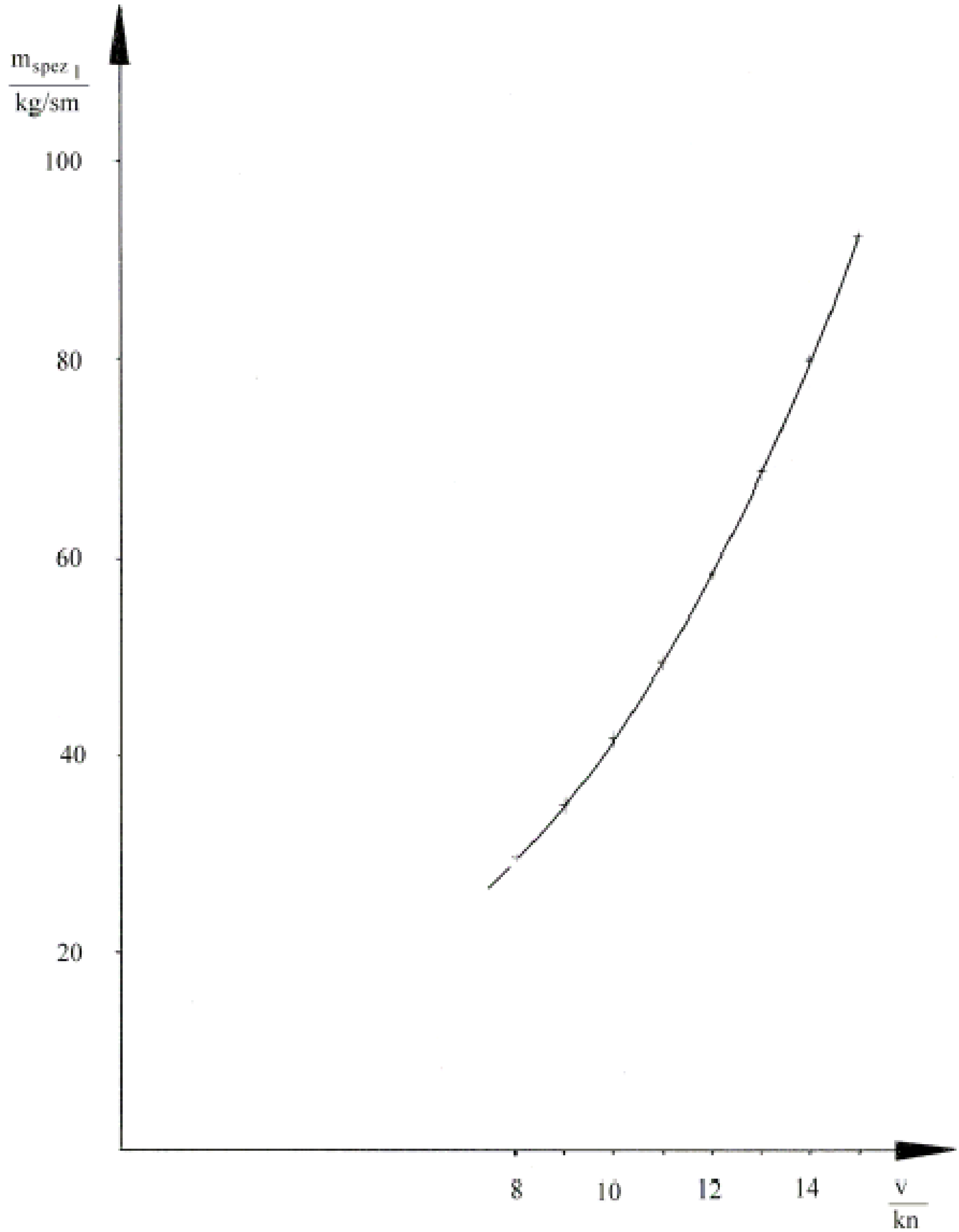


Illustration 3: Specific fuel consumption per nautical mile sailed

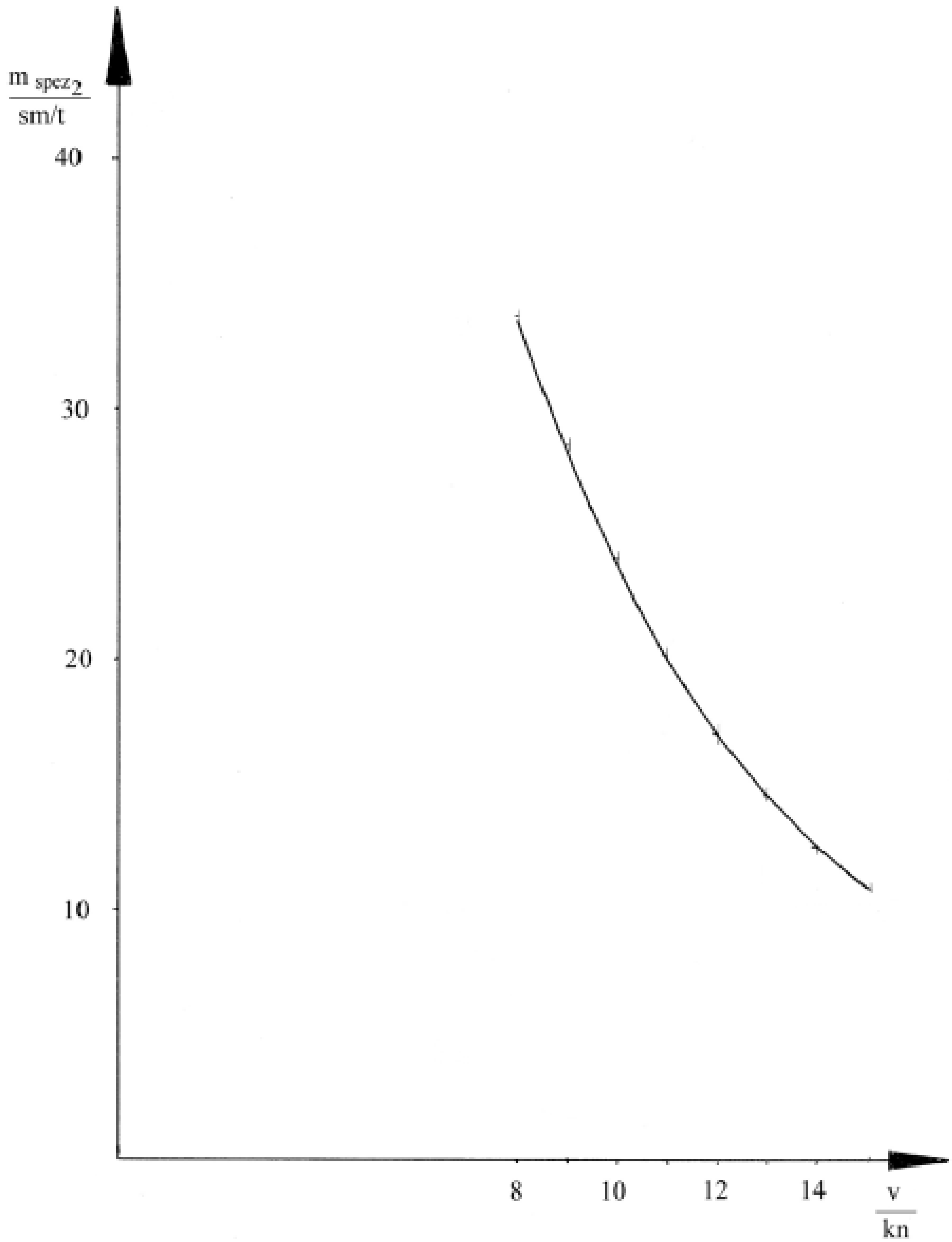


Illustration 4: Sailed distance in nm per ton of fuel

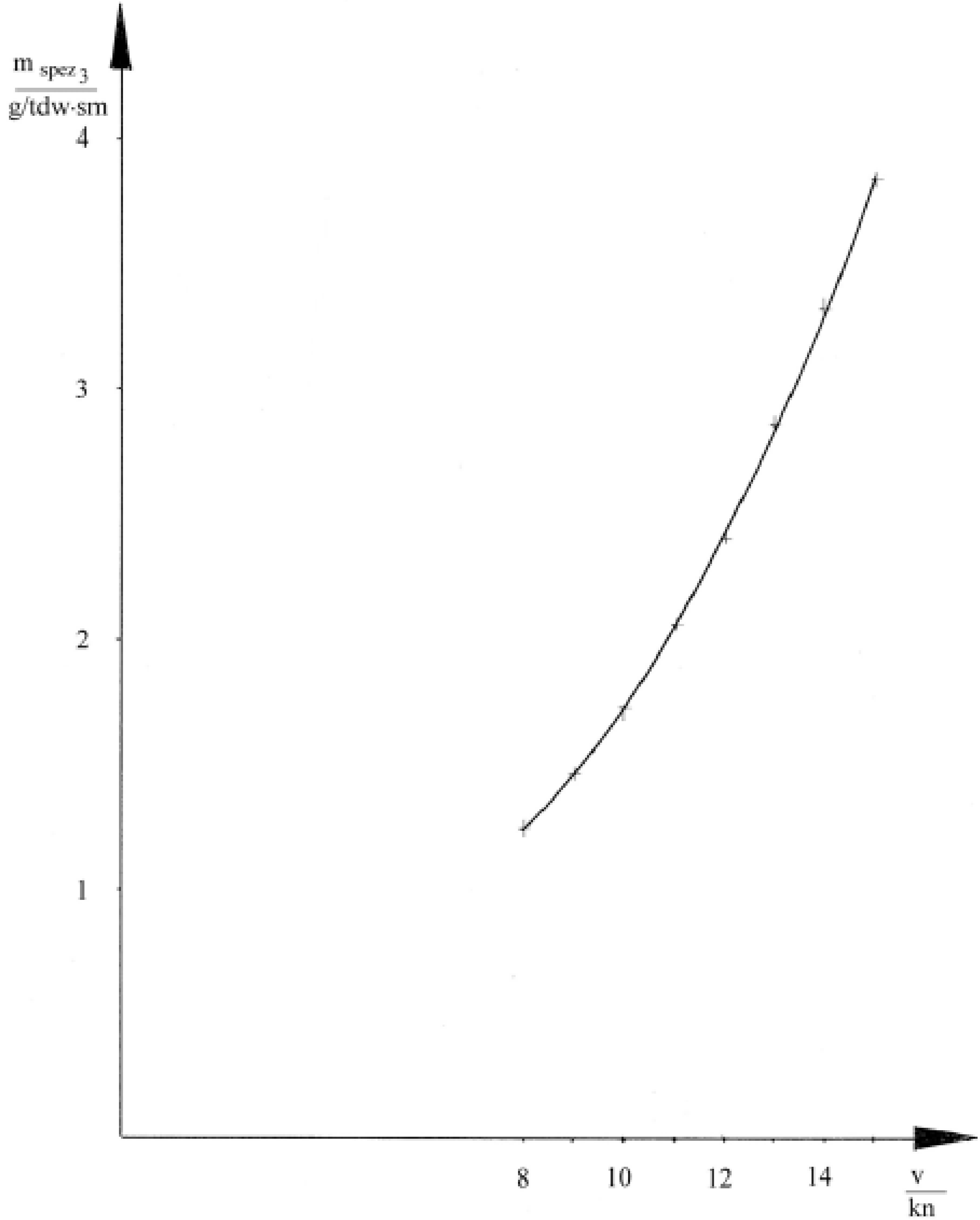


Illustration 5: Consumption in gram per tdw and sailed distance

2.8 Calculating the real fuel consumption

Conventional method of calculating the real fuel consumption

If the MFO is separated the bunkered fuel mass has to exceed the measured daily consumption by the proportion of sludge, water, soot, and metal. Depending on the refinery the values lie between 2% to 5%. A value of 2% is assumed for calculations.

Therefore the real average fuel consumption at 14 knots is increased by 0.536 t/d to 27.32 t/d.

The gas emission rate is not quantifiable. If the actual heat value changes, the daily consumption changes as well. The daily consumption is usually identified by a volume meter which is installed between day fuel tank and standpipe. The meter displays the volume that is passed throughin a digital format. In order to calculate the daily consumption the display has to be read in time intervals, the density ρ of the fuel has to be found out, and the outcome has to be converted to t/d:

$$\dot{m}_{krst\,d} = \dot{V}_{krst\,d} \cdot \rho_{krst} \qquad \text{in} \qquad \frac{t}{d}$$

Imprecision can be caused by:

- the quality of the volume meter
- different fuel temperatures during the considered time
- a change of fluid level in the day fuel tank and standpipe
- variation of sludge quantity

Calculating the real fuel consumption electronically

Instead of detecting consumption manually, volume measurement systems prove to be satisfactory. The main feature of this system is the fact that changes in operation mode instantly show the effect on fuel consumption.

The major advantage of electronic volume measurement is its accuracy. With of a flow control unit in flow and return flow the current fuel consumption can be detected with a very small tolerance of plus/minus 0.5%. Is the mass flow identified (calculated with the help of the known density) and route or speed known, the specific fuel consumption can directly be read in kg/nm. Hence, changes in trim or draught instantly show a reduction or increase of fuel consumption.

Therefore, engine operations can be evaluated according to their effect on fuel consumption in near real time.

Modern systems feature interfaces with which existing control systems can be connected.

3 Interrelation between power engine and work machine

3.1 Interrelation between engine output and resistance

Regarding the design calculation (determining the most favourable data of the system ship-propeller-power-unit) assumptions have to be made concerning external requirements under service conditions. These do not only depend on the technical system data but on the state of the shell plating, the propeller, the sea surface, and the atmosphere. Each of these states causes increased resistance on the ship and propeller blades. It also causes side effects like ship movement and a change in wake. Together with restrictions in the engine operating map, this displacement of characteristic curves of ship and propeller results in a number of different operating points. The difficulty of interpreting statistically changed operating points is usually avoided by regarding an alternative operating point which results from the ideal trial trip conditions including possible overall resistance allowance.

3.2 Estimating and calculating the engine output

In a towing test a model ship is towed through the water and the resistance of the model is measured in N. This resistance is the sum of hull resistance and frictional resistance. With the following equation the engine output can be calculated:

$$P = \frac{W_s \cdot V_s}{\eta_o \cdot \eta_m} = \frac{1-\psi}{1-\vartheta} \qquad \text{in Watt}$$

W_s = total resistance of the vessel

v_s = vessel speed

η_o = propeller efficiency factor

η_m = mechanical efficiency factor

ψ = wake coefficient

ϑ = thrust-deduction coefficient

A rough estimation of the propulsion power can by obtained by the so called "Admiralty Formula":

$$P = \frac{D^{0,567} \cdot v^{3,6}}{1670 \cdot 0,52} \quad \text{in} \quad \text{kW}$$

D in t

v in knots

Example:

A tanker with 24000 t displacement is supposed to sail with v = 15 kts.

$$P = \frac{24000^{0,567} \cdot 15^{3,6}}{1670 \cdot 0,52} = 6008 kW$$

3.3 Diesel engines and their coaction with the propeller

The operating point is accomplished if the torques of the driving section M_M and engine M_A are equal. In this case the revolution speed remains constant. The stability implies that an increased revolution speed is impeded by the engine; similarly a decrease is impeded by the drive force. If the operating point persists so long that no changes in the measured values occur, a steady state has been achieved.

For starting Diesel engines compressed air is applied. In the starting point with the starting revolution speed n_A the engine torque M_M is identical to the propeller torque M_A. For the acceleration process the fuel feed is increased which results in the characteristic engine curve M_{M1}. The engine torque surplus $M_{M1} - M_A$ accelerates engine and propeller until the operating point is reached in which $M_{M1} = M_A$.

In order to increase revolution speed, fuel feed is raised which results in the characteristic engine curve M_{M2}. In the acceleration process a similar procedure occurs with a torque surplus of $M_{M2} - M_A$. If the fuel feed is constantly increased by a run-up programme, the change in load is approximate to the propeller curve M_A which the engine has adapted to.

3.4 Interrelation between vessel speed and revolution speed of the propeller

The theoretical speed v_{theor} in m/s is the calculated product of revolution speed n in $\min^{-1}$ and propeller pitch H in m. The real speed v is lower, higher, or identical. Differences are called propeller-slip. If the propeller-slip is considered to be constant the revolution speed n is proportionate to the speed v.

$$\frac{n_1}{n_2} = \frac{v_1}{v_2}$$

Example for the combined operation mode:

At 14 knots the propeller is doing n = 125 revolutions per minute. The revolutions per minute of the propeller at 10 knots is requested.

$$n_2 = n_1 \cdot \frac{v_2}{v_1} = 125 \frac{1}{\min} \cdot \frac{10kn}{14kn} = 89 \min^{-1}$$

3.5 Interrelation between engine power and revolution speed of the propeller

In case of a constant propeller-slip the following proportion applies:

$$\frac{P_1}{P_2} = \left(\frac{n_1}{n_2} \right)^x$$

The engine powers without SG[4] behave in the same way as the revolution speed of the propeller to the power of x.

Example for the combined operation mode:

P_1 = 2620kW, n_1 = 92 $\min^{-1}$

P_2 = 7280kW, n_2 = 125 $\min^{-1}$

We are searching for the ship exponent x: $x = \frac{\ln_{P_1} - \ln_{P_2}}{\ln_{n_1} - \ln_{n_2}} = \frac{\ln 2620 - \ln 7280}{\ln 92 - \ln 125} = \underline{\underline{3,3}}$

[4] SG = Shaft Generator

3.6 Interrelation between engine power and vessel speed

If P1 and P2 are two metered engine powers in kW, and v1 and v2 are the related vessel speeds in knots, the following equation applies:

$$\frac{P_1}{P_2} = \left(\frac{v_1}{v_2}\right)^x$$

The engine powers behave in the same way as the vessel speed to the power of x. *x* is the ship exponent which can be calculated for every vessel if other variables are known.

Example for the operation with shaft generator:

P_1 = 5800 *kW* v_1 =14 *kts*

P_2 = 3490 *kW* v_2 =12 *kts*

We are searching for the ship exponent *x*: $x = \frac{\ln_{P_1} - \ln_{P_2}}{\ln_{v_1} - \ln_{v_2}} = \frac{\ln 5800 - \ln 3490}{\ln 14 - \ln 12} = \underline{\underline{3{,}3}}$

For the example data, this ship exponent of 3.3 is to be used with sufficient accuracy between 14 *kts* and 12 *kts*. For other speeds however, new calculations of the exponent become necessary. Although there is no linearity, at lower speeds the exponent gets smaller; at higher speeds it gets bigger.

Knowing the ship exponent allows an approximate calculation of the engine power for different speeds.

The ship exponent varies because of the fact that the wave curve that is generated at the stern at various speeds can either be valley or mountain shaped. The wave length λ is

$$\lambda = \frac{2 \cdot \pi}{g} \cdot v^2$$ and the division factor m

$$m = \frac{L_W}{x}$$ which should be 1.5; 2.5; 3.5; 4.5.

Example:

$P_1 = 5800\ kW$ $v_1 = 14\ kts$

$x = 3.3$ $v_2 = 10.5\ kts$

We are searching for the engine power that is necessary for a speed of 10.5 *kts*.

$\ln P1 - \ln P2 = x(\ln_{v1} - \ln_{v2})$ $\ln 5800 - \ln P_2 = 3.3(\ln 14 - \ln 10.5)$ $P2 = 1275\ kW$

The engine power is reduced from 5800 *kW* to 2244 *kW*, whereas the speed is reduced from 14*kts* to 10.5 *kts*.

3.7 Interrelation between vessel speed and fuel consumption

The hourly fuel consumption of the main engine $\dot{m}_{krst_h}$ is the product of the specific fuel consumption in *kg/kWh* and the engine power *P* in *kW*:

$$\dot{m}_{krst_h} = be \cdot P$$

The equation is written as:

$$\frac{\dot{m}_{krst_{h1}}}{\dot{m}_{krst_{h2}}} = \frac{be_1 \cdot P_1}{be_2 \cdot P_2}$$

According to chapter 3.6 the following equation applies:

$$\frac{P_1}{P_2} = \left(\frac{v_1}{v_2}\right)^x$$

Hence, it follows:

$$\frac{\dot{m}_{krst_{h1}}}{\dot{m}_{krst_{h2}}} = \frac{be_1}{be_2} \cdot \left(\frac{v_1}{v_2}\right)^x$$

The hourly fuel consumptions behave the same as the vessel speed to the power of x multiplied with the quotient of the specific fuel consumptions.

Example:

For a speed of 14 *kts* a tanker needs an engine power of 5800 *kW* without SG; the ship exponent is 3.3. The voyage should be continued with a speed of 12.3 kts. The hourly fuel consumption is to be calculated for both vessel speeds.

$$P_2 = \frac{P_1}{\left(\frac{v_1}{v_2}\right)^x} = \frac{5800kW}{\left(\frac{14kn}{12{,}3kn}\right)^{3{,}3}} = \underline{\underline{3783kW}}$$

$$\frac{3783kW}{5800kW} = 0{,}65$$

Using the engine manufacturer's manual, the specific fuel consumption for full load and 0.65 x full load should be determined.

be_{14} = $0.18kg / kW \text{ x } h$

$be_{0.65 \text{ x } 12.3}$ = $0.179kg / kW \text{ x } h$

$\dot{m}_{krst_{14}}$ = $0.18kg / kW \text{ x } h \text{ x } 5800kW = \underline{\underline{1044kg / h}}$

$\dot{m}_{krst_{12,3}}$ = $0.179kg / kW \text{ x } h \text{ x } 3783kW = \underline{\underline{677kg / h}}$

Due to a 12% speed reduction from 14 *kts* to 12.3 *kts* 35% less fuel was consumed.

3.8 Fuel consumption per nautical mile sailed [5]

duration of voyage t = distance s / medium speed v

If the fuel mass $\dot{m}_{krst_h}$ is used per hour, the consumption for the voyage can be calculated.

$$m_{\text{Reise}} = \dot{m}_{krst_h} \cdot t = \dot{m}_{krst_h} \cdot \frac{s}{v}$$

The following equations are used in order to determine the fuel consumption at various speeds:

$$m_{\text{Reise}_1} = \dot{m}_{krst_{h1}} \cdot \frac{s}{v_1} \qquad \text{and} \qquad m_{\text{Reise}_2} = \dot{m}_{krst_{h2}} \cdot \frac{s}{v_2}$$

$$\frac{m_{\text{Reise}_1}}{m_{\text{Reise}_2}} = \frac{\dot{m}_{krst_{h1}}}{\dot{m}_{krst_{h2}}} \cdot \frac{v_2}{v_1}$$

[5] The German word "Reise" stands for the English term "voyage"

According to chapter 3.7 the following equation applies:

$$\frac{\dot{m}_{krst_{h1}}}{\dot{m}_{krst_{h2}}} = \frac{be_1}{be_2} \cdot \left(\frac{v_1}{v_2}\right)^x$$

Hence, it follows:

$$\frac{m_{\mathrm{Reise}_1}}{m_{\mathrm{Reise}_2}} = \frac{be_1}{be_2} \cdot \frac{v_1{}^x}{v_2{}^x} \cdot \frac{v_2}{v_1} = \frac{be_1}{be_2} \cdot \left(\frac{v_1}{v_2}\right)^{x-1}$$

The fuel consumptions for a whole voyage behave the same as the vessel speeds to the power of (x-1) multiplied with the quotient of the specific fuel consumptions.

Example:

The fuel consumption for a voyage of 1000 nautical miles (excluding river distance and SG) is calculated using the values from chapter 3.7:

$$m_{\mathrm{Reise}_1} = \frac{1044kg/h}{1000kg/t} \cdot \frac{1000sm}{14sm/h} = \underline{\underline{74{,}57t}}, \qquad t_{\mathrm{Reise}_1} = \frac{1000sm \cdot h}{14sm} = \underline{\underline{71{,}43h}}$$

$$m_{\mathrm{Reise}_2} = \frac{677kg/h}{1000kg/t} \cdot \frac{1000sm}{12{,}3sm/h} = \underline{\underline{55{,}04t}}, \qquad t_{\mathrm{Reise}_2} = \frac{1000sm \cdot h}{12{,}3sm} = \underline{\underline{81{,}30h}}$$

3.9 Interrelation between engine power and draught

According to the *admiralty formula* the following can be roughly assumed:

$$P = \frac{(L \cdot B \cdot T \cdot c_B)^{2/3} \cdot v^3 \cdot 0{,}736}{C_e}$$ in kW or rather $$P = \frac{D^{0{,}567} \cdot v^{3{,}6}}{1670 \cdot 0{,}52}$$

L = length of the ship in m

B = width of the ship in m

T = draught of the ship in m

C_B = block coefficient (C_B)

v = speed in knots

C_e = admiralty constant

If the speed v is unchanging and the relation between engine power P and draught T is to be determined, the following variables are used as constants in order to simplify matters: length of the ship L, width of the ship B, block coefficient C_B, speed v, and admiralty constant C_e.

$$\frac{P_1}{P_2} = \frac{L_1^{2/3} \cdot B_1^{2/3} \cdot T_1^{2/3} \cdot c_{B_1}^{2/3} \cdot v_1^3 \cdot 0{,}736 \cdot C_{e_2}}{L_2^{2/3} \cdot B_2^{2/3} \cdot T_2^{2/3} \cdot c_{B_2}^{2/3} \cdot v_2^3 \cdot 0{,}736 \cdot C_{e_1}}$$

This leaves:

$$\frac{P_1}{P_2} = \left(\frac{T_1}{T_2}\right)^{2/3}$$

Theoretically the engine powers behave in the same way as the draughts to the power of 2/3 at a constant speed.

Example:

At a draught of $T = 8.36$ m and at a speed of 14 knots 5600 *kW* are needed. We are searching for the necessary power at a draught of 7.9 *m*.

$$P_2 = \frac{P_1}{\left(\frac{T_1}{T_2}\right)^{2/3}} = \frac{5600kW}{\left(\frac{8{,}36m}{7{,}9m}\right)^{2/3}} = 5395kW$$

In real practise this calculation is not totally accurate because the ship length and especially the block coefficient as well as the flow conditions at bow and stern do not remain constant if draughts vary. Nevertheless, it is advisable to sail with as little ballast as possible and to clear the ship out.

3.10 Interrelation between vessel speed and draught

If the vessel is operated with a constant engine power P, the relations can be calculated as follows; whereas the same simplifications as described in chapter 3.9 are assumed.

$$v = \sqrt[3]{\frac{P \cdot C_e}{(L \cdot B \cdot T \cdot c_B)^{2/3} \cdot 0{,}736}}$$

$$\frac{v_1}{v_2} = \frac{\sqrt[3]{\dfrac{P_1 \cdot C_{e1}}{(L_1 \cdot B_1 \cdot T_1 \cdot c_{B_1})^{2/3} \cdot 0{,}736}}}{\sqrt[3]{\dfrac{P_2 \cdot C_{e2}}{(L_2 \cdot B_2 \cdot T_2 \cdot c_{B_2})^{2/3} \cdot 0{,}736}}} = \frac{\sqrt[3]{\left(\dfrac{1}{T_1}\right)^{2/3}}}{\sqrt[3]{\left(\dfrac{1}{T_2}\right)^{2/3}}} = \left(\frac{T_2}{T_1}\right)^{2/9}$$

The vessel speeds behave in the contrary way as the draughts to the power of 2/9.

Example[6]:

v_1 = 14 *kts* T_1 = 8.36 *m*

T_2 = 7 *m* v_2 = ? *kts*

$$v_2 = \frac{v_1}{\left(\dfrac{T_2}{T_1}\right)^{2/9}} = \frac{14kn}{\left(\dfrac{7{,}0m}{8{,}36m}\right)^{2/9}} = \underline{\underline{14{,}56kn}}$$

3.11 Designing and operating the pitch propeller

Designing a propeller is a science in itself. But optimum performance data can only be produced if the shape of the ship is considered. Future operating conditions of the ship and her propulsion engine arrangement are important as well. In addition, it is significant to consult the ship owner to find out for what purpose the propeller should be optimised. There are three different possibilities:

- The propeller is optimised for 85% MCR with 15% sea margin at a certain draught. The revolution speed of the propeller can be determined with the help of the propeller graph.
- The propeller is optimised for a vessel speed of e.g. 14 knots at a draught of e.g. 9 metres including 15% sea margin. The revolution speed of the propeller can be determined with the help of the combinator curve. This scenario is similar to the first

[6] kn = kts

one; the only difference is that the engine power and not the vessel speed is needed for calculations. This operating mode is called combined operating mode.

- The propeller is optimised for 90% MCR including e.g. 320 *kW* shaft generator power with 15% sea margin and a draught of e.g. 9 metres. The constant revolution speed of the propeller can be calculated with the board frequency 60 *Hz* and its corresponding gear box design. This operating mode is called shaft generator operating mode.

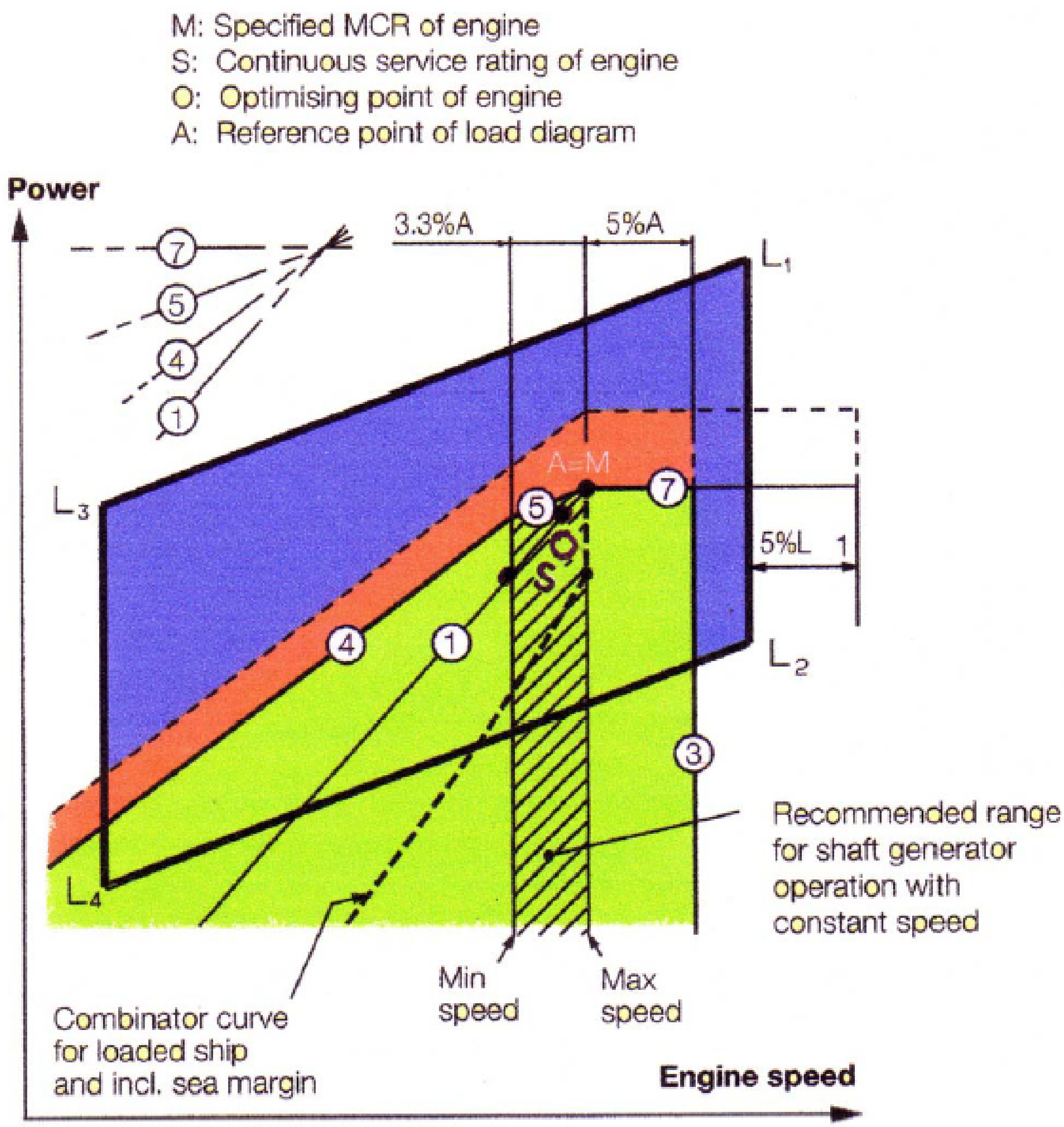


Illustration 6: CPP - combinatory curve

source: MAN publication “Basic Principles of Ship Propulsion”

3.12 Operating modes of pitch propellers

Providing a pitch propeller is operated with the whole amount of energy produced by the main engine, it should be operated in combined operating mode. If the vessel speed is decreased, the main engine reduces its revolution speed while the pitch of the propeller remains the same or is reduced as well. This operation mode results in lower friction force

- in the engine
- in the gearbox
- in the shaft bearing and thrust block
- in the stern tube and its gaskets
- on the propeller surface.

This operation method also reduces fuel consumption opposed to the operating mode with shaft generator.

If the shaft generator is used for electricity generation for the on-board circuit or for the bow thrusters, and if no direct current link was installed, the revolution speed of the propeller has to be kept constant. In this case the value and direction of the propulsion force are only determined by the pitch of the propeller. The fuel consumption would be accordingly increased.

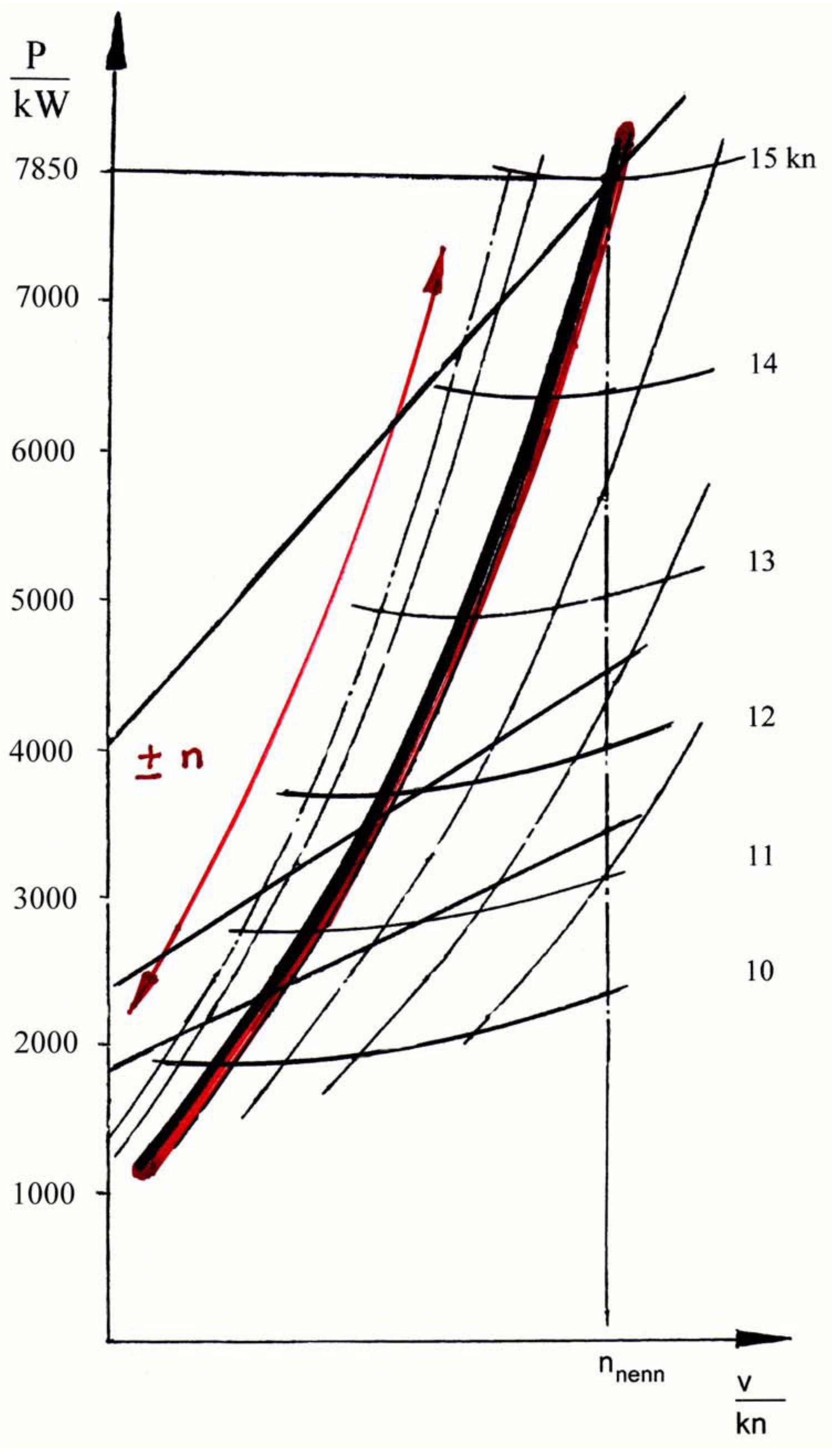


Illustration 7: Combined operating mode

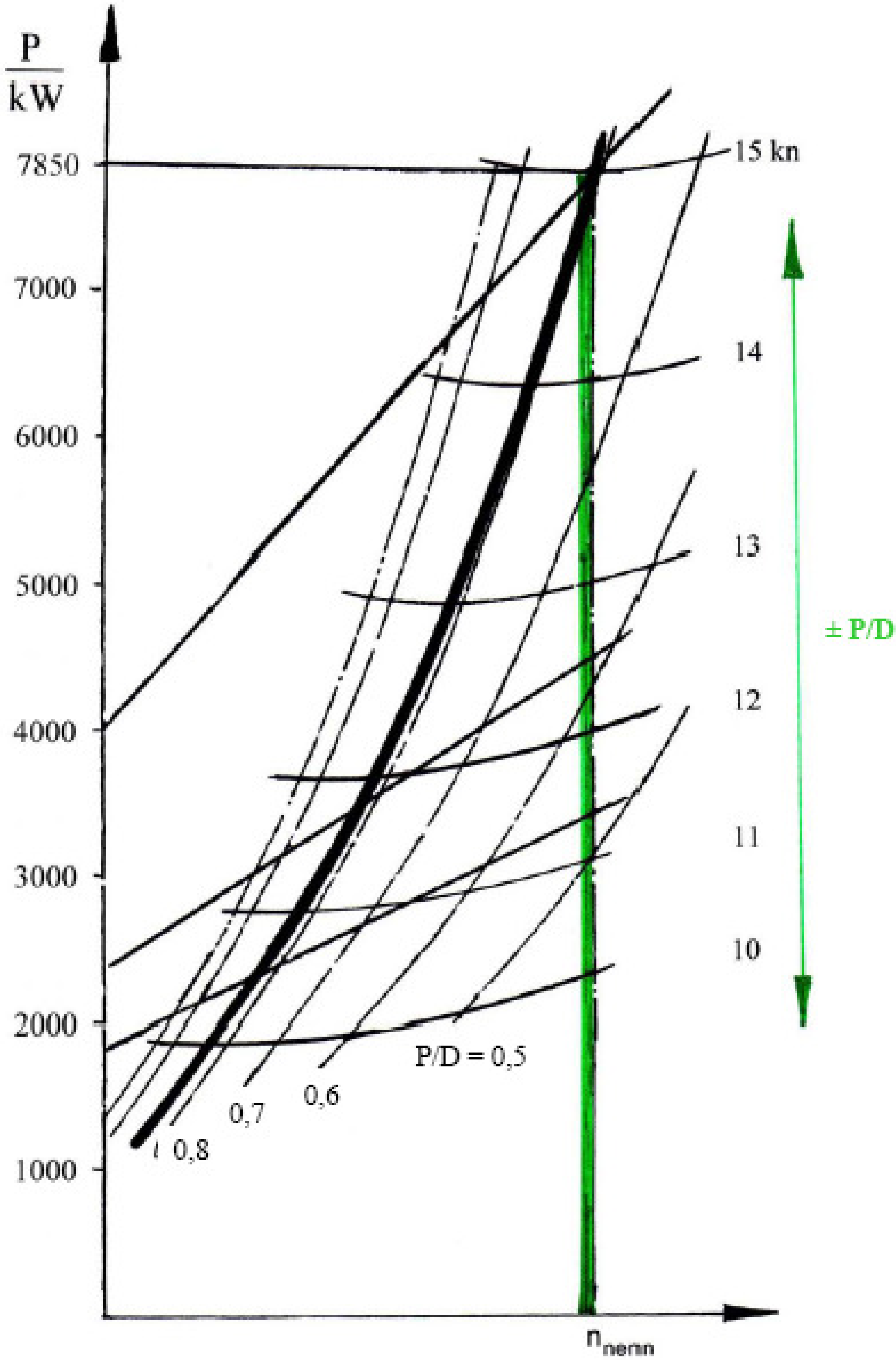


Illustration 8: Shaft generator operating mode

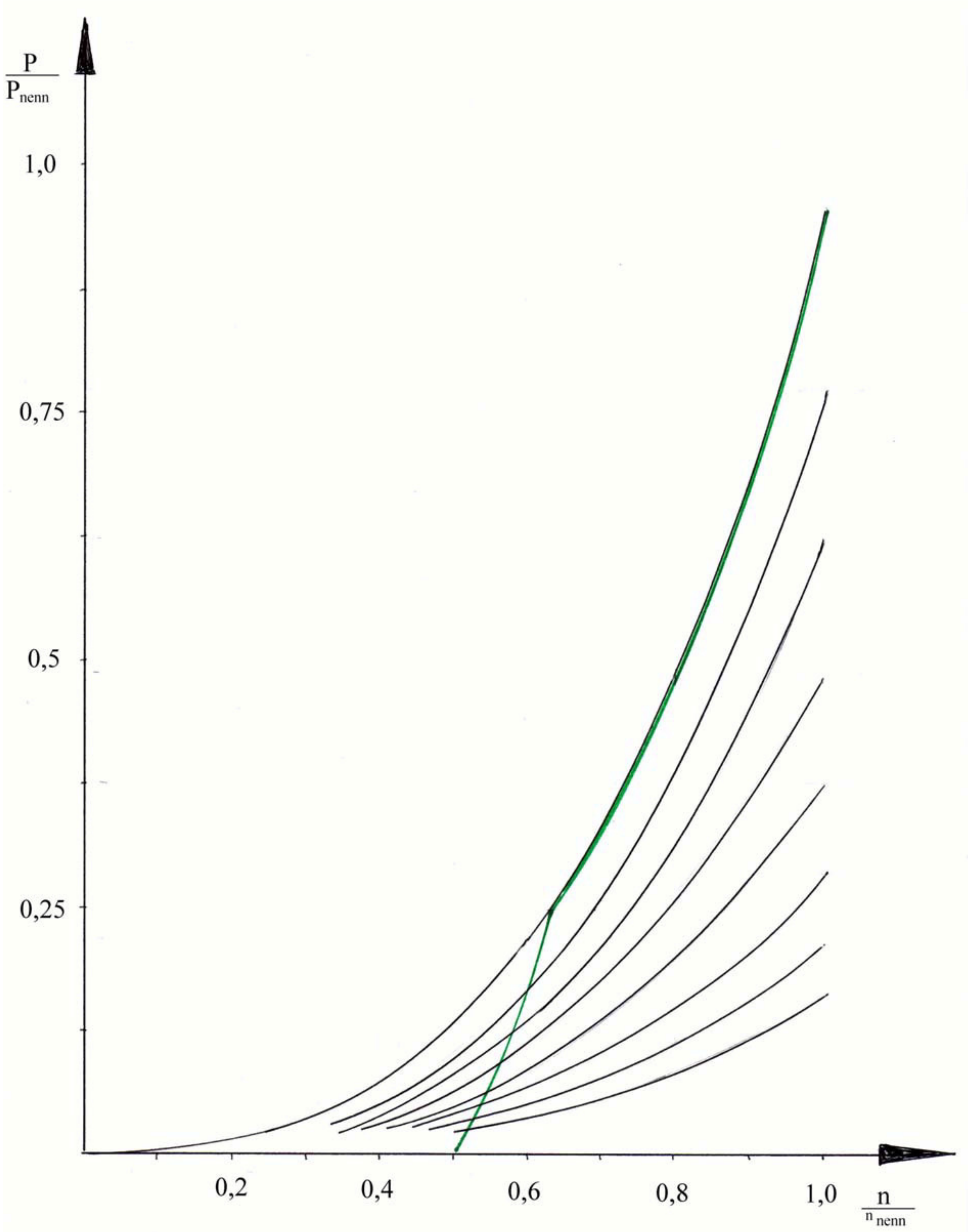


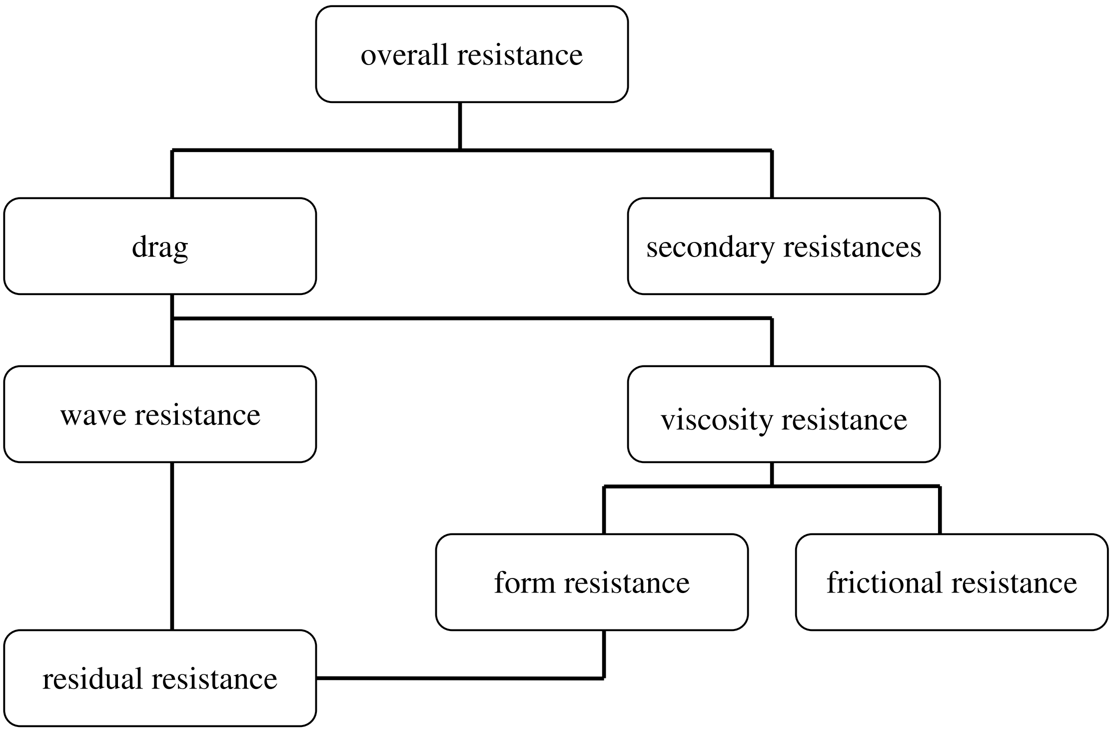
Illustration 9: Combined operating mode with various pitches

4 Methods of improving vessel movement through water

The resistance which affects engine output and therefore the economic efficiency of the vessel is tried to be kept as small as possible. This is mainly achieved by contemplating the design of the ship, but the navigation officer can help as well.

In order to keep moving forward, the overall resistance of a ship has to be overborne by the engine power. If both are the same the ship moves with a constant speed. Changes in resistance affect speed.

Naval architects brake down the overall resistance into separate components.



The main parameter affecting resistance is friction which has a Froude's number of

$$F_n = \frac{v}{\sqrt{g \cdot L}} = \frac{7{,}82 m/s}{\sqrt{9{,}81 m/s^2 \cdot 164 m}} = 0{,}195$$

.

Friction resistance results from the friction caused by water passing the shell plating of the hull. Friction increases with fouling, dents, corrosion, sacrificial anodes, and bilge keel.

This together with form resistance which is determined by the shape of the ship and is also known as turbulence resistance determines viscosity resistance. It depends on the underwater surface, underwater shape, surface roughness of the shell plating, speed of passing water, and viscosity of the water.

Wave resistance is generated due to waves developing at bow and stern. If a ship moves through deep enough water, the water passes its hull with ship speed. This causes an expansion of flow lines at bow and stern, and a compression of flow lines amidships.

According to Bernoulli's equation a pressure increase or a wave crest is caused at bow and stern and therefore a speed reduction (of the water). Amidships a pressure decrease or wave trough is caused and therefore a speed increase (of the water).

Bow and stern waves expand with approx. 20° deviation off course. This generates a wave system that consists of two kinds of waves: slightly curved longitudinal waves that are caused by pressure at the bow and are not depending on the speed of the ship; and transverse waves that are speed dependant and moving at a 90° angle to the course of the ship.

Expanding waves from bow and stern can interfere with each other so that the wave crest caused at the bow hits the one caused at the stern. This increases resistance. On the other hand, if a wave trough hits another wave trough at the stern, resistance is reduced. Speed bands for which this is the case are dealt with in the chapter "slow steaming".

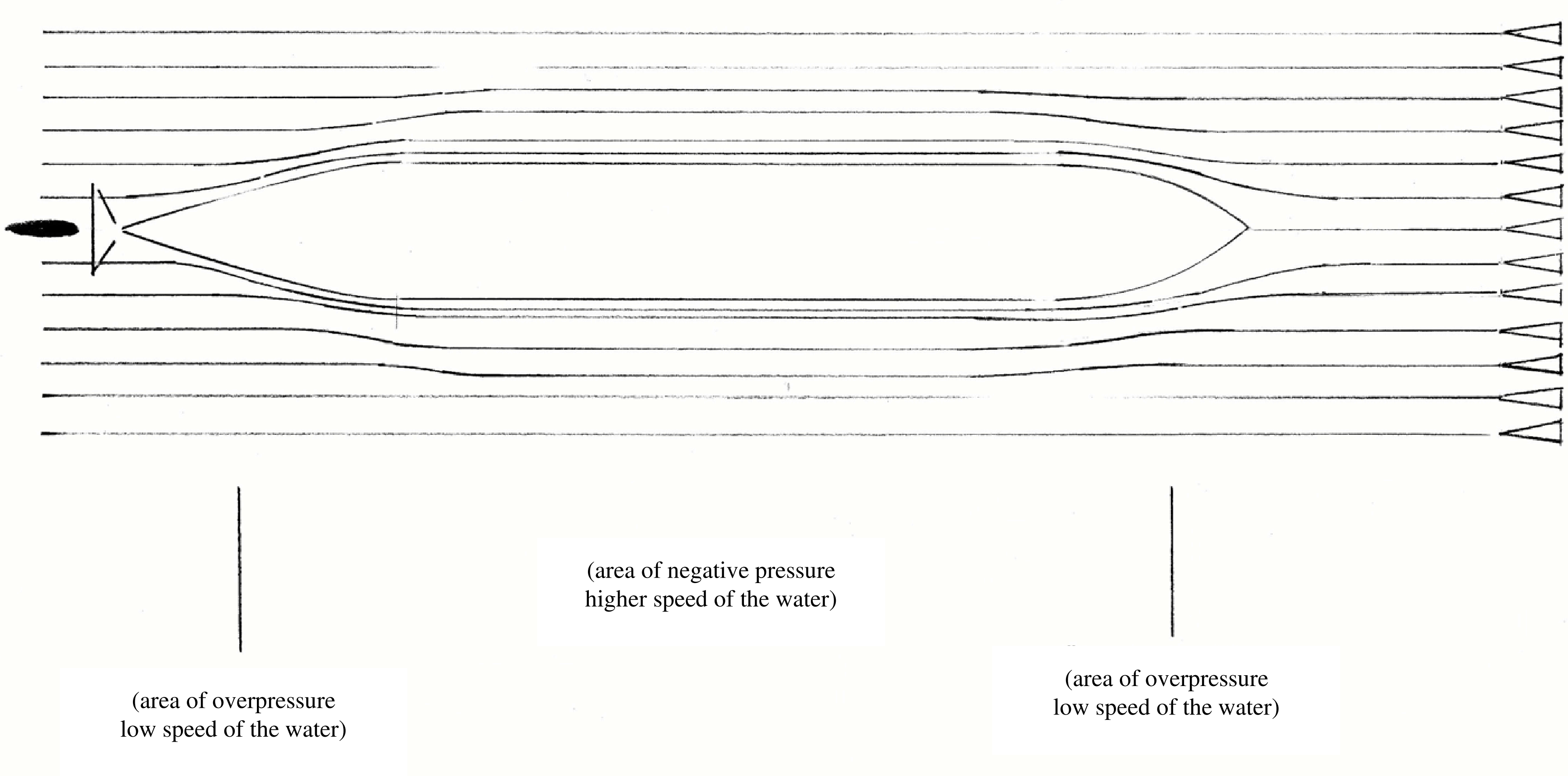


Illustration 10: Flow and pressure conditions at a moving ship

4.1 Ship design with the main components bow and stern

Nowadays, product tankers have a bulbous bow. This generates an additional wave system that interferes with the overall wave system of the ship and reduces it. An ideal bulbous bow decreases the waterline feeding angle and the wave crest at the bow. This reduces the wave resistance. Presently it is only possible to determine an ideal bulbous bow in an experimental setting. In addition, it can only be optimised for a certain draught, speed and trim.

Once the bulbous bow is constructed, changes would include unjustifiable costs. Therefore a noticeable reduction in resistance can only be reckoned with if the ship operates under the conditions that the bulbous bow is optimised for.

At the stern, a lot of constructions try to improve propulsion efficiency. By decreasing or eliminating the spin, the thrust is increased.

Procedures to improve propulsion

The efficiency of propulsion is known as the relation of ship performance (mileage) and driving power at the propeller. This can be shown as following:

η_D = $\eta_o \times \eta_R \times \eta_H$

η_o = efficiency of the propulsion system (e.g. propeller, propeller and guide wheel, or propeller and duct) in homogeneous inflow

η_R = quality of configuration of the propulsion system behind the ship

η_H = grade of hull influence

In order to increase propulsion efficiency various aspects have to be considered: improving the propulsion system, improving the configuration of the propulsion system behind the ship, and optimising the grade of hull influence.

In order to optimise the grade of hull influence, the inflow to the propulsion system has to be influenced in a way that utilizes the oncoming current optimally. This can be achieved by measures that have been known for quite a while: improving lines at the stern, construction of deflectors, fins, and tunnels. An improvement can especially be noticed if the stern is constructed asymmetrical. This improves efficiency in the region of 5-8%.

At a proposed ship speed and shape, possible variations include optimising the diameter, number of revolutions, area ratio, and number of blades.

In this context it has to be mentioned that the material choice is important too. Opposed to complex alloy, aluminium multi-component bronze is favoured especially regarding prevention of cavitation pitting and corrosion. Due to the higher stability of aluminium multi-component bronze the propeller blades can be designed slimmer. This improves efficiency and is therefore already seen as an effective procedure to improve propulsion.

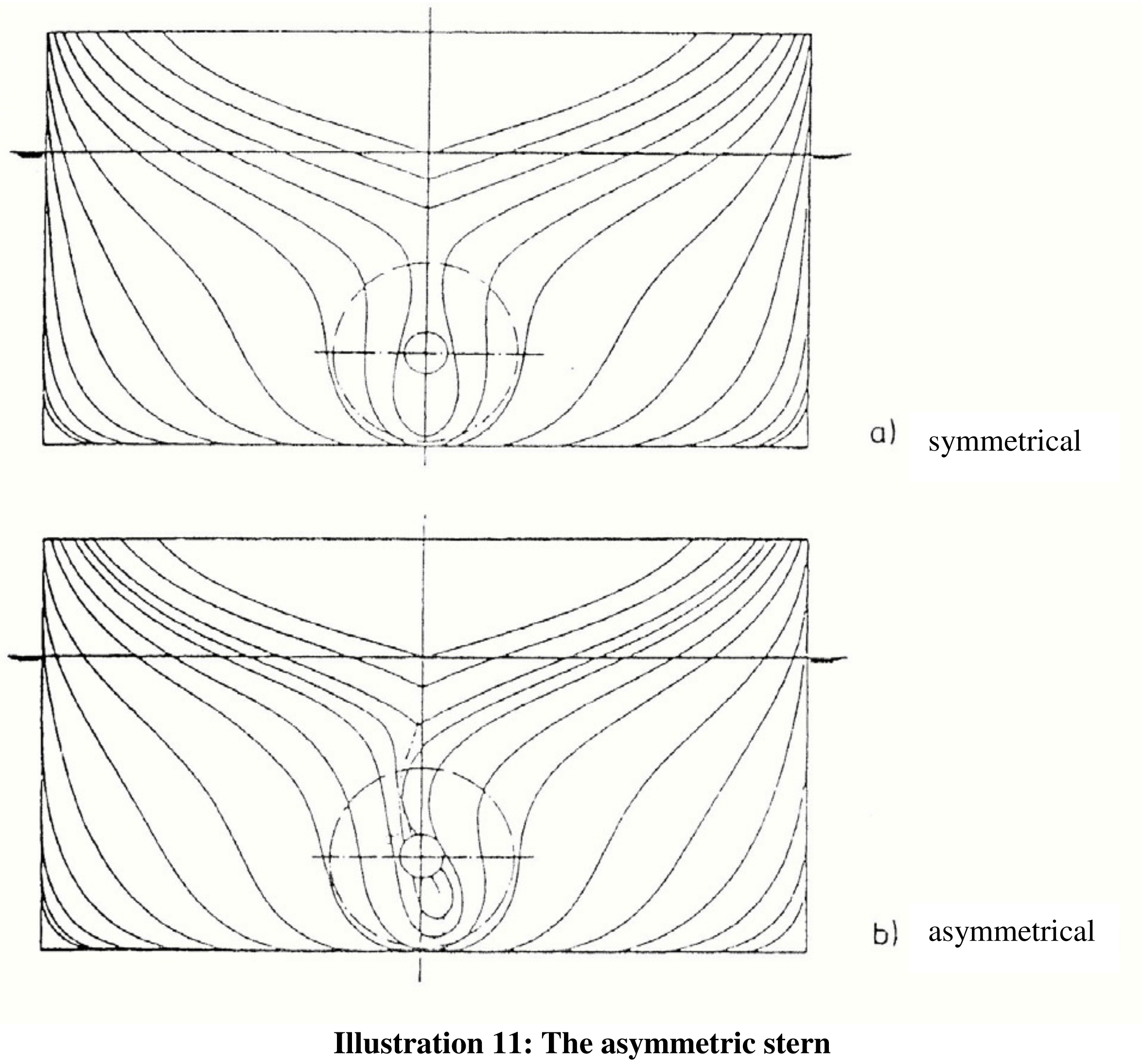


Illustration 11: The asymmetric stern

source: Bremer Vulkan, Bremen

Generally, propeller efficiency is improved with increasing diameter and decreasing revolution speed. However this is limited by the dimensions of the ship. It also requires reduction gearing as it is known from turbine systems and medium speed four stroke engines. Sometimes even slow running two stroke engines are produced with reduction gearing. In recent years very slow running two stroke engines with long stroke were developed. In most cases, this allows implementing the optimum relation between diameter and revolution of the propeller without using gearing.

If further improvements on propulsion efficiency want to be achieved, a second propeller has to be added to the first one.

In this context, “contra rotating propellers” have to be mentioned. However, the realisation of a system like that involves a lot of technical problems if the aim is a mere mechanical reversion of the revolution speed of the added propeller.

Other options are “overlapping propellers” which might have the possibility to increase efficiency at low revolution speeds.

Especially *Grim’s guide wheel* and the propeller duct have to be pointed out. Both of these add-ons can have a very positive effect on efficiency.

The guide wheel on the M/S “Pharos” had a diameter of 7.5 m and weighed approx. 16 t. The following table shows required power, daily fuel consumption and the percentaged loss of efficiency (which is a result of each component and their combination) for four different speeds.

A light breeze was hypothesized (force 2).

Efficiency of different propulsion components in dependence of the thrust force

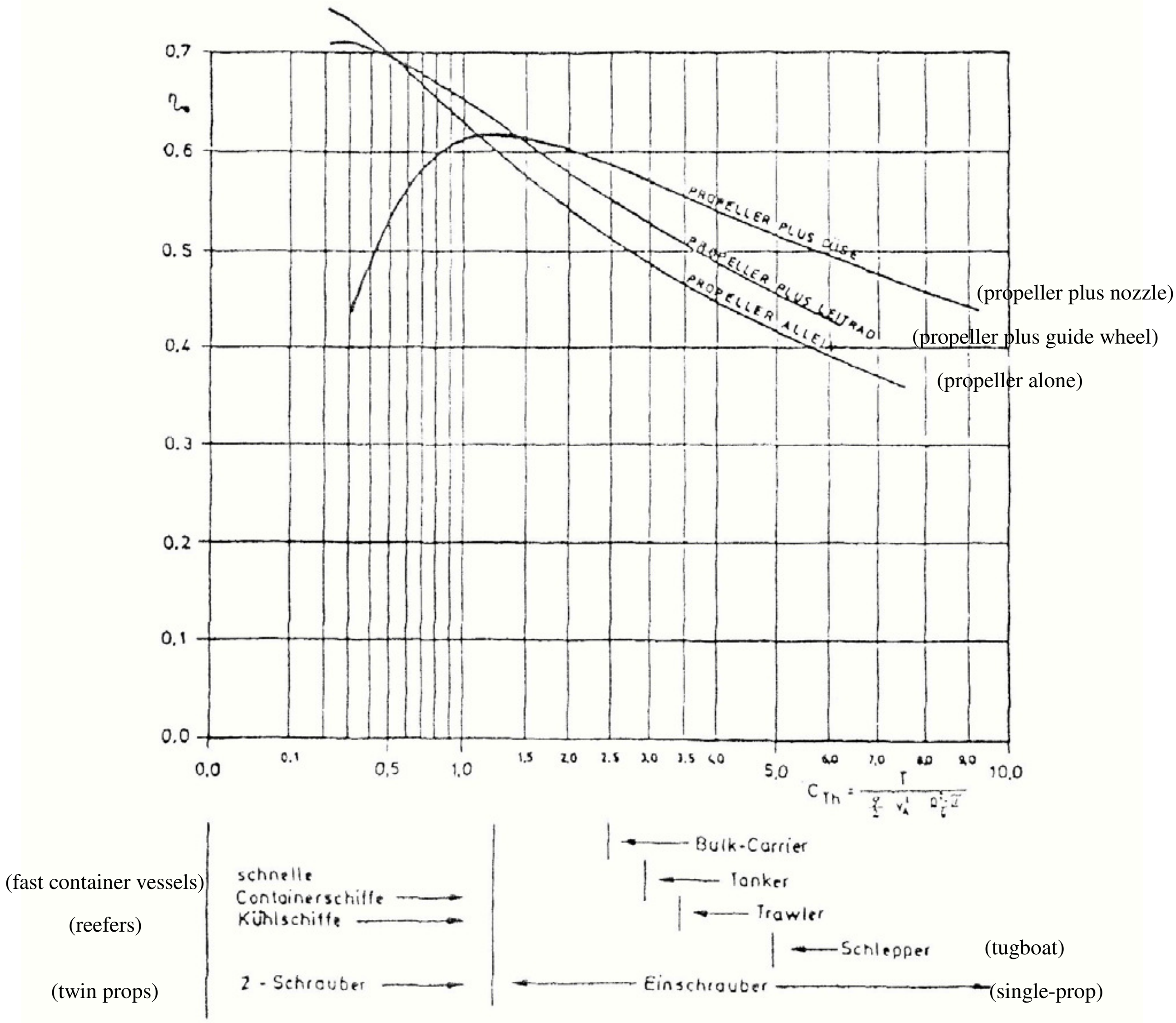


Illustration 12: Efficiency of propulsion systems

source: Bremer Vulkan, Bremen

description			vessel speed			
			15kts	16kts	17kts	18kts
construction No. 39 with symmetric stern	main engine output	kW	4456	5496	6809	8529
	daily fuel consumption	t/d	20.1	24.2	29.3	36.2
construction No. 39 with symmetric stern and guide wheel	main engine output	kW	4022	5007	6224	7904
	daily fuel consumption	t/d	18.4	22.3	27.0	33.6
	output reduction due to the guide wheel	%	9.7	8.9	8.6	7.3
construction No. 34 with asymmetric stern	main engine output	kW	4346	5191	6316	7882
	daily fuel consumption	t/d	19.7	23.0	27.4	33.5
	output reduction due to the asym. stern	%	2.5	5.5	7.2	7.6
construction No. 34 with asymmetric stern and guide wheel	main engine output	kW	3875	4825	5975	7522
	daily fuel consumption	t/d	17.8	21.6	26.0	32.1
	output reduction due to the guide wheel	%	10.8	7.1	5.4	4.6
	output reduction due to the asym. stern + guide wheel	%	13.0	12.2	12.2	11.8

Table 5: Saving fuel consumption due to additional construction at the stern

The following table compares the propeller output with the output reduction of the new constructions 39, 34, and 45. The illustrated values refer to "ship in ballast"-conditions.

	new construction 39		new construction 34 (asym.)		new construction 45 [7] (asym., wake equalizing duct)	
	(1) without guide wheel	(2) with guide wheel	(3) without guide wheel	(4) with guide wheel	(5) without guide wheel	(6) with guide wheel
v [kts]	P_D [HP]	P_D [HP] ΔP_D [%] referring to (1)	P_D [HP] ΔP_D [%] referring to (1)	P_D [HP] ΔP_D [%] referring to (1) ΔP_D [%] referring to (3)		P_D [HP] ΔP_D [%] referring to (1) ΔP_D [%] referring to (4)
15	6090	5775 – 5.2	5560 – 8.7	5100 – 16.3 – 8.3		5000 – 17.9 – 2.0
16	7275	6900 – 5.2	6850 – 5.8	6410 – 11.9 – 6.4		6300 – 13.4 – 1.7
17	8680	8200 – 5.5	8180 – 5.8	7780 – 10.4 – 4.9		7580 – 12.7 – 2.6
18	10530	9975 – 5.3	9700 – 7.9	9360 – 11.1 – 3.5		9100 – 13.6 – 2.8
19	13030	12720 – 2.4	11800 – 9.4	11530 – 11.5 – 2.3		11590 – 11.1 + 0.5

Table 6: Percentaged fuel savings

[7] Output values are converted into LBP (length between perpendiculars) = 152 m

single measures	output reduction	ship
Grim's guide wheel	10%	MS "Grootsand" MS "Pharos"
asymmetric stern	6 – 8%	MS "Thea S"
wake equalizing duct	5 – 12%	MS "Amado"
Grothues spoiler	4 – 6%	MS "Ambrosia"
semi tunnel	10 – 12%	MS "Canadia Enterprise"
MIDP HZ nozzle	4 – 12%	MS "Esso Copenhagen"
TVF propeller	10 – 12%	container vessel
Mitsubishi Reaction Fin	5 – 7%	MS "Shinsho Maru" MS "Shinei Maru"
stern bulge SEB	4 – 7%	MS "Sutoretia Maru"
twin-rudder	approx. 8%	model
fin rudder	1 – 2%	MS "Maris"
wing shaped control surface	2 – 6%	model

Table 7: Single measures

combined measures	output reduction	ship
asymmetry + guide wheel	12 – 13%	MS "Merkus Sea"
asym. + guide wheel + wake equalizing duct	11 – 18%	MS "Arkona"
asymmetry + wake equalizing duct (WED)	10 – 14%	model [8]
TVF propeller + WED + semi tunnel	approx. 15%	MS "Rio Tinto"
Grothues spoiler + guide wheel	approx. 14%	MS "Kerstin"

Table 8: Combined measures

Note: The shown data in both tables and graphs are ship specific and therefore only comparable to a certain extent.

[8] After the analysis of the trial trip of the MS „Arkona“ it was noted that the output saving data from the model experiment (combination of asymmetry and WED) were too optimistic.

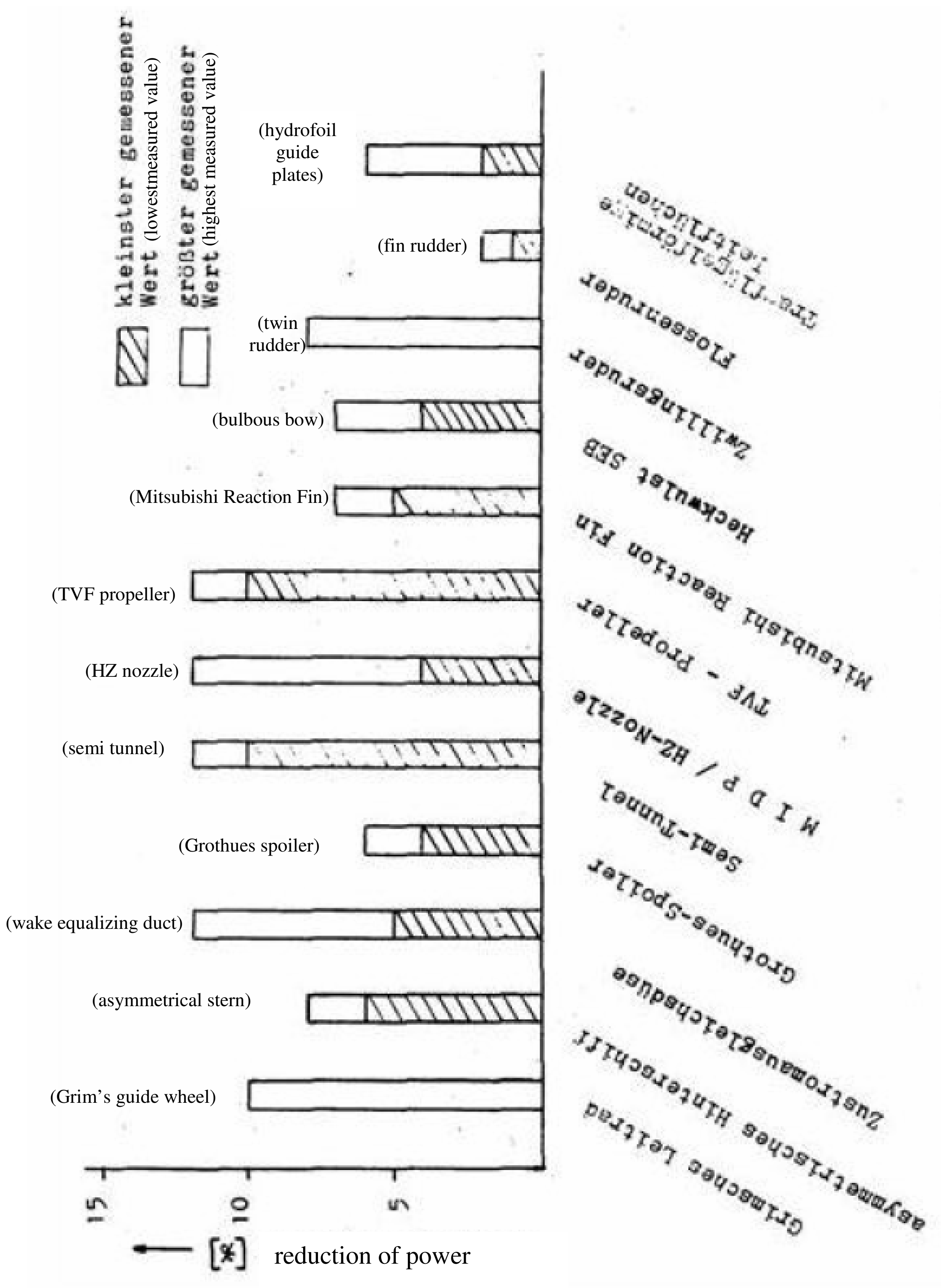


Table 9: Illustration of single measures

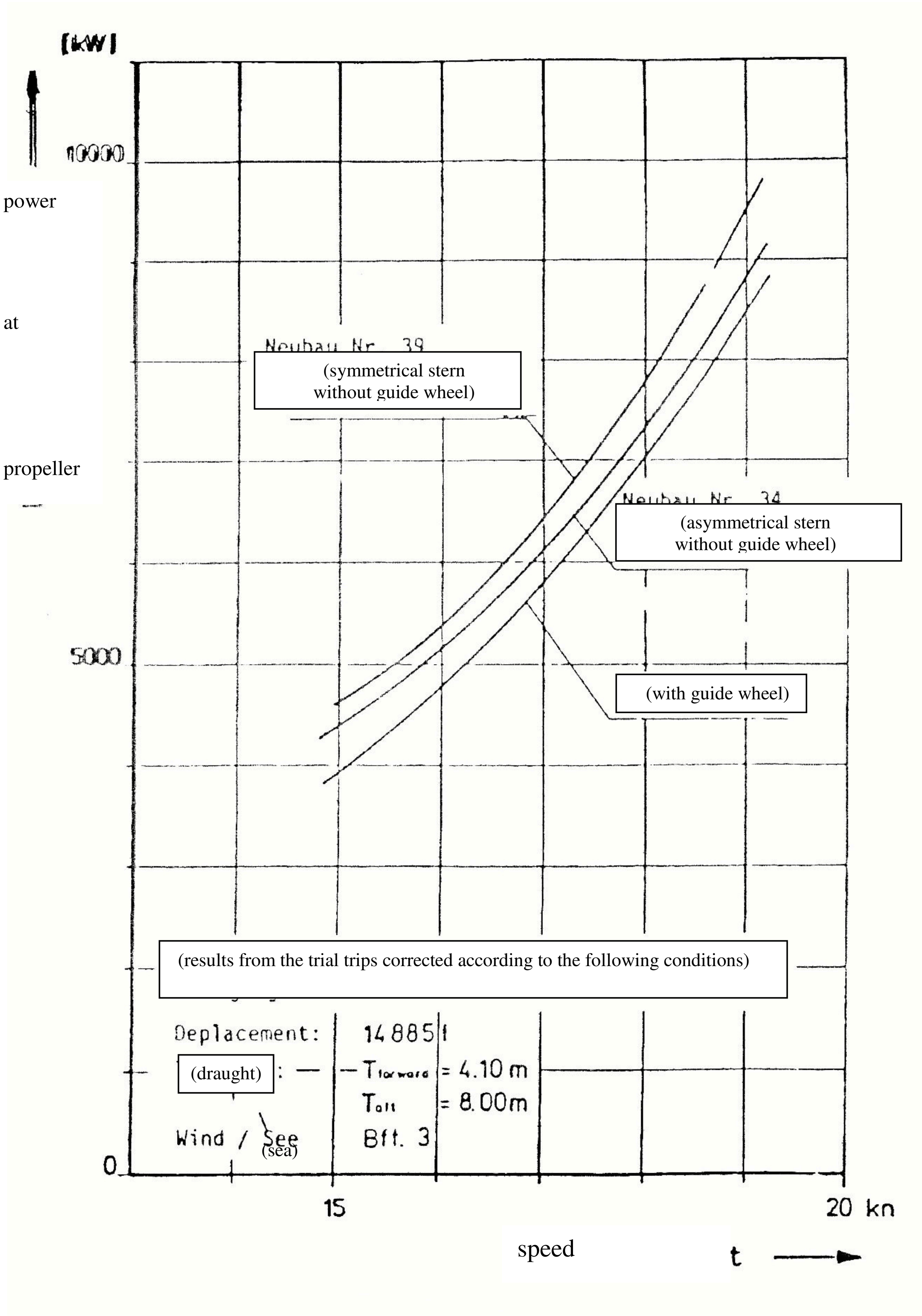


Illustration 13: Asymmetric stern with and without guide wheel

source: Bremer Vulkan, Bremen

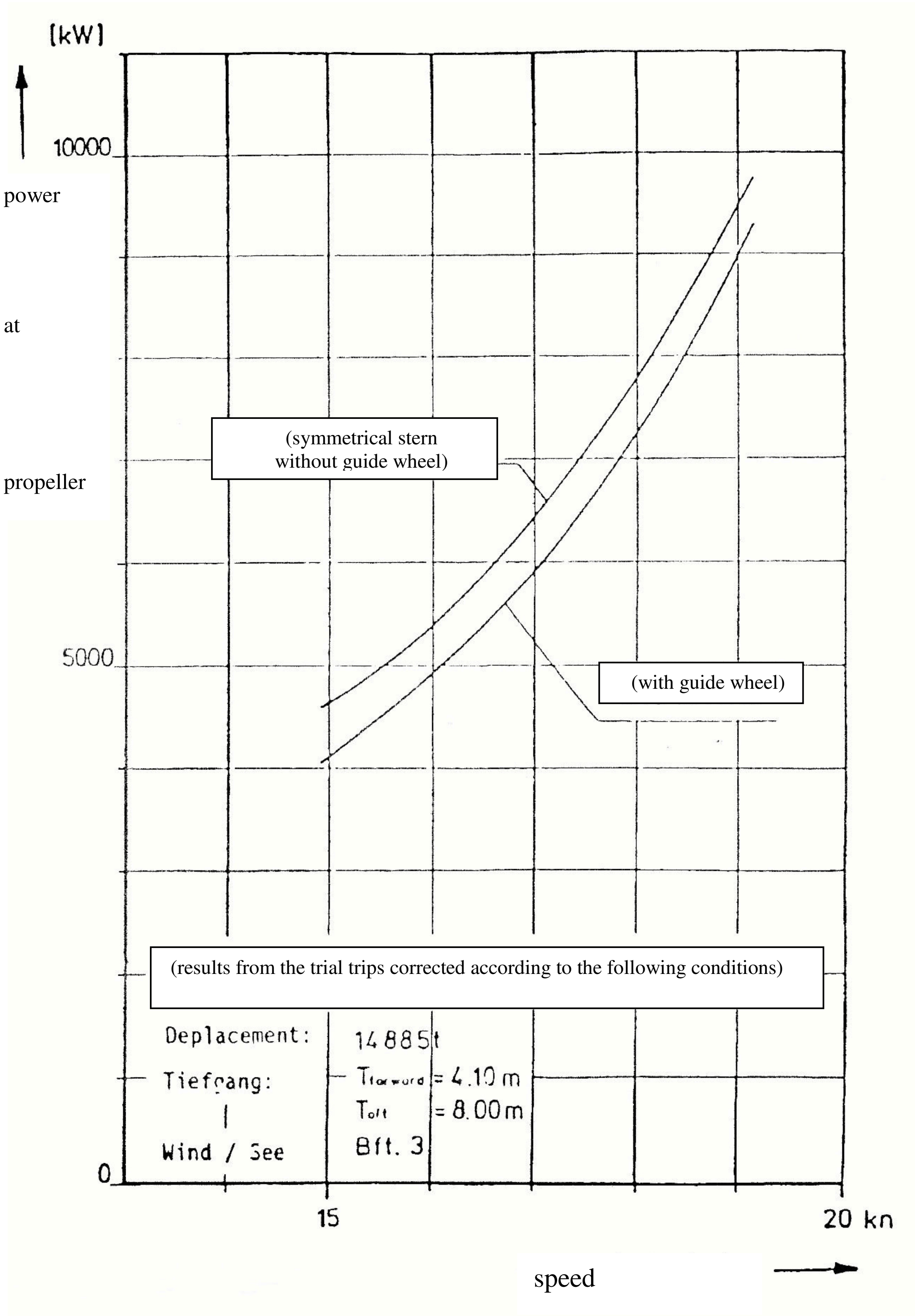


Illustration 14: Stern with and without guide wheel

source: Bremer Vulkan, Bremen

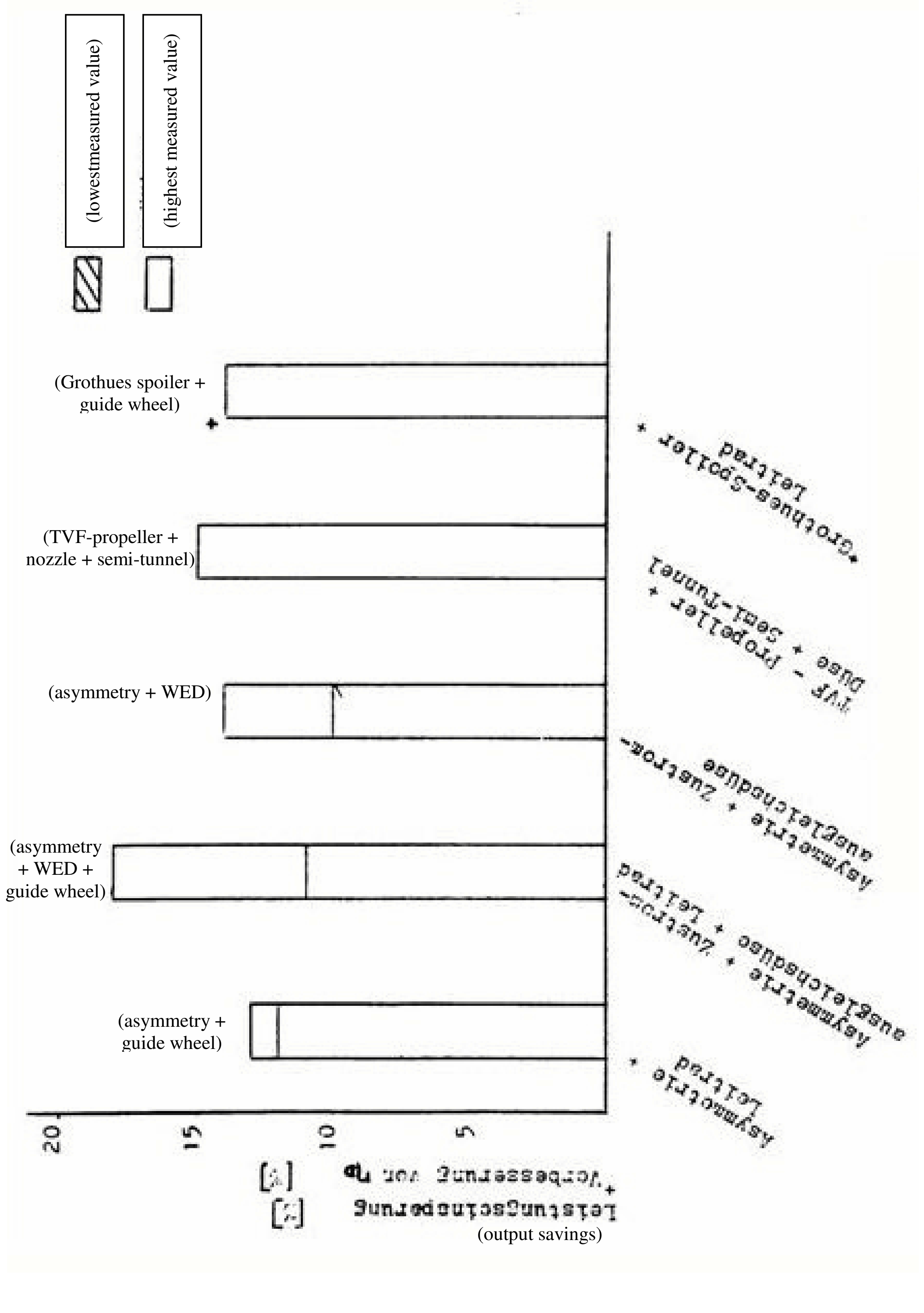


Table 10: Graphical comparison of combined measures

The wake equalizing duct (WED)

In the inflow, the WED is situated in front of the upper semi-circle of the propeller. The water inlet port is bigger than the outlet port. This causes the water to accelerate due to the speed of the ship. This acceleration happens at a point at which the inflow velocity at the propeller without WED is reduced principally would only be ¼ of the vessel speed especially on ships with a “bellied” hullform. Near the lower blade tips of the propeller the inflow velocity is approximately the same as the vessel speed. The propeller has to be designed for medium inflow velocity. During the propeller revolution the real axial inflow velocity deviates by more of half the value up or down – referring to a medium inflow velocity.

Opposed to a steady inflow, this decreases efficiency. The WED, as the name suggests, equalizes the flow. It does not only accelerate the inflow near the inlet port but decelerates the flow in the surrounding area. This equalization improves propeller efficiency and propulsion at a given speed. However, this is only one small effect in the overall improvement of the power requirement.

A further effect is the partial de-spinning in the slipstream. The slipstream does not flow along an axis but in a spiral shape. The duct causes a slight spin in the inflow. The duct has different side angles on portside and starboard. The biggest effect is the decrease of necessary propeller thrust at a given speed; i.e. the water resistance of the ship is reduced. There are two major factors:

1. The WED, just like a Kort nozzle, produces propulsion. This hydrodynamic propulsion is bigger than its inherent resistance.
2. Regarding conventional vessel stern shapes, water is swirled around at the stern. This causes energy loss. The main turbulence can be found in the area of the duct and in front of it. The duct is reducing this effect. Around it, a circulating flow is produced which at the front is directed at the shell plating. In other words, the flow along the shell plating is pressed against it.

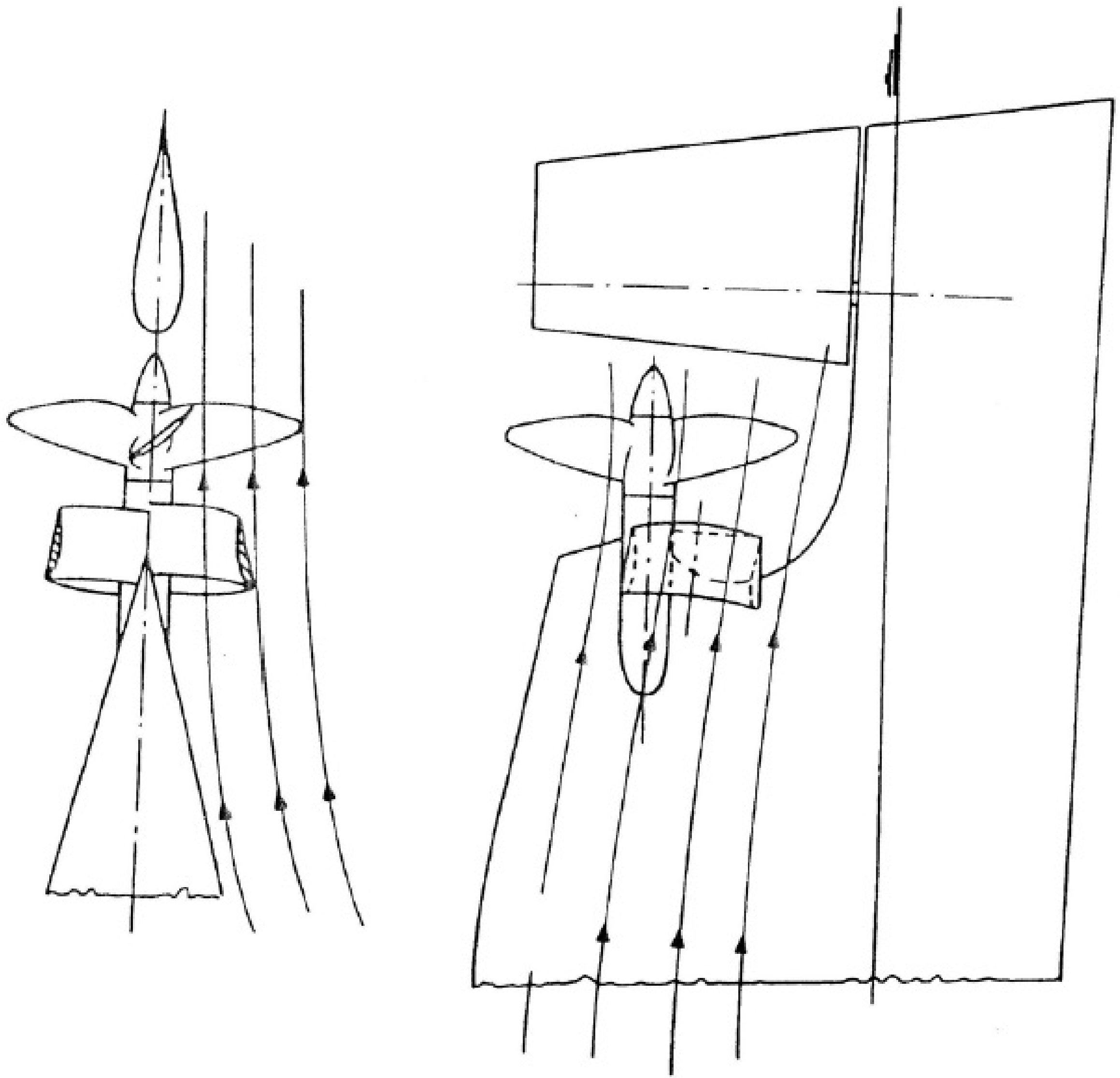


Illustration 15: Plan of the Schneekluth wake equalizing duct

source: Bremer Vulkan, Bremen

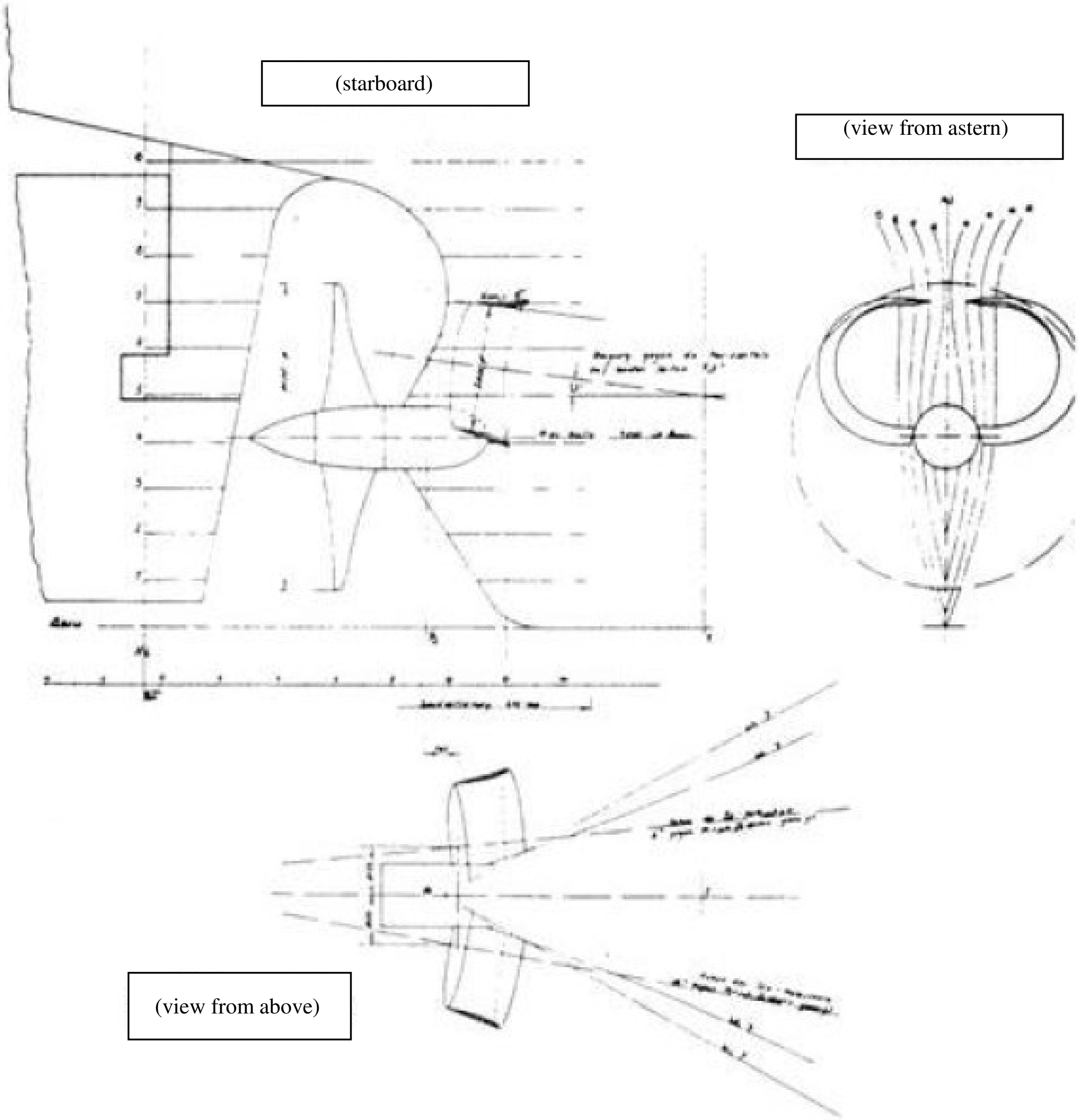


Illustration 16: Construction of the WED at the stern

source: Bremer Vulkan, Bremen

Illustration 17: The Schneekluth WED at the stern

source: Schneekluth Wake Improvement Duct, info@vonpereiralegal.de

The advantage of the WED increases with the block coefficient of the ship. It starts with a block coefficient of 0.6 and goes up to a block coefficient of 0.8 to approximately 10% - this is if the propeller diameter is not increased. Hence, bulk carriers and tankers would be best suited. Here, an output decrease of 7-10% or a speed increase of 0.3 to 0.4 *kts* can be achieved.

Summary

The new wake equalizing duct is no propeller shroud or propulsion device, but a simple add-on part that inheres in little resistance and is used within a small field of the propeller inflow. The mentioned output decrease ranges from 6 – 11%. Model experiments have proven these figures to be correct not only for a certain ship type but for various ship types with various hull shapes. The low costs of installation both as part of new builds and as later add-ons are plausible. They are a result of the relatively small size of the duct and the easy construction – as it can be seen in the illustrations.

Grim's guide wheel

Within hydrodynamics, engineers try to improve lines and bulbous bow designs as well as the design of the propeller which influences the utilisation of wake. The development of skewed propellers made it possible to increase the diameter of the propeller which had a positive effect on efficiency.

In the list of procedures that improve propulsion Grim's guide wheel stood out. It improved propulsion between 5-15%, depending on the strain on the propeller and the design of the ship. When it was first installed on the research vessel "Gauss" by the DHI (German Hydrographic Institute) it showed an improvement of 9% and no disadvantages. In April 1983, the 85000-cbf-reefer "Grootsand" (Harmstorf Group) was equipped. With this, the application of guide wheels in merchant shipping began.

The following table shows the two main existent users of guide wheels and their positive results from trial trips.

ship	mile	output	revolution speed	speed	fuel consumption				
	No.	kW	min^{-1}	kts	l/h	t/24h	%	kg/nm	%
"Konkar Hyphestos" without guide wheel	4 A/B	10388	122.3	16.1	2067	46.6	100	121	100
"Pharos" without guide wheel	4 A/B	10220	120.0	16.6	2033	45.9	98.5	115	95.0
"Pharos" with guide wheel	3 A/B	9386	116.5	16.2	1872	42.2	90.6	109	90.1

Table 11: Fuel consumption M.S. "Pharos"

ship	mile	output	revolution speed	speed	fuel consumption				
	No.	kW	min^{-1}	kts	l/h	t/24h	%	kg/nm	%
MS "Norasia Karsten" without guide wheel	1+2	6900	124.0	15.73	1536	34.7	100	92	100
MS "Norasia Karsten" with guide wheel	3+4	7194	124.0	16.17	1564	35.3	102	91	99
MS "Norasia Karsten" with guide wheel	5+6	6374	119.25	15.65	1375	31.0	89	82.5	90

Table 12: Fuel consumption M.S. "Norasia Karsten"

source: Bremer Vulkan, Bremen
HDW

The principle of operation

The diameter of the guide wheel is larger than that of the propeller. It is fitted behind the propeller and can freely rotate. Its blades are constructed in a way (similar to the turboprop principle) that allows it to withdraw energy from the inner slipstream (turbine part) and release it in the outer stream (propeller part) which increases thrust. This improvement through a guide wheel can be explained in two ways:

1. **Utilising bigger volumes of water**

   According to simple stream theory this increases efficiency. Such an effect can be achieved even with a big propeller; however, this requires extremely low revolution speed and is limited by the propeller clearance due to vibrations. The less strained guide wheel can be installed a lot closer to the shell plating and work together with a faster rotating propeller.

2. **Reducing the losses through spinning in the slipstream**

   This energy is otherwise lost. The revolution speed of the guide wheel is regulated hydrodynamically, i.e. through the turbine pitch. The optimum guide wheel revolution speed depends on the number of blades and usually ranges from 35 – 50% of the propeller revolution speed. The advantages gained through the guide wheel are mainly determined by the strain on the propeller, i.e. the energy content in the slipstream. Propeller revolution speed, pitch, and number of blades only play a minor role, which has a positive effect especially on pitch propellers with a constant revolution speed (i.e. permanently varying pitches). Of course, an important factor is also the relation between the diameters of guide wheel and propeller; if the proportion increases, higher advantages can be achieved.

   After numerous calculations, model experiments and trial trips it can be shown that there is a certain range of propeller strain for which the interaction of propeller and guide wheel is most efficient. However, this strain (from which onwards a ducted propeller is to be more efficient than the system of propeller and guide wheel), cannot be calculated as an exact value. To the best of today's knowledge, it can be assumed at a thrust utilisation factor of c_{TH} = 2.5 – 3. Nowadays, most vessels are operating at or below this value.

   The mode of operation of the guide wheel within the propulsion system "propeller plus guide wheel" can be recognized if the results of trial trips with the propeller only on the one hand and with a guide wheel arranged behind the propeller on the other hand are observed.

Due to the fact that the shaft is only transferring friction torque to the guide wheel and because hydrodynamic feedback effects onto the propeller are insignificantly low (as long as a certain distance is kept) the torque of both units is the same. Hence, the efficiency of the guide wheel shows itself almost solely as additional thrust. Its efficiency increases with increased propeller strain.

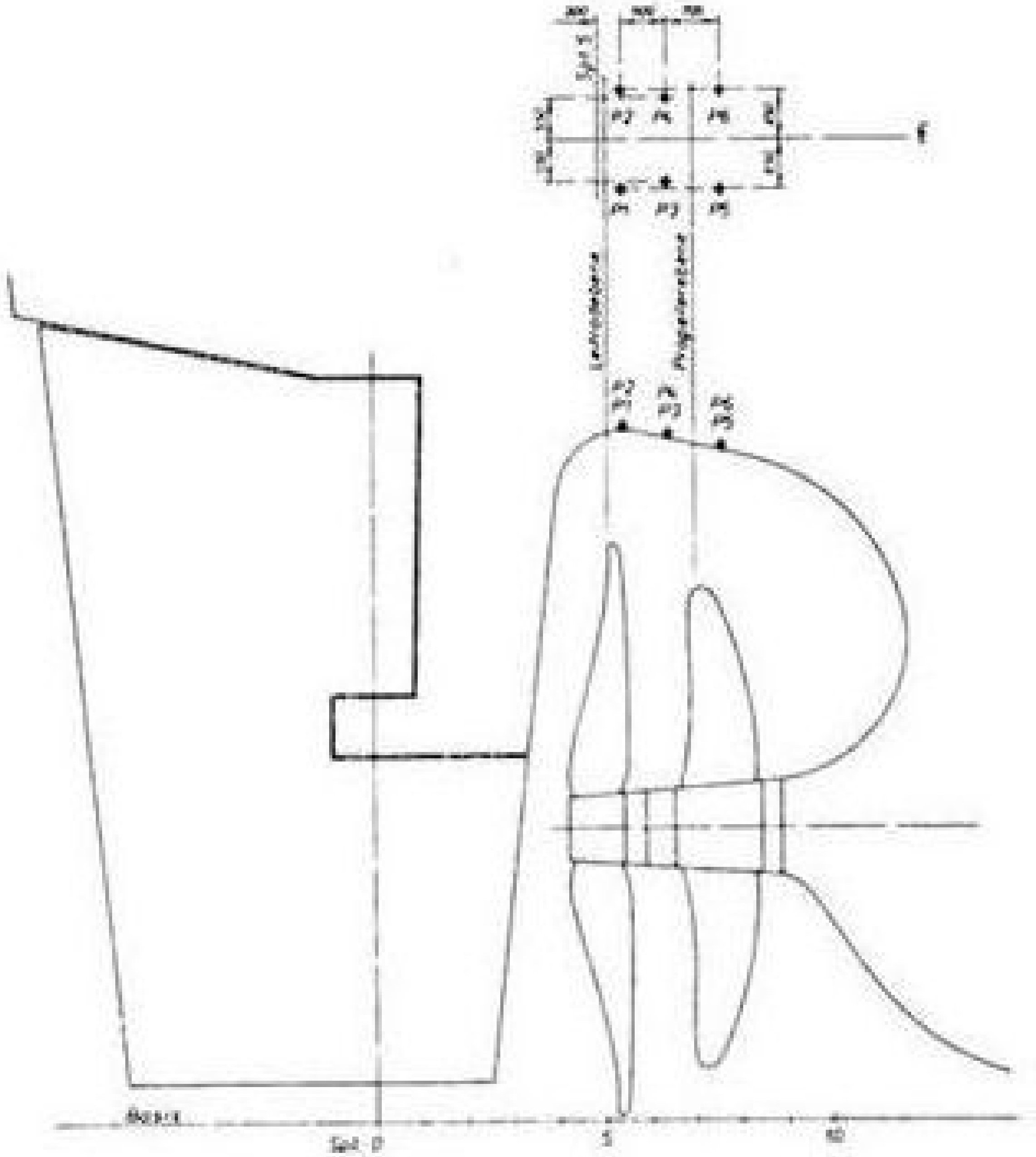
Effect on ship, engine and propeller

All trial trips and model experiments by the Hamburg Ship Model Basin (HSVA) show that the propulsion unit "propeller and guide wheel" does virtually not affect the manoeuvrability of the ship. The measurements of stopping distances have shown that the guide wheel even brings about an improvement. The guide wheel hardly influences output and torque of the propulsion engine. Test runs and model experiments have sometimes shown a slight improvement, sometimes a slight degradation in propeller revolution. However, the deviation in revolution frequency was always lower as or round about 1%.

Measuring pressure variations during the dockyard trial trip of the M.S. „Pharos“

New Building No. 37; on 29th/30th November 1983

Arrangement of measuring points



Arrangement of measuring points at the multi-purpose carrier “Pharos”

Illustration 18: Guide wheel configuration

source: Bremer Vulkan, Bremen

Illustration 19: Grim's guide wheel

source: Bremer Vulkan, Bremen

Illustration 20: Grothues spoiler with guide wheel

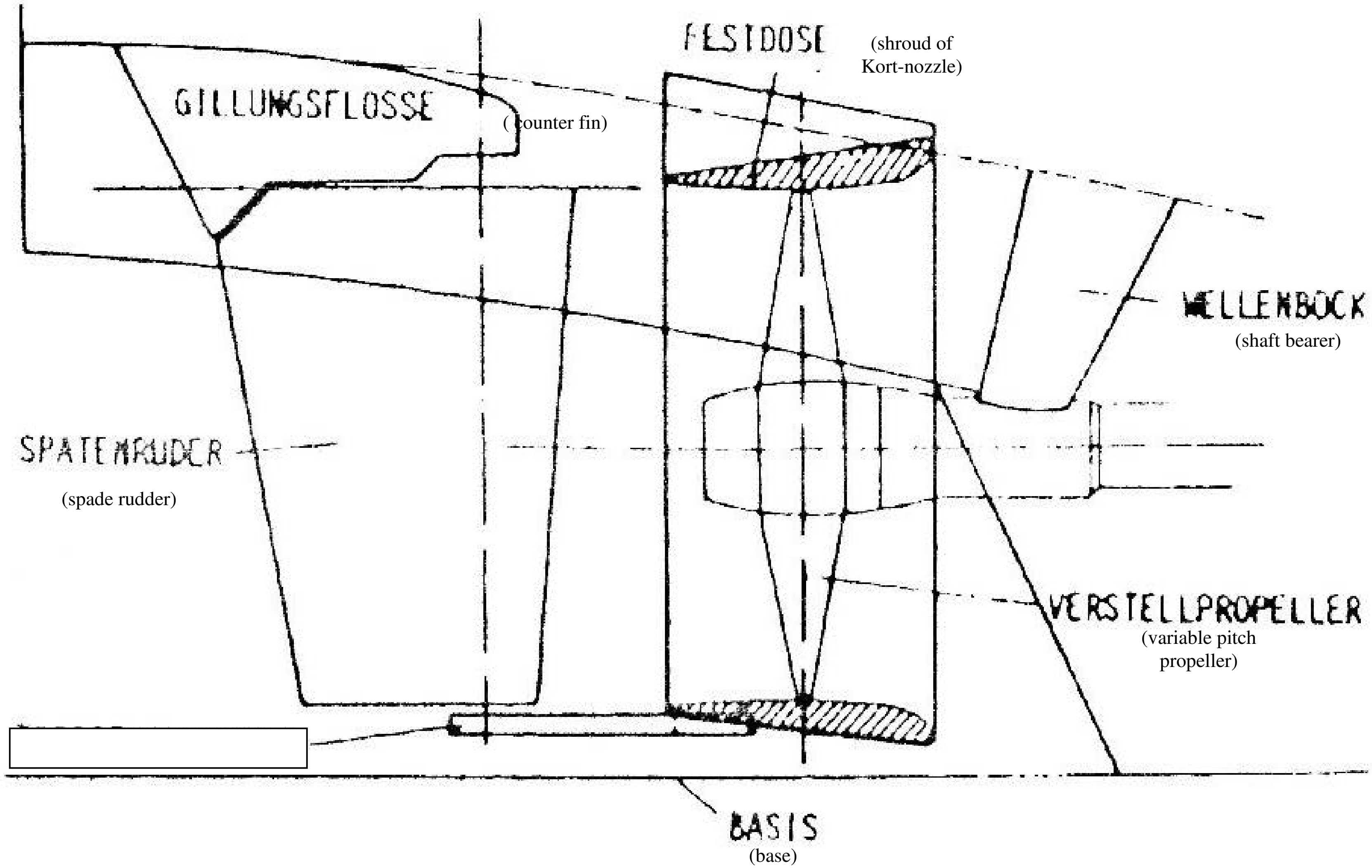
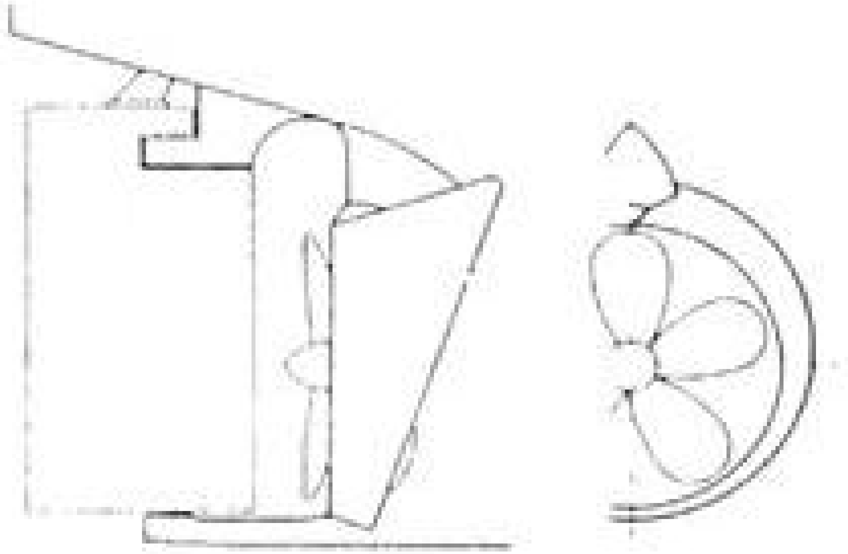


Illustration 21: Kort nozzle

Configuration of the Hitachi HZ nozzle. Note that, unlike conventional ducts, it does not enclose the propeller.



Right: Power savings achieved by the Hitachi HZ nozzle

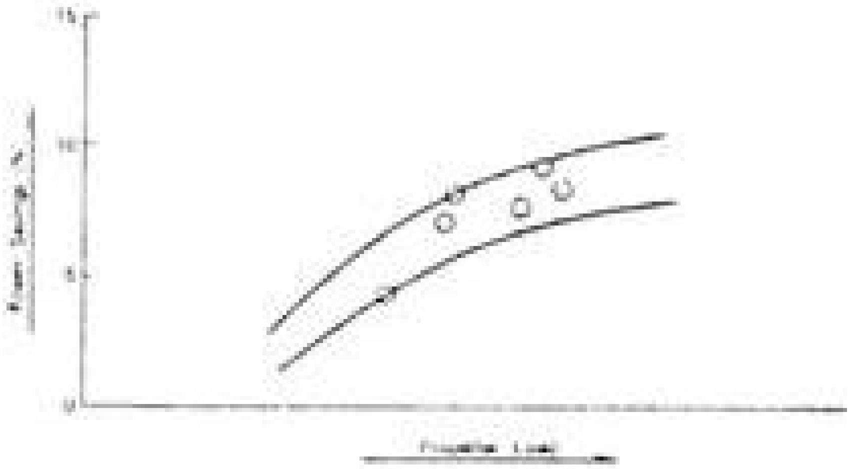


Illustration 22: Hitachi HZ nozzle

source: Hitachi, Japan

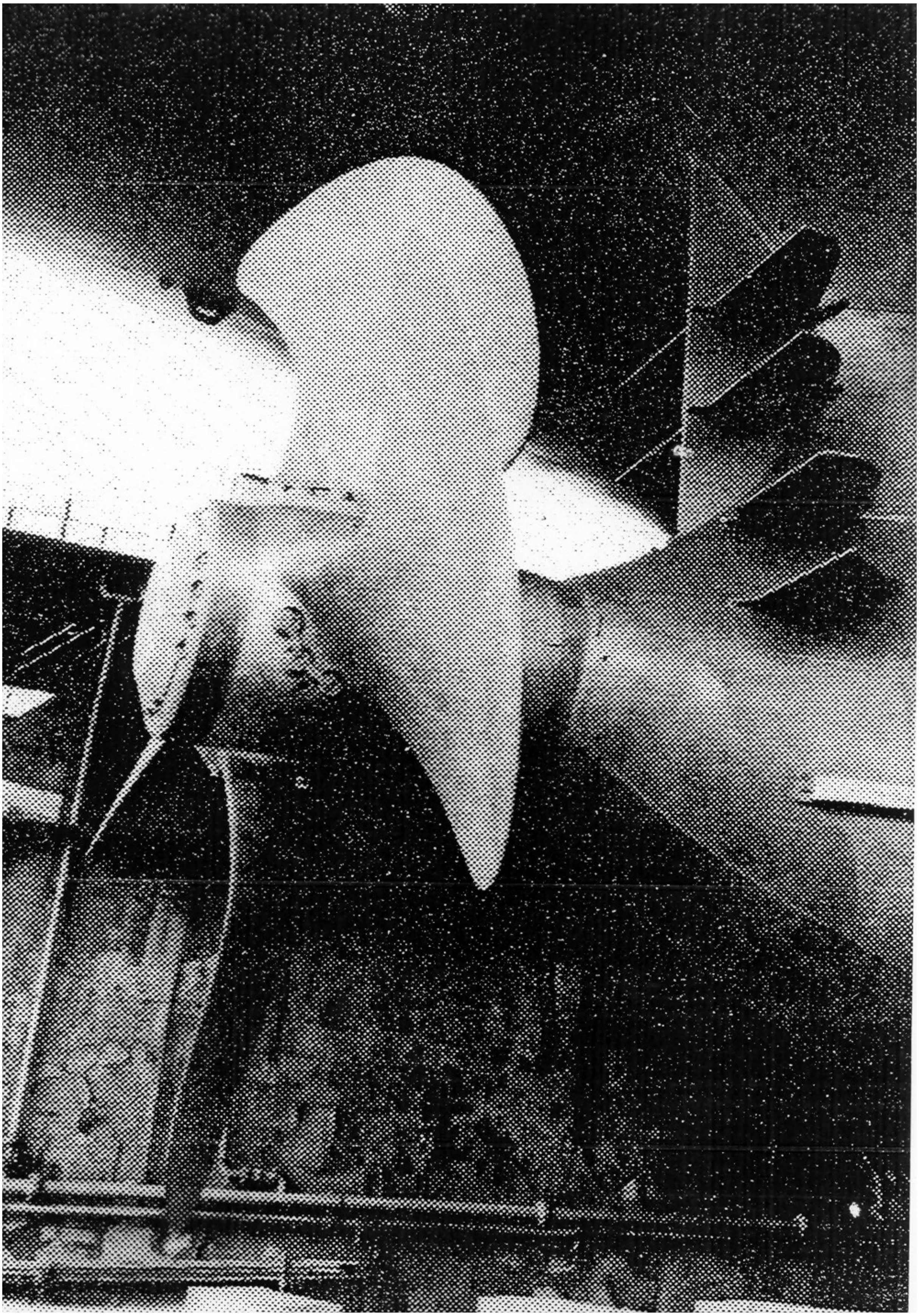


Illustration 23: CPP with Grothues Spoiler

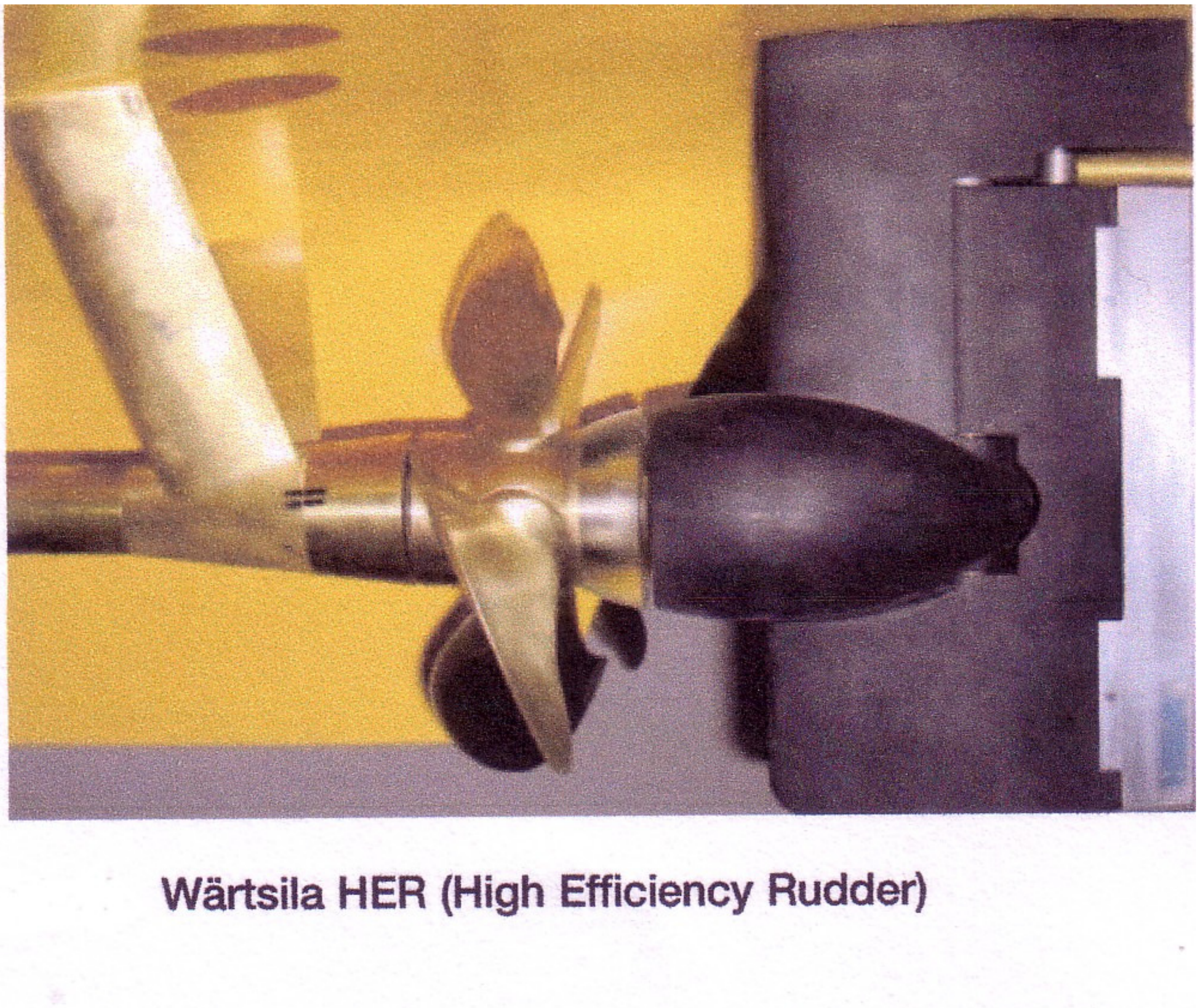
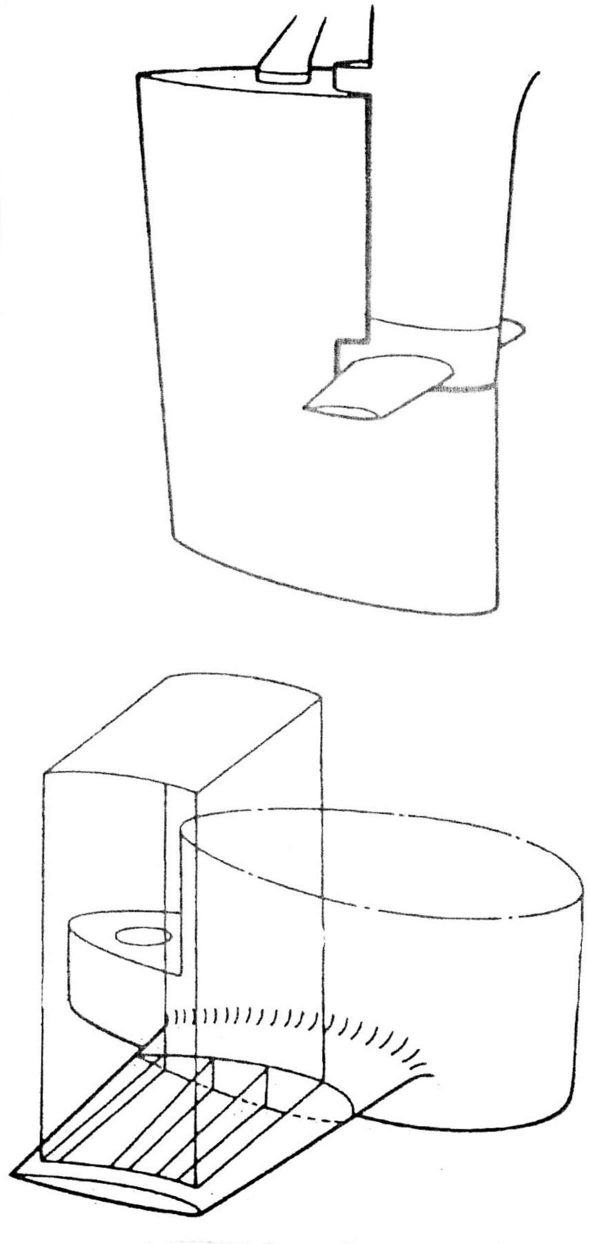
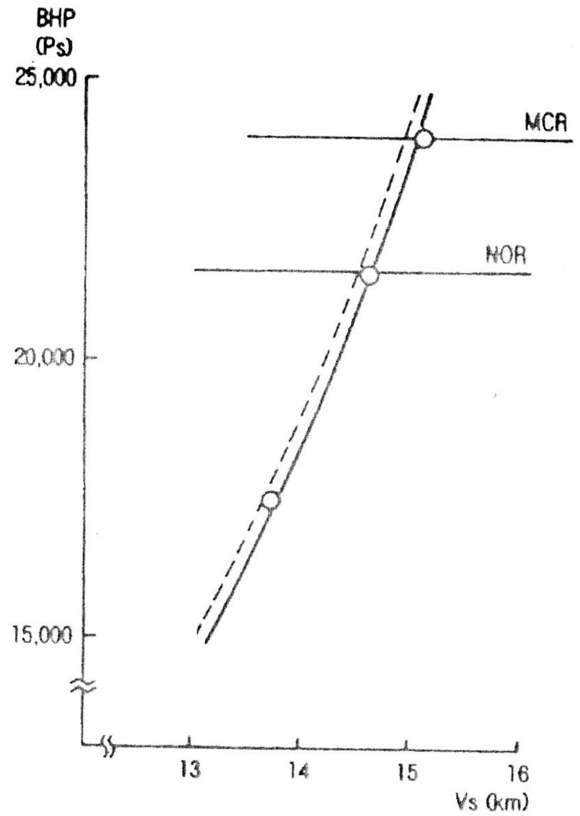


Illustration 24: Rudder form

source: product information CPP with pear-shaped rudder form





Arrangement of IHI's AT (additional thrust) fins installed for the first time on Tohkai Maru. Mounted on the Mariner type balanced rudder, the device converts some of the otherwise wasted energy in the rotational flow into extra propulsive thrust. A 3 per cent saving in fuel consumption was reported from the fully loaded sea trial at main engine mcr. In the graphs the trial performance of Tohkai Maru is shown by the unbroken line and compared with a similar vessel's results without AT fins. Less power is required for a given ship speed.

Illustration 25: Blades on the rudder

source: IHI, Japan

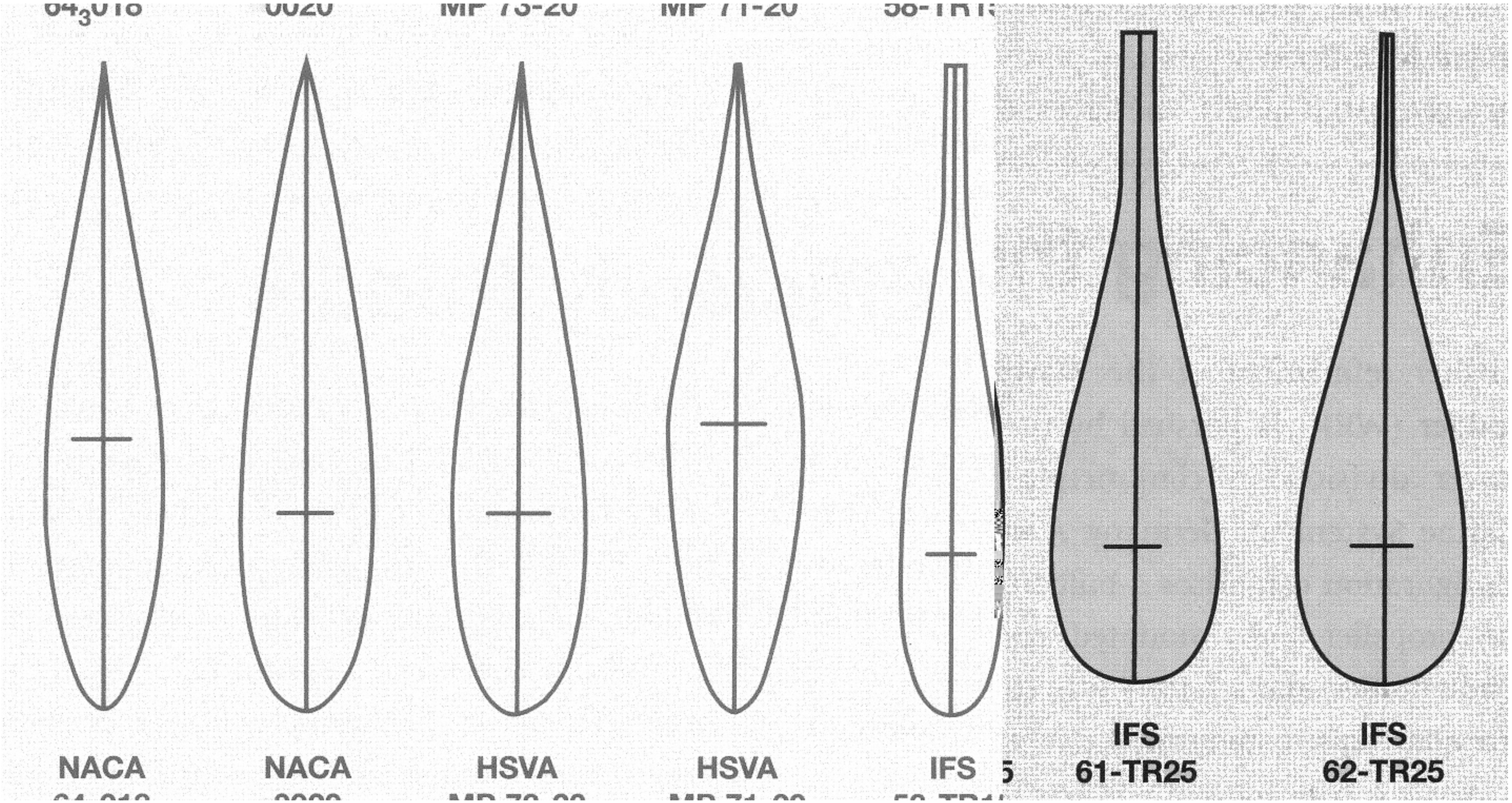


Illustration 26: Different rudder profiles

source: Marine Propulsion 06//07/2008 p. 27

4.2 Coating the underwater hull

One way of reducing daily fuel consumption is to modify the under-water surface. This surface should be as smooth as possible. Paint manufacturers are testing "slick" coats that aim to simulate fish skin. This would reduce friction resistance and would reduce fuel consumption by approx. 4%. [9]

In 2005, four ships of the Antwerpen Express Class by the shipping company Hapag Lloyd were coated with silicon. Opposed to SPC paint, the amount of paint that had to be applied was reduced to only 40%. No pigments are given off into the water, and the durability of the coating is five years. Fuel Consumption was reduced by approx. 6% under similar conditions. In August 2006, the shipping company applied the same paint on their Hamburg Express Class. [10]

4.3 Reducing resistance

Attachments to the under-water hull (e.g. bilge keel, sacrificial anodes, rudder) increase resistance and therefore fuel consumption.

A simple and cost-effective way to reduce rolling is a large profile height of the bilge keel. It should keep a safety clearance of approx. 1% of the beam of the ship in order to avoid damage from the rectangle contour which surrounds the midship section.

The bilge keel is 0.25 – 0.33 L long. Using model experiments, it was designed for a certain vessel speed. Other speeds increase resistance as the oncoming water hits the keel at an angle. The swell resistance of a smoothly moving ship with bilge keel is higher than that of a heavily rolling ship without bilge keel. It is roughly 1% of the under-water hull alone.

Under-water coatings protect the structural steel of the ship through the passive anticorrosive system. Damaged and uncoated areas of the shell plating at docking as well as uncoated areas at the propeller shaft, rudder shaft and the propeller as such are protected through cathodic corrosion protection.

Another cost-effective method is using sacrificial anodes. The protection is a result of bonding the metal of the under-water hull with a less noble metal. This causes the steel of the

[9] Do Report fort he Department for Transport, Newcastle University.
[10] Speech held by Adolf Adisson at the Shipping Federation of Canada 01/04/2008.

under-water hull to become a cathode and the less noble metal a sacrificial anode. Zinc and aluminium compositions have been proven to be of value. Zinc can make up to 780Ah/kg and aluminium composition 2000 - 2800Ah/kg.

The required amount of anodes can be calculated with the following equation:

$$m = \frac{A \cdot I \cdot t \cdot 24 \cdot 365}{I_v} \qquad \text{in kg}$$

whereas

m	=	amount of anodes in *kg*.
A	=	area to be protected in m^2
I	=	density of the protective current in A/m^2, (~ 20mA/m^2)
t	=	protection period in years
I_v	=	usable current of the anode material (e.g. Zn = 780 *Ah/kg*)

Experience has shown that sacrificial anodes should be positioned as follows:

20 – 25% of the whole amount of anodes should be positioned at the stern. 20% of these should be positioned at the rudder. The area in front of the propeller must be kept clear of anodes in order not to impair the inflow to the propeller.

The rest of the anodes is to be spread out evenly over the rest of the under-water hull, being careful not to leave more than 8 metres between each of them. This then defines the individual weight of each sacrificial anode.

Common are 3cm high, 10cm wide and 20cm long forms with weights of 70kg and more. Streamlined, bar-, drop-, star-, and circular shaped anodes as well as anodes that are composed of two end parts and various middle sections are the most common.

The anode material is cast in its desired shape around the fitting, which consists of 3 – 6mm thick and 20 – 40mm wide flat bars.

The fitting is welded to the bent off clips at the hull. Often doublings can be found on the shell plating that prevent the hull from weakening when exhausted anodes are removed. Each individual anode increases resistance and turbulences in the current are caused. The fewer sacrificial anodes are fitted the less additional fuel is consumed.

An elegant method of corrosion protection is using external current. The negative pole of a D.C. source is connected to the shell plating. The positive pole with insulated protective anodes is attached to a different part of the shell plating. This way, only a few anodes are installed at both sides of the ship and sit smoothly against the shell plating.

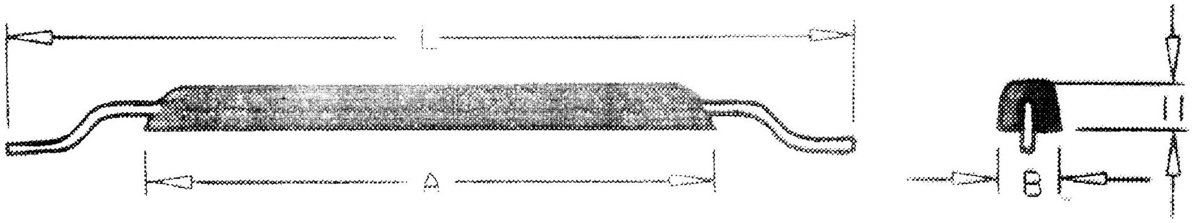


Illustration 27: Sacrificial anode

source: product information Bera Zinc Anodes, Netherlands

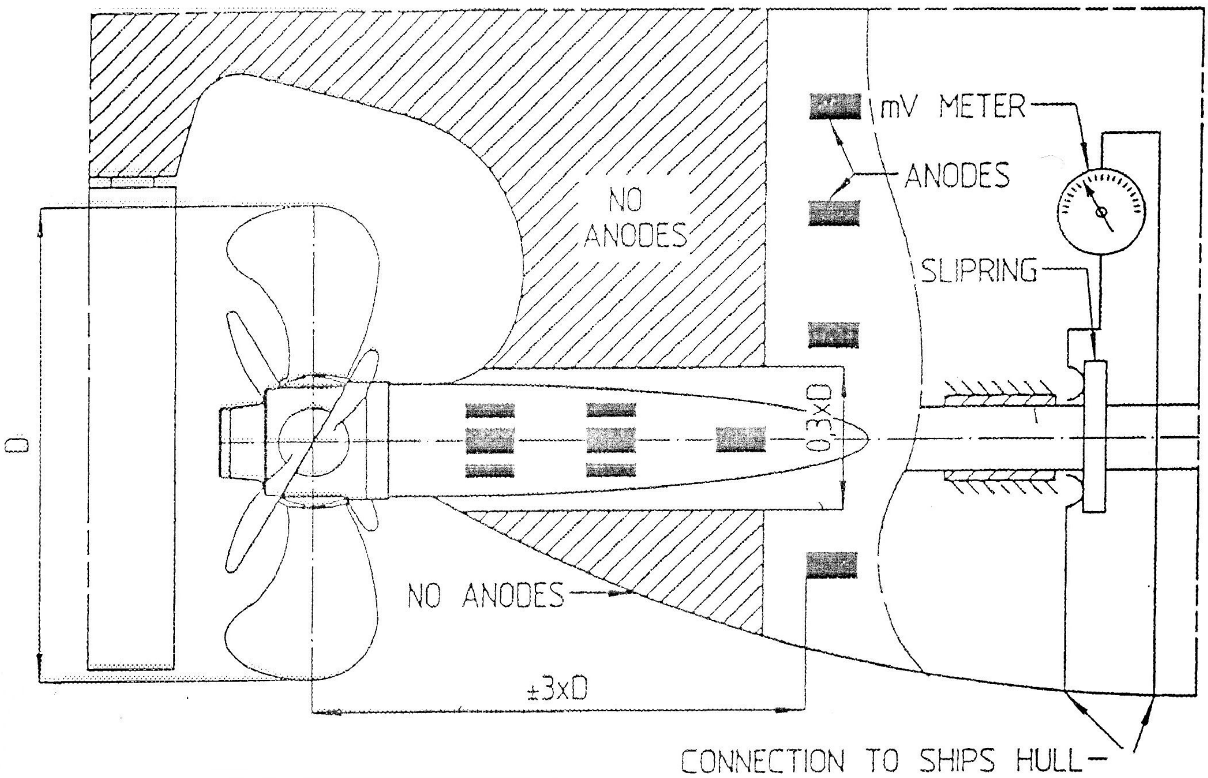


Illustration 28: Positioning the anodes at the stern

source: product information Bera Zinc Anodes, Netherlands

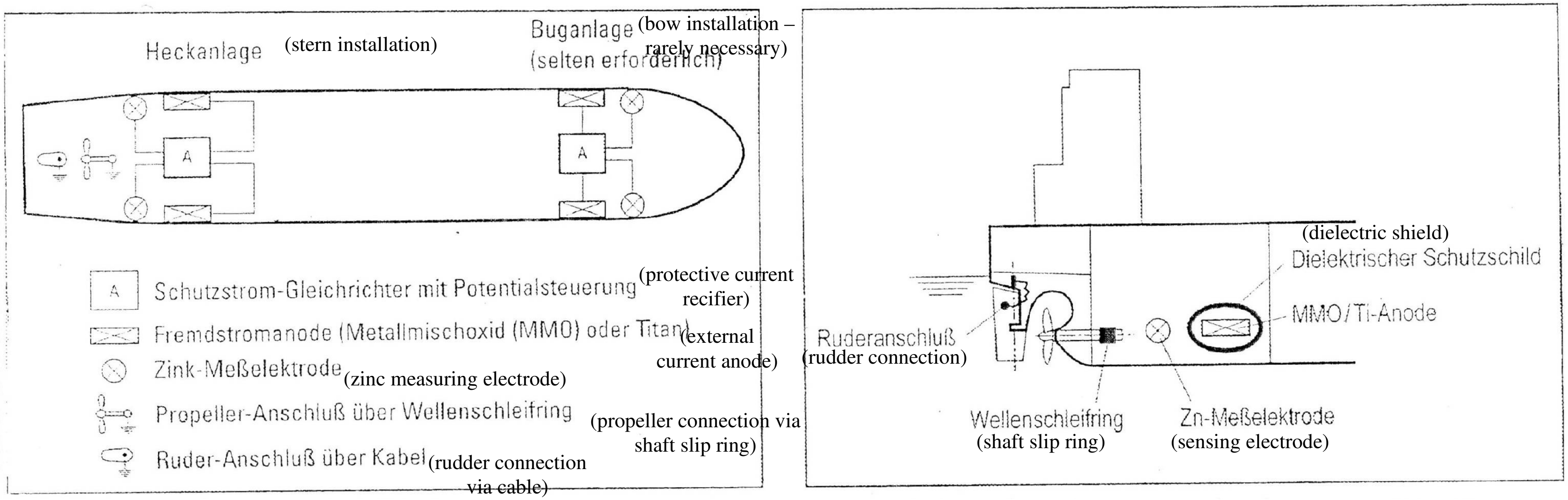


Illustration 29: Schematic diagram of external current

source: product information of the company Cathelco, Great Britain

4.4 Automatic steering gear

Principle of operation

The actual course signal from the gyro compass telecommunication system is constantly compared with the signal of the manual set course adjuster. As long as actual course and set course are the same, both indicators are lying upon each other and no voltage is set off. As soon as the vessel is deviating from her course or if the set course is altered, a signal is transmitted. The PID (proportional plus integral plus derivative) controller uses this course deviation signal in three parts:

- P-part, which is proportional to the course deviation
- I-part, which represents the integral or sum of the course deviation in connection to time
- D-part, which represents the course deviation in connection to speed.

Calculating the difference to the shown rudder angle causes an error signal. This signal is transmitted through a dip switch to the steering gear which is then automatically set back to zero.

In order to be able to adapt the automatic system to different conditions such as weather, swell, load etc. the main operating controls in this controlling circuit are adjustable.

4.5 Operating devices

Rudder angleturn-switch

The switch can be set to different positions and regulates the swing of the rudder (from small to large rudder angle).

Turn-switch to control the angle of the yawing

The switch can be set to different positions and regulates the sensitivity of the automatic steering gear. Beside the momentary course deviation also the rate of turn is taken into consideration. In good weather conditions when the ship yaws only little, “Yawing” should be set to a low position. This would mean a high proximity to the set course. In bad weather conditions a higher “Yawing”-position is to be chosen.

Counter rudder turn-switch

It can be set to various positions. It controls the speed which the ship turns with. In the highest setting the impact is at a maximum, in the lowest setting the impact is zero. Sailing without counter rudder can cause hunting around the set course. During a change of course the ship can also vastly overshoot the set course. Using a larger counter rudder minimises hunting and prevents the ship from overshooting. On the other hand, at rough sea conditions, a large counter rudder would continuously set off the automatic steering gear as the fast movements of the ship caused by swell would be noticed at the same time. In this case, an enlargement of the "Yawing" should be preferred instead of minimising the "Counter Rudder".

Course monitor

If the actual course deviates more than 18° from the set course the course monitor activates an acoustic signal. Pressing the button that regulates the set course the signal can be switched off. If the course is altered manually, no signal will be given.

Automatic rudder trim

The automatic rudder trim automatically eliminates the effect of lateral forces (swell or wind) if the course deviation is less than 10°. The integral part can be switched off.

The automatic steering integrates the course deviation and when it reaches respond threshold it produces a slightly larger rudder angle.

Course deviations

Having altered the set course the ship is correcting her course. If the alterations are vast, the correction of course is either done step-by-step or very slowly using the ROT[11] limit.

Rudder

The rudder parameter can be set to different positions and controls the swing of the rudder (from small to large rudder angle).

[11] Rate of Turn

Depending on the circumstances, other rudders angles have to be preset. As long as the weather allows, the ship should be sailed with the values 0.3, 0.5, 0.7 or 1.0. On rivers and estuaries a higher value should be set. The same applies to rough , following sea conditions. At slow speed the “Rudder” should be increased. If carrying deck cargo a maximum of 0.7 should be set only.

Yawing

The yawing control switch can be set on different positions and controls the sensitivity. At calm weather conditions, setting 2 should be chosen, whereas a higher setting is better for rough weather conditions. In no case, the periodic yawing movements of the ship caused by swell should be corrected.

Counter rudder

This parameter has a wide scope. It controls the impact of ship speed on the control process.

Sailing without counter rudder can cause hunting around the set course, and at a change of course the ship can also vastly overshoot the set course. Using a larger counter rudder minimises hunting and prevents the ship from overshooting. On the other hand, at rough sea conditions, a large counter rudder would continuously activate the automatic steering gear as the fast movements of the ship caused by swell would be noticed at the same time. In this case, it should be preferred to increase the yawing angle instead of minimising the counter rudder. As a basic principle, the counter rudder should be set to a position that sets off the steering gear as rarely as possible but keeps the ship on the set course with justifiable accuracy. If overshooting can be noticed when altering the course, the counter rudder parameter is set too low.

If the hunting is stronger than the corresponding with the yawing caused by swell, counter rudder has to be set higher. If the course changes are too slow, the counter rudder is set too high or the rudder too low. If this then activates the steering gear too often, also the “Yawing” has to be increased. A loaded vessel generally needs more counter rudder than a ship in ballast.

Rules for settings

- At calm sea conditions “Yawing” can be set low.
- At rough sea conditions “Yawing” has to be set higher.
- If the course oscillates between two high values that do not correspond to the yawing of the ship, “Counter Rudder” has to be increased.
- If this activates the steering gear too often, “Yawing” also has to be increased.
- At normal weather conditions “Rudder” should be put to setting 1 or 2.
- On rivers and estuaries the “Rudder” setting should be one setting higher.
- At rough, following seas, “Rudder” needs to be set higher; possibly “Yawing” too.
- At *half ahead*, *slow ahead*, and *dead slow ahead*, “Rudder” should be set higher.
- Operating with deck cargo, no course changes should be driven with a higher “Rudder” setting than 2.
- If the ship overshoots, “Counter Rudder” has to be set higher.
- If the course changes are too slow, the “Counter Rudder” is set too high and “Rudder´” possibly too low.
- A loaded vessel generally needs more “Counter Rudder” than a ship in ballast.
- At a higher time constant, “Counter Rudder” needs to be increased.
- When altering course, “Rudder Trim” is to be switched off.

Course control with a PID controller

If a PID controller is used, the rudder angle δ is determined by three parameters:

- the course deviation $\Delta\Psi$
- the present ROT $\dot{\psi}$
- unsymmetrical disturbances (propeller, wind) $\int \Delta\Psi \cdot dt$

In order to be able to describe the dynamic behaviour of the control circuit it is necessary to know the equations and their corresponding parameters that make up the base for setting the controllers. These parameters concern the ship movement in the course plane depending on the rudder angle. Nomoto's first-order approximation can be described as the simplest equation of motion.

$$T_S \cdot \ddot{\psi} + \dot{\psi} = K_S \cdot \delta$$

$\ddot{\psi}$ = circular acceleration

$\dot{\psi}$ = rate of turn

δ = rudder angle

T_S = time constant (measure of the inertia of the ship)

K_S = transfer coefficient (measure of rudder efficiency)

The rudder angle δ consists of a proportional part, a differential part, and an integral part. These can be adjusted through exterior settings:

- the P-part through "Rudder"
- the D-part through "Counter Rudder"
- the I-part through "Rudder Trim"

A fourth potentiometer is "Yawing".

Optimisation

Possible aims could be:

- low course deviation
- low yawing speed
- small rudder angle
- small number of rudder manoeuvres
- small increase of distance
- possibly no hull resistance increase

Methods of parameter optimisation are:

- the empiric method
- the mathematic analytical method
- the auto-adaptive method

By altering the course by e.g. 20° the parameters T_S and K_S can be determined. With the Ψ-t-diagram both values can be determined. However they are specific to a certain draught and trim of the ship.

Adaptive course control

Characteristics of ship and weather have to be separated in order not to respond to influences of swell by putting the helm.

This requires a mathematical model of the ship. At a certain rudder angle the model should react in the same way as the actual ship would. If the amplitudes are not right, K_S of the model has to be modified until it matches with the ship. If the phasing is incorrect, T_S has to be changed. If there is no other model error, the ship should react in the same way as the model to the putting the helm. Remaining course deviations which cannot be eliminated are explained through swell. Accordingly, “Yawing” is automatically adjusted to swell. Even if the weather changes, the course control only reacts to ship influences not to weather influences. The helm will be put less.

The development of the model ship already occurs at the start of the voyage during the manoeuvres.

Trim of the ship

An exact working fuel-volume-measuring-system can determine whether fuel consumption changes per nautical mile. This is done by trimming the ship and using ballast water and/or fuel. Usually for the trim is optimal if the bulbous bow is submerged.

Experiments have shown that a propeller that emerges a maximum of 0.2 D out of the water is not damaged by erosion, cavitation, or corrosion. If the ship is trimmed by the head, daily fuel consumption is usually reduced.

Without model experiments it is difficult to determine the lowest fuel consumption at variable draught, trim and speed.

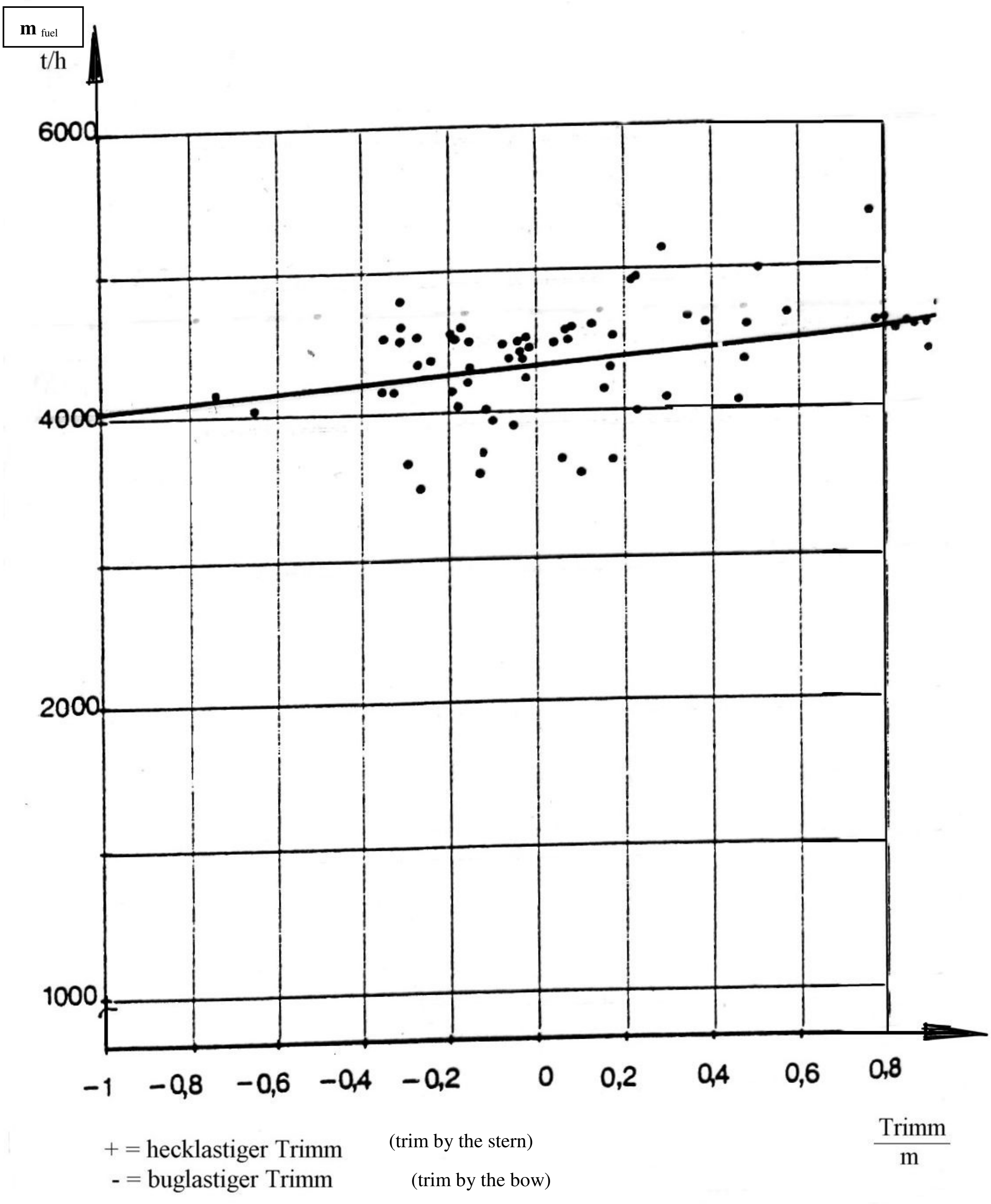


Illustration 30: Fuel consumption in relation to trim measured on a ferry

Source: Schiff & Hafen

5 Methods of improving energy conversion and energy transport

5.1 Reducing fuel consumption on the main engine

In order to determine the average indexed pressure during a combustion stroke, the output is usually determined on board. The revolution speed can be determined at the same time. With the known efficiency factor η_{mech} it is possible to calculate the effective output.

$$Pe = \eta_{mech} \cdot Pi \qquad Pi = \frac{A \cdot pi \cdot 2 \cdot s \cdot n}{T} \qquad Pe = M \cdot \omega$$

Torque can be measured by stress gauges directly behind the engine or the PTO[12] of the shaft generator. If this value is combined with the momentary fuel mass flow rate, the specific fuel consumption as shown in chapter 3 can be illustrated.

Fuel consumption

Instead of referring to the efficiency factor, fuel consumption is often mentioned.

$$\eta_e = \frac{Nutzen}{Aufwand} = \frac{P_e}{\dot{m}_{Krst} \cdot H_u}$$ (Nutzen = benefit; Aufwand = input; Krst = fuel)

The specific fuel oil consumption is described as the consumption per kW and hour.

$$\eta_e = \frac{P_e \cdot 3600}{\dot{m}_{Krst} \cdot H_u} \quad \text{in} \quad \frac{kJ/s}{kg/h \cdot kJ/kg} \cdot 3600 \frac{s}{h}$$

$$\dot{m}_{Krst} = \frac{P_e \cdot 3600}{\eta_e \cdot H_u} \quad \text{in} \quad \frac{kg}{h}$$ whereas H_u = 42707 kj/kg according to ISO

$$b_e = \frac{3600 s/h}{\eta_e \cdot 42707 kJ/kg} \quad \text{in} \quad \frac{kg}{kWh}$$

[12] Power Take Of

Consumption of lubrication oil

Throughout the running-in of pistons, rings and liners (smoothing the surface) the consumption of lubrication oil is high. It decreases asymptotically towards a value of 1–1.5 g/kW. Too high consumptions of lubrication oil make the engine too uneconomic, whereas using too little increases abrasive wear. The consumption of lubrication oil also depends on the diameter of the piston.

The cost relation between the qualities of lubrication oil can be as much as 1:7. High-performance lubrication oils for fast and medium running diesel engines can be up to 20 times more expensive than the fuel.

The total operating costs of a 4000kW- vessel engine including capital costs can be broken down as follows:

- fuel costs 64%
- capital cost 27%
- maintenance costs 6%
- lubrication oil costs 3%

An Alpha Lubricator can lower lubrication oil costs. Tests have shown that a reduction of cylinder oil also reduces particulate emissions.

Reducing fuel consumption

Consumptions cannot be incessantly improved because physically set boundaries cannot be overcome. The investment of material and effort increase with each g/kWh improvement of fuel consumption. Already at this stage, a 5% additional expenditure is calculated for a new engine that improves consumption by 1%. However, as long as this additional expenditure is amortised through fuel cost savings within a few years, engineers will be asked to carry on trying to reduce fuel consumptions.

A typical example for additional expenditure to save fuel is the usage of power-reduced engines. Through 15% output reduction a decrease in fuel consumption of more than 2% can be achieved.

The same focus has the application of highly effective turbo chargers. Nowadays, turbo-chargers which are operating at there limits in daily operation are not fitted any more. Instead, an improved efficiency factor is used to decrease fuel consumption. This resulted in new model series to come out.

In this context, it is interesting to note, that more and more power-reduced engines are sold. The actual power output in various engine models are still increasing; however, if the real used power (when the vessel is actually in use) is applied, a tendency towards smaller specific engine output can be noticed.

Not all measures that lower fuel consumption have to be cost-intensive. Some are possible because experience has shown a better usage of a construction. This primarily includes ignition pressure. The advantage of a high ignition pressure is the fact that even up to rarely used limits it directly correlates with fuel consumption. The higher the pressure in the combustion cylinder (at a given average operating pressure onto the piston), the less fuel is consumed.

The disadvantage of a high ignition pressure is that more material is needed for the engine. Unfortunately it does not help to use high-tensile materials. Bigger diesel engines need a high degree of stiffness in order for pistons and bearing to operate well. It directly depends on the amount and modulus of elasticity. The high gas pressure at the piston rings results in increased friction. This can be reduced by choosing a well-shaped piston ring and by using especially abrasion resistant material.

It sounds like a paradox that friction work is reduced in slide bearings if the load is increased.

If the lubrication gap is reduced by 25% through increasing the temperature of the used lubrication oil, a similar reduction of friction work can be noted. Important factors for a change in bearing friction are: bearing clearance, the diameter of the bearing, and its width. A gain in friction work is especially important as it fully appears as a reduction of fuel consumption.

For the engine operator it is also important that an engine with low mechanical friction work performs particularly well in the partial-load operational range. It was proven, that reducing friction work in engine and turbo-charger arrangement resulted in a fuel consumption gain of 9 g/kWh at 25% engine power.

Better utilisation of an engine due to experience can for instance be carried out when choosing valve timings. Up to now, engines are operated with relatively big valve overlap. This means that the charge air from the supercharger is partly let into the exhaust gas line and there reduces the high temperature.

Meanwhile, engine manufacturers found out in many systems that the used charge very rarely causes dirty supercharger arrangements. Obviously, not only the exhaust gas temperature respectively the temperature of the dirt particles is important but also the average temperature of the exhaust gas flow and the different supercharger elements as well as a smooth and as straight as possible direction of flow in the turbine. The amount of air passing the combustion camber during the valve overlap can now be reduced, which results in a reduction of fuel consumption.

In connection with the application of high-efficient supercharger arrangements another effect is caused: Superchargers, especially if they have low bearing friction, supply the engine even in part-load operation with a lot of air. With same or even reduced thermal load the used pressure of the intake air can be reduced. Together with a high compression ratio (which is generally increasing efficiency anyway) an optimum full load air pressure can be set. This again results in a reduction of fuel consumption.

As described additional engine expenditure can result in lower fuel consumptions. To the same extent a lot can be achieved if fine tuning certain steps. In this context, the different possibilities of injecting fuel, especially electronic injection, should be mentioned.

So far the utilisation of the engine waste heat was not mentioned. A majority of the already mentioned measures helps to enhance this energy. The warmer the engine cooling water, the lubrication oil, or the exhaust gases are after the supercharger, the more heat can be fed back into the thermal cycle.xxxx

Engineers welcome the fact that data like power-weight ratio, specific piston surface efficiency, and performance-related installation volume are not as important any more as plain matter-of-fact amortisation calculations. It is therefore not the cheapest engine that is the most cost effective, but the one that at the end of its life time will have cost the least amount of money per generated kWh. If this way of thinking is developed further, a lot can be done to increase energy efficiency.

Device for controlling the ignition point

Due to the good experiences made with various controlling devices that were fitted in tested engines, it was decided to standardly fit all engines with a device for controlling the ignition point. This reduces the fuel consumption.

Maximum permissible combustion pressure → lowest fuel consumption

The device for controlling the ignition point automatically sets combustion pressure to a value that is permitted for acceptable bearing pressure. At an engine load of 85% to 100% the combustion pressure is therefore kept more or less on its maximum and is reduced in relation to the engine load.

Setting fuel quality → readjusting for low fuel consumption

A separate lever at the device for controlling the ignition point makes it possible to manually adjust the ignition point – the setting adapted to the fuel quality.

The use of heavy fuels can cause ignition delays and therefore a reduction of the maximum combustion pressure which would increase fuel consumption. While the engine is running combustion pressure can be set to its normal value. This can be achieved by simply readjusting the fuel quality lever towards “advanced ignition”. Fuel consumption is decreased to its best possible value.

This simple mechanism is connected with the load-adjustment shaft of the governor. Through connecting elements an integrated cam system (which is controlled by using the lever of the device for controlling fuel quality) controls the simultaneous regulation of the suction valve closing process (for the beginning of fuel supply) and the overflow valve opening process (end of fuel supply). Ignition point and fuel supply to the injector nozzle is controlled load-dependently.

In connection with a simple combustion pressure display unit, the device for controlling the ignition point offers the chief engineer a huge amount of flexibility when dealing with a wide range of low quality fuels and during the automatic engine operating mode with lowest possible fuel consumption.

Economy ratings for slow-running engines

The advantages of decreased fuel consumption (through holding the maximum nominal combustion pressure at part-load operation) are also used for available engine optimisations – the economy ratings.

This means that an engine is optimised for reduced output and/or revolution speed but the maximum nominal combustion pressure remains 100%. This can reduce fuel consumption by another 3%.

It has to be noted that the low fuel consumption that results from reduced engine output is opposed to higher capital investment. In most cases this means that an additional cylinder has to be installed because the best cost-benefit ratio of capital investments and lowest fuel consumption results from an economy rating which is determined by the propeller rule. This optimisation also offers the possibility of a higher propulsion efficiency factor thanks to lower revolution speed and reduced fuel consumption at the engine.

Economy ratings → maximum continuous output

Economy rating means that an engine is not used to its maximum continuous output (nominal rating) but limited to the design output of all auxiliary operations. These auxiliary operations are usually adjusted to a lower output.

Economy rating → device for controlling the ignition point

If an engine is fitted with a device for controlling the ignition point, no further reduction of fuel consumption can be achieved with this mechanism. This is due to the fact that the economy rating already includes the effect of 100% maximum combustion pressure. The specific fuel consumption is therefore specified for the chosen economy rating. However, the device for controlling the ignition point offers the flexibility that is needed in order to always achieve the lowest possible fuel consumption regarding a wide range of fuels.

Electronically controlled diesel injection

This provides uniform ignition pressure across the whole load range.

At an injection system, three parameters are controllable:

- start of injection
- average injection pressure
- injection pressure profile.

The electronic injection system operates with a near rectangular pressure profile before the nozzle bores. This allows the energy to be used in its best possible way in order to inject a large amount of fuel in a short time.

It has to be noted, that the optimum pressure in the high pressure accumulator has to be adjusted based on output. As the output is the product of revolution speed, injection time and fuel pressure and all these values are fed into the controlling unit, its adjustment is easy. This is why every operating point can be set optimally; even outside the theoretical propeller curve.

Injection pressure has to be lowered in order to achieve optimum fuel consumption and a low thermal impact in the cylinder liner at low outputs. This is related to the fact that at constantly high fuel pressure and against the low gas pressure in the cylinder the fuel jets would hit the combustion chamber too hard. Fuel/air distribution and combustion would be accordingly disadvantageous.

Electronic injection also makes it possible to adjust to environmental conditions. For example: a two-stroke engine is optimally set for ISO conditions. If the ship is now sailing into tropical waters without adjusting the injection point, the ignition pressure would sink. As also the air supply to the engine would get worse with increasing temperature, an increased fuel consumption of about 4.5 g/kWh would be the result. However, if the ignition pressure is adjusted to a constant value, the fuel consumption increase could be reduced by around a third.

It was assumed that the charge air at full load is fuel-efficiently cooled as far as the sea water temperature allows. At smaller partial loads this would not be done. Instead it would be tried to keep the temperature after the intercooler high, in order to achieve more advantageous combustion conditions.

If the ship, on which the engine is optimised for ISO conditions, sails into a cooler climate, the output cannot be achieved using the in itself economically low charge air temperature because the permissible ignition pressure would be exceeded. Re-adjusting the ignition pressure cannot only help to achieve the output but also results in decreased fuel consumption.

The ideal consumption is achieved if the engine is utilising the ambient temperatures of the sea water as well as constantly setting optimum ignition pressure. Hence, the engine is operating in wide areas with the design ignition pressure. This is really only possible with an electronically controlled injection system.

Environmental impact

The electronically controlled injection does not only optimise fuel consumption regarding the temperature of various components. In addition, it is also a sensible solution regarding the environmental impact.

With unvarying exhaust-gas opacity, the NO_x-content can be lowered by changing the start of injection. This is accompanied by a justifiable increase of fuel consumption as it only occurs during port operations.

5.2 Consumption reduction in auxiliary power mode

Energy savings are possible at:

- pumps
- compressors and ventilators
- separators
- heat exchangers
- chillers and air-conditioning systems
- hydraulic and pneumatic systems
- pipe systems

5.2.1 Pumps

With increasing volume flow most centrifugal pumps on board show an ascending output curve. If less volume per time unit is needed, power consumption can be reduced. This is achieved by reducing the revolution speed at the driving engine or by throttling the shut-off valve at the pressure side of the pump.

The overall efficiency of a centrifugal pump $\eta_{Pumpe} = \frac{P_N}{P}$ consists of the individual efficiencies $\eta_{Pumpe} = \eta_h \cdot \lambda_L \cdot \eta_m$ and $\eta_{Pumpe} = \eta_h \cdot \eta_v \cdot \eta_m$.

Cavitation at the impeller inlet and the casing worsens the hydraulic effiency η_h. Leaking wear rings reduce the volumetric efficiency λ_L. The overall efficiency can be calculated on board and therefore an increase in the driving power at constant effective output can be noticed. The effective output can be shown as $P_N = \dot{V} \cdot H_N \cdot \rho \cdot g$. Therefore it follows that

$$\eta_{Pumpe} = \frac{\dot{V} \cdot H_N \cdot \rho \cdot g}{P} .$$

The law of similitude

If the pressure valve setting is unchanged, the following theoretical relationship exists between delivery rate, pressure head and power input on the one hand and revolution speed on the other hand:

$$\frac{\dot{V}_x}{\dot{V}} = \frac{n_x}{n} \qquad \frac{H_x}{H} = \frac{n_x^{\ 2}}{n^2} \qquad \frac{P_x}{P} = \frac{n_x^{\ 3}}{n^3}$$

If at a new revolution speed setting the delivery rate is changed proportionally to the revolution speed, the pressure head changes proportionally to the second power; the effective power changes proportionally to the third power of the revolution speed relation at the same efficiency.

The characteristic curve

In the characteristic curve you can find:

- maximum impeller diameter
- minimum impeller diameter
- maximum $\dot{V}$
- minimum $\dot{V}$
- maximum P
- minimum P
- NPSH[13] $_{required}$
- characteristic zone of the pump efficiency

This is all regarding water with ρ = 1000 kg/m^3, and the revolution speed is indicated for 50/60 Hz.

Centrifugal pump models according to datasheet:

- high pressure head = small output
- low pressure head = big output

[13] The NPSH (Net Positive Suction Head) is an expression of the suction performance. A low NPSH means that the pump is able to deliver with high capacity throughout the whole pumping period, without cavitation.

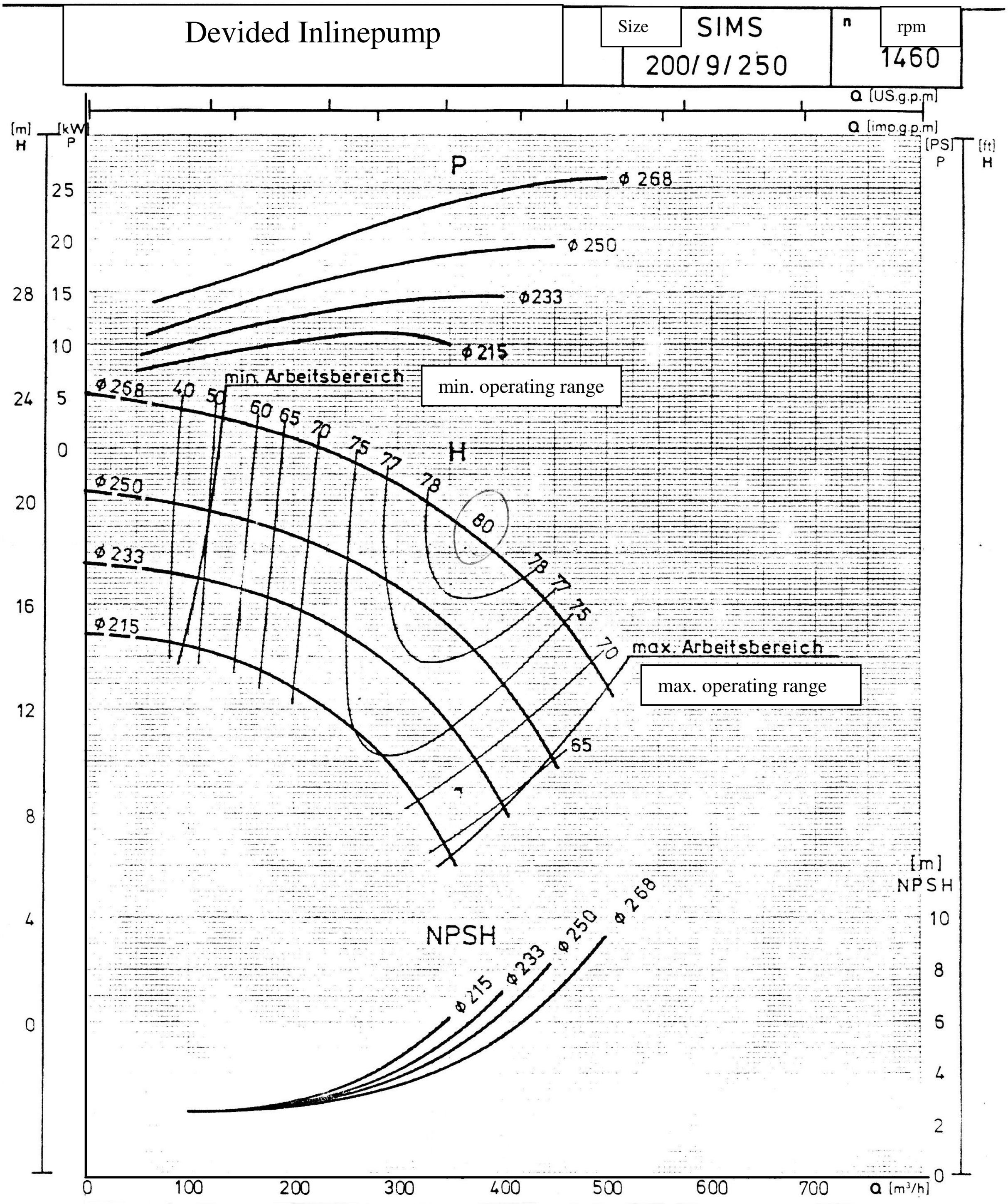


Illustration 31: Characteristic curve of a centrifugal pump

source: Svanehoj, Denmark

The pump type plate shows one of the infinite value pairs, e.g.

$\dot{V}$ = 200 m^3/h H = 25 m n = 1750 min^{-1}

The engineer assumed that after a long operating time the characteristic system curve would go through this point or intersects the characteristic pump curve.

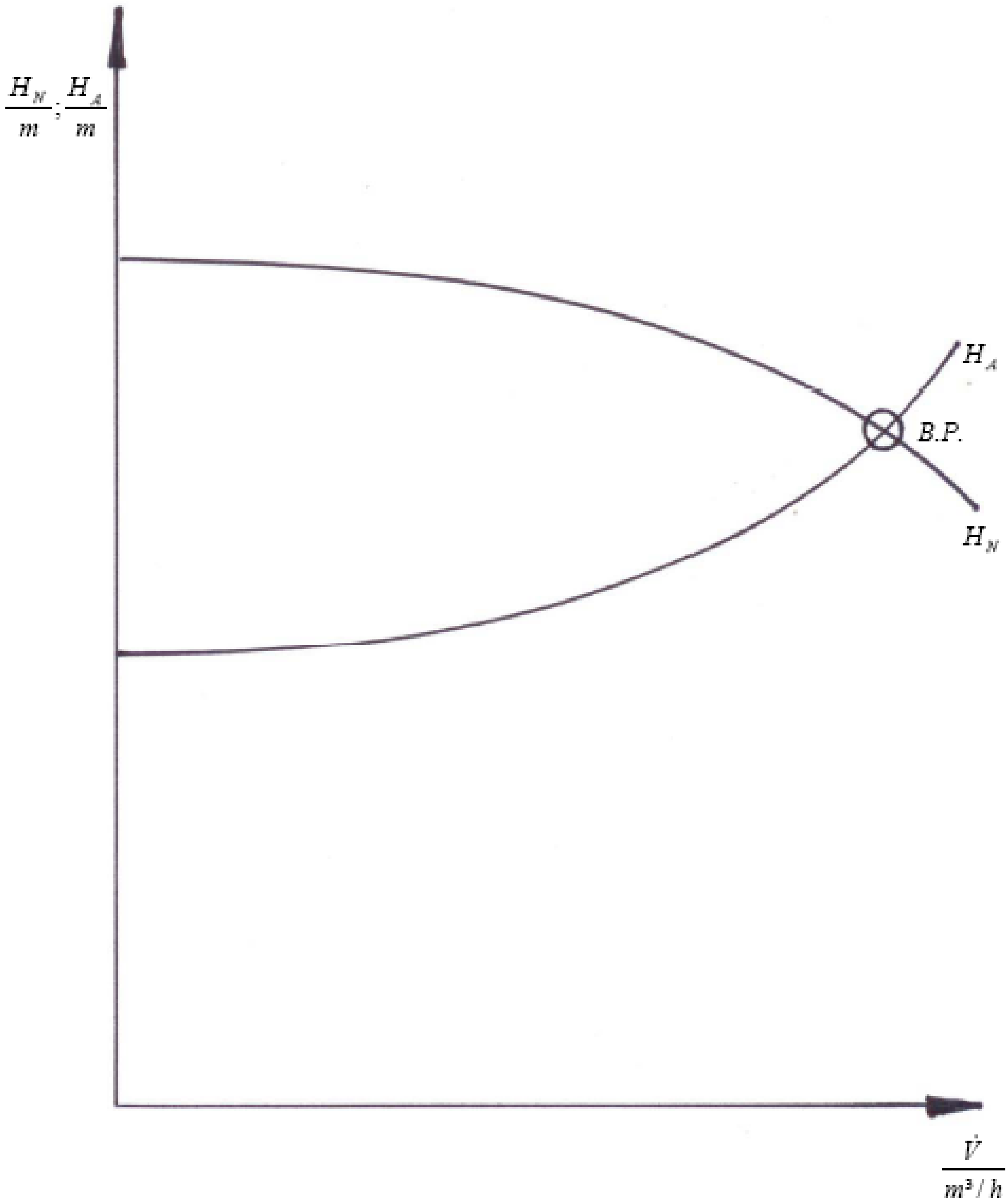


Illustration 32: Graphical determination of the operating point

The pump should be set for the operation mode with the most frequent occurrence as follows:

- $d_{impeller}$ ~ 5… 10% smaller as $d_{max.\ impeller}$
- the operating point should reach the best possible efficiency of the pump
- the operating point should be within[14] $\dot{V}_{tats} < \dot{V}_{\max}$ and $\dot{V}_{tats} > \dot{V}_{\min}$

Determining the operation point

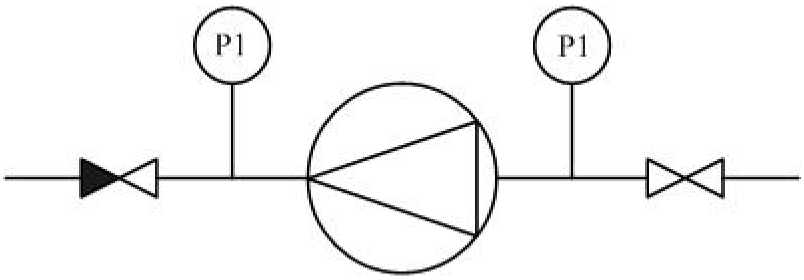


Illustration 33: Pump symbol

$$H_{Nutz} = \frac{P_D - P_S}{\rho \cdot g} + Z_{SD} + \frac{v_D^{\ 2} - v_S^{\ 2}}{2g} \quad \text{in} \quad m$$

$H_A = H_{Nutz}$ is in operation[15]

- H_{Nutz} is determined
- From H_{Nutz} on the ordinate of the characteristic pump curve a line which is parallel to the abscissa is drawn, which intersects the characteristic pump curve.
- From this intersection the perpendicular is dropped onto the abscissa; or a line is drawn parallel to the ordinate.
- On the abscissa the real flow rate can be seen.

[14] *tats.* stands for *actual*
[15] *Nutz* stands for *used* or *utilised*

Changes in the operation point

Changes in H_{geo} and/or H_p would cause the characteristic system curve to move parallel up or down. This would mean that the operation point on the characteristic curve moves to the left or right.

Causes for changes in H_{geo} are e. g.:

- tidal range during unloading
- fluid level changes in the tanks on board/ashore
- increase of resistance in the pipe system

The characteristic map (mussel diagram)

The abscissa $\dot{V}$ changes linearly; the ordinate H changes quadratically with the revolution speed. Calculated values for various revolution speeds or throttling curves are to be found on parables which have their vertices in the origin of ordinates. The lines of same efficiencies build closed, shell shaped curves. The efficiency should be constant along the parables. However, due to cavitation and hydraulic losses that are not following the quadratic law, these mussel-like lines are produced.

The optimum control

In order to influence the volume flow, controlling throttling and revolution speed is common. If control tasks are rare, the simple throttling control is used. Here, the valve is throttled on the pressure side of the pump. At frequent changes in volume flow the more economical revolution speed control is used. A power unit with variable revolution speed adjusts the revolution speed of the pump to the desired volume flow, so maximum efficiency is achieved.

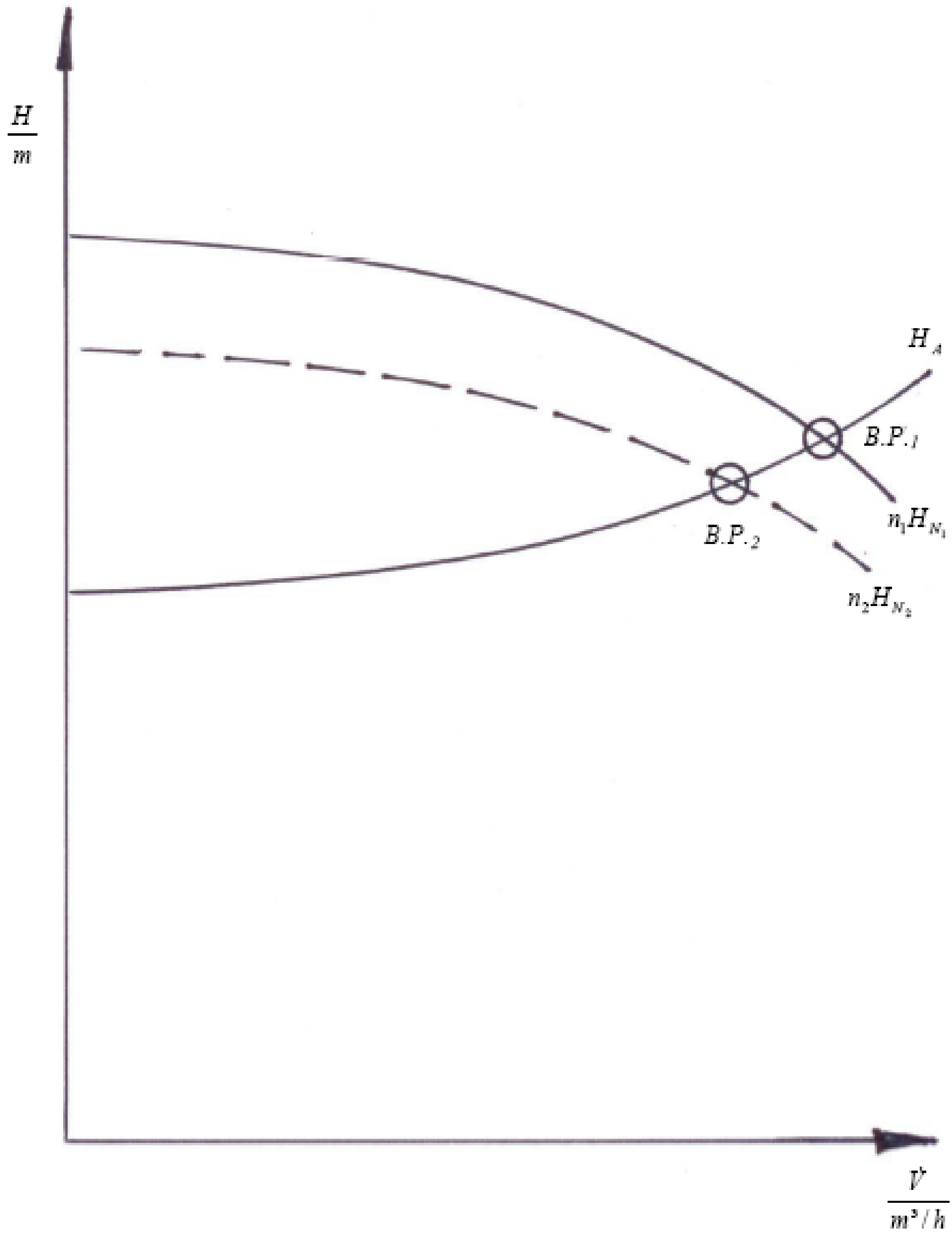


Illustration 34: Controlling revolution speed

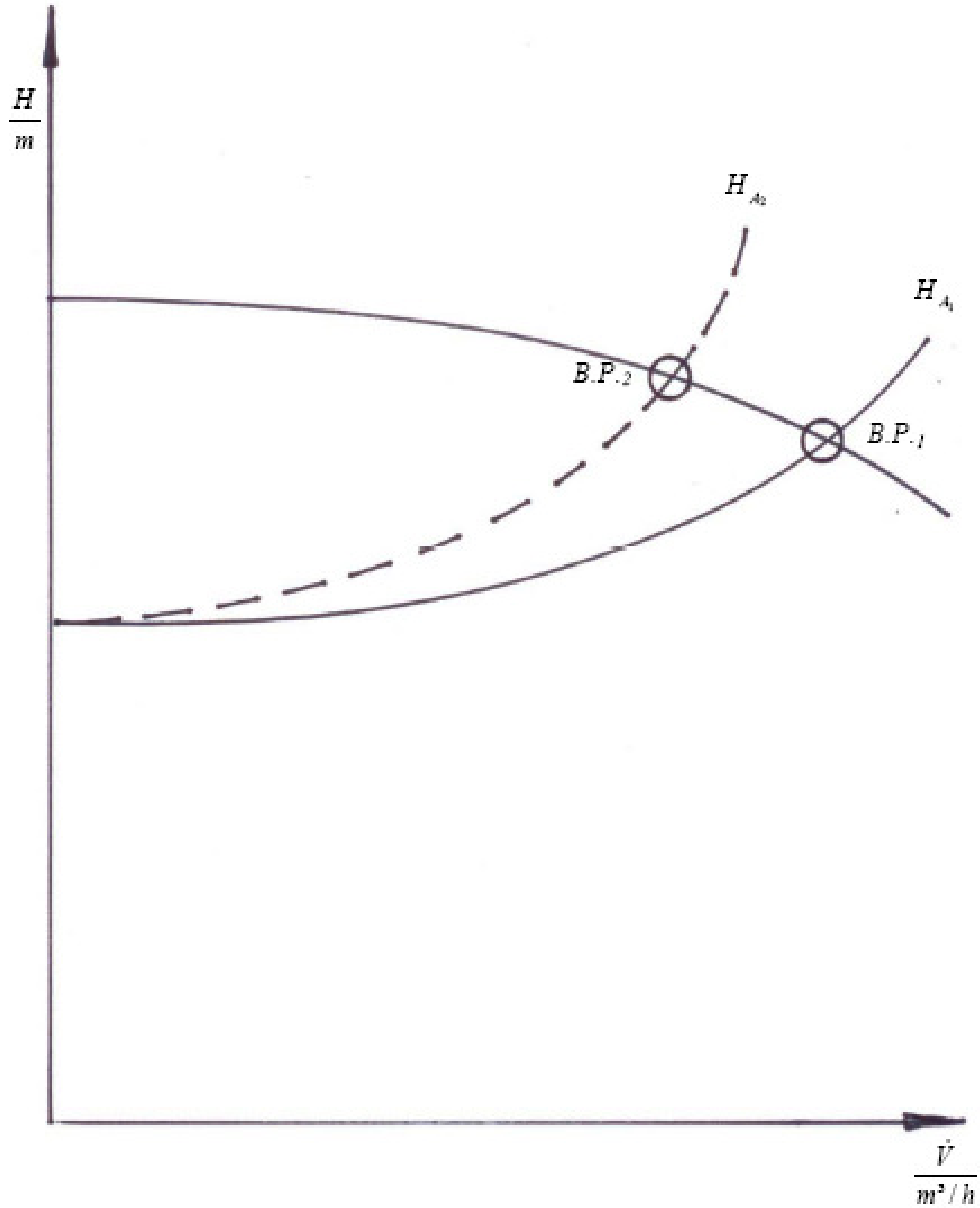


Illustration 35: Controlling throttling

Example:

Controlling throttling:

$n = 2700 \min^{-1}$

$\dot{V} = 26;\ 20;\ 16;\ 10\ m^3/h$

$H = 35;\ 40.2;\ 41.5;\ 425\ m$

$\eta_p = 49;\ 50;\ 45;\ 35\ \%$

$$P_{n26} = \dot{V} \cdot H \cdot \rho \cdot g = \frac{26}{3600} \cdot 35 \cdot 1000 \cdot 9{,}81 = 2479{,}75W$$

$$P_{26} = \frac{Pn}{\eta} \cdot \frac{2497{,}75W}{0{,}49} = 5{,}06kW$$

$P_{20} = 4.381kW$ $P_{16} = 4.02kW$ $P_{10} = 3.308kW$

Controlling revolution speed:

$P_{20} = 5.06\ kW$

$P_{20} \Rightarrow n \cong 2000 \min^{-1}$ $H = 19m$ $\eta = 51\ \%$

$P_{20} = 2.03kW$

$P_{16} \Rightarrow n \cong 1600 \min^{-1}$ $H = 12.5m$ $\eta = 50\ \%$

$P_{16} = 1{,}09kW$

$P_{10} \Rightarrow n \cong 1000 \min^{-1}$ $H = 4m$ $\eta = 47\ \%$

$P_{10} = 0.232kW$

	controlling throttling				controlling revolution speed			
$\dot{V}$ [m³/h]	26	20	16	10	26	20	16	10
H [m]	35	40.2	41.5	42.5	35	19	12.5	4
P [kW]	5.06	4.381	4.02	3.308	5.06	2.03	1.09	0.232

Table 13: Pump values during control of revolution speed and throttling

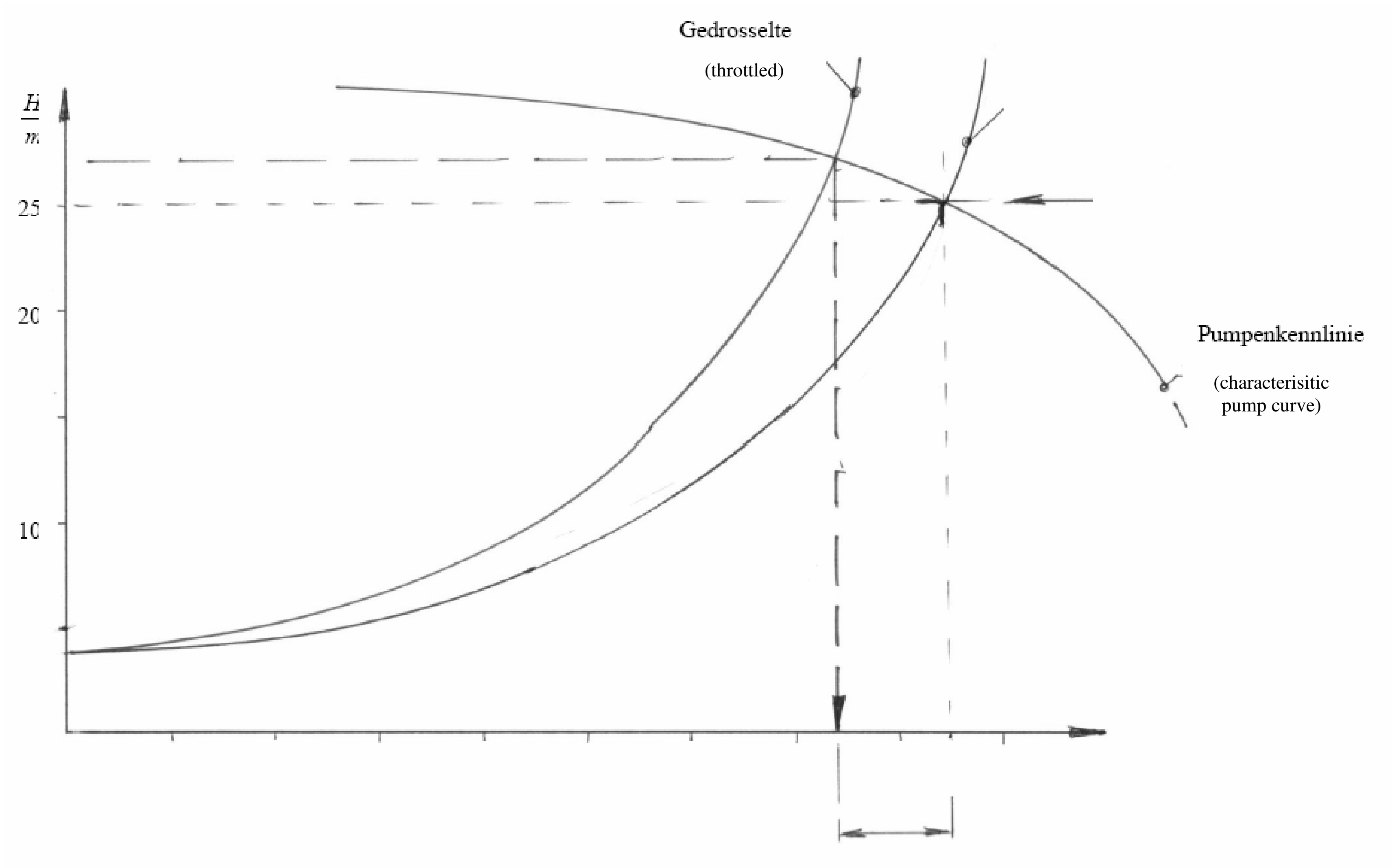


Illustration 36: Disadvantages of throttling control and increasing roughness of pipe work

5.2.2 Compressors and ventilators

Ventilators show the same relations as centrifugal pumps. Regarding compressors inter-coolers and after-coolers should be beneficial. A three-step compression is advantageous as the compression temperature can be lowered.

5.2.3 Separators

The separated sludge means a loss. For instance, the auxiliary boiler can be operated with unseparated heavy fuel oil. During the automatic cleaning process of the separator the drum should contain as little oil as possible before it is opened.

5.2.4 Heat exchangers

Soiling at the heat exchanger surfaces causes higher flow resistance. This would increase the pump head and therefore the power input of the pump. On the sea water side coolers should be fitted with filters that are cleaned when necessary.

5.2.5 Chillers and climate control units

The two important rules “never cool more than necessary” and “undercool as far as possible” should be considered. Throttling on the suction side of the compressor should be avoided. Regular defrosting is important in order to ensure good heat transfer at the evaporator.

5.2.6 Hydraulic and pneumatic systems

Bigger accumulators allow to switch off the driving system. If the volume flow is reduced for a short time, pressureless circulation is to be preferred to the safety circulation valve.

5.2.7 Pipework

Bending radii, zeta values of the fittings, filter dimensions, roughness of pipe walls, and driving speed influence the resistance level of the characteristic curve. Smooth inner walls and fully opened fittings as well as clean filters keep resistance low.

5.2.8 Converter supplied power for compressors, pumps and ventilators

Static converters are devices that use a net with constant voltage and frequency in order to generate a variable voltage and frequency that is used to supply 3-phase-current squirrel-cage motors. This allows a low-loss revolution speed control of 3-phase-current motors. Mainly U- and I-converters are available.

Voltage intermediate-circuit converters

On the net-side, U-converters feature a three phase diode rectifier bridge which charges a capacitor battery. Hence, a constant intermediate circuit voltage is available with the help of which the inverter generates the variable output voltage. This is done by pulsing the intermediate circuit voltage. In an output range of 50 kW U-converters are used almost exclusively.

Current intermediate-circuit converter

On the input side, I-converters feature a controlled rectifier bridge and a DC smoothing choke in the DC link. The inverter is built as thyristor bridge and consists of a series connection of thyristors and rectifier diodes. A current is fed to the engine. This converter is suitable for pumps and ventilators with $P > 50$ kW.

Engine room ventilators

Especially in partial load range of the engine the air volume can be reduced. Converter supplied ventilators ensure sufficient fresh air supply.

Compressor drives

By varying revolution speeds, chillers and climate control units can be efficiently adjusted to the coolness requirements.

Cooling water pumps

They are designed for tropical conditions with 32°C sea water temperature. If there is a lower temperature, the revolution speed the main sea water cooling pump can be lowered which would reduce the output. Controlling revolution speed by converters is a low-loss version.

5.2.9 Frequency regulation of the main sea water cooling pump

At P = 7500kW about 400 m^3/h sea water with a delivery height of 25 m and a pump efficiency factor of 0.8 are needed. The engine output is:

$$P_{32^\circ C} = \frac{400\frac{m^3}{h}\cdot 25m\cdot 9{,}81\frac{m}{s^2}\cdot 1020\frac{kg}{m^3}\cdot 1h}{3600\cdot 0{,}8\cdot 1000}$$

$$P_{32^\circ C} = 34{,}8kW$$

At a sea water temperature of 20°C it is possible to drive with a smaller sea water volume flow. This requires 200 m^3/h. When using throttling control the input comes to:

$$P_{20^\circ C_{Drosselr.}} = \frac{200\cdot 30\cdot 9{,}81\cdot 1020}{3600\cdot 0{,}6\cdot 1000} = 27{,}8kW$$ (Drosselr. = throttling control)

If a frequency regulator for the two main sea water cooling pumps is used, revolution speed control becomes possible.

$$P_{20^\circ C_{Drezahlr.}} = \frac{200\cdot 15\cdot 9{,}81\cdot 1020}{3600\cdot 0{,}8\cdot 1000} = 10{,}5kW$$ (Drehzahlr. = revolution speed control)

During a time period of 250 days and at a sea water temperature of 20°C or below, and even if only average savings of 50% are assumed, the following cost savings would be the result:

$$\Delta K_a = 17{,}4kW\cdot 0{,}2\frac{kg}{kWh}\cdot 24\frac{h}{d}\cdot 250\frac{d}{a}\cdot 0{,}85\frac{\$}{kg} = 17750\frac{\$}{a}$$

5.2.10 Engine room ventilator

The calculations are based on the assumption that engine room ventilation makes up about 10% of the overall electric demand of the sea operation. That would be 30 *kW*.

The need for air decreases

- with partial load at the main engine
- in zones colder than 45/32° C
- in the harbour.

In the harbour, the air volume can be reduced to about 1/3 of that of the sea operation, so to about 10kW. Calculating with 50 days in the harbour this would mean cost savings of

$$\Delta K_a = 20kW \cdot 0{,}2\frac{kg}{kWh} \cdot 24\frac{h}{d} \cdot 50\frac{d}{a} \cdot \frac{1t}{1000kg} \cdot 850\frac{\$}{t} = 4080\frac{\$}{a}$$

Also in this case, frequency regulation is the best technical solution.

5.3 Heat recovery systems

Illustration 37 shows that even diesel engines with maximum efficiency produce only 50-23% (depending on how it is looked at) of the generated energy to propulsion. The bigger part is released as heat energy via exhaust gases or sea cooling water to the environment. If it was possible to use part of this energy for propulsion, fuel consumption would decrease. Presently two options are technically possible:

- With the help of the exhaust gas boiler more steam is produced than it would be needed for heating the fuel. This steam is led into a steam turbine which generates electricity.
- Part of the exhaust gas that is not needed for steam production is used to power a gas turbine. Using a reduction gear unit it helps to power the propeller.

In both cases the efficiency of the whole system increases while fuel consumption decreases. For bigger main engines with two-stroke diesel engines turbo-generator-units and turbo-compound-systems are available. These achieve at MCR a 5% power increase at the shaft.

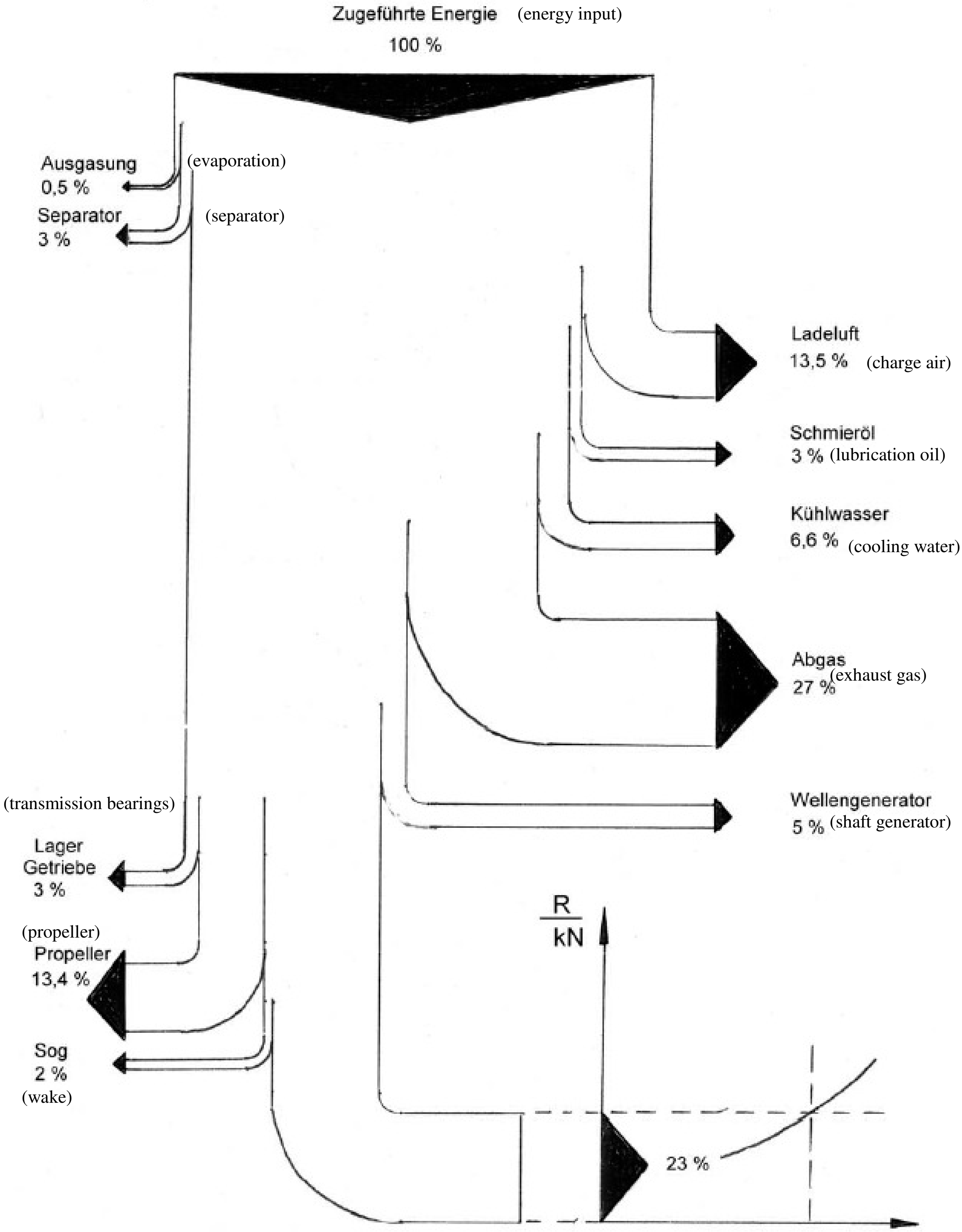


Illustration 37: Distribution of fed in energy

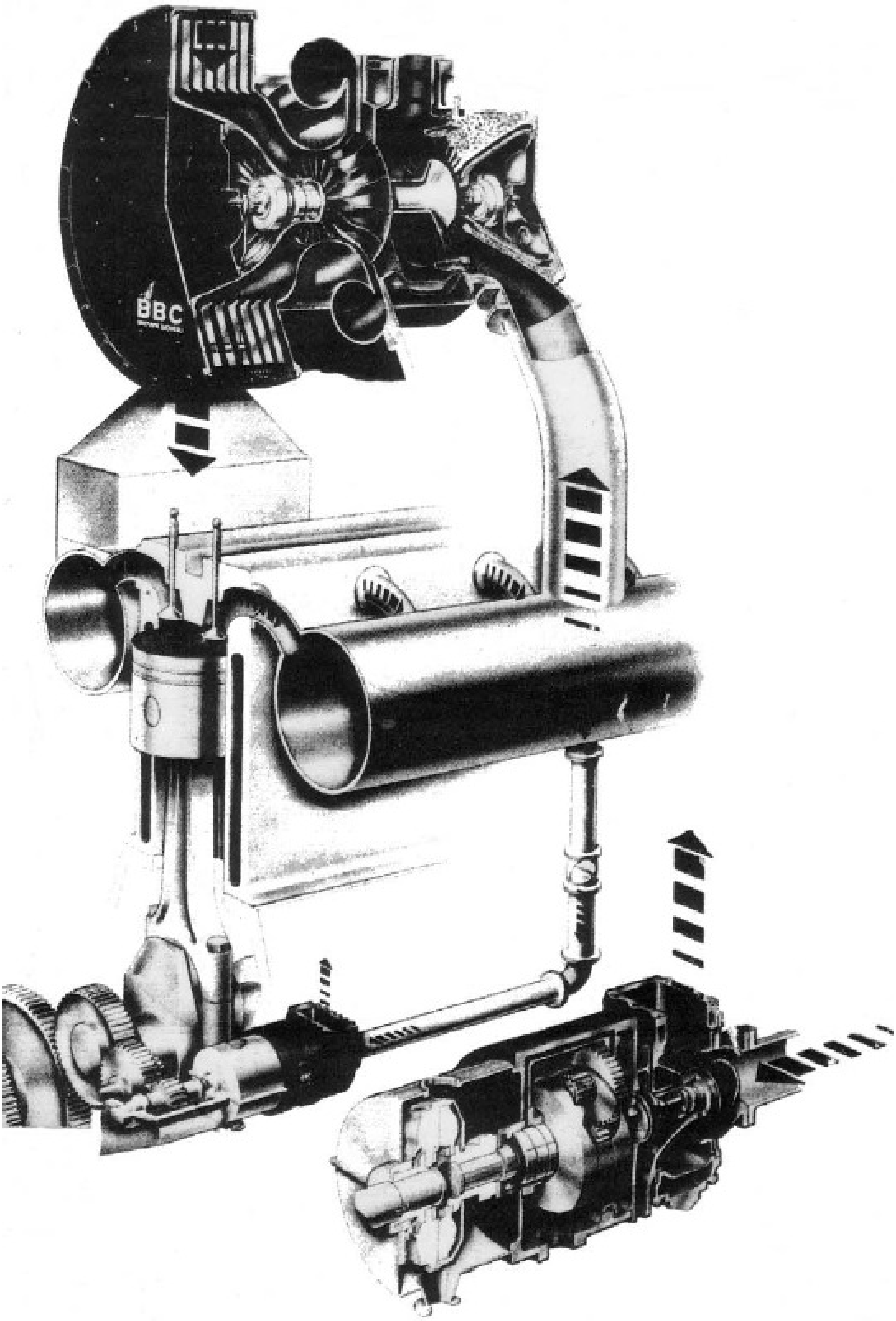


Illustration 38: Heat recovery

source: BBC

5.4 Switching to other fuel grades

A cheaper fuel grade can lower fuel costs. If a diesel engine is fitted, coal, LNG or LPG, nuclear energy, solar energy or wind power as alternative energy source are not an option. At the moment the only alternatives are refined palm oil, palm methyl esther and rape methyl esther. Whether a conversion is technically possible can only be decided by the engine manufacturer. And whether this would be economically viable has to be decided by the shipping company.

5.5 Improving propeller efficiency

Propeller efficiency is reduced by the surface roughness on the propeller, which can be caused by cavitation and/or chemical exposure. Surface roughness is mainly noticeable as increased torque take-up under otherwise similar conditions.

At average operation conditions and after an operating time of 5 years the propeller efficiency reduces by around 3%.

In order to assess surface roughness galvano-plastic surface normals are available. They allow a numerical recording and monitoring of the surface quality of machined surfaces through comparing visual and tactile data. These suface normals are available individually or in sets and for all kind of roughness conditions.

Instructions for use:

1. Each manufacturing process produces different surface structures which recording methods have to adapt to. On the back of the sets notes can be found that should be considered carefully.
2. Both the normal and the to be tested surface should be carefully cleaned with a soft cloth. The cloth should be wiped in a motion that is parallel to the surface grooves; exceptions can be made for surfaces that were produced with methods like cross sanding, sandblasting or spark erosion.
3. Usually (albeit not always) a reliable method is to compare the surface by testing with the fingernail. Before touching the surface, the tip of the fingernail has to be cleaned

thoroughly because even the smallest dust particles can act as an abrasive. If used with medium pressure, the fingernail alone does not damage the surface.

4. Now the fingernail is lead several times crossways over the to be tested surface.
5. The same fingernail then has to be led over the surface normals which have been arranged in the order of the grade of roughness. Here, it is important to use the same pressure and speed, and to go across the surface grooves. If no normal can be found that matches the roughness of the tested material, the nearest matching normal determines the measured value.
6. For roughness values that are lower than Ra 0.1/µm(Rt about 1/µm; Rp about 0.2/µm) the diameter of a fingernail is too big. More reliable test results can be achieved if a small copper disc (1-Cent coin) is used with very low pressure. Also having a close look at the surface and the normal is advisable to draw a comparison.
7. Reliable results can only be achieved if the to be tested surface is compared to normals that have been produced using the same manufacturing process. Comparing for instance turned material with a grinded normal would be totally worthless because the outcome would be false test results. Therefore the whole test method would be devalued.

Each individual surface normal is marked with its specific surface value and nominal roughness in µm. In addition, the effective value is noted. The effective values do usually not deviate more than ±10% from the nominal values.

Fingernail and eye notice the distance between grooves and the radius of curvature of the roughness peaks, but not the groove depth. The accuracy of comparison therefore depends on the relation of groove distance and groove depth. If this relation is almost constant (e.g. sanding), the tactile test values only show low deviations (around ± 20% to 30%). Periodic profiles (e.g. turning) would show a still sufficient accuracy of ± 40% to 60%.

Light reflection and shine of a surface are often misleading, so that roughness values are assessed wrongly. Therefore, it is advisable to only use visual comparison in connection with tactile tests.

PROPELLER ROUGHNESS

The Rubert comparator scale consists of 6 specimens, A, B, C, D, E & F which are exact replicas of the surface roughness of propeller blades.

Specimens A & B are replicas of the surface roughness of new or reconditioned propeller blades to be used as a standard for comparison with similar surface roughness taken from propellers eroded by periods of service, since propeller efficiency deteriorates in time due to the increasing surface roughness and also with the growth of marine fouling. Specimens C, D, E & F can be used to assess and report upon the propeller blade surface condition after periods of service.

Propellers in service should be examined frequently and any fouling removed as soon as it is noticed.

After cleaning, the surface condition should be checked using the comparator and the roughness recorded.

The propeller should be repolished if the roughness exceeds the maximum allowable in FIG. 1

PROPELLER INSPECTION & REPAIR

The outer half radius of the blade should be maintained at or near-equal to specimen B. Surfaces which have been generally roughened to D, E or F can be restored to near B by the use of 36 grit discs, followed by 80 grit discs.

Surfaces approximating to C should respond to 80 grit without the need to employ a 36 grit disc. Hand polishing should be done in the direction of the water flow.

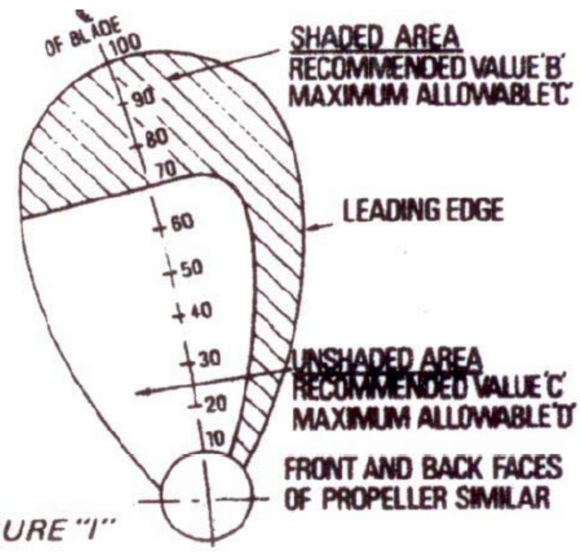


FIGURE "I"

Illustration 39: Blade inspection

Note: Take care when polishing not to change the profile of the propeller blade edge, particularly the leading edge. Seek the advice of the propeller manufacturer or his agent if the leading edge is eroded or damaged. Cavitation erosion is usually localised and, in its more severe forms can be seen as roughening several millimetres in depth and occasionally penetrating through the blades. This type of attack, unless of a minor nature, will not be improved by the use of grinding discs. Almost inevitably it will require cutting to solid metal to produce a smoother base for welding. Contact the propeller manufacturer or his accredited agent. It is essential to carefully examine the area forward of the cavitation for signs of unfairness, perhaps due to previous inexpert repair work and to look particularly for leading edge damage or distortion. The use of plastic epoxy fillers to fill cavitation erosion is of little benefit as its life is very limited.

The table below shows the mean values of the parameters Ra and Rz represented by the specimens A, B, C, D, E and F derived from 10 measurements from each specimen surface, 5 longitudinal and 5 transverse.

SPECIMEN	Ra (CLA)		Rz	
	Micrometre	Microinch	Micrometre	Microinch
A	0.65	26.0	5.0	200.0
B	1.92	76.8	12.0	480.0
C	4.70	188.0	32.0	1280.0
D	8.24	329.6	51.0	2040.0
E	16.6	664.0	97.0	3880.0
F	29.9	1196.0	154.0	6160.0

DEFINITIONS:–

Ra—The arithmetical mean of the absolute values of the profile departure within the sampling length.

Rz—The average value of the absolute values of heights of five maximum profile peaks and the depths of five maximum profile valleys within the sampling length.

Table 14: Propeller roughness

source: manufacturer notes

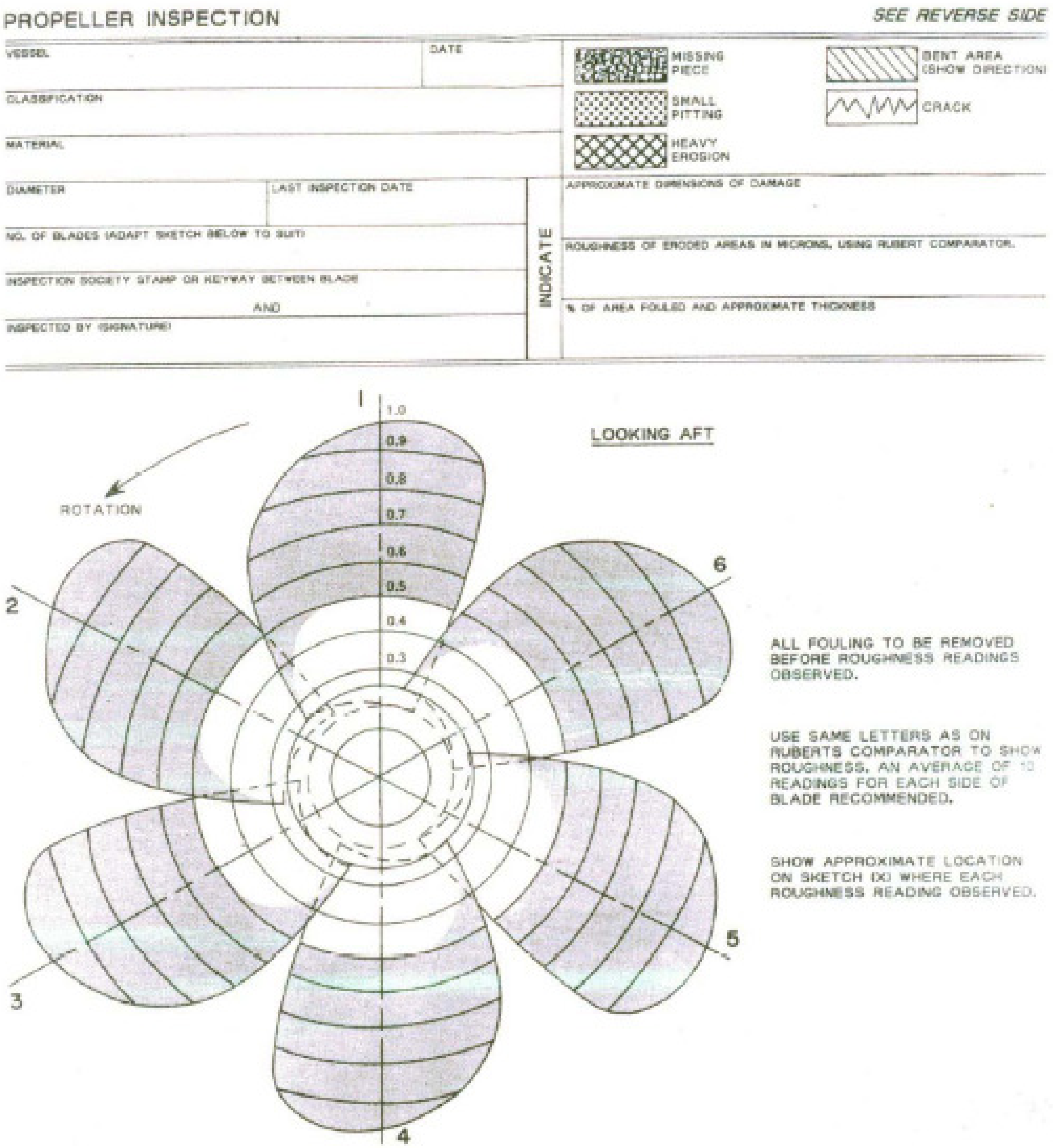


Illustration 40: Propeller inspection

source: manufacturer notes

RESULTS OF INITIAL PROPELLER INSPECTION

BLADE NUMBER		1	2	3	4	5	6
MAXIMUM ROUGHNESS	SHADED						
	UNSHADED						
AVERAGE ROUGHNESS	SHADED						
	UNSHADED						

Table 15: Measurement sheet of the propeller

The propeller manufacturer can possibly improve propeller efficiency by redesigning the shape of the blades, changing the diameter and average pitch.

The two ferries "Stena Germanica" and "Stena Scandinavia" were operating with pitch propellers for 20 years.

In 2006, the propeller blades were renewed with the aim to save fuel. After tests, Kamewa blades were fitted. In comparison to the old blades, fuel savings of 10% were achieved.[16]

[16] source: Marine Propulsion 02/03 2006; p. 63

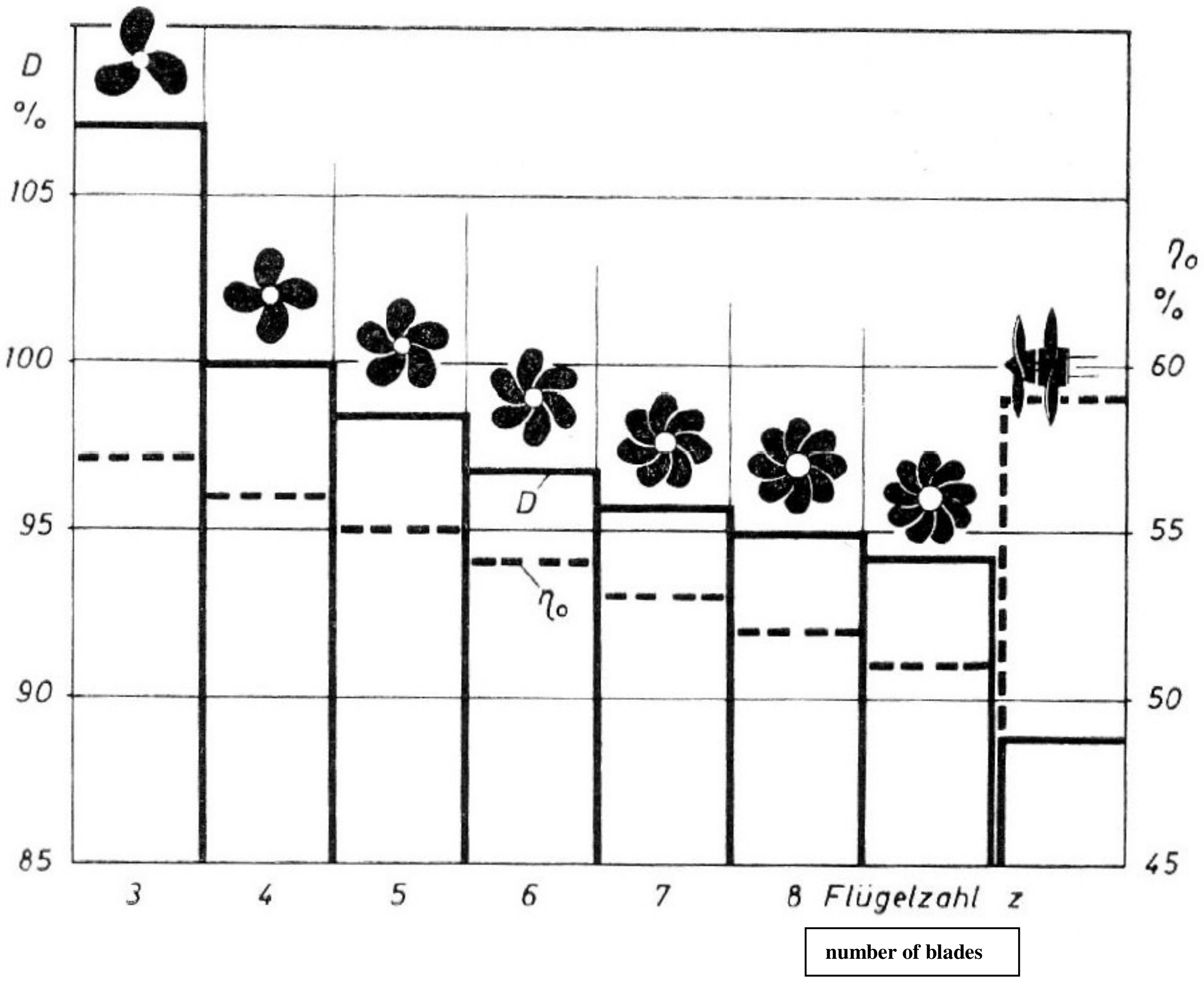


Illustration 41: Propeller efficiency and diameters in dependence of the numbers of blades

source: year book of the German Society for Maritime Technology 1969; p.145

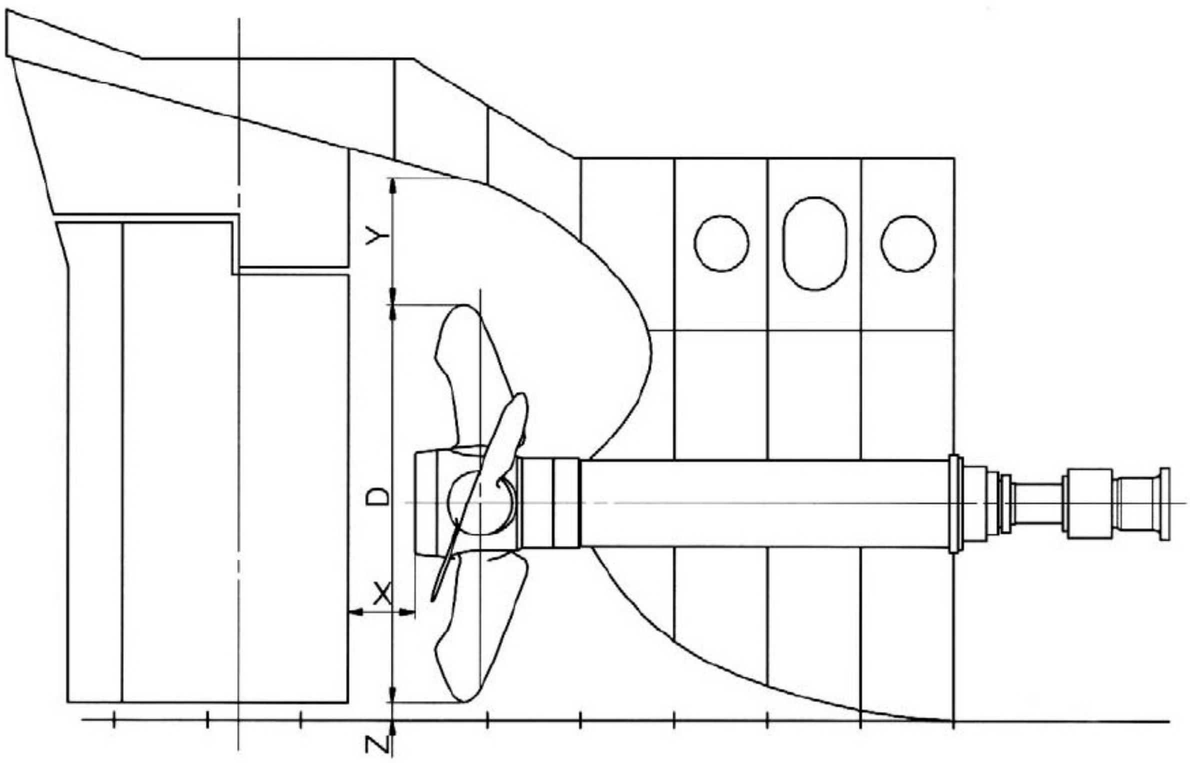


Illustration 42: Propeller clearance that enables an almost vibration free rotation of the propeller

source: B & W Alpha, Product Information, CP Propeller Equipment, p.19

x depends on the dimensions of the hood

y should be 20 … 25% of D

Z = 50 … 100 mm

5.6 The influence of wind

If only the superstructure with wind from ahead is considered, the necessary power to overcome it can be calculated as follows:

area that is exposed to wind	A	=	$26.4m \times 19.7m = 520\ m^2$
relative wind speed of the “apparent wind”	υ	=	$8\ m/s$
wind power coefficient	c_{ah}	=	0.8 0.85
air density	ρ	=	$1.226\ kg/m^3$

$$W = c \cdot A \cdot \rho \cdot v^2$$

$$W = 0{,}85 \cdot 520m^2 \cdot 1{,}226\frac{kg}{m^3} \cdot \left(8\frac{m}{s}\right)^2$$

$$W = 34680\ N$$

The necessary power is:

$$P = F \cdot v = 34680N \cdot 8\frac{m}{s} = \underline{277{,}5kW}$$

The speed of the ”apparent wind” was calculated with 8m/s, which is equivalent to still air. If the wind is blowing from ahead with $v > 0m/s$, the engine output is increased accordingly. There have already been shipping companies that reduced this resistance by using a spoiler.

5.7 Generating electricity

Shaft generators on ships are generators that are powered by the main engine and that supply the onboard electricity network. Two different systems are possible:

- f ~ n of the propeller shaft; the shaft generator produces a frequency that is proportional to the revolution speed of the main engine.
- Independent from the revolution speed of the main engine, the frequency is held constant within a wide range.

In the first variant, it is only possible to generate electricity if a constant revolution speed and therefore ship speed is held, if a pitch propeller is in use, or if a pitch propeller with constant revolution speed and variable pitch can be used.

In the second variant, the systems are operating in a speed range of 60 … 100% of the nominal revolution speed.

Using SG-systems is economic. The advantages of this system are:

- A decrease of fuel costs if MFO instead of MDO is used
- A reduction of maintenance costs and lubrication oil costs due to shorter runtimes of diesel gensets
- A simplification of the onboard network
- Low-noise energy generation
- The effective efficiency of the main engine is higher than that of auxiliary diesel engines.

Slip frequency

The classification society allows a frequency deviation of ± 5%. So instead of 60 *Hz* it can be operated with 58 *Hz*. The slip frequency exponent is to be 2.

When reducing the onboard frequency from 60 to 58 *Hz* the output in sea operations can be reduced to

$$P = P_{Nenn} \cdot \frac{f_X}{f_N} = 300kW \cdot \left(\frac{58}{60}\right)^2$$

$$P_{58Hz} = 280kW$$

If using a specific fuel consumption of 0.2 *kg/kWh* in calculations and if 200 days at sea are assumed, the following savings can be achieved:

$$\Delta m_{Krst_a} = 20kW \cdot 0{,}2\frac{kg}{kWh} \cdot 24\frac{h}{d} \cdot 200\frac{d}{a} \cdot \frac{1t}{1000kg}$$

$$\Delta m_{Krst_a} = 19{,}2\frac{t}{a}$$

$$\Delta K_a = 19{,}2\frac{t}{a} \cdot 850\frac{\$}{t}$$

$$\Delta K_a = 16320\frac{\$}{a}\ \text{Ersparnis}$$

(Ersparnis = savings)

Before disconnecting a large electricity consumer, the frequency should be shortly increased to 60 *Hz* in order not to cause a black-out.

Installing a phase shifter

On 200 days at sea at 320 *kW* with cos $\varphi = 0.8$ the efficiency factor shall be improved to 0.95 by using capacitor batteries which would reduce fuel consumption.

With cos $\varphi_I = 0.8$

$$I_1 = \frac{P}{U \cdot \cos\varphi_1 \cdot \sqrt{3}} = 513A$$

$$S_1 = U \cdot I_1 \cdot \sqrt{3} = 400kVA$$

With cos $\varphi_I = 0.95$

$$I_2 = \frac{P}{U \cdot \cos\varphi_2 \cdot \sqrt{3}} = 456A$$

$$S_2 = U \cdot I_2 \cdot \sqrt{3} = 355kVA$$

$$\Delta S = 45\ kVA$$

Installing a phase shifter would reduce costs to:

$$\Delta K_a = 45kVA \cdot 0{,}2\frac{kg}{kWh} \cdot 24\frac{h}{d} \cdot \frac{1t}{1000kg} \cdot 850\frac{\$}{t} \cdot 200\frac{d}{a} = \underline{\underline{36720\frac{\$}{a}}}$$

5.8 Shore side power supply

In the harbours it is thought about the question whether shore side power supply could be useful for seagoing ships. It is thought that during their stay in the harbour ships could be supplied economically and environmentally friendly with electricity from the local medium voltage network.

Whether this is economically viable can only be shown through comparative calculations.

Seagoing ships usually operating on their trade in North Sea and Baltic Sea with a board network of 400Volt/50Hz, would need to be retrofitted with cables, plugs, controllers and circuit breaking transformers. Ships with an onboard-network of 450Volt/60Hz also need to be fitted with a DC intermediate circuit and a frequency generator downstream.

In addition to the costs of the supplied kWh, costs arise for the connection, maintenance and technical monitoring.

In Lübeck facilities for three Ro-Ro-ships have been put into operation.[17]

In May 2006, the European Commission included the “recommendation of the promotion of shore-side electricity for use by ships at berths in EU ports” in their work programme.

[17] First shore side power supply in operation in Lübeck, Schiff und Hafen No. 07/08; page 22

6 Managing the ship

Through an adjusted management fuel can be saved without any investment.

A study by the Newcastle University on behalf of the Department for Transport, UK, ED 05465, Issue 3, March 2007 shows the following savings:

area	savings in %	Potential savings through combined measures in %
transport management	5 … 40	1 …40
weather routing	2 … 4	
„Just in time“ strategy	1 … 5	
constant engine revolution speed	0 … 2	

Table 16: Potential savings
source: Newcastle University, report fort he Department for Transport

6.1 Fleet management

Effective planning and management of a fleet can reduce fuel consumption by 5% to 40%.[18] Ballast trips or partly loaded only as well as arriving too early in the harbour should be avoided in order to reduce fuel consumption. However, findings are difficult to prove.

[18] IMO, Study of greenhouse gas emissions from ships, Issue 2, March 2000

6.2 Weather routing

Illustration 43 shows daily consumption under various weather conditions, variable vessel speed and present condition of the under water hull.[19]

bad weather, (rough under water hull)	
$v[kts]$	$\dot{m}_{Krst_d}[t/d]$
13.5	**32.5**
13	**27.5**
12	**20.4**
11	**15**
10	**11.5**
9	**8.5**
8	**6.2**

Table 17: Fuel consumption under bad weather conditions

[19] Krst. = fuel

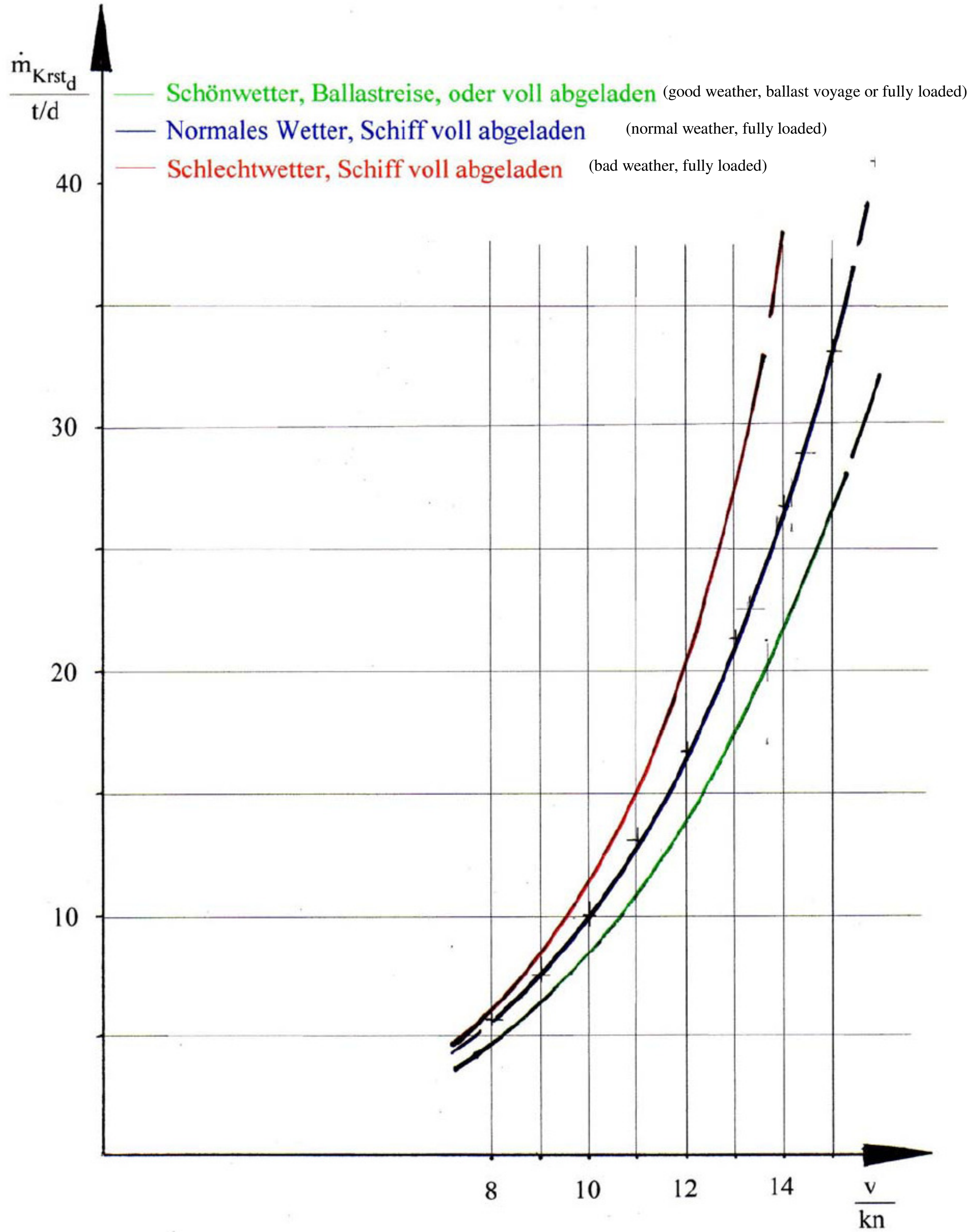


Illustration 43: Daily fuel consumption in connection with weather conditions

normal weather	
$v[kts]$	$\dot{m}_{Krst_d}[t/d]$
15	**33.2**
14	**26.7**
13	**21.4**
12	**16.7**
11	**13.1**
10	**10.0**
9	**7.6**
8	**5.7**

Table 18: Fuel consumption under normal weather conditions

good weather	
$v[kts]$	$\dot{m}_{Krst_d}[t/d]$
15	**26.9**
14	**21.8**
13	**17.3**
12	**13.8**
11	**11.0**
10	**8.5**
9	**6.3**
8	**4.7**

Table 19: Fuel consumption under good weather conditions

Normal weather conditions

For the duration of the whole voyage the vessel speed is:

$$\upsilon_{\phi} = \frac{\Delta s}{\Delta t} = \frac{3000sm}{220h} = \underline{\underline{13{,}64\frac{sm}{h}}}$$

According to illustration 43, daily fuel consumption under these weather conditions are[20]:

$$\dot{m}_{Krst_d} = 24{,}8\frac{t}{d}$$

$$\dot{m}_{\mathrm{Reise}} = 24{,}8\frac{t}{d} \cdot \frac{220h \cdot d}{24h} = \underline{\underline{227{,}3\frac{t}{\mathrm{Re}\,ise}}}$$

Bad weather conditions

On her voyage the ship is going to pass through an area of bad weather starting 3 days after she has left the port.

What speed should the vessel do in order to:

- meet the given time of arrival after 220 hours?
- consume the minimum amount of fuel?

After three days at sea under normal weather conditions and with a speed of v = 13.64 *nm/h* a distance of s = 982 *nm* has been sailed. The remaining distance is s_{rest} = 3000 *nm* – 982*nm* = 2018*nm*. It is planned to pass the bad weather area with a maximum fuel consumption of 25 *t/d* at a corresponding speed of v = 12.6 knots.

$$\Delta s_{bad\ weather} = 2d \cdot 24\frac{h}{d} \cdot 12{,}6\frac{sm}{h} = 604sm$$

The remaining distance is:

3000*nm* – 982*nm* – 604 *nm*

Δs_{rest} = 1414*nm*

[20] Reise = voyage

The necessary speed to arrive after 220 hours is[21]:

$$\upsilon_{Rest} = \frac{1414sm}{220h - 3 \cdot 24h - 2 \cdot 24h} = 14{,}14\frac{sm}{h}$$

For this speed 27.5 *t/d* fuel is consumed every day.

υ $[kn]$	weather conditions	s $[sm]$	t $[h]$	$\dot{m}_{Krst_d}$ $[t/d]$	consumption $[t]$
13.64	**normal**	**982**	**72**	**24.8**	**74.4**
12.60	**bad**	**604**	**48**	**25.0**	**50.0**
14.14	**normal**	**1414**	**100**	**27.5**	**114.6**
$\sum$**:**		**3000**	**220**		**239**

Table 20: Fuel consumption during a voyage under partly bad weather conditions

Fuel consumption is to be reduced under same weather conditions. Therefore, on the first three days at sea, the vessel is operating at a speed of v = 13.9 knots. In the bad weather area it is operating with 12.6 knots. The following distance is covered:

$$s_1 = 3d \cdot 24h \cdot 13{,}9\frac{sm}{h} = 1001sm$$

$$s_2 = 2d \cdot 24h \cdot 12{,}6\frac{sm}{h} = 604sm$$

$$s_{Rest} = 3000sm - 1001sm - 604sm$$

$$s_{Rest} = 1395sm$$

The speed to be sailed with on the remaining distance is:

$$\upsilon_{Rest} = \frac{1395sm}{100h} = 13{,}95\frac{sm}{h}$$

25.9 *t/d* fuel would be consumed per day.

[21] sm = nautical mile, nm

υ $[kn]$	**weather conditions**	s $[sm]$	t $[h]$	$\dot{m}_{Krst_d}$ $[t/d]$	**consumption** $[t]$
13.90	**normal**	**1001**	**72**	**25.8**	**77.4**
12.60	**bad**	**604**	**48**	**25.0**	**50.0**
13.95	**normal**	**1395**	**100**	**25.9**	**107.9**
$\sum$**:**		**3000**	**220**		**235.3**

Table 21: Reduced fuel consumption

Further optimisations could be made by going slightly slower through the bad weather area. Before and after, the same speed should be kept in order to arrive after 220 hours. Further possible reductions would then be <–1*t/voyage*.

Good weather

If there is a good weather area on the voyage, the same procedure can be applied, which would decrease fuel consumption.

Example:

distance: s = 3000 nautical miles

duration t = 220 hours, without ”river steaming”

We assume seven days with normal weather conditions, the rest of the time is “good weather”. What speed should the vessel be doing and what is the fuel consumption on her voyage?

$$\upsilon_{\phi} = \frac{\Delta s}{\Delta t} = \frac{3000sm}{220h} = 13{,}64\frac{sm}{h}$$

According to illustration 43, the daily fuel consumption for the seven days under normal weather conditions is:

$$\dot{m}_{Krst_d} = 24{,}8t/d.$$

The remaining time of 220*h* – 7x24*h* =52*h* is done with the same speed in good weather with a daily fuel consumption of 20.3 *t/d*.

v $[kts]$	weather conditions	s $[nm]$	t $[h]$	$\dot{m}_{Krst_d}$ $[t/d]$	consumption $[t]$
13.64	**normal**	**2291**	**168**	**24.8**	**173.6**
13.64	**good**	**709**	**52**	**20.3**	**44.0**
$\sum$ **:**		**3000**	**220**		**217.6**

Table 22: Reduced fuel consumption under good weather conditions

Adjusting daily consumption depending on weather conditions can save a certain amount of fuel during this voyage. The lower engine output resulted in lower consumption in the area of good weather.

Avoiding an area of bad weather

Is it worth it to avoid an area of bad weather?

The assumed distance is again $s = 3000nm$ and the duration $220h$. There is also an area of bad weather that could be passed through at $v = 13.64$ knots within two days.

Extension of the bad weather area: $2d \cdot 24\frac{h}{d} \cdot 13{,}64\frac{sm}{h}$

$s_{\text{bad weather}} = 654nm$

According to illustration 44 the following equation applies:

$$Y = \frac{327sm}{\sin 30°} = 654sm$$

$$x = \frac{327sm}{\tan 30°} = 566sm$$

The circular arc length is:

$$\frac{b}{d \cdot \pi} = \frac{\alpha}{360^\circ}$$

$$b = \frac{60^\circ \cdot 654sm \cdot \pi}{360^\circ}$$

$$\underline{b = 342sm}$$

The total distance can be calculated as follows:

normal distance:	3000 *nm* – 2 x 654 *nm*	= 1692 *nm*
2 x x:	2 x 566 *nm*	= 1132 *nm*
circular arc:	342 *nm*	= 342 *nm*
total distance:		= 3166 *nm*

The added distance is 166 *nm*.

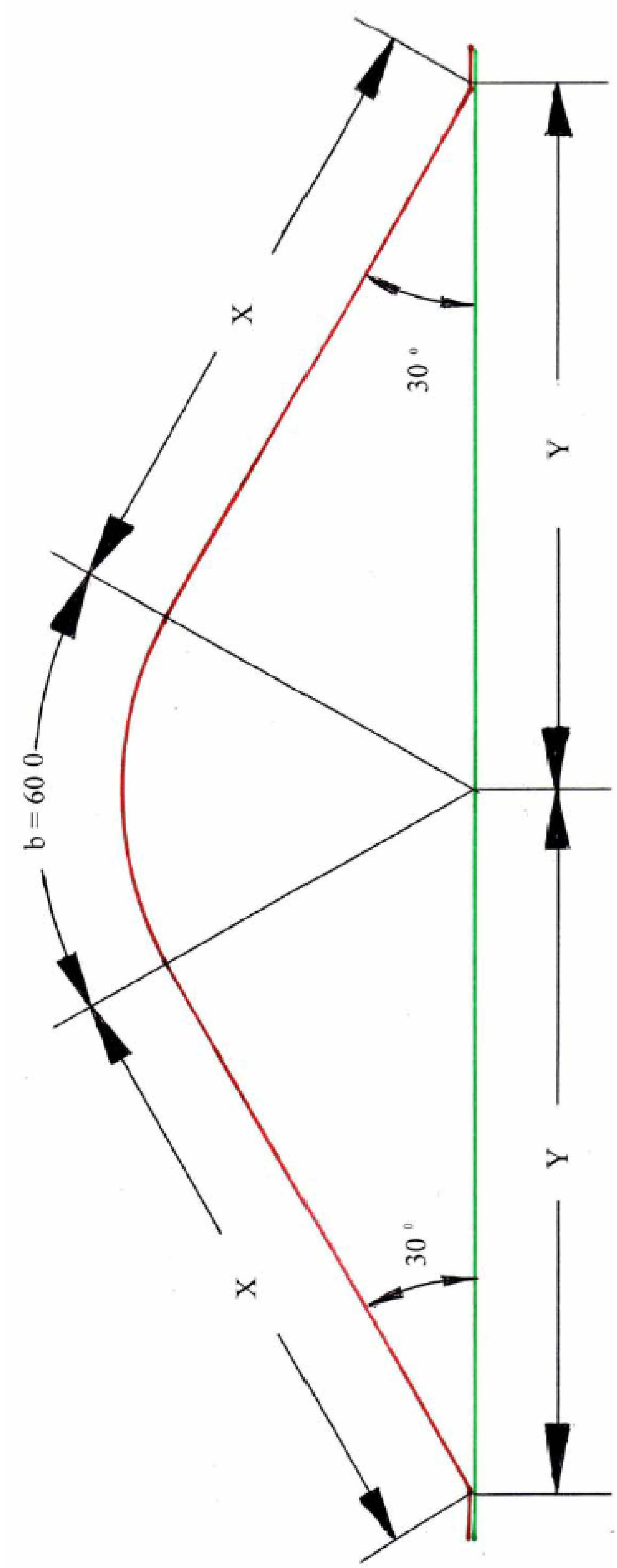


Illustration 44: Avoiding an area of bad weather

In order to reach the destination after 220h without "river steaming", the following speed needs to be applied:

$$\upsilon\phi = \frac{\Delta s}{\Delta t} = \frac{3166 sm}{220 h} = 14{,}4 \frac{sm}{h}$$

Under normal weather conditions and with a speed of 14.4 knots, a daily fuel consumption of 28.8 *t/d* would be the result.

The fuel consumption for the whole voyage would then be:

$$\dot{m}_{\mathrm{Reise}} = \dot{m}_{Krst_d} \cdot t = 28{,}8 \frac{t}{a} \cdot \frac{220h \cdot d}{24h}$$

$$\dot{m}_{\mathrm{Reise}} = 264{,}0 \frac{t}{\mathrm{Reise}}.$$

Passing through the area of bad weather would result in a fuel consumption of "only" 239*t* for the whole voyage. Regarding a relatively short total distance of 3000*nm*, it would not be worth it to avoid the area of bad weather and accept a further distance of 166*nm*. Only if the weather is very bad and the ship is operating with a speed lower than 12.6*nm/h*, it may become economically sensible.

6.3 Fair current and head current

The following illustration shows the influence of ocean current on a change of vessel speed over ground at the same speed through the water. The vector labelled with v_{Schiff} (= v_{ship}) illustrates the desired speed and course of the ship over ground. At a current of v_{s_1} the ship can reduce the speed through water by the amount of ΔvG, in order to keep the desired speed over ground. At a current of v_{s_2} the ship has to increase the speed by the amount of ΔvV, in order to keep the desired speed over ground. The current v_{s_3} ends on the neutral circular arc and does not change consumption. All current vectors that point into the circle with the radius v_{ship}, reduce fuel consumption. If the current vector points outside the circle, fuel consumption is increased. Regarding a lateral current vector, like v_{s_3}, rudder has to be controlled accordingly, which results in increased friction.

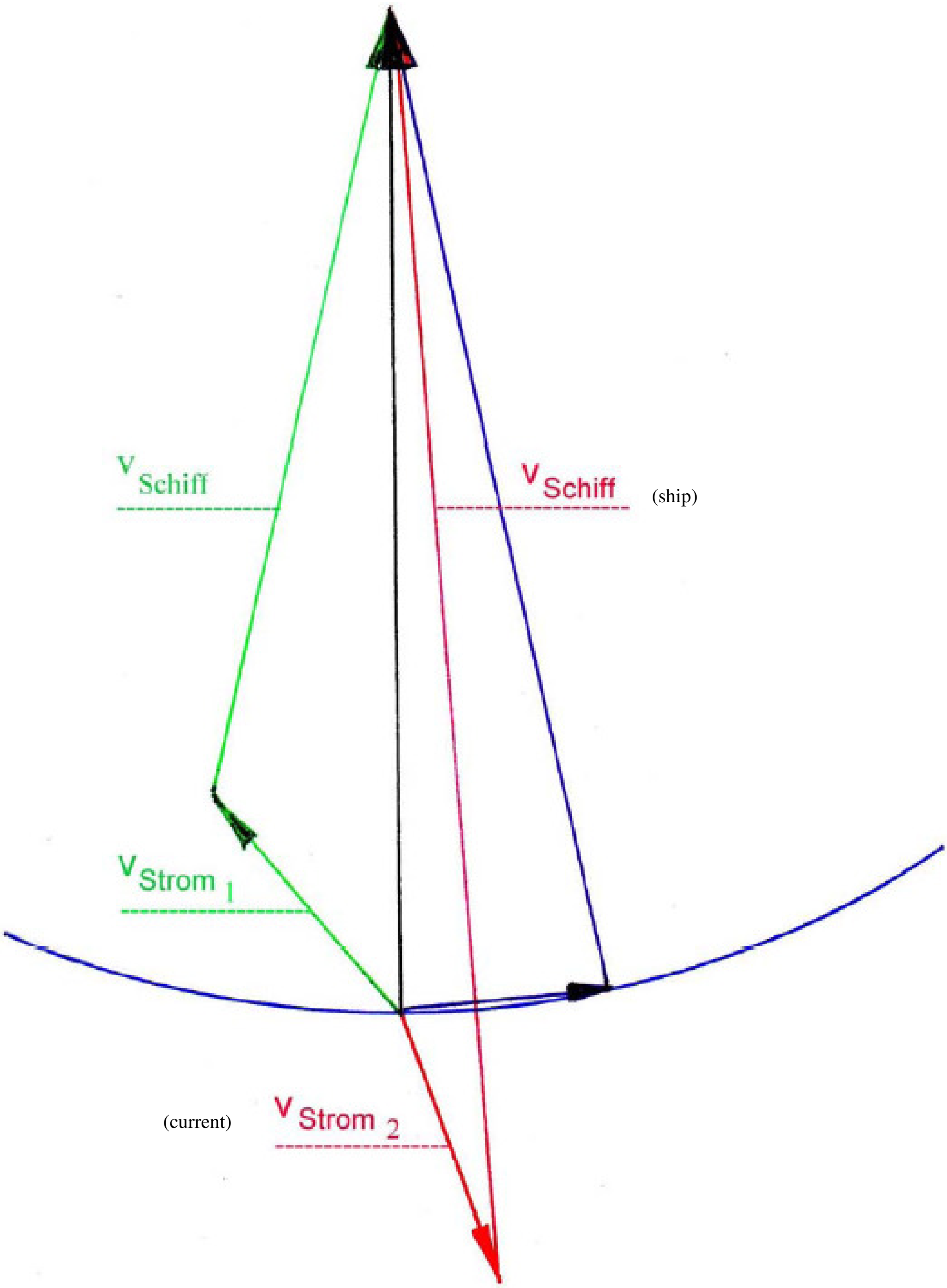


Illustration 45: Influence of ocean current

Fair current

During the voyage to the port of discharge a total distance of s_1 = 3000*nm* should be covered. Within this voyage a fair current section of 2 knots that spans *s2*= 500*nm* should be taken advantage of. For the whole voyage the charterer gives a time limit 220*h* without ”river steaming”.

- What speed should the ship sail with?
- How big is the total fuel consumption with and without fair current?

$s_1 = 3000\ sm$ $\qquad\qquad$ $\upsilon = ?$

$s_2 = 500\ sm$ $\qquad\qquad$ $\upsilon_2 = 2$ Knoten $\qquad$ (Knoten = knots)

$$\upsilon = \frac{\Delta s}{\Delta t}; \qquad \Delta t = \frac{\Delta s}{\upsilon}$$

$$\Delta t = \frac{\Delta s_1}{\upsilon_1} + \frac{\Delta s_2}{\upsilon_2} = \frac{2500sm}{\upsilon} + \frac{500sm}{\upsilon + 2Knoten}$$

$$220h = \frac{2500sm(\upsilon + 2) + 500sm \cdot \upsilon}{\upsilon^2 + 2\upsilon}$$

$$220h = \frac{2500\upsilon + 5000 + 500\upsilon}{\upsilon^2 + 2\upsilon}$$

$$\upsilon^2 + 2\upsilon = \frac{3000\upsilon + 5000}{220}$$

$$\upsilon^2 + 2\upsilon = 13{,}636\upsilon + 22{,}727$$

$$\upsilon^2 - 11{,}636\upsilon - 22{,}727 = 0$$

$$\upsilon_{1,2} = -\frac{p}{2} \pm \sqrt{\left(\frac{p_2}{2}\right)^2 - q}$$

$$\upsilon_1 = \frac{11{,}636}{2} \pm \sqrt{\left(\frac{11{,}636}{2}\right)^2 + 22{,}727}$$

$$\underline{\underline{\upsilon_1 = 13{,}34 \frac{sm}{h}}}$$

In the area of fair current and at a constant speed, the ship is sailing through the water with v_2 = 15.34 *nm/h* over ground.

According to table 43 the daily fuel consumption is therefore 22.5 *t*.

$$\dot{m}_{\mathrm{Reise}_{13,34}} = 22{,}5 \frac{t}{d} \cdot \frac{220h \cdot d}{24h} = 206{,}3 \frac{t}{\mathrm{Reise}}$$

Without fair current and at a speed of v = 13.64 nm/h and a daily fuel consumption of 24.8 t, the fuel consumption for the whole voyage would be:

$$\dot{m}_{\mathrm{Reise}_{13,64}} = 24{,}8 \frac{t}{d} \cdot \frac{220h \cdot d}{24h} = 227{,}3 \frac{t}{\mathrm{Reise}}$$

Head current

What would the fuel consumption be for a voyage under the same conditions as above but with 2 knots head current?

$s_1 = 3000\ sm$ $\qquad$ $\upsilon = ?$

$s_2 = 500\ sm$ $\qquad$ $\upsilon_2 = 2$ Knoten

$$\Delta t = \frac{\Delta s_1}{\upsilon_1} + \frac{\Delta s_2}{\upsilon_2} = \frac{2500sm}{\upsilon} + \frac{500sm}{\upsilon - 2}$$

$$220h = \frac{2500sm(\upsilon - 2) + 500 \cdot \upsilon}{\upsilon(\upsilon - 2)}$$

$$220 = \frac{2500\upsilon - 5000 + 500\upsilon}{\upsilon^2 - 2\upsilon}$$

$$220 = \frac{3000\upsilon - 5000}{\upsilon^2 - 2\upsilon}$$

$$\upsilon^2 - 2\upsilon = \frac{3000\upsilon - 5000}{220}$$

$$\upsilon^2 - 2\upsilon = 13{,}636\upsilon - 22{,}727$$

$$\upsilon^2 - 15{,}636\upsilon + 22{,}727 = 0$$

$$\upsilon_{1,2} = \frac{15{,}636}{2} \pm \sqrt{\left(\frac{15{,}636}{2}\right)^2 - 22{,}727}$$

$$\upsilon_1 = 14{,}014 \frac{sm}{h}$$ constant speed through the water

Over ground, the area of head current is passed through with v = 12.014 knots. Fuel consumption for the whole voyage now comes up to[22]:

$$\dot{m}_{\mathrm{Reise}_{Gegenstrom}} = 26{,}7 \frac{t}{d} \cdot \frac{220h \cdot d}{24h} = 244{,}8 \frac{t}{\mathrm{Reise}}$$)

6.4 Utilising a fair current area

If there is an area of fair current close to the set course, it has to be considered whether it would be advisable to accept a longer distance or deviation.

An example should illustrate this:

$s_{fair\ current}$ = $500nm$

$v_{fair\ current}$ = 2 knots

v_{ship} = 14 knots

[22] Gegenstrom = head current

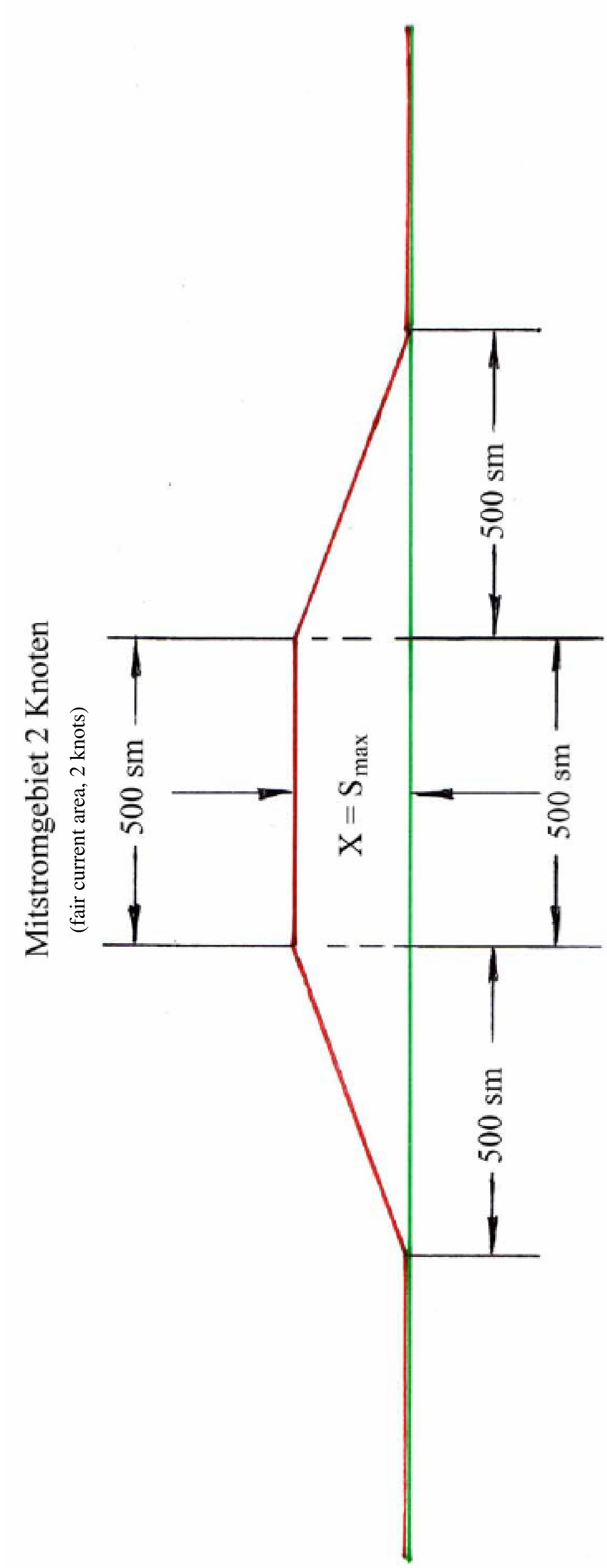


Illustration 46: Is the deviation worth it?

During the time in the area of fair current the vessel speed over ground increases from 14 knots to 16 knots.

$$\Delta t_{Mitstrom} = \frac{500sm \cdot h}{16sm} = 31{,}25h$$ (Mitstrom = fair current)

In these 31.25 hours the following additional distance is covered:

$$\Delta s_{Mitstrom} = 31{,}25h \cdot 2\frac{sm}{h} = 62{,}5sm$$

The angle α is calculated as:

$$\cos\alpha = \frac{500sm}{500sm + \frac{62{,}5sm}{2}} = 0{,}941 \qquad \arccos\alpha = 19{,}75°$$

A deviation, which is labelled with x in illustration 46, is only allowed to reach the following maximum values in order to have no influence on fuel consumption.

Smaller course alterations x would mean a reduction of fuel consumption.

$$\sin 19{,}75° = \frac{x}{531{,}25m}$$

$$x = \sin 19{,}75 \cdot 531{,}25sm$$

$x = 179.78\ nm$ (maximum deviation)

6.5 Constant speed through water or over ground?

Of course, the question is which of the following methods is the most fuel efficient one:

- constant speed over ground, or
- constant speed through the water

This can be calculated. The result shows that slightly less fuel is consumed, if a constant speed through the water is kept. A special advantage is also, that neither engine output nor propeller pitch have to be changed.

6.6 The influence of shallow water

Ilustration 47 shows weather shallow water causes a reduction in vessel speed. Froude's number is plotted on the ordinate.

$$F_{nh} = \frac{\upsilon}{\sqrt{g \cdot h}}$$

F_{nh} = Froude's number

v = vessel speed in *m/s*

h = water depth in *m*

The quotient of water depth h and draught T of the vessel is plotted on the abscissa.

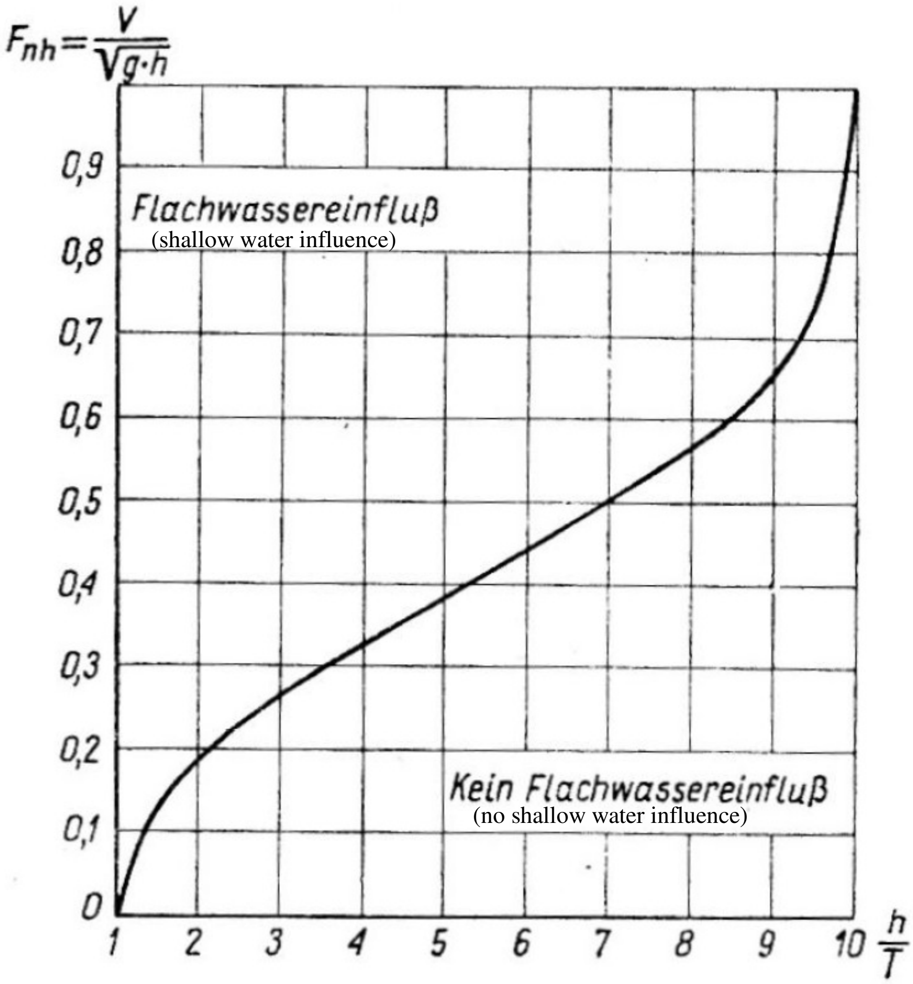


Illustration 47: Determining whether there is a shallow water influence

source: manual of the SBT, 1972, p.167

The extent of the reduction can be determined with the help of illustration 48. Here, the term $\frac{\sqrt{A_M}}{h}$ with $A_M = B \times T \times c_B$ is plotted on the ordinate.

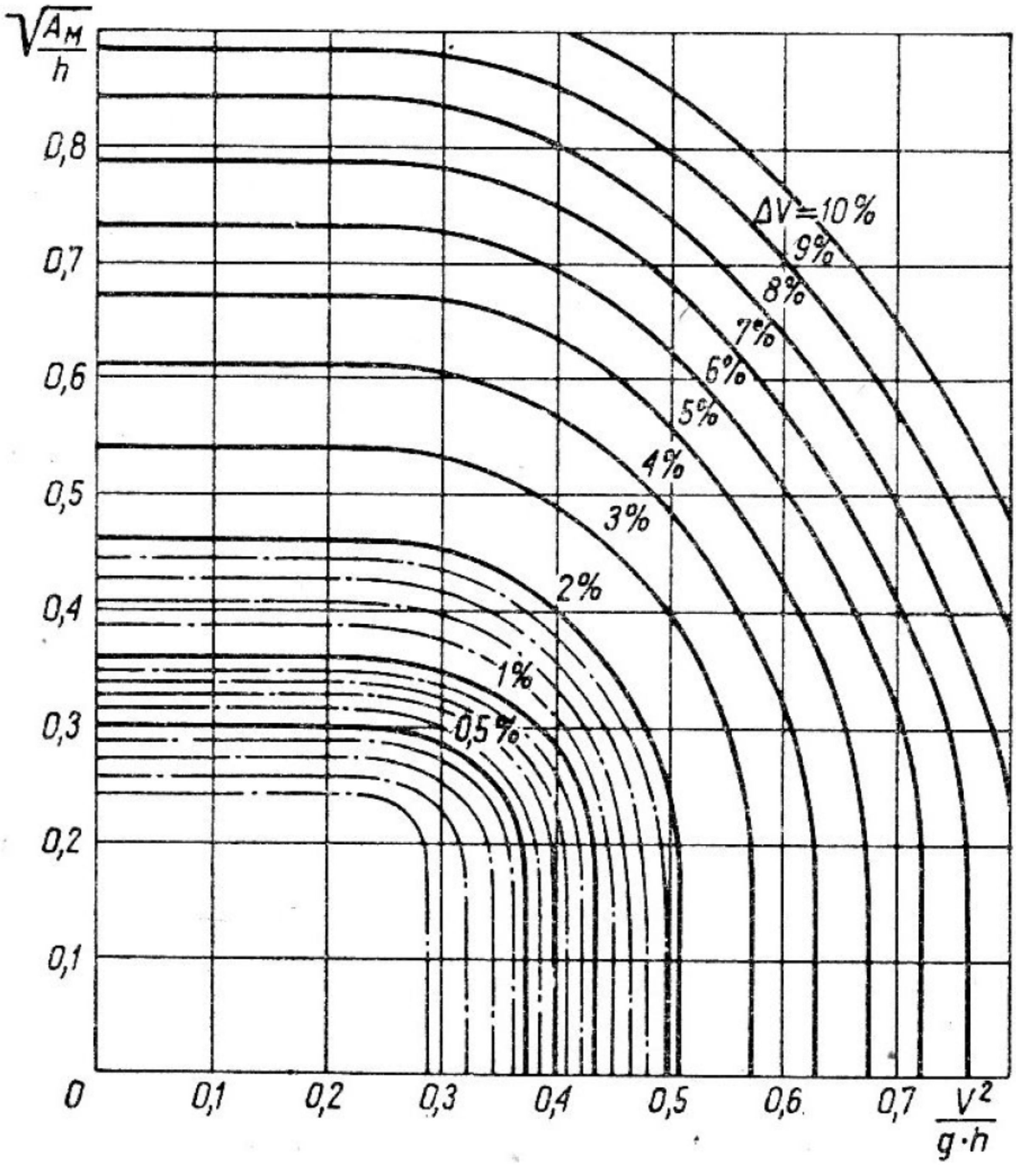


Illustration 48: Speed reduction under shallow water influence

source: manual of the SBT, 1972, p.167

B = beam of the ship in m

T = draught in m

c_B = block coefficient of the under water hull

h = water depth in m

Example:

Beam of the ship B = 26.4 m, draught T = 9.19 m, ship speed of 14 knots which equates to v = 7.2 m/s, block coefficient c_B = 0.85, and water depth h = 15 m.

- using illustration 47 to check whether there is a shallow water influence

$$F_{nh} = \frac{\upsilon}{\sqrt{g \cdot h}} = \frac{7{,}2m/s}{\sqrt{9{,}81m/s^2 \cdot 15m}} = 0{,}6$$

$$\frac{h}{t} = \frac{15m}{9{,}19m} = 1{,}632$$

At the intersection it can be seen that there is a shallow water influence.

- determining the size

The size of the shallow water influence can be determined with the help of illustration 48.

$$\frac{\sqrt{A_M}}{h} = \frac{\sqrt{B \cdot T \cdot c_B}}{h} = \frac{\sqrt{26{,}4m \cdot 9{,}19m \cdot 0{,}85}}{15m} = 0{,}957$$

$$\frac{\upsilon^2}{g \cdot h} = \frac{(7{,}2m/s)^2}{9{,}81m/s^2 \cdot 15m} = 0{,}35$$

With illustration 47 the size of shallow water influence can be determined to ~10%.

If speed is reduced to v = 12 knots, resistance is reduced and less speed is lost.

7 Alternative energies

Hypothetically, what alternative energies are available for ship operations? There are:

- fossil primary energy e.g. coal, oil shale, natural gas, biomass
- and/or nuclear energy e.g. nuclear fission, uranium fission, breeder reaction
- and/or nuclear fusion e.g. fusion reactors
- and/or solar energy e.g. solar radiation, wave energy
- and/or wind power

In the context of ship operations, an American study took a closer look at the following (regarding a power range from 7 … 11 MW):

- diesel engine
- steam turbine
- stirling engine
- gas turbine
- fuel cell
- free piston gas generator

According to this, coal-fired boilers are most economical for new ships. At higher fuel costs, slow running diesel engines could be of interest, if they can be operated with unrefined oil shale oil or coal/oil mix.

Coal

The first vessels with coal-fired boilers have been commissioned. At 60 bar and 491°C the boilers generate 62510 *kg/h* steam, which at 85 min^{-1} generates 14000 *kW* in a steam turbine.

Gas

In LNG tankers the undesirable boil-off gas is burnt in SDEs (Small Diesel Engine), that only have a smaller oil-fired burner for ignition. Also gas engines have been used. However, this LNG fuel will probably only be used in specialised ships, if the reliquefaction system operates with higher costs.

Nuclear energy

At the moment, about 200 ships are operated with nuclear energy. This is mainly the case in the navy, where high output and a big radius of action are required.

Solar energy

The collected and usable energy per m² is so low, that it cannot be used for main propulsion system of seagoing ships .

Wind

There have been numerous studies that have dealt with the question how wind power can be used. In professional journals the number of articles that concern new constructions such as kites has increased. Nevertheless, shipping companies are presently not convinced that a more cost effective transportation would be possible with a sail.

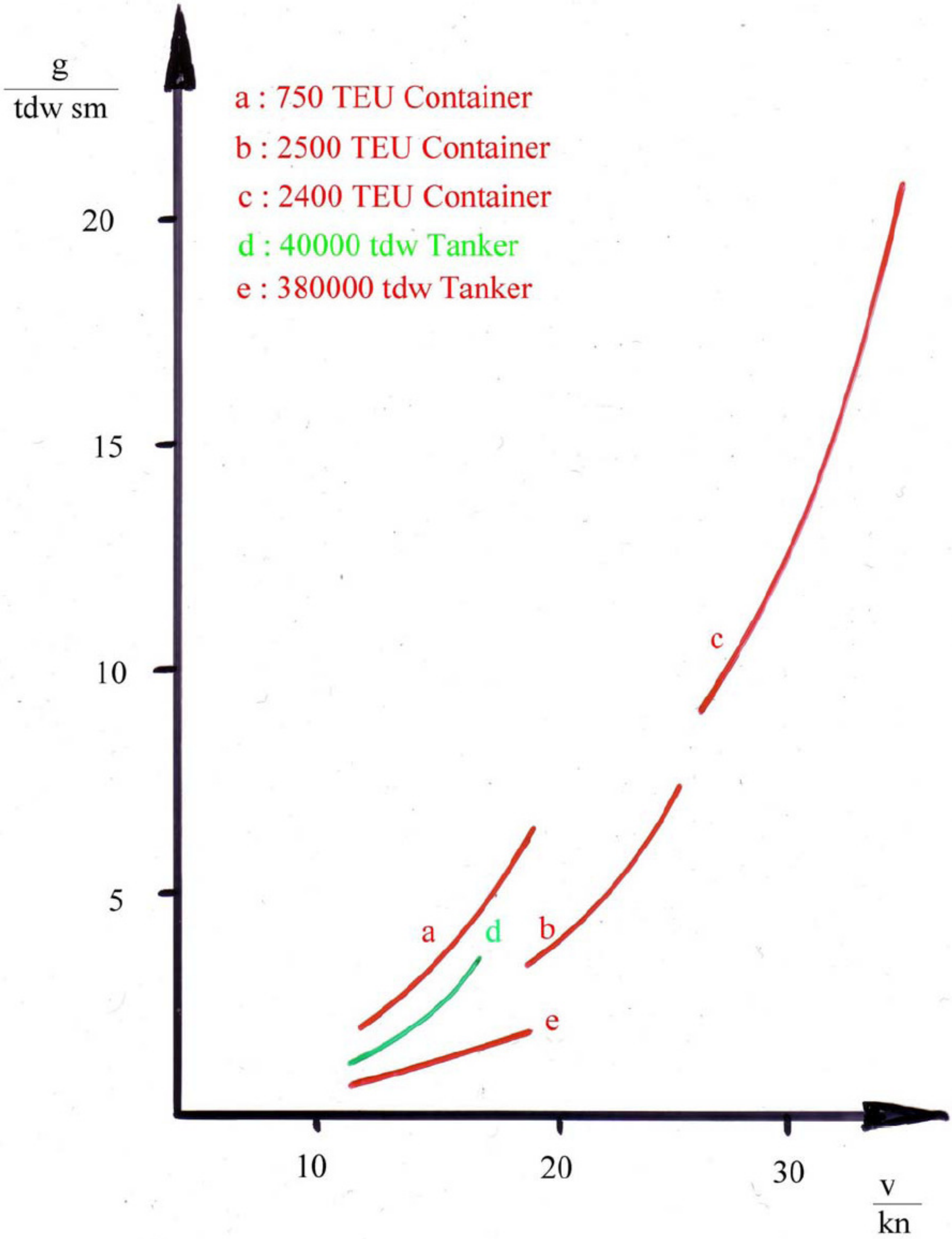


Illustration 49: Specific fuel demand in gram per tdw and nautical mile

MEASURES TO INCREASE PROPULSION EFFICIENCY

Losses	Measures	Improvement
Separations in the aft body	Schneekluth – nozzle Grothus – spoiler Fins (Peters / Mewis) Vortex generator	up to 4% power up to 3% power up to 3% power losses up to 2% for optimum arrangement but reduces pressure pulses by up to 50%
Frictional losses	Reducing the area ratio of the propeller to the minimum. This is only possible when the propeller operates in an optimised wake field. Additionally requirements regarding cavitation have to be observed.	depending on the area ratio of the propeller
Rotational losses	Pre-swirl-fins Rudder fins Twisted rudder (with Costa-Bulb)	up to 5% power up to 5% power up to 2% power up to 4% power
Axial jet losses	Grim's vane wheel	up to 9% power
Hub vortex losses	Efficiency Rudders Costa Bulb Boss Cap Fins (PBCB) Divergent propeller cap	up to 6% power up to 3% power up to 3% power up to 2% power

Table 23: Possible saving potential
source: HSVA Newswave 2006/1, p. 4

8 Summary

8.1 Voyage on the MT "Apatura"

The steering gear has to be adjusted. According to captain Günther it frequently happens that under normal weather conditions up to 20° the steering gear swings to both sides. If this is an adaptive system, then this is not right. If it is a normal PID controller, it has to be set better. It is an adaptive system.

The chief suggested using a central switch at the entrance to the engine room to switch off all lights in the engine room if nobody it is in there. With 546 neon lights at 18 Watt this would be 9.8 kWh.

The governor of the ME has to operate faster. From force 5 Bft. onwards a black-out can be caused because due to the rolling ship the power frequency can alternate so much that the maximum tolerance of 60 *Hz* can be exceeded. That is why, from this force onwards, an auxiliary diesel engine is started and the SG is taken off the network.

Captain Günther likes sailing.

There are no problems with exhaust gas, fuel or its storage. One could use a computer to set sail, just as it can be seen in French cruise ships. Also the indosail and the Japanese plate sail could be interesting, once the time for MFO in North and Baltic Sea is over.

The programmes on board have been installed that way, that the propeller remains immersed under all loading and ballast conditions. Experiments conducted by Shell International have shown on the class of "Lagena, Lottia, Liotina, et." that no damages are caused by cavitation to a 20% emerged propeller. These ships were operating with a speed of 15.5 knots. As long as the sea conditions allow this, the ship should be trimmed a little by the head. It would be even better to clad the forecastle of the ship in order to get less or no water on deck. This would reduce friction and reduce maintenance work on board.

A stability programme should calculate whether it is necessary to use 11500m^3 of sea water as ballast under calm sea conditions. The ballast water tanks need to be checked regularly for deposits in order to reduce the weight of the ship.

Ballast voyages are not undertaken at the expense of the charterer and should be reduced to a minimum. (Of course, this is already aimed for, but is quite difficult.)

On board, it was constantly operated with 60.5 Hz. I am aware that fluctuations in the electric net can cause a black-out, but it can be operated with 57 … 59 Hz without a problem.

Are no funds released, fuel costs can only be reduced by:

1. Choosing the correct speed under bad or good weather conditions and fair- or head current.
2. Choosing the necessary ballast water amount and its distribution.
3. Choosing the best trim, in relation to fuel consumption.
4. Reducing on board power frequency to less than 60.5 Hz.
5. Shutting down diesel generators early, if there is no demand.
6. Shutting down the main engine early, if there is no demand.
7. Shutting down an auxiliary diesel early, if there is no demand.
8. Switching off unnecessary electric auxiliary engines.
9. Regular cleaning and rinsing of the plate cooler filter on the sea water side.
10. Regular cleaning of the turbocharger according to operative regulations.
11. Reducing the power of fans and air conditioning whilst in the harbour.

8.2 Continuative notes

All in all, the potential of reducing fuel consumption can be summarised as follows:

- Controlling and maybe improving form- and friction-components of the under water hull by changing the shape of the hull at bow and stern.
- Switching to a under water hull coating that causes less friction, or reducing friction by blowing compressed air underneath the hull. [23]
- Improving efficiency of main and auxiliary engines.
- Improving energy transfer by changing the propeller, utilising waste heat, utilising the (propeller-) spin.
- Adjusting auxiliary engines to different conditions than tropical conditions. These concern the quantity of pumped sea water, fans and air conditioning.

[23] source: Germanischer Lloyd „non Stopp“, issue 3/2008, p.19

- Applying transport management. Increasing the quantity of cargo per nautical mile by reducing or shortening ballast voyages. The bigger the fleet, the easier this is.
- Weather routing. In order to do this, personnel and computer facilities need to be provided on shore. It would be advantageous if the responsible person (by me called "route planner") could forward the speed recommendations to the whole crew well before the voyage starts.
- Optimum speed means keeping a constant speed throughout the voyage. Again the route planner should be responsible for this. With the help of a current atlas and tide tables, he should find the optimum speed for the route, ship, season, draught, trim, and time.
- Possibilities to reduce fuel consumption that are free of cost:

transport management	5 – 40%
weather routing	2 – 4 %
just in time strategy	1 – 5 %
constant vessel speed	0 – 2 % [24]

8.3 Practical specifications

If more time is available, a slower speed should be chosen. However, the influence of bad weather on the set course has to be considered. The necessary vessel speed can be determined with the following equation:

$$v_{ship} = \frac{\text{distance that has to be sailed (in nautical miles)}}{\text{available time (in hours)}} \quad \text{in nautical miles per hour}$$

Afterwards, it should be tested with the help of illustration 3 ("slow steaming") whether the result is in the clear. If not, the next higher speed range is to be chosen.

After about 12 hours operating time, the engine output should be increased to 70 - 80% MCR for about 5 - 15 minutes. Afterwards it can be reduced again.

[24] source: report for the Department of Transport, Newcastle University AEA/ED 05465/Issue 3, p.13

In principle, it is better to operate with a high engine revolution speed and low pitch, compared to a mere combination mode. If the engine output is smaller than 35 – 40%, the electrically powered auxiliary fans run on combination with the turbocharger.

It is not worth doing for instance 14 knots, if afterwards the time is spend anchored. It is better to just do 6, 8, or 10 knots which would reduce specific fuel consumption in gram per tdw and nautical mile.

If the charterer however pays already from time of arrival or if the berth can be occupied by somebody else and the own vessel has to wait, going at full speed might be the better solution. The decision of appropriate speed cannot be made by the captain alone. The charter payment modalities have to be made know onboard by the charter department in due time.

9 Problems with bunkering

The problem is often that a ship gets 400 m³ MFO from a supplier that is only dealing for the first or second time with this ship. Then, the procedure is usually the following:

- The supplier comes on board.
- To the chief he shows a delivery note of 400 m³ with a density of for instance 925 kg/m³ at 42°C corresponding to 370 t with a sulphur content ≤ 1.5% (volume or weight %).
- The chief signs the delivery note, otherwise bunkering will not begin.
- With the signature he confirms that he received the stated amount.
- If the amount does not fully come to 400m³, which is often the case, still the full amount has to be paid.
- At a 1°C higher temperature actually 2.8 m³ would be missing, that still have to be paid.
- According to ISO 8217 (2005) the water content can be up to 0.5%, which would equate to another 2m³ that have to be paid and laboriously separated.
- It has to be assumed that at least 2.5% are not fuel but extortion and bogus manipulation. Another 2.5% are sludge.

In order to knock this on the head, it would be very beneficial for merchant shipping if a gauged fuel-volume-meter was installed between bunker pipe ashore and bunker nozzle on board. It would also be beneficial to recognise gases in the bunker. A fuel testing laboratory, which can measure density, water and air content, would definitely be advantageous to the chief.

This does not criticise the chief engineers as they do not have the means against the manipulations by bunker suppliers.

10 Checklist

Main engine

- set ignition pressure as high as possible
- set the temperature of lubrication oil as high as possible
- set HT cooling water temperature as high as possible
- set NT cooling water temperature as high as possible
- set lubrication oil consumption so that wearing of the cylinder liner and the cost of lubrication oil are kept at a minimum
- adjust ignition point to fuel quality

Power generation

- switch of all unnecessary consumers
- operate in combined mode if nautically possible
- operate the shaft generator instead of auxiliary diesel, if a longer voyage is foreseeable
- control the power factor cos φ; it should be ≥ 0.8
- if possible, reduce frequency to < 60 Hz, or < 50 Hz!

Pumps and pipes

- by making use of manometer readings and datasheet, operate all centrifugal pumps at the best efficiency
- clean and backwash all filters when necessary
- operate with all valves completely open
- avoid gas bubbles
- reliable suction

Fans / air conditioning

- reduce fan operation whilst in the harbour
- in the summer switch air conditioning to fresh air and reduce air amount
- in the autumn / winter / spring operate air con with at least 80% circulating air
- keep air conditioning and cooling systems clean and defrost regularly

Other

- check sludge tank whether any MFO remains; if so, pump into the settling tank
- operate with a minimum amount of ballast water
- during a ballast voyage trim the ship on the head
- immediately shut down main and auxiliary engines after use
- check steering gear is set correctly (few movements per minute)
- Are fair current areas utilised?
- Does the ship have the correct trim?
- Is there too much ballast on board?
- Is a constant speed through the water kept?
- Are visible patches of rust on the under water hull removed?

11 List of illustrations

12 List of tables