D6.3 Powering

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Responsible: University of Belgrade,
Faculty of Mechanical Engineering,
Department of Naval Architecture,
Dr. Dejan Radojčić

ABSTRACT

Main objective of this analysis is to establish the practical limits of ship size that can still be propelled effectively. For that purposes two typical single-propeller IWW ships were chosen – MV "Hendrik" and MV "Rheinland". Through the analysis draught and breadth of the ships were kept constant, while different ships lengths were considered (virtual lengthening was performed within Task 6.1). Although the increase of ship length leads to the increase of ship displacement and therefore to increase of propeller loading for the same ship speed, the propeller diameter could not be changed due to limited space.

Virtual repowering was done for both vessels. Contemporary high-speed Diesel engines were considered for retrofitting (derived from general application engines applied in the road vehicles that satisfy all present requirements concerning emissions etc.) as these are more efficient, cleaner, cheaper (for maintenance too) and lighter than conventional ship engines. More advanced propulsors (then Diesel engines, conventional propellers etc.) suppose to be investigated within other MoveIt WP, as for instance WP2 – Hydrodynamic improvements, WP4 – Power etc., WP6, in general, deals with mature and proven technologies.

Amongst the lessons learned within Task 6.3, it was concluded, that the power needed for achieving certain speed is not significantly influenced by lengthening, so the same power train (engine/gearbox/propeller) was considered for all lengthening steps. Water depth, however, is the main factor that influences power.

Also, original naked propeller was replaced with a propeller in nozzle as these are considered to be more effective for IWW shallow draught vessels.

From the results of analysis the following was concluded:

- Due to the lengthening, speed reduction is 1 to 2 km/h (when the same engine power is engaged).

- Speed reduction for *Hendrik* and *Rheinland* from deep to shallow water (deep to h=5 m, and then from 5 m to 3.5 m) is around 4 km/h and 2 km/h, respectively.

- Propulsive efficiency can be significantly improved if naked propeller is replaced with propeller in nozzle (improvement of ~10%, which increases speed up to 1 km/h).

- In very shallow water, due to squat effect (and wave wake too), reduction of navigational speed is necessary. Maximal allowed speed for *Hendrik* is 13 km/h and 8 km/h for h=5 m and 3.5 m respectively (in deep water –18 ÷ 20 km/h depending on ship length), while for *Rheinland* speed should be reduced to around 10 km/h for h=3.5 (in deep water – 16.8 ÷ 18.2 km/h depending on ship length).

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No.	Organisation Name	Name	Email
	University of Belgrade – Faculty of Mechanical Engineering	Dejan Radojčić	radojcic@beotel.rs
	University of Belgrade – Faculty of Mechanical Engineering	Aleksandar Simić	asimic@mas.bg.ac.rs

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1 INTRODUCTION

1.1 Main parameters of considered ships

MV "HENDRIK"

Inland waterway dry bulk cargo ship "Hendrik" was built in 1975 as a single-propeller ship with main engine SKL 6NVD48-2U (installed power is 660 HP).

Figure 1 – MV "Hendrik" as initially built [1]

Main ship particulars, as it was initially built, are shown in Table 1.

Table 1 – MV "Hendrik" – main ship particulars

Length over all	[m]	69.98
Breadth	[m]	8.60
Draught	[m]	2.95
Depth	[m]	3.00
Displacement	[t]	1360
Propeller diameter	[m]	1.5

All data presented in Table 1 were taken from the Deliverable 6.1 (Ship Structure), except propeller diameter which was estimated from the General Arrangement plan which is shown in Figure 2.

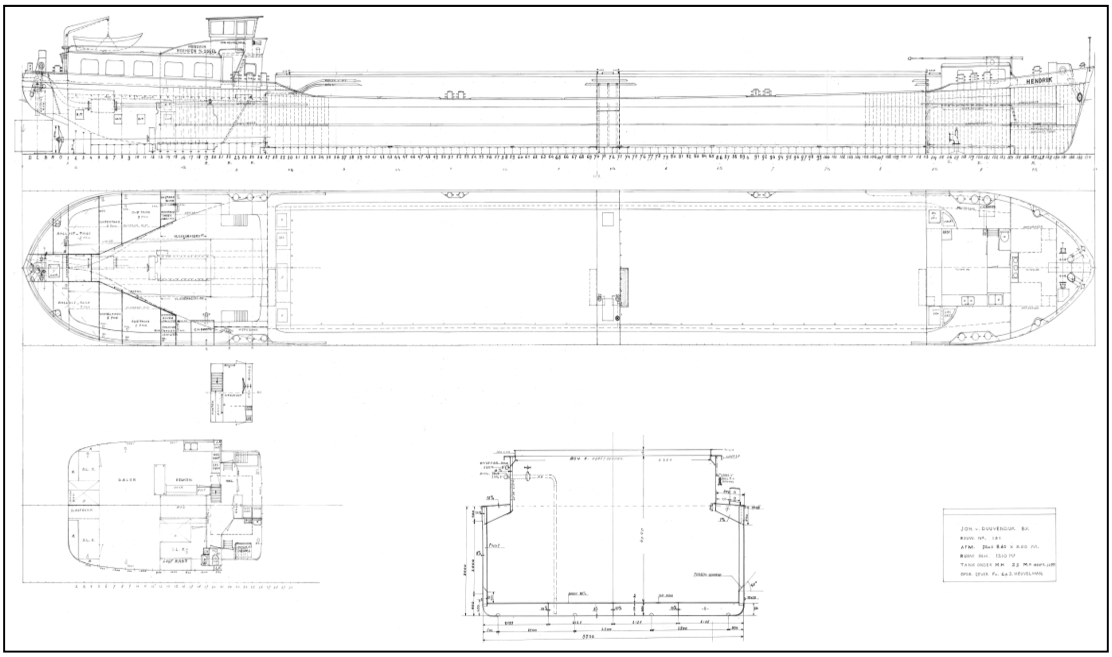


Figure 2 – General arrangement drawing of MV “Hendrik” [1]

MV “RHEINLAND”

Inland waterway dry bulk cargo ship “RHEINLAND” was built in 1959 as a single-propeller ship. According to available data [3] installed power of the main engine was 375 HP.

Figure 3 – MV “Rheinland” after reconstruction [3]

Main ship particulars, as it was initially built, are shown in the Table 2.

Table 2 – MV “Rheinland” – main ship particulars

Length over all	[m]	57.5
Breadth	[m]	6.34
Draught	[m]	2.43
Depth	[m]	2.5
Displacement	[t]	724
Propeller diameter	[m]	1

All data presented in Table 2 are taken from the Deliverable 6.1, (Ship Structure), except propeller diameter which was estimated from the General Arrangement plan shown in Figure 4. From this figure it can be noticed, like in case of MV “Hendik”, that the propeller without nozzle was installed.

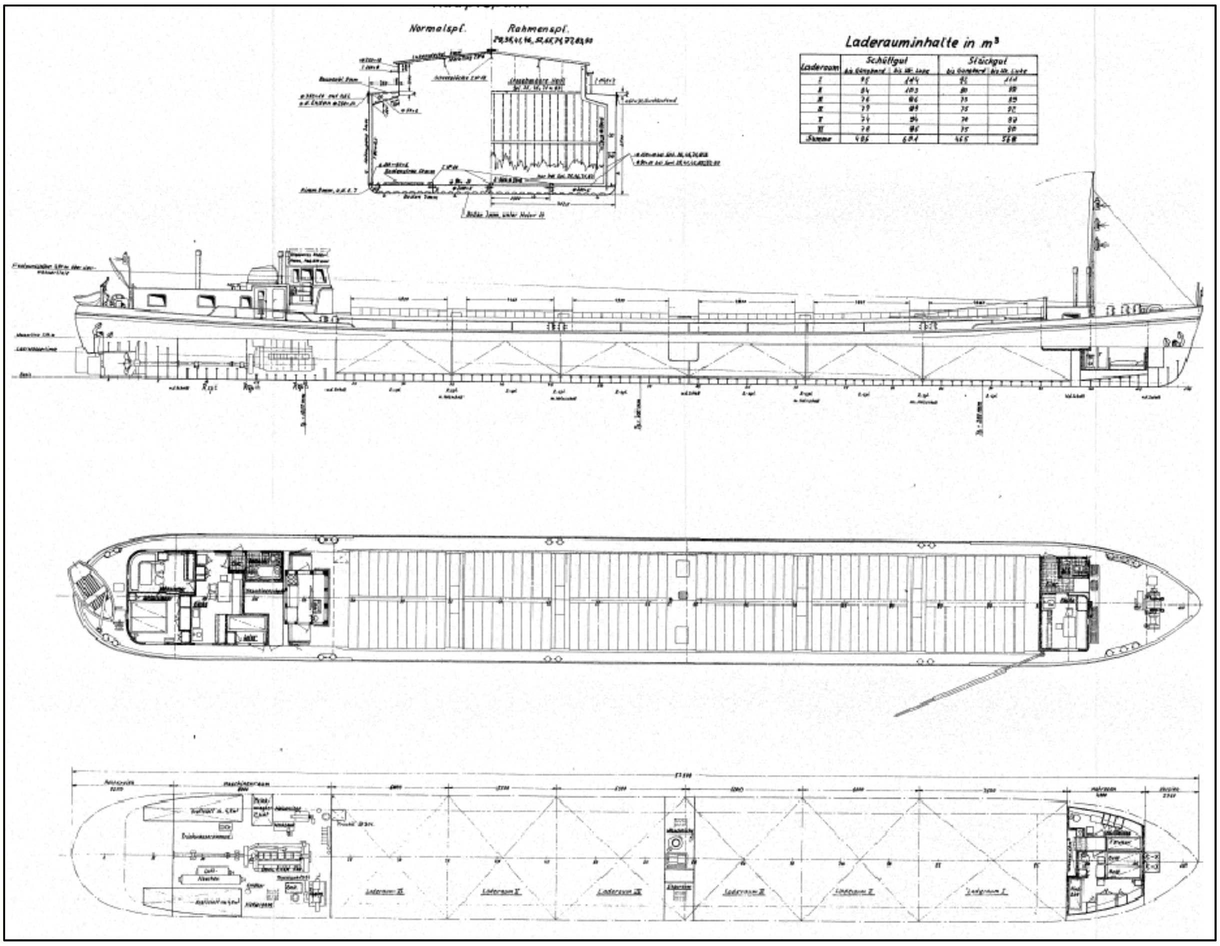


Figure 4 – General arrangement drawing of MV “Rheinland” [1]

1.2 Comparison of considered ships

Although different in size, vessels are similar, i.e. conventional, single-propeller, IWW cargo ships and are good candidates for (virtual) lengthening and retrofitting.

Table 3 – Important parameters of considered ships

MV	L/B	B/T	L/T	L/h, h=3.5 – ∞	h/T, h=3.5 – ∞
Hendrik	8.1	2.9	23.6	19.9 – 0	1.2 – 0
Rheinland	9.0	2.6	23.3	16.2 – 0	1.4 – 0

1.3 Considered lengthening possibilities

For the purposes of the analysis the lengthening step has been set to intervals of 6 meters which corresponds approximately to the length of one TEU container.

Some ship dimensions that are needed for calculations, such as length between perpendiculars, waterline length, wetted surface and longitudinal centre of buoyancy, were estimated according to statistics based on similar ships of the same type. Prismatic coefficient values were estimated too.

MV “HENDRIK”

Maximum considerable length was set to 94.99 m because 95 m forms the transition into a higher CEMT class with additional requirements. All ship particulars used for powering analysis are given in Table 4. Estimated data that are needed for further evaluations are marked in Table 4 by italic font.

Table 4 – Particulars of MV "Hendrik" used for calculations

Dimensions		Initially built	Lengthening 1	Lengthening 2	Lengthening 3	Lengthening 5
Length OA	[m]	69.98	76.00	82.00	88.00	94.99
Length BP	[m]	*67.30*	*73.30*	*79.30*	*85.3*	*92.3*
Length WL	[m]	*69.60*	*75.48*	*81.34*	*87.20*	*94.02*
Breadth	[m]	8.6	8.6	8.6	8.6	8.6
Draught	[m]	2.95	2.95	2.95	2.94	2.934
Depth	[m]	3	3	3	3	3
LCB	[m]	*34.47*	*37.51*	*40.56*	*43.62*	*47.19*
Displacement	[t]	1360	1508	1664	1812	1988
CB	[-]	*0.770*	*0.787*	*0.808*	*0.822*	*0.838*
CP	[-]	*0.774*	*0.791*	*0.812*	*0.826*	*0.842*
Carrying capacity	[t]	1114	1241	1372	1502	1653
Wetted surface	[m^2]	*939*	*1026*	*1113*	*1200*	*1301*

Longitudinal centre of buoyancy (LCB) was measured from aft perpendicular.

MV "RHEINLAND"

Maximum considerable length was set to 69 m. Ship particulars used for powering analysis are given in the Table 5. Estimated data that are needed for further evaluations are marked in Table 5 by italic font.

Table 5 – Particulars of MV "Rhenland" used for calculations

Dimensions		Initially built	Lengthening 1	Lengthening 2
Length OA	[m]	57.50	63.00	69.00
Length BP	[m]	*55.30*	*61.30*	*67.30*
Length WL	[m]	*56.65*	*62.03*	*67.88*
Breadth	[m]	6.3	6.3	6.3
Draught	[m]	2.43	2.43	2.42
Depth	[m]	3	3	3
LCB	[m]	*28.13*	*31.15*	*34.17*
Displacement	[t]	724	816	908
CB	[-]	*0.829*	*0.854*	*0.872*
CP	[-]	*0.834*	*0.858*	*0.876*
Carrying capacity	[t]	538	615	694
Wetted surface	[m^2]	*582*	*628*	*680*

Longitudinal centre of buoyancy (LCB) was measured from aft perpendicular.

2 INFLUENCE of LENGTHENING (PHASE I - POWER TRAIN UNCHANGED)

2.1 Evaluation of effective power with respect to ship size and water depth

Effective power of the ship, according to definition, depends on ship speed and corresponding total resistance:

$$P_E = V \cdot R_T$$

For resistance evaluation of IWW ships it is common to apply slightly corrected methods developed for resistance evaluation of sea-going ships [4]. For the purpose of this analysis, two methods for resistance evaluation were considered: Guldhammer & Harvald (GH) [5] and Holtorp & Mannen (HM) [6].
The influence of shallow water on ship resistance, hence effective power too, Lackenby's method [9, 10] was applied. According to this method, speed loss due to shallow water is evaluated for constant effective power.

MV "HENDRIK"

Effective power calculations in case of deep water, according to methods mentioned above, are presented in Table 6.

Table 6 – MV "Hendrik" – Effective power in deep water

P_E [kW]	V [km/h]	3	6	9	12	15	18	21
69.98 m	GH	0.86	6.40	20.97	49.29	97.47	175.61	306.71
	HM	0.85	6.18	19.87	45.99	91.37	169.38	301.49
76 m	GH	0.92	6.90	22.64	53.44	106.47	193.73	340.32
	HM	0.92	6.71	21.56	49.99	99.45	184.03	324.93
82 m	GH	0.99	7.38	24.25	57.43	115.07	210.97	372.18
	HM	0.99	7.21	23.19	53.86	107.52	199.56	352.64
88 m	GH	1.05	7.86	25.83	61.28	123.27	227.12	401.72
	HM	1.05	7.70	24.78	57.71	116.02	217.16	386.35
94.99 m	GH	1.12	8.40	27.64	65.80	133.15	247.45	441.33
	HM	1.13	8.27	26.64	62.34	126.62	239.94	430.88

Negligible discrepancies between GH and HM results are noticeable. For all analysis conservative approach, i.e. larger values, were adopted.

Since the influence of shallow water on ship resistance has to be taken into account, in this analysis two different water depths were considered: 5m and 3.5m.

Expected sustainable ship speed in shallow water (for the same P_E as in deep water) is presented in Tables 7 and 8.

Table 7 – Reduced speed of MV "Hendrik" due to influence of shallow water (5m)

L_{OA}	Vh [km/h]						
69.98 m	2.642	5.285	7.927	10.568	13.160	15.502	17.353
76 m	2.642	5.285	7.927	10.568	13.160	15.502	17.353
82 m	2.642	5.285	7.927	10.568	13.160	15.502	17.353
88 m	2.644	5.287	7.931	10.573	13.166	15.510	17.361
94.99 m	2.644	5.289	7.933	10.576	13.170	15.514	17.367

Table 8 – Reduced speed of MV "Hendrik" due to influence of shallow water (3.5m)

L_{OA}	Vh [km/h]						
69.98 m	2.251	4.502	6.753	8.979	10.970	12.386	13.128
76 m	2.251	4.502	6.753	8.979	10.970	12.386	13.128
82 m	2.251	4.502	6.753	8.979	10.970	12.386	13.128
88 m	2.253	4.507	6.760	8.989	10.983	12.401	13.146
94.99 m	2.255	4.510	6.765	8.995	10.990	12.410	13.157

All results, including influence of shallow water on effective power, are presented in Figures 5 and 6.

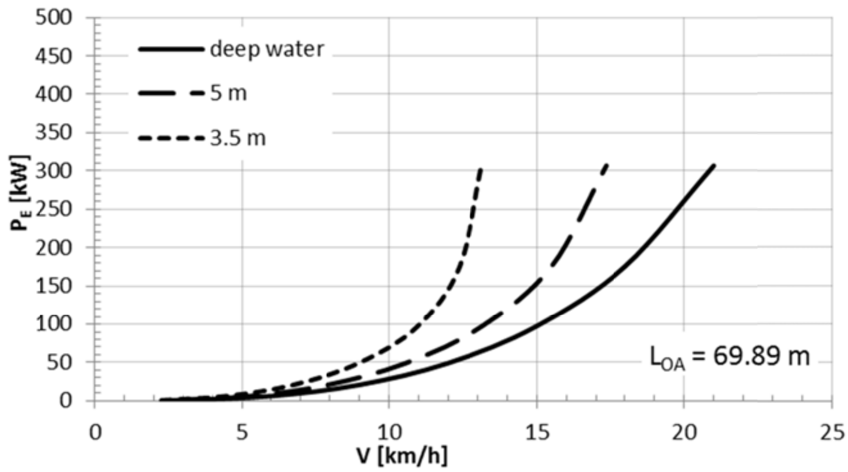


Figure 5 – Effective power vs. ship speed in deep and shallow water (MV "Hendrik" – initially built ship)

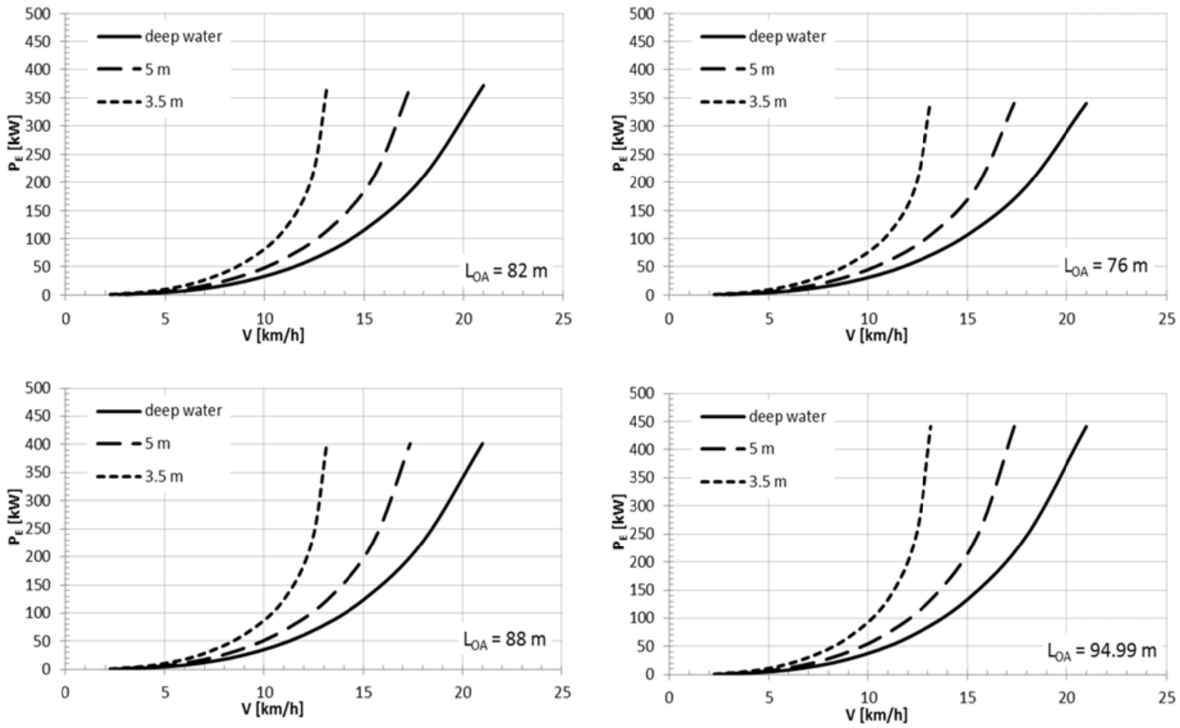


Figure 6 – Effective power vs. ship speed in deep and shallow water (MV "Hendrik" – in case of considered ship lengthenings)

Due to the lengthening of MV "Hendrik" expected speed reduction is up to 2 km/h, when the same engine power is engaged.

MV "RHEINLAND"

Effective power in deep water was evaluated according to adapted Holtrop & Mannen method only. Main results are shown Table 9. Speed losses (for the same P_E as in deep water) for water depths of 5 m and 3.5 m are presented in Tables 10 and 11 respectively.

Table 9 – MV "Rheinland" –Effective power in deep water

P_E [kW]	V [km/h]	3	6	9	12	15	18	21
L_{OA}	57.5 m	0.56	4.10	13.18	31.47	67.22	135.80	260.06
	63 m	0.60	4.40	14.18	34.18	74.25	152.17	291.58
	69 m	0.65	4.73	15.29	37.34	82.86	172.77	332.29

Table 10 – Reduced speed of MV "Rheinland" due to influence of shallow water (5m)

L_{OA}	Vh [km/h]					
57.5 m	2.790	5.580	8.370	11.159	13.898	16.389	18.387
63 m	2.790	5.580	8.370	11.159	13.898	16.389	18.387
69 m	2.791	5.582	8.373	11.162	13.903	16.394	18.393

Table 11 – Reduced speed of MV "Rheinland" due to influence of shallow water (3.5m)

L_{OA}	Vh [km/h]						
57.5 m	2.552	5.105	7.657	10.185	12.477	14.194	15.238
63 m	2.552	5.105	7.657	10.185	12.477	14.194	15.238
69 m	2.554	5.108	7.662	10.192	12.486	14.205	15.251

All results, including influence of shallow water, are presented in Figures 7 and 8.

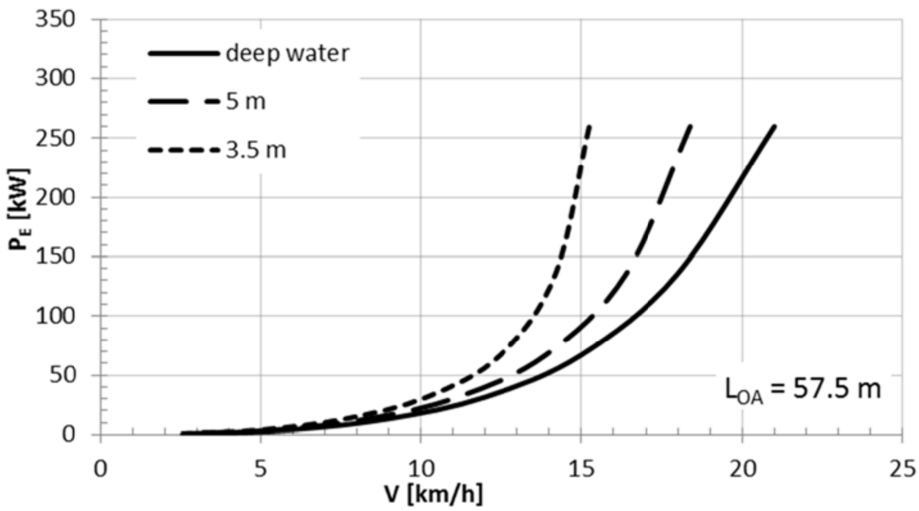
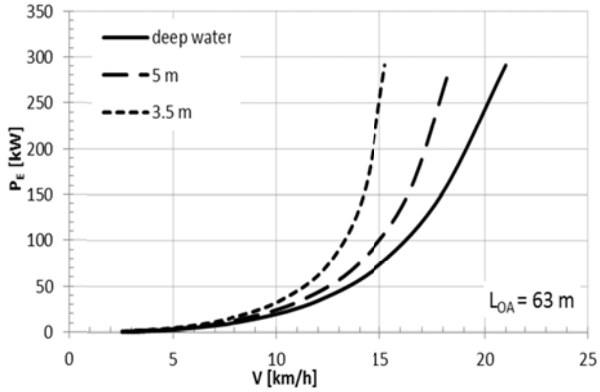


Figure 7 – Effective power vs. ship speed in deep and shallow water (MV "Rheinland" – initially built ship)



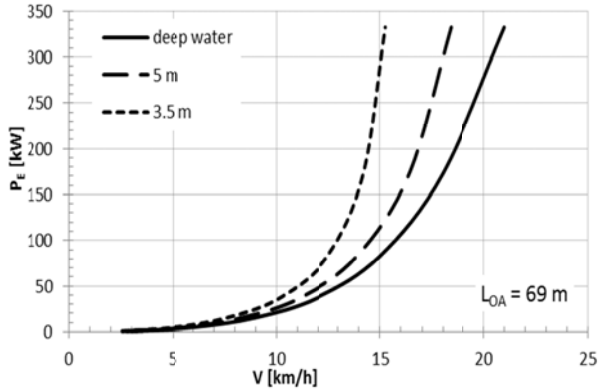


Figure 8. Effective power vs. ship speed in deep and shallow water (in case of considered ship lengthenings)

Due to the lengthening of MV "Rheinland" expected speed reduction is up to 1 km/h, when the same engine power is engaged.

2.2 Evaluation of maximal ship speed and estimation of initial (naked) propeller characteristics

Since data regarding installed propellers were not available, it was necessary to estimate basic propeller characteristics for each ship. For that, maximal speed in deep water was estimated by a statistical method (mathematical model) developed in [11] which is based on main ship dimensions and installed engine power. Characteristics of installed propellers were then estimated under the assumption that they were initially optimised for maximal ship speed for unrestricted fairway conditions. It was assumed that naked propellers were of Wageningen B-screw series [12]. Optimal propellers were evaluated by computer program developed at the Department of Naval Architecture in Belgrade [13].

In both cases wake fraction was assumed to be 0.3, thrust deduction 0.2 and relative rotative coefficient 1.05. Shaft & gear losses were assumed to be 6%.

MV "HENDRIK"

Taking into account size of the ship and power of installed engine (660 HP) it can be expected that maximal ship speed in calm and unrestricted water, without other external disturbances (waves, wind, etc.), is about 19.5 km/h.

Assuming that mechanical losses of propeller shaft and in reduction gear are about 6%, approximately 456 kW can be delivered to the propeller. As propeller diameter is limited to 1.5 m due to shape of the stern, characteristics of (optimal) propeller are shown in Table 12.

Table 12 – Estimated initial propeller characteristics

Number of blades	[-]	4
Propeller diameter	[m]	1.5
Propeller revolutions	[rpm]	404.9
Propeller area ratio	[-]	0.8
Pitch-diameter ratio	[-]	0.827

MV "RHEINLAND"

Taking into account size of the ship and installed engine power (375 HP) it can be expected that maximal ship speed in calm and unrestricted water, without other external disturbances (waves, wind, etc.), is about 17.8 km/h.

Assuming that mechanical losses of propeller shaft and in reduction gear are about 6%, approximately 260 kW can be delivered to the propeller. As propeller diameter is limited to 1.0 m due to shape of the stern, characteristics of optimal propeller are shown in Table 13.

Table 13 – Estimated initial propeller characteristics

Number of blades	[-]	4
Propeller diameter	[m]	1
Propeller revolutions	[rpm]	658.7
Propeller area ratio	[-]	0.8
Pitch-diameter ratio	[-]	0.800

2.3 Evaluation of propulsive efficiency and delivered power

In this phase delivered power was evaluated taking into account ship resistance in deep and shallow water, as well as the initial propeller characteristics.
More details are given in the Appendix 1.

MV "HENDRIK"

Required delivered power is presented in Figure 9, taking into account selected propeller, increase of resistance due to the lengthening and considered waterway depths.

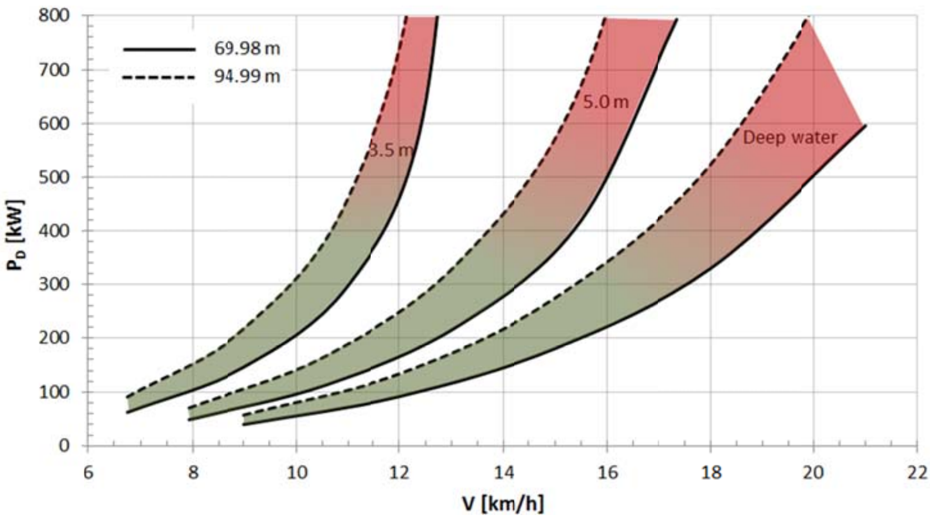


Figure 9 – Estimated required delivered power

Only curves for initially built ship (the smallest one) and the longest analysed option are shown. Delivered power demands for the rest of examined lengthening possibilities are between those curves. Consequently, maximal expected speed reduction caused by ship lengthening, for the same engine power engaged, is between 1 and 2 km/h.

According to same results, propulsive (hydrodynamic) efficiency with respect to ship speed, considered ship length and waterway depth is shown in Figure 10. Results presented in Figure 10 clearly illustrate the significant impact of fairway restrictions on the hydrodynamic efficiency, i.e. hydrodynamic efficiency dramatically drops due to restrictions of the waterway.

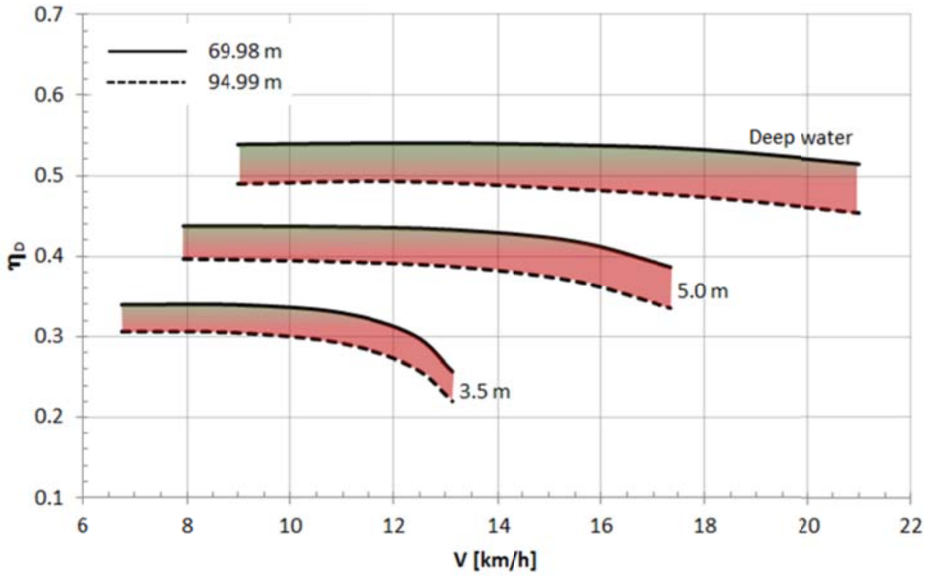


Figure 10 – Estimated propulsion efficiency

MV “RHEINLAND”

In case of another analysed ship, obtained results presented in the same manner are given in Figures 11 and 12 respectively.

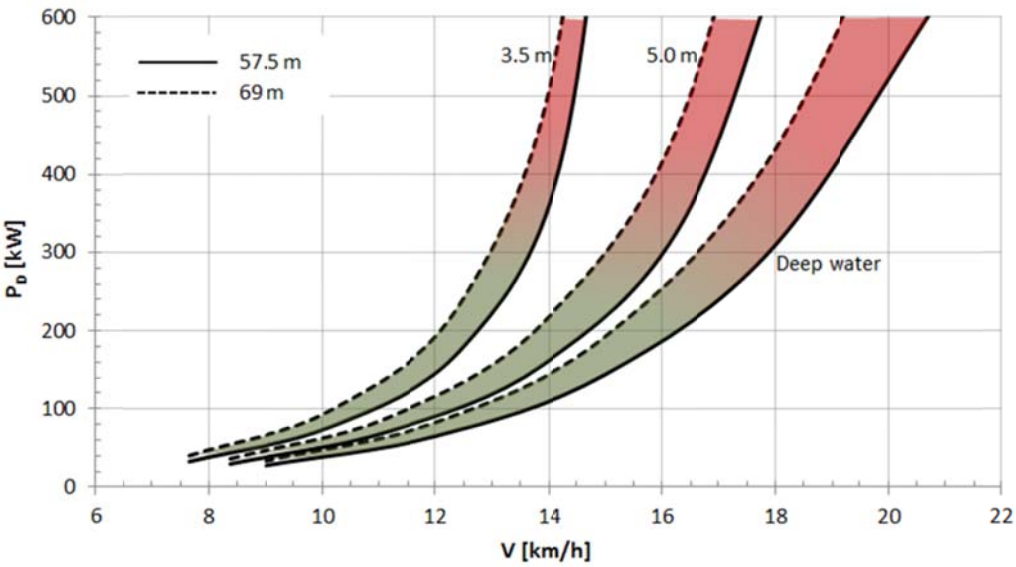


Figure 11 – Estimated required delivered power

Expected speed drop due to ship lengthening is less than 1.5 km/h.

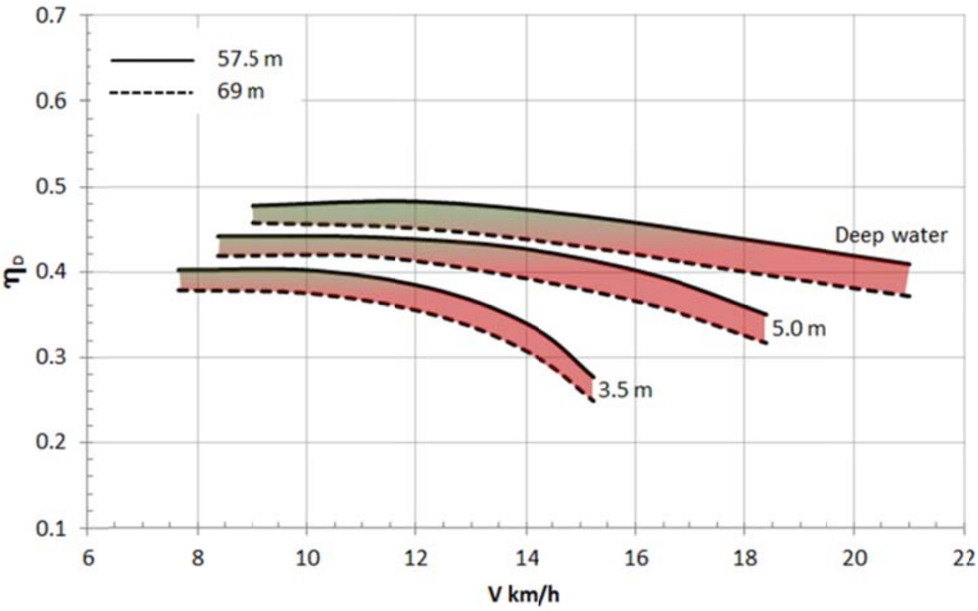


Figure 12 - Estimated propulsion efficiency

Results presented in Figure 12 depict less pronounced propulsive efficiency reduction caused by shallow water effects than in case of MV “Hendrik” (see Figure 10). This is expected due to the fact that the depth-draught ratio of MV “Rheinland” is about 1.44, while the same ratio for MV “Hendrik” is about 1.18 only.

3 PROPELLER IN NOZZLE (PHASE II - REPLACEMENT OF NAKED PROPELLER)

3.1 Selection of an optimal propeller in nozzle

In order to increase the propulsive efficiency, ducted propellers should be selected for the same estimated maximal ship speed (as in previous case) and unrestricted fairway conditions. For the further analysis the propeller of Ka 4-70 series with nozzle No. 19A [12] were chosen. Namely, ducted propellers in accelerating nozzle are usually used for all cases when the ship screw is heavily loaded or is limited in diameter. The length-diameter ratio of this nozzle is 0.5. As the nozzle has some thickness, allowed propeller diameter was reduced for 10% (compared to already selected naked propeller), hence the draught of the vessel with nozzle will be the same as with the naked propeller.

Characteristics of optimal propellers are determined by computer program developed at the Department of Naval Architecture in Belgrade [13].
More details are given in the Appendix 2.

MV “HENDRIK”

For the same initial conditions as are those given in the Section 2.2, characteristics of optimal propeller in nozzle are shown in Table 14.

Table 14 – Characteristics of optimal Ka 4-70 propeller

Number of blades	[-]	4
Propeller diameter	[m]	1.35
Propeller revolutions	[rpm]	394.5
Propeller area ratio	[-]	0.7
Pitch-diameter ratio	[-]	1.200

MV “RHEINLAND”

For the same initial conditions as are those given in the Section 2.2, characteristics of optimal propeller in nozzle are shown in Table 15.

Table 15 – Characteristics of optimal Ka 4-70 propeller

Number of blades	[-]	4
Propeller diameter	[m]	0.9
Propeller revolutions	[rpm]	656.9
Propeller area ratio	[-]	0.7
Pitch-diameter ratio	[-]	1.150

3.2 *Propulsive efficiency improvements*

MV "HENDRIK"

By replacing conventional propeller (optimal naked propeller) with the selected propeller in nozzle (see 3.1) expected propulsive efficiency dramatically increased – see Figure 13. Accordingly, required delivered power with respect to ship size, water depth and ship speed is shown in Figure 14.

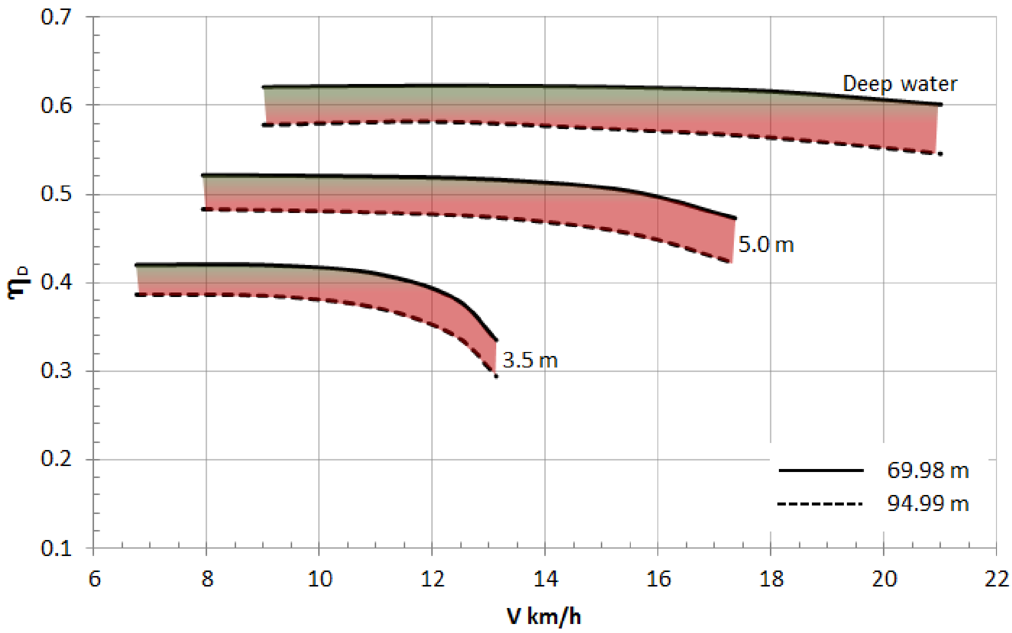


Figure 13 – Estimated propulsion efficiency with propeller in nozzle

Propulsion efficiency improvements due to nozzle, compared to the naked propeller, are shown in Figure 15.

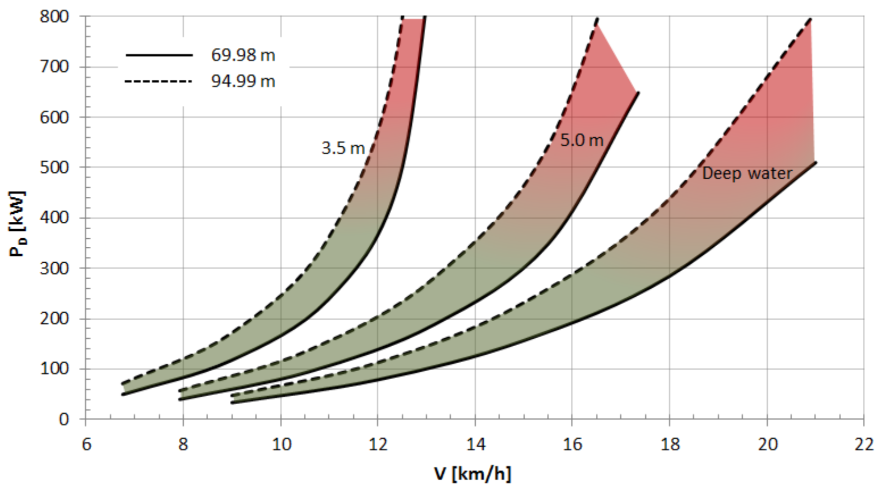


Figure 14 – Estimated required delivered power with propeller in nozzle

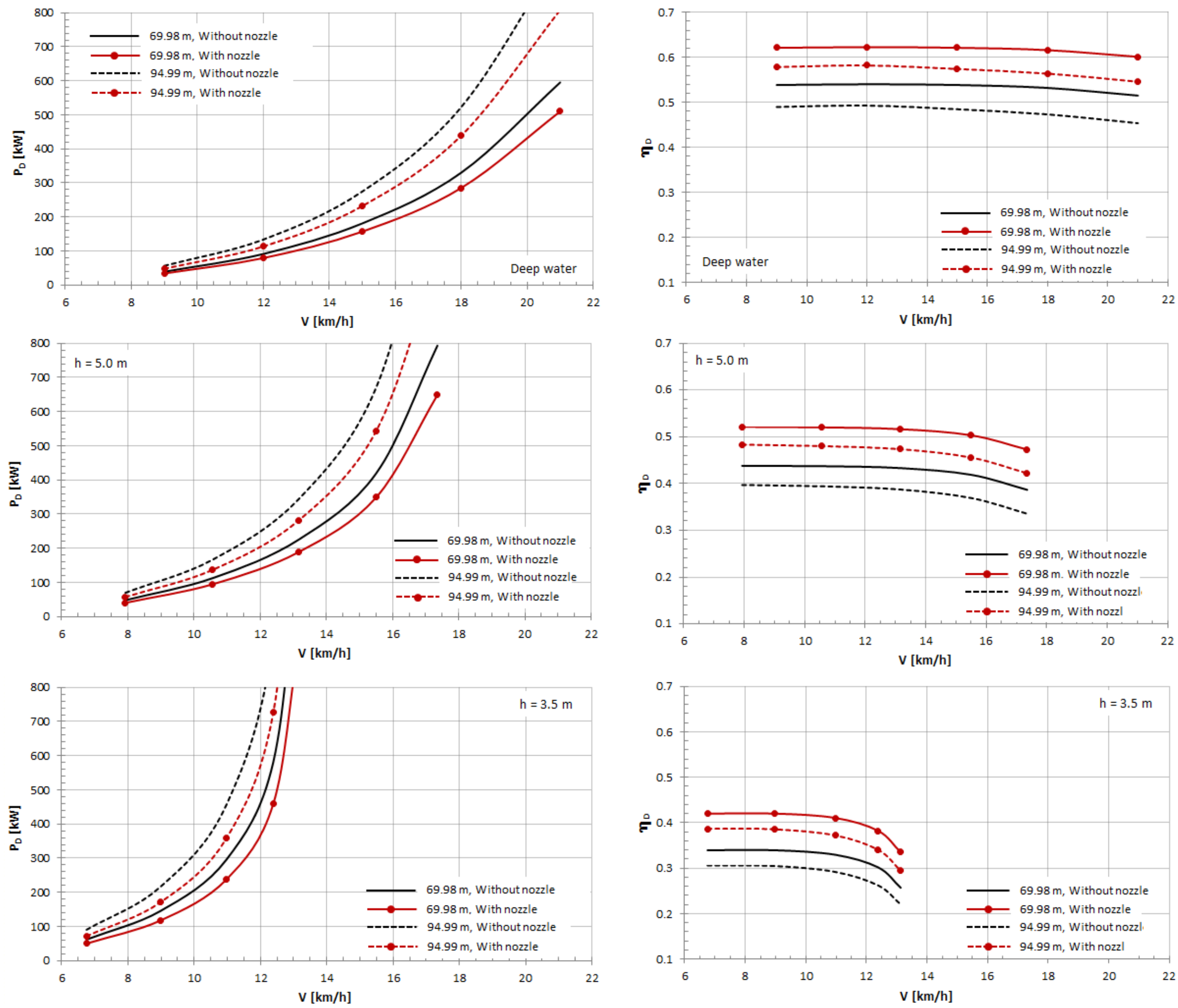


Figure 15 – Improvements due to nozzle

MV “RHEINLAND”

Application of propeller in nozzle instead of the naked one is justified, the efficiency is higher even in deep water – see Figures 16 and 17.

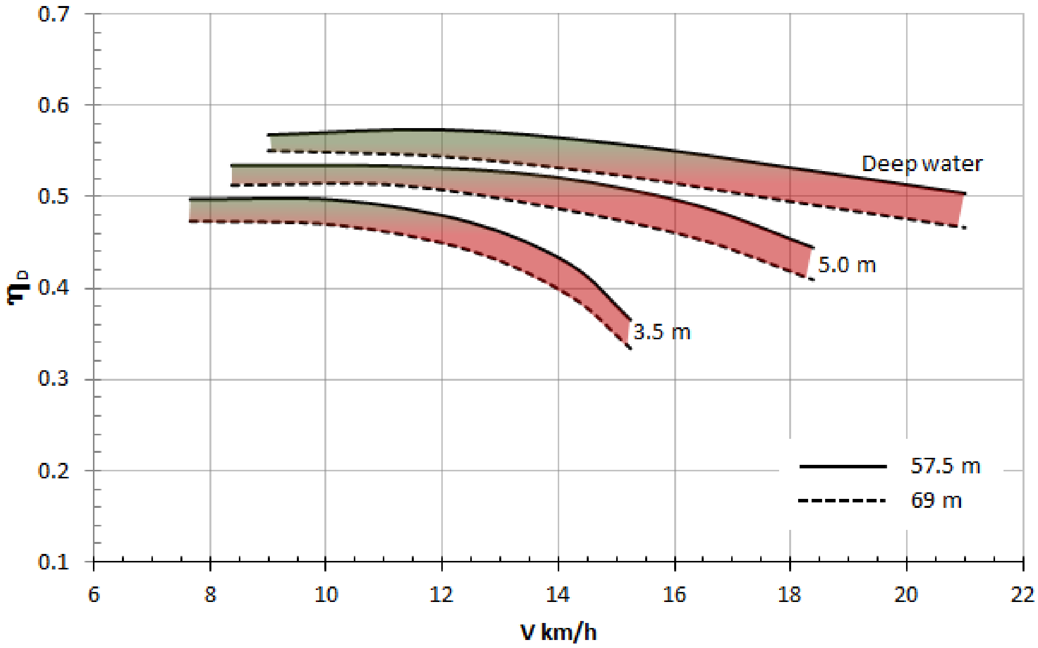


Figure 16 – Estimated propulsion efficiency with propeller in nozzle

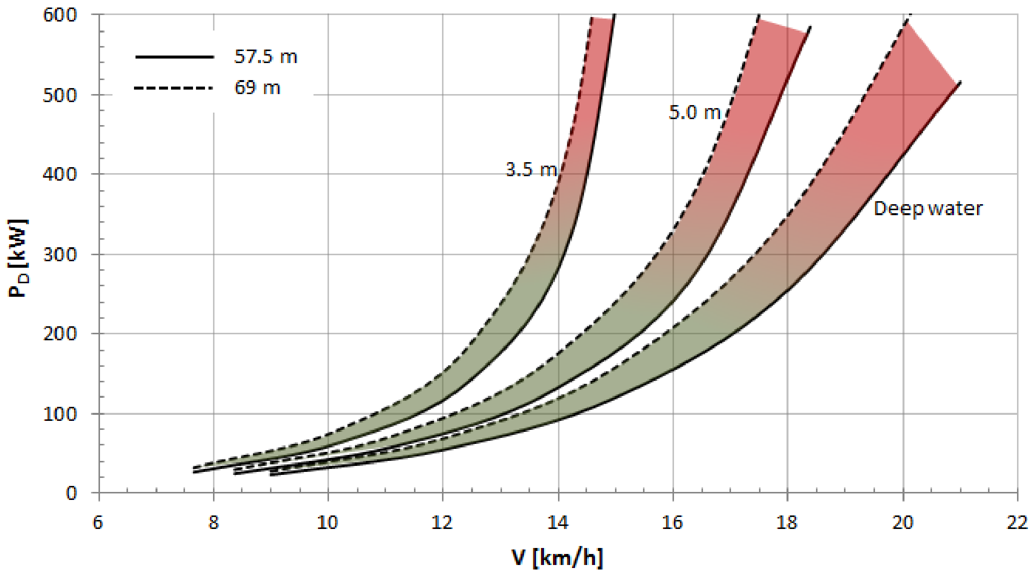


Figure 17 – Estimated required delivered power with propeller in nozzle

Propulsion efficiency improvements due to nozzle, compared to the naked propeller, are shown in Figure 18.

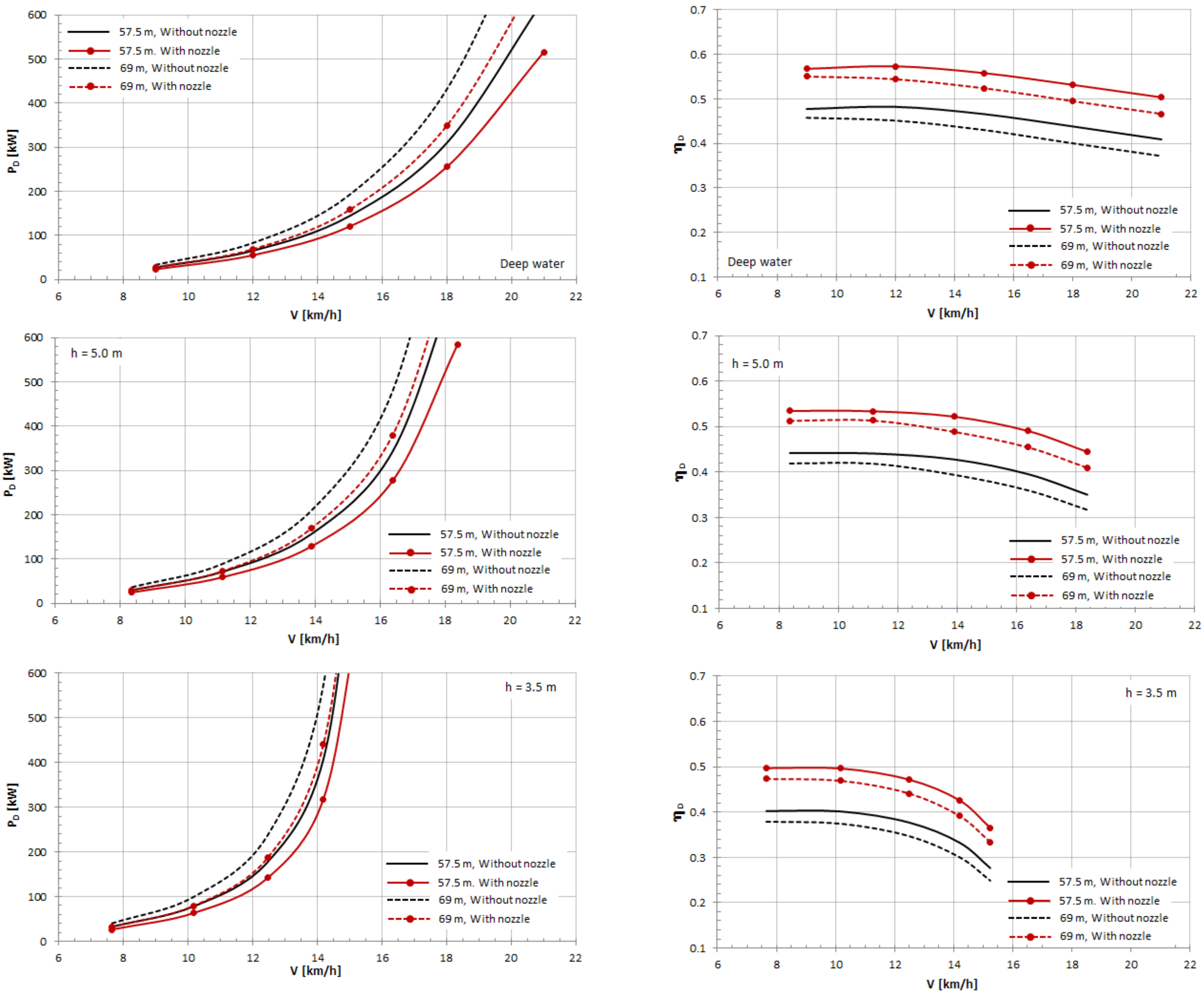
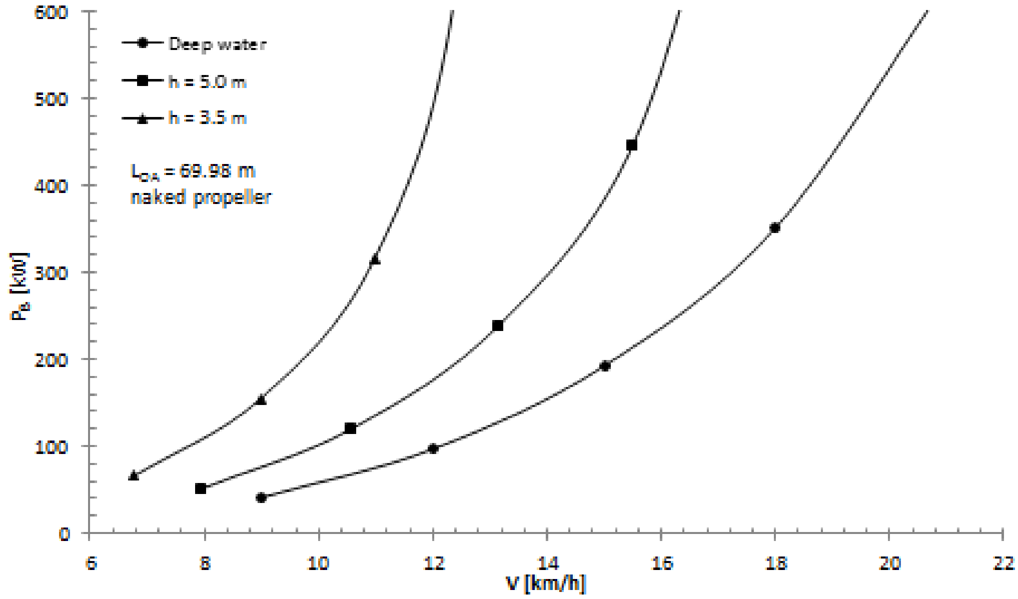


Figure 18 – Improvements due to nozzle

3.3 Installed engine power

All results concerning power needed for achieving certain speed that are presented so far, regardless the length of analysed ships and the type of propellers (with or without the nozzle), having in mind that shaft and gear loses were assumed to be 6%, within considered water depths are summarized in Figures 19 and 20.

MV "HENDRIK"



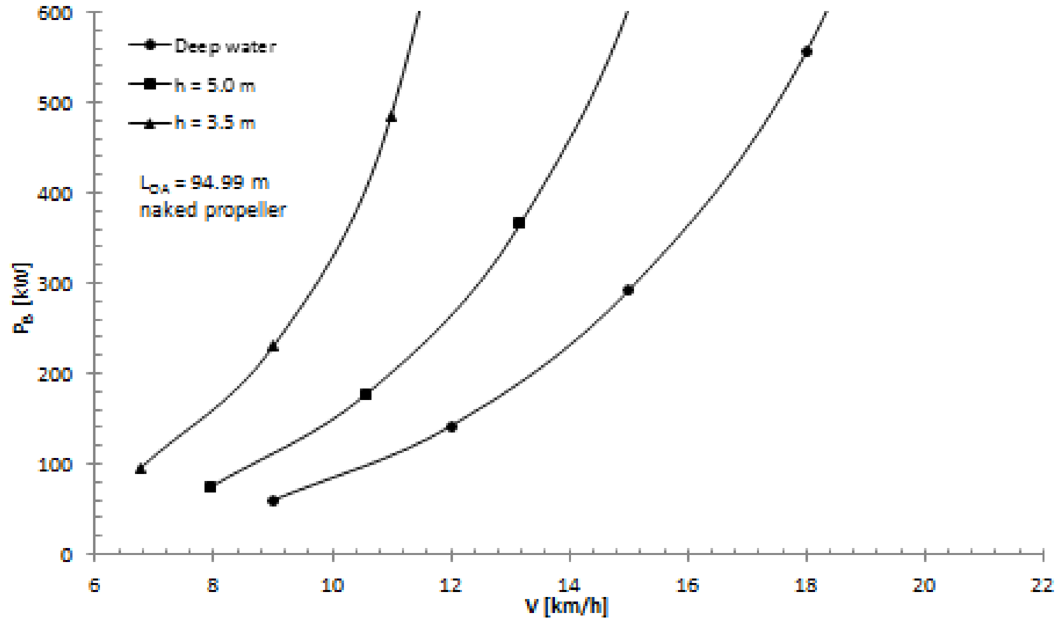
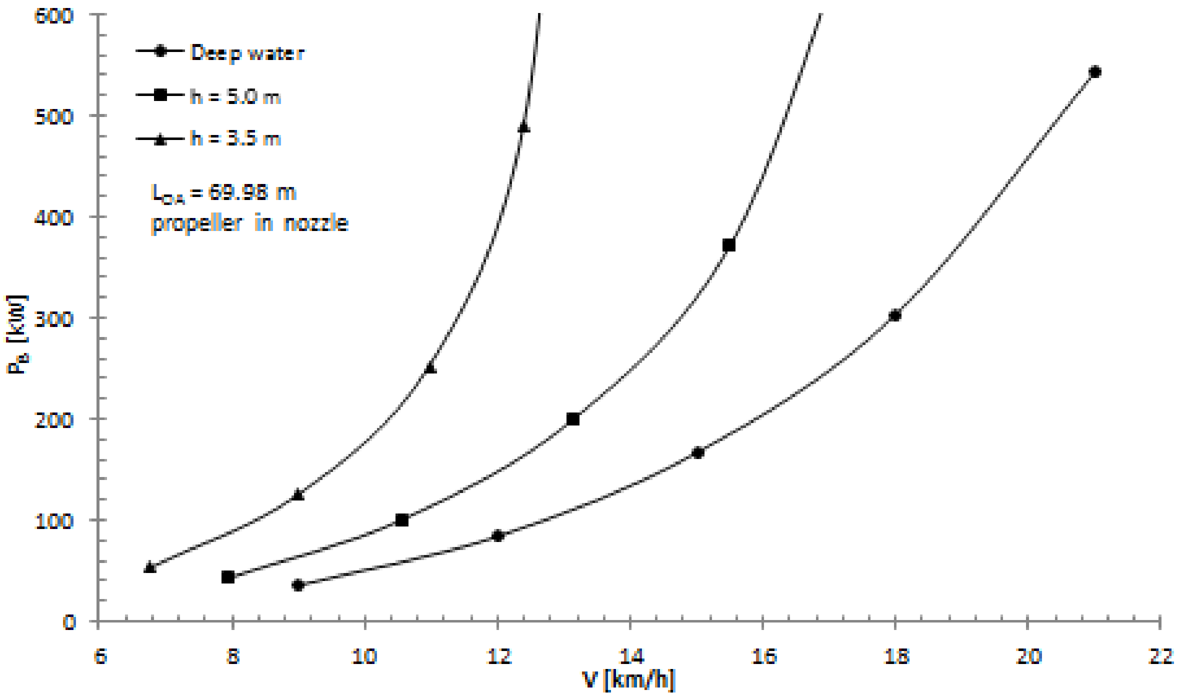


Figure 19a – Installed power P_B kW as function of ship speed V (naked propeller)



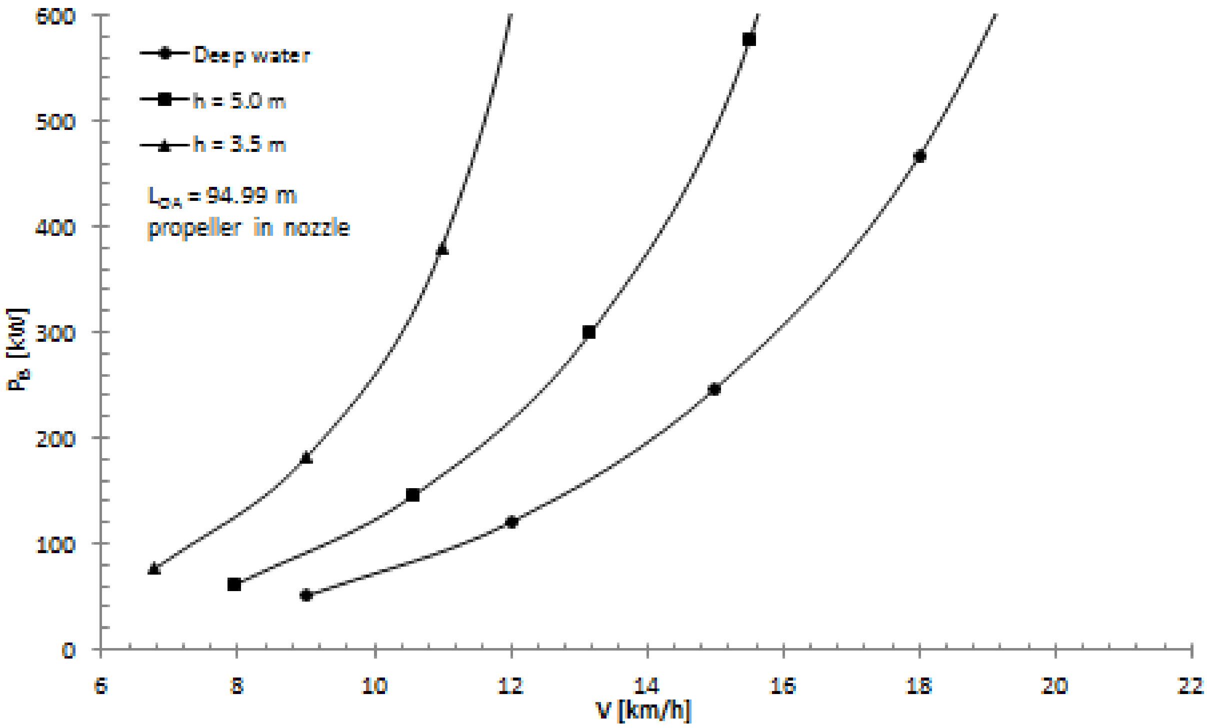
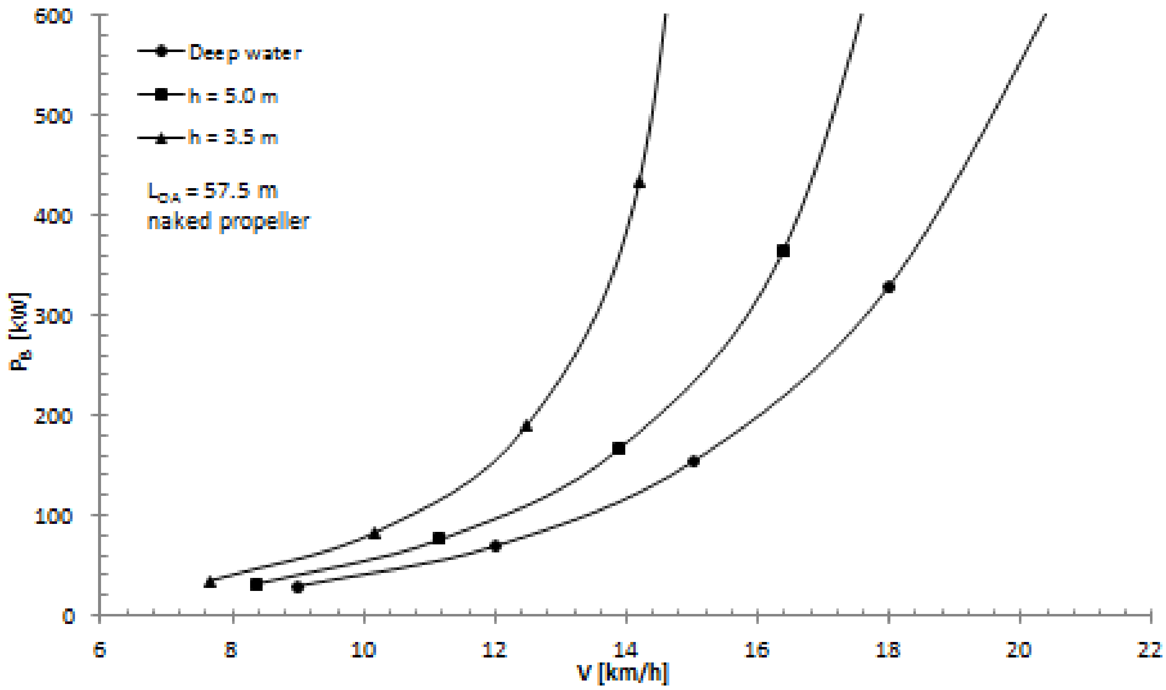


Figure 19b – Installed power P_B kW as function of ship speed V (propeller in nozzle)

MV “RHEINLAND”



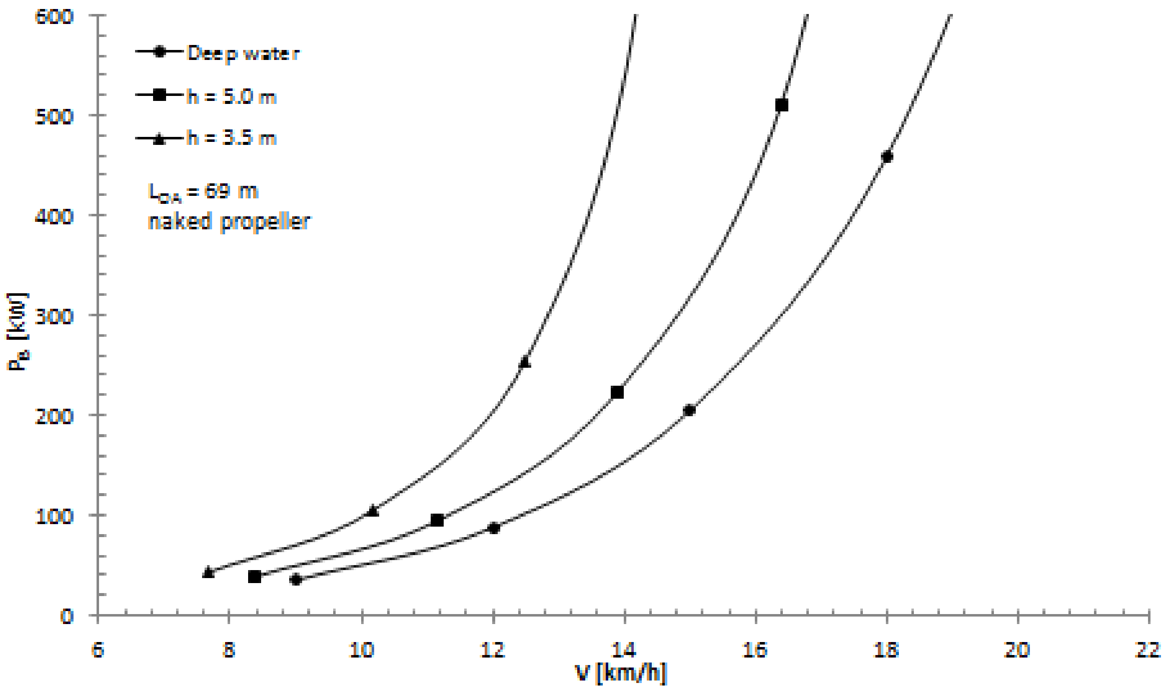
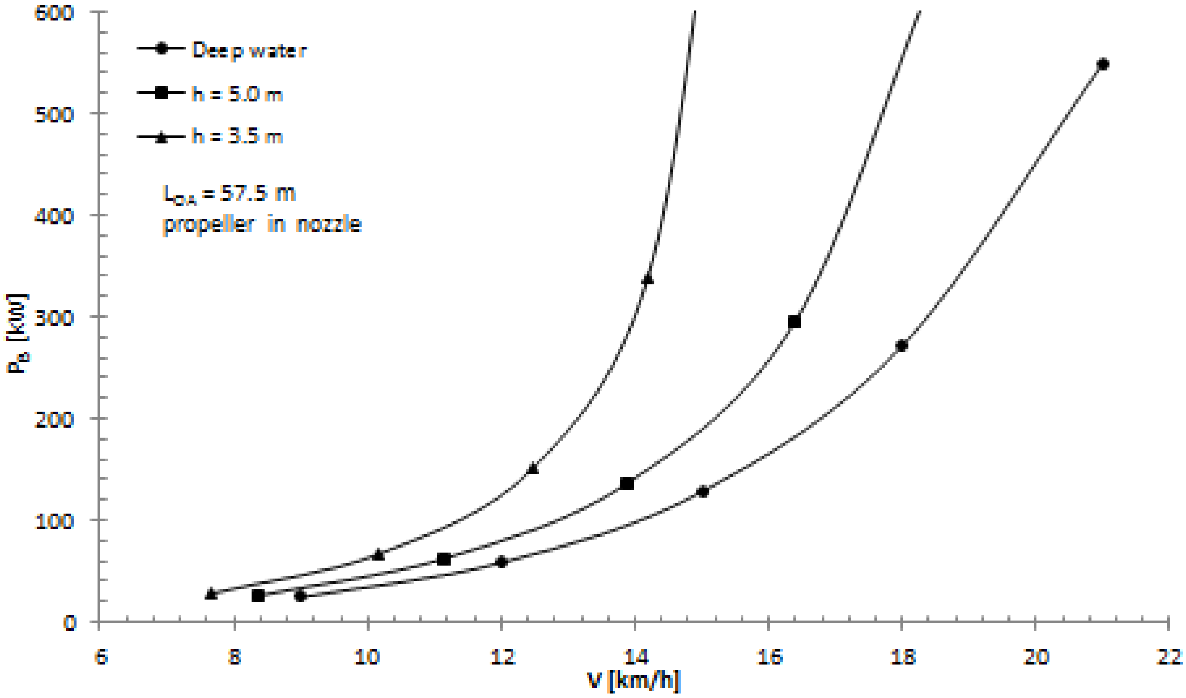


Figure 20a – Installed power P_B kW as function ship speed V (naked propeller)



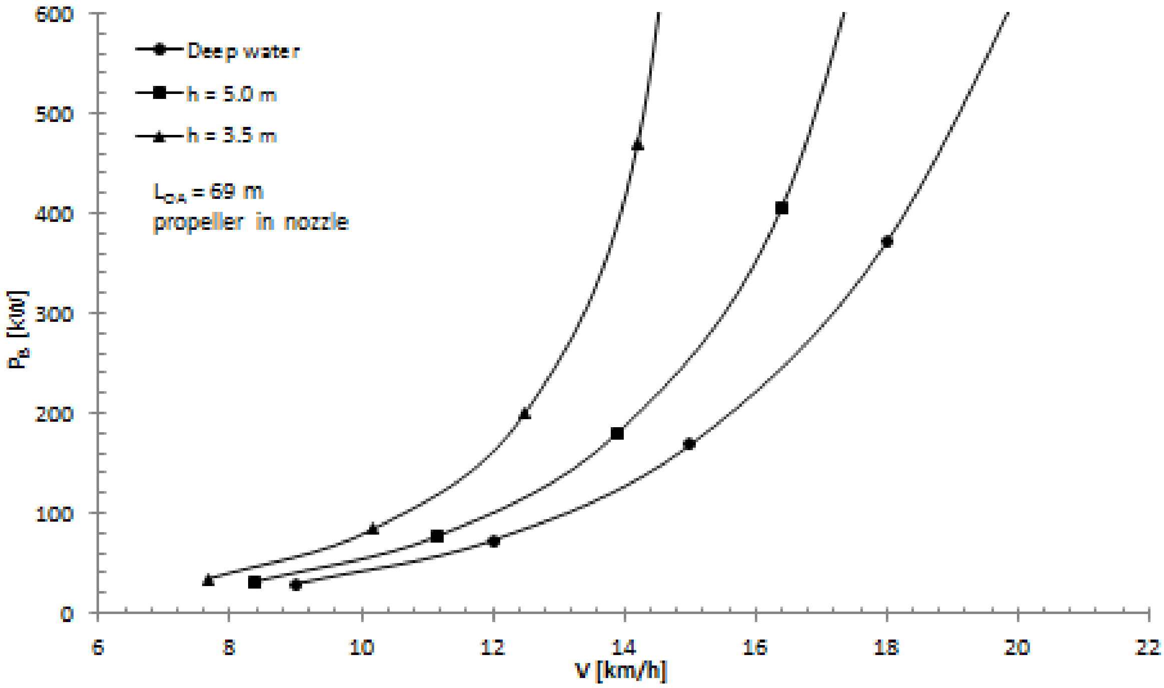


Figure 20b – Installed power P_B kW as function ship speed V (propeller in nozzle)

3.4 Evaluation of power for any ship length

Procedure (based on interpolation) for evaluation of ship speed in case of ship length variation between initial (minimal) and maximal considered length is described, and is as follows:

- Speed of ship should be read form the diagrams given in the Figures 19 and 20 (for MV “Hendrik” and for MV “Rheinland” respectively) for the same engine power and considered water depth, i.e.
  - Vmin – the speed of a ship with maximal length (Lmax)
  - Vmax – the speed of a ship with minimal length (Lmin)

- Then, for the same engine power and fairway depth, speed of ship of any length can be evaluated from the following equation:

$$V = V_{min} + \frac{(L_{max} - L) \cdot (V_{max} - V_{min})}{L_{max} - L_{min}}$$

(where L is a target length of a ship which must be between minimal and maximal considered values).

This procedure can be used for evaluation of ship speed regardless of propeller type (naked propeller or propeller in nozzle). It is important, however, to read both Vmin and Vmax from the diagrams related to the same propeller type.
Similarly, interpolation should be applied when power should be evaluated for water depths other than considered (3.5, 5 and ∞ m).

4 SPEED REDUCTION WHEN SAILING IN SHALLOW WATER

4.1 SQUAT estimation

Ship navigation in shallow water follows hydrodynamic phenomenon called squat. Namely, ship additionally sinks and changes trim while moving through the water at certain speed due to the reduction of pressure beneath the hull. If not taken into account, squat might be dangerous and can cause grounding and damages. Squat depends of water depth and ship dimensions, but of the main influence is actually ship speed.

Methods applied here for squat prediction, according to [14], are:

- Huuska (1976),
- Eryuzlu&Hausser (1978),
- Romisch (1989),
- Millward (1990) and
- Millward (1992)

More details are given in Appendix 5.

MV “HENDRIK”

Average values of estimated squat effects with respect to ship size, speed and water depth are presented in Figures 21 and 22.

According to presented results the following can be summarized:

- In case of waterway depth of 3.5m the maximal ship speed should not exceed 8 km/h
- In case of waterway depth of 5.0m the maximal ship speed should not exceed 13 km/h.

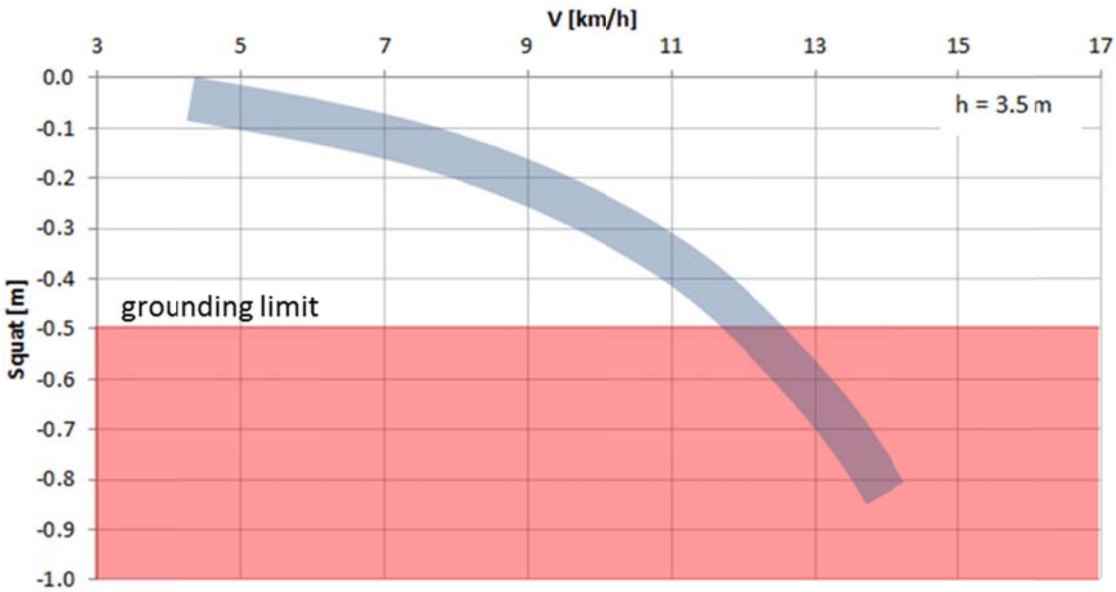


Figure 21 – Estimated squat (h=3.5m)

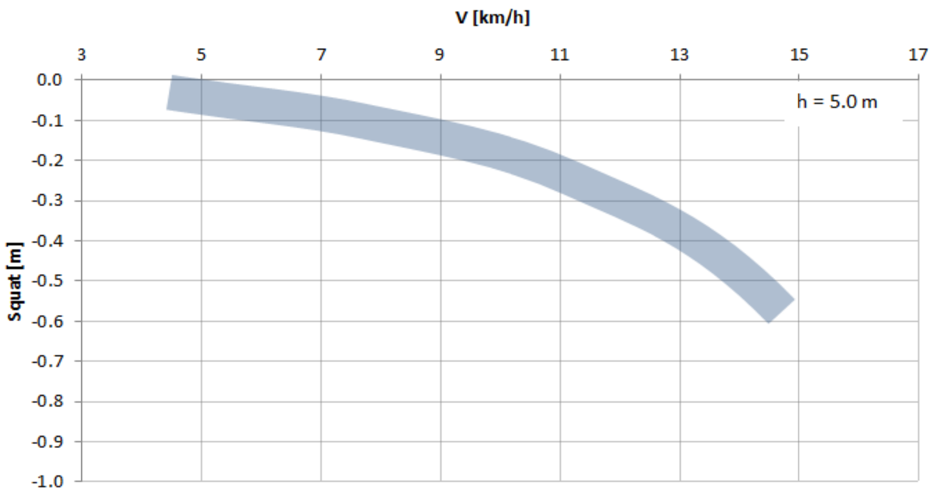


Figure 22 – Estimated squat (h=5.0m)

MV "RHEINLAND"

Average values of estimated squat effects with respect to ship size and speed are presented in Figure 23.

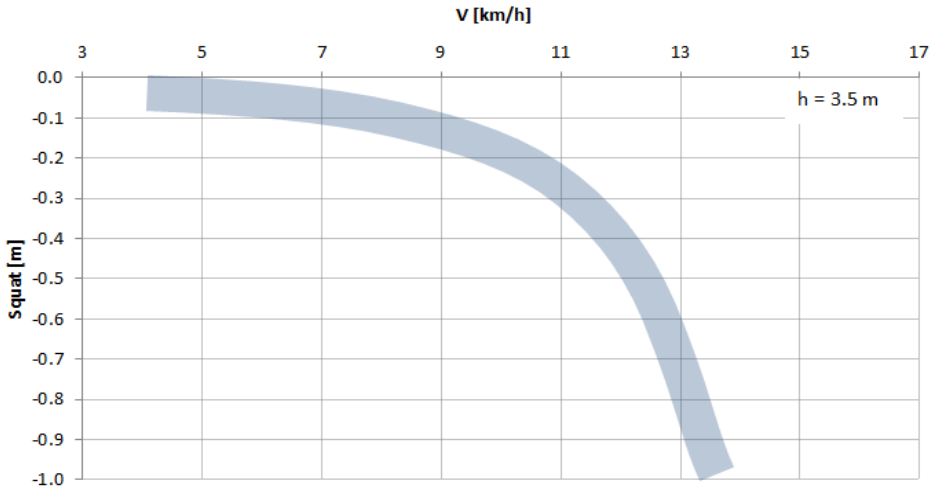


Figure 23 – Estimated squat (h=3.5m)

Accordingly, the maximal ship speed should not exceed 10 km/h.

5 REPOWERING (PHASE III - NEW POWER TRAIN)

5.1 Selection of Main engines and gearboxes

Diesel engines dominate IWW sector nowadays. Modern engines that are used on inland ships are often marinized general-application diesel engines (generating-set engines having 1500 or 1800 rpm for 50 or 60 Hz, respectively) or are truck engines. Both engine types are much lighter and cheaper than their predecessors, not to mention that they are an order of magnitude cleaner than older ship engines. As a consequence, contemporary gearboxes have to have higher gear ratios than those of few decades ago.

MV "HENDRIK"

According to power requirements related to ship navigation in deep water (see Section 2.2), basic characteristics of diesel engine that is selected for this analysis for all considered lengthening options are given in Table 16.

Table 16 – Basic characteristic of selected diesel engine [15]

Cummins	**CUMMINS INC.** Columbus, IN 47201 Marine Performance Curves	Basic Engine Model **QSK19-M**	Curve Number: **M-4532**	
		Engine Configuration **D193102MX03**	CPL Code: **3455**	Date: **21-Dec-11**

Displacement:	**18.9 liter**	**[1150 in³]**	Rated	**492 kw**	**[660 bhp]**
Bore:	**159 mm**	**[6.25 in]**	Rated	**1800 rpm**	
Stroke:	**159 mm**	**[6.25 in]**	Rating Type:	**Continuous Duty**	
Cylinders:	**6**		Aspiration:	**Turbocharged / LTA**	
Fuel System:	**Modular Common Rail (MCRS) with C3.0 Injectors**				

CERTIFIED: This diesel engine complies with or is certified to the following agencies requirements:
EPA Tier 2 - Model year requirements of the EPA marine regulation (40CFR94)
EU Stage IIIa - EC Nonroad Mobile Machinery Directive (2004/26/EC)
IMO Tier II (Two) NOx requirements of International Maritime Organization (IMO), MARPOL 73/78 Annex VI, Regulation 13

Based on engine characteristics (rpm) and required propeller revolutions for optimal performance in deep water, the following gearbox was selected: ZF W2300 or similar with gear ratio equal to 4.444.

Table 17 – Basic characteristic of selected gearbox [16]

RATIOS	MAX. TORQUE		POWER/RPM		INPUT POWER CAPACITY						MAX. RPM
	Nm	ftlb	kW	hp	kW	hp	kW	hp	kW	hp	
					1600 rpm		1800 rpm		2100 rpm		
3.028*, 3.500*, 4.000, 4.444, 4.760*	2692	1986	0.2819	0.3780	451	605	507	680	592	794	2100

More detailed characteristics of selected diesel engine are given in the Appendix 3.

For optimal propeller performances it is suggested that engine revolutions should be blocked to 1750 rpm.

MV "RHEINLAND"

According to power requirements related to ship navigation in deep water, basic characteristics of Volvo Penta D13 MH or similar inboard diesel engine that is selected for all considered lengthening options are given in Table 18.

Table 18 – Basic characteristic of selected diesel engine [17]

Technical Data

Engine designation	**D13 MH**
No. of cylinders and configuration	in-line 6
Method of operation	4-stroke, direct-injected, turbocharged
	diesel engine with charge air cooler
Bore/stroke, mm (in.)	131/158 (5.16/6.22)
Displacement, l (in^3)	12.78 (779.7)
Compression ratio	18.5
Dry weight bobtail (KC), kg (lb)	1480 (3263)
Dry weight bobtail (HE), kg (lb)	1520 (3351)
Rating/rpm	R1/1800 rpm
Crankshaft power, kW (hp)	294 (400)
Max. torque, Nm (lbf.ft) @ 1400 rpm	1756 (1295)
g/kWh (lb/hph) @1800 rpm	208 (0.336)
Certificates	IMO NOx,
	EU IWW,
	CCNR Stage 2

Technical data according to ISO 3046 Fuel Stop Power and ISO 8665. Fuel with a lower calorific value of 42700 kJ/kg and density of 840 g/liter at 15°C (60°F). Merchant fuel may differ from this specification which will influence engine power output and fuel consumption.
Ratings R1 & R2, see explanation in Volvo Penta's Sales Guide.
The engine is classifiable by major classification societies.

Based on engine characteristics (rpm) and required propeller revolutions for optimal performance in deep water the following gearbox was selected: ZF 360 or similar with gear ratio equal to 2.625.

Table 19. Basic characteristic of selected gearbox [16]

RATIOS	MAX. TORQUE		POWER/RPM		INPUT POWER CAPACITY						MAX.
	Nm	ftlb	kW	hp	kW	hp	kW	hp	kW	hp	RPM
					1600 rpm		1800 rpm		2100 rpm		
0.925*, 1.000, 1.045, 1.125*, 1.237, 1.500, 1.774, 1.966, 2.185, 2.480, 2.625	1721	1269	0.1802	0.2417	288	387	324	435	378	507	3000

More detailed characteristics of selected diesel engine is given in the Appendix 3.

For optimal propeller performances it is suggested that engine revolutions should be blocked to 1750 rpm.

5.2 Layout diagrams

MV "HENDRIK"

Layout diagrams for MV "Hendrik", considering modernized power train (engine/gearbox/propeller) for initially built ship, as well as for the longest analyzed option, with respect to depth of the fairway, are shown in Figures 24 and 25 respectively.

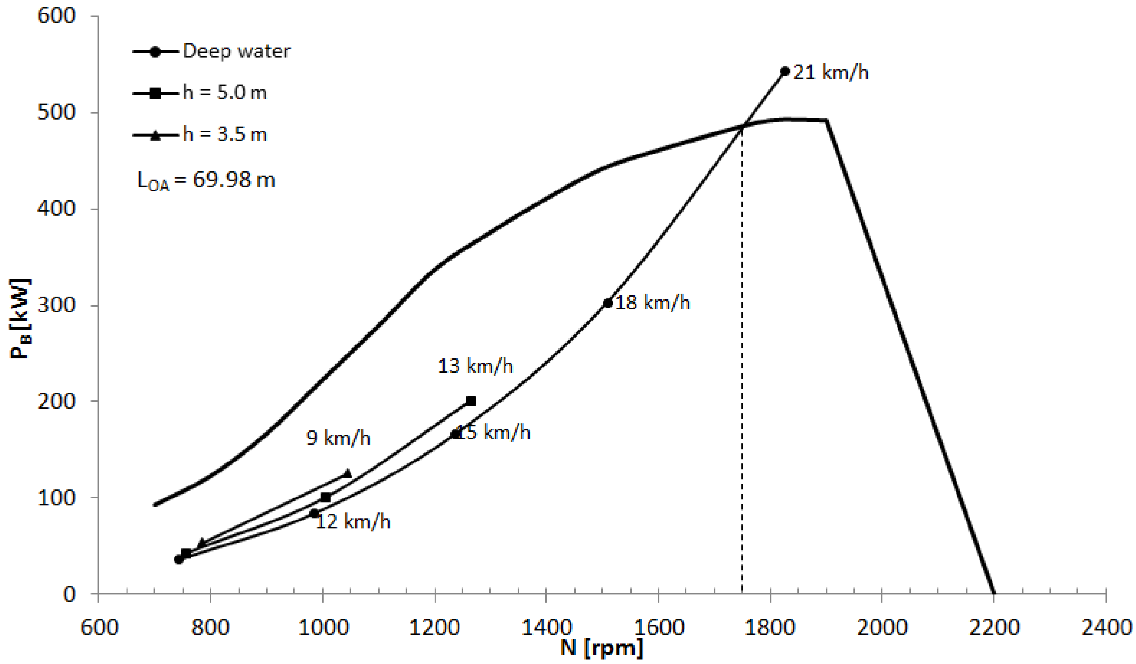


Figure 24 – Initially built ship with modernized power train

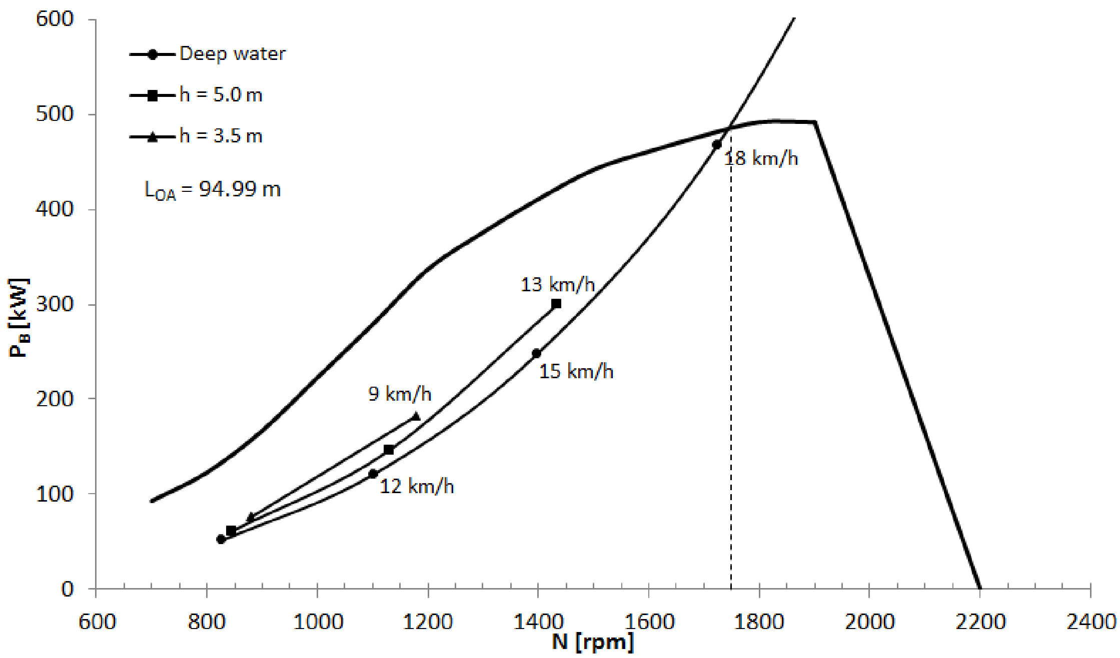


Figure 25 – Maximal considered lengthening option with modernized power train

MV "RHEINLAND"

Layout diagrams for MV "Rheinland", considering modernized power train (engine/gearbox/propeller) for initially built ship, as well as for the longest analyzed option, with respect to depth of the fairway, are shown in Figures 26 and 27 respectively.

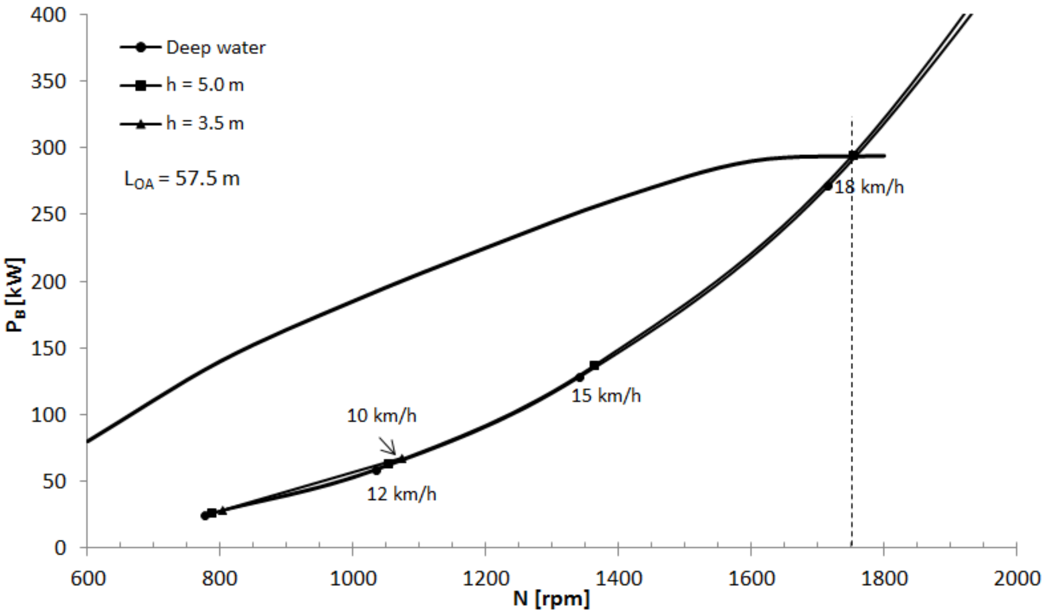


Figure 26 – Initially built ship with modernized power train

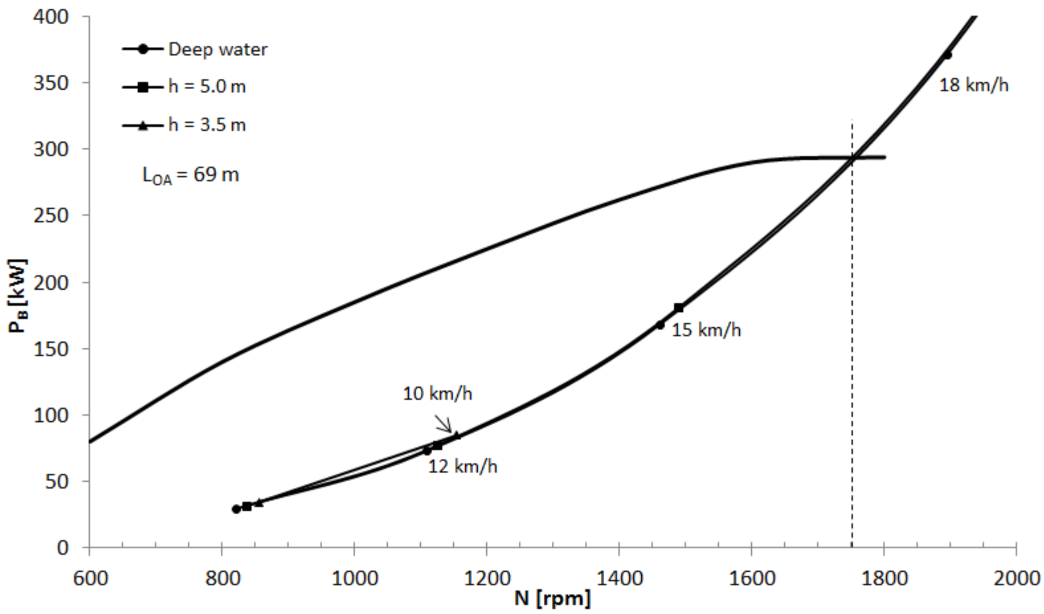


Figure 27 – Maximal considered lengthening option with modernized power train

6 CONCLUDING REMARKS

From the results of the analysis the following can be summarized:

- Repowering for two typical forty or so years old IWW single-propeller ships was considered. Both ships were virtually lengthened while the bow and stern sections were not changed. Also, naked propeller was replaced with a propeller in nozzle. Special attention was paid to shallow water effects.

- Contemporary high-speed Diesel engines were considered for retrofitting (derived from general application engines that satisfy all contemporary requirements regarding emissions etc.) as these are more efficient, cleaner, cheaper (for maintenance too) and lighter than conventional ship engines.

- Since power needed for achieving certain speed was not significantly influenced by lengthening, the same power train (engine/gearbox/propeller) was considered for all lengthening steps.

- Due to the lengthening, speed reduction is 1 to 2 km/h (when the same engine power is engaged).

- Water depth is the main factor that influences power needed for achieving certain ship speed. Speed reduction for MV “Hendrik” and MV “Rheinland” from deep to shallow water (deep to h=5 m, and then from 5 m to 3.5 m) is around 4 km/h and 2 km/h, respectively.

- Propulsive efficiency can be significantly improved if naked propeller is replaced with the propeller in nozzle (improvement of ~10%, which increases speed up to 1 km/h).

- In very shallow water, due to squat effect (and wave wake too), reduction of navigational speed is necessary. Maximal allowed speed for *Hendrik* is 13 km/h and 8 km/h for h=5 m and 3.5 m respectively (in deep water – 18 ÷ 20 km/h depending on ship length), while for MV “Rheinland” speed should be reduced to around 10 km/h for h=3.5 (in deep water – 16.8 ÷ 18.2 km/h depending on ship length).

- For evaluation of power needed for achieving certain speed for any considered length, water depth or propulsor type, diagrams 19 and 20 should be used (Section 3.3). Interpolation should be applied when power is evaluated for intermediate values of lengths and water depths – procedure is given in Section 3.4. Fuel consumption depends on engine type and for those virtually chosen for repowering of MV “Hendrik” and MV “Rheinland” is given in the Appendix 3.

NOMENCLATURE

B [m]	–	breadth
C_B	–	block coefficient
C_P	–	prismatic coefficient
Frh	–	Froude number based on water depth
h [m]	–	water depth
LCB [m]	–	longitudinal centre of buoyancy
L_{OA} [m]	–	length over all
L_{BP} [m]	–	length between perpendiculars
L_{WL} [m	–	waterline length
N [rpm]	–	engine speed
N_P [rpm]	–	the propeller's rotational speed in revolutions per unit of time
P_B [kW]	–	brake power
P_D [kW]	–	delivered power
P_E [kW]	–	effective power
R_T [kN]	–	ship resistance
S [m]	–	squat
T [m]	–	draught

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APPENDICES

APPENDIX 1

Delivered power evaluation - naked propeller

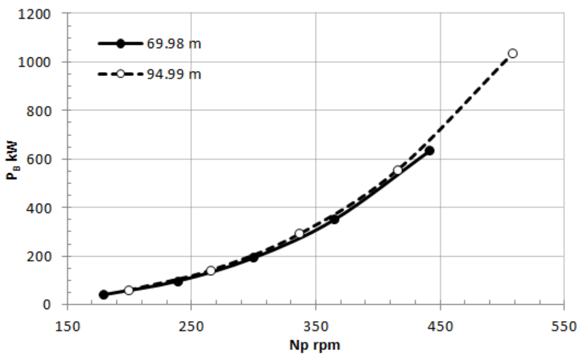
MV "HENDRIK"

69.98 m - Deep water

V	km/h	9	12	15	18	21
P_E	kW	20.97	49.29	97.47	175.61	306.71
V	kn	4.86	6.48	8.10	9.72	11.34
R_T	kN	8.4	14.8	23.4	35.1	52.6
Np	rpm	180	239	300	365	441
P_B	kW	41	97	193	351	633

94.99 m - Deep water

V	km/h	9	12	15	18	21
P_E	kW	27.64	65.80	133.15	247.45	441.33
V	kn	4.86	6.48	8.10	9.72	11.34
R_T	kN	11.1	19.7	32.0	49.5	75.7
Np	rpm	199	266	337	416	508
P_B	kW	60	142	292	556	1035



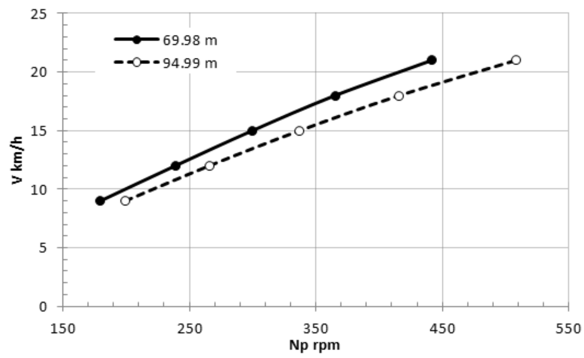


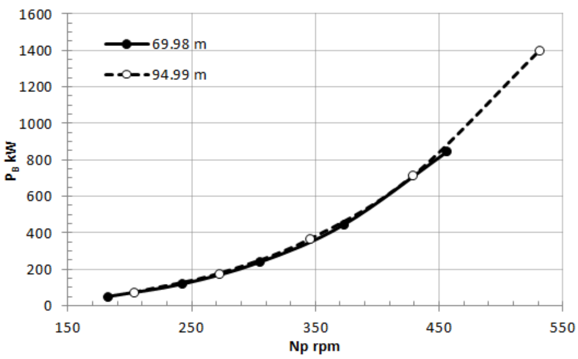
Figure 28 – Power requirements (naked propeller) in deep water

69.98 m - h = 5.0 m

V	km/h	7.93	10.57	13.16	15.50	17.35
P_E	kW	20.97	49.29	97.47	175.61	306.71
V	kn	4.28	5.71	7.11	8.37	9.37
R_T	kN	9.5	16.8	26.7	40.8	63.6
Np	rpm	182	243	305	373	456
P_B	kW	51	120	239	446	844

94.99 m - h = 5.0 m

V	km/h	7.93	10.58	13.17	15.51	17.37
P_E	kW	27.64	65.80	133.15	247.45	441.33
V	kn	4.28	5.71	7.11	8.38	9.38
R_T	kN	12.5	22.4	36.4	57.4	91.5
Np	rpm	203	272	345	429	531
P_B	kW	74	178	366	713	1400



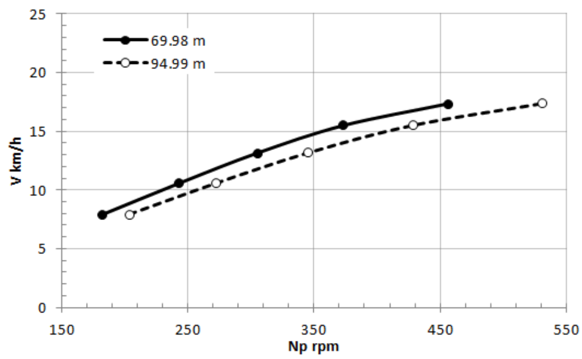


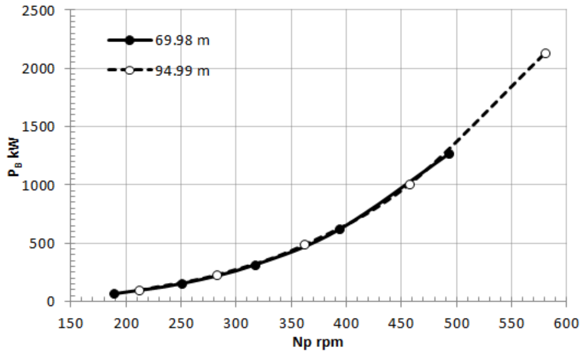
Figure 29 – Power requirements (naked propeller) in shallow water (h=5.0m)

69.98 m - h = 3.5 m

V	km/h	6.75	8.98	10.97	12.39	13.13
P_E	kW	20.97	49.29	97.47	175.61	306.71
V	kn	3.65	4.85	5.92	6.69	7.09
R_T	kN	11.2	19.8	32.0	51.0	84.1
Np	rpm	189	251	317	394	494
P_B	kW	66	154	315	619	1269

94.99 m - h = 3.5 m

V	km/h	6.76	9.00	10.99	12.41	13.16
P_E	kW	27.64	65.80	133.15	247.45	441.33
V	kn	3.65	4.86	5.93	6.70	7.10
R_T	kN	14.7	26.3	43.6	71.8	120.8
Np	rpm	212	283	362	457	580
P_B	kW	96	230	485	1005	2132



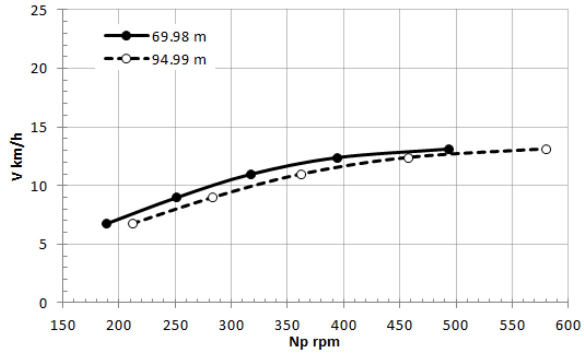


Figure 30 – Power requirements (naked propeller) in shallow water (h=3.5m)

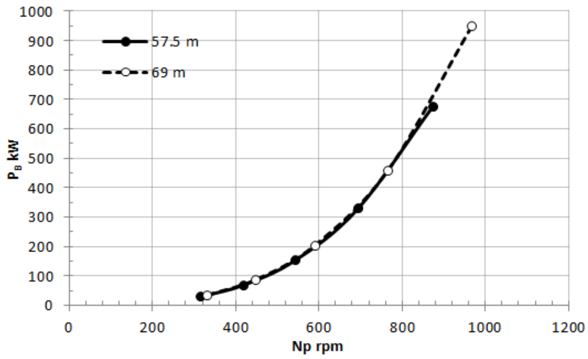
MV “RHEINLAND”

57.5 m - Deep water

V	km/h	9	12	15	18	21
P_E	kW	13.18	31.47	67.22	135.80	260.06
V	kn	4.86	6.48	8.10	9.72	11.34
R_T	kN	5.3	9.4	16.1	27.2	44.6
Np	rpm	315	419	543	694	874
P_B	kW	29	69	153	330	676

69 m - Deep water

V	km/h	9	12	15	18	21
P_E	kW	15.29	37.34	82.86	172.77	332.29
V	kn	4.86	6.48	8.10	9.72	11.34
R_T	kN	6.1	11.2	19.9	34.6	57.0
Np	rpm	332	449	591	766	968
P_B	kW	36	88	205	459	950



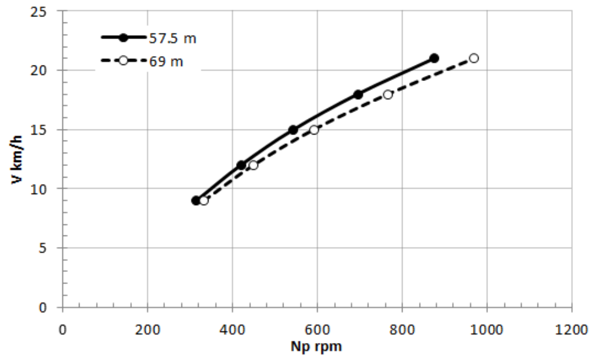


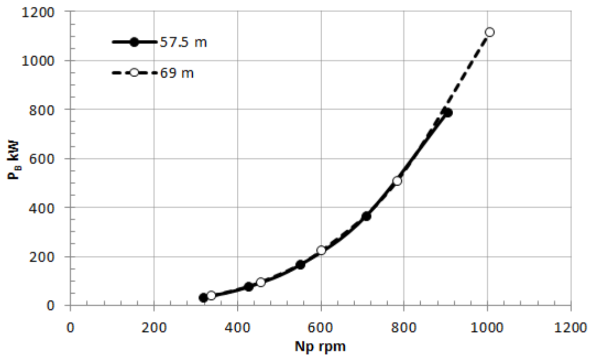
Figure 31 – Power requirements (naked propeller) in deep water

57.5 m - h = 5.0 m

V	km/h	8.37	11.16	13.90	16.39	18.39
P_E	kW	13.18	31.47	67.22	135.80	260.06
V	kn	4.52	6.03	7.51	8.85	9.93
R_T	kN	5.7	10.2	17.4	29.8	50.9
Np	rpm	319	426	552	708	904
P_B	kW	32	76	167	365	790

69 m - h = 5.0 m

V	km/h	8.37	11.16	13.90	16.39	18.39
P_E	kW	15.29	37.34	82.86	172.77	332.29
V	kn	4.52	6.03	7.51	8.85	9.93
R_T	kN	6.6	12.0	21.5	37.9	65.0
Np	rpm	338	455	602	784	1005
P_B	kW	39	95	224	511	1116



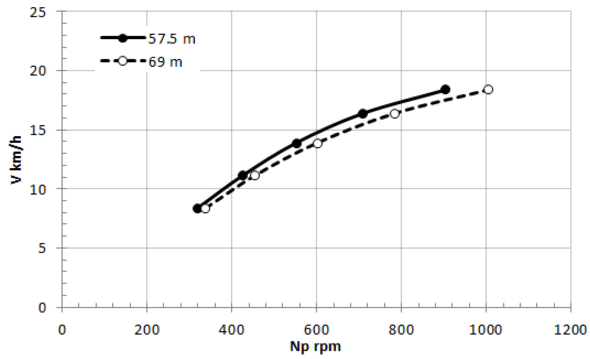


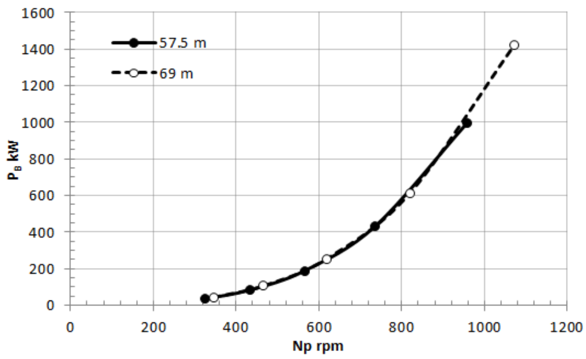
Figure 32 – Power requirements (naked propeller) in shallow water (h = 5.0 m)

57.5 m - h = 3.5 m

V	km/h	7.66	10.18	12.48	14.19	15.24
P_E	kW	13.18	31.47	67.22	135.80	260.06
V	kn	4.13	5.50	6.74	7.67	8.23
R_T	kN	6.2	11.1	19.4	34.4	61.4
Np	rpm	324	434	566	737	959
P_B	kW	35	83	189	434	1000

69 m - h = 3.5 m

V	km/h	7.66	10.19	12.49	14.21	15.25
P_E	kW	15.29	37.34	82.86	172.77	332.29
V	kn	4.14	5.50	6.74	7.67	8.24
R_T	kN	7.2	13.2	23.9	43.8	78.4
Np	rpm	345	466	619	819	1071
P_B	kW	43	106	254	611	1420



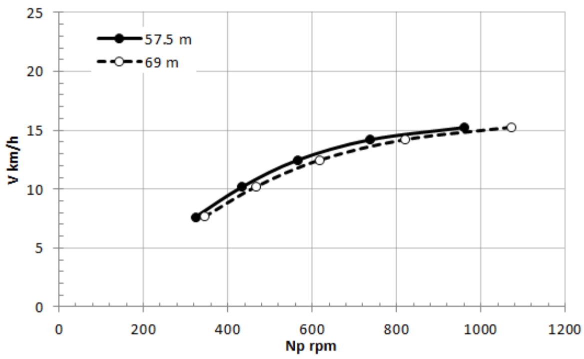


Figure 33 – Power requirements (naked propeller) in shallow water (h = 3.5 m)

APPENDIX 2

Delivered power evaluation - propeller in nozzle

MV “HENDRIK”

69.98 m - Deep water

V	km/h	9	12	15	18	21
P_E	kW	20.97	49.29	97.47	175.61	306.71
V	kn	4.86	6.48	8.10	9.72	11.34
R_T	kN	8.4	14.8	23.4	35.1	52.6
Np	rpm	167	222	279	339	411
P_B	kW	36	84	167	303	543

94.99 m - Deep water

V	km/h	9	12	15	18	21
P_E	kW	27.64	65.80	133.15	247.45	441.33
V	kn	4.86	6.48	8.10	9.72	11.34
R_T	kN	11.1	19.7	32.0	49.5	75.7
Np	rpm	186	248	314	388	474
P_B	kW	51	120	247	467	860

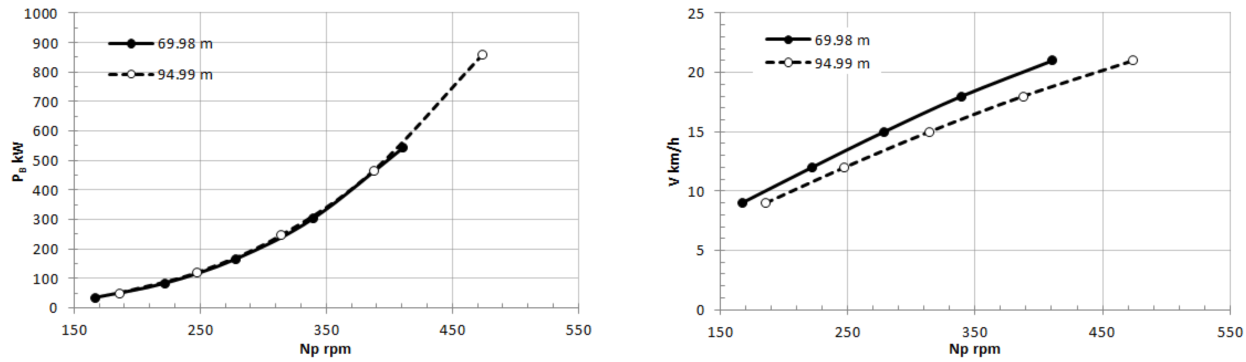


Figure 34 – Power requirements (propeller in nozzle) in deep water – MV “Hendrik”

69.98 m - h = 5.0 m

V	km/h	7.93	10.57	13.16	15.50	17.35
P_E	kW	20.97	49.29	97.47	175.61	306.71
V	kn	4.28	5.71	7.11	8.37	9.37
R_T	kN	9.5	16.8	26.7	40.8	63.6
Np	rpm	170	226	285	348	426
P_B	kW	43	101	201	371	690

94.99 m - h = 5.0 m

V	km/h	7.93	10.58	13.17	15.51	17.37
P_E	kW	27.64	65.80	133.15	247.45	441.33
V	kn	4.28	5.71	7.11	8.38	9.38
R_T	kN	12.5	22.4	36.4	57.4	91.5
Np	rpm	190	254	323	401	496
P_B	kW	61	146	299	578	1113

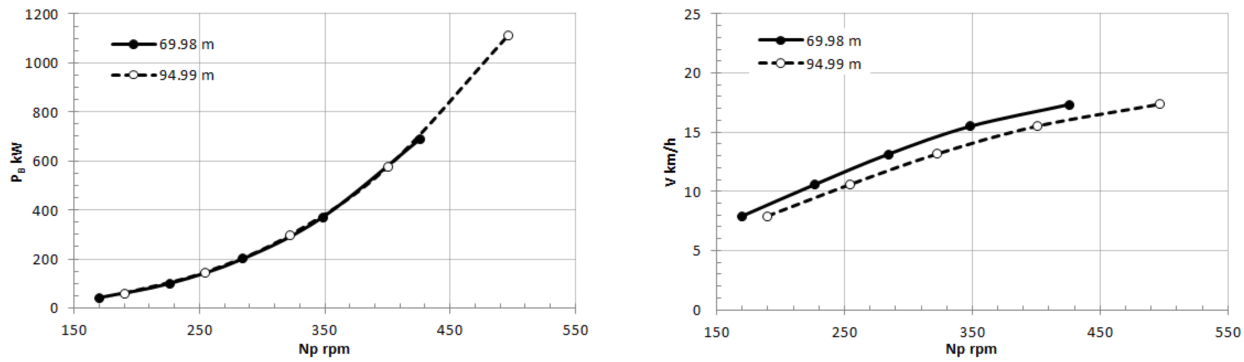


Figure 35 – Power requirements (propeller in nozzle) in shallow water (h = 5.0 m) – MV “Hendrik”

69.98 m - h = 3.5 m

V	km/h	6.75	8.98	10.97	12.39	13.13
P_E	kW	20.97	49.29	97.47	175.61	306.71
V	kn	3.65	4.85	5.92	6.69	7.09
R_T	kN	11.2	19.8	32.0	51.0	84.1
Np	rpm	177	235	297	368	461
P_B	kW	53	125	253	489	974

94.99 m - h = 3.5 m

V	km/h	6.76	9.00	10.99	12.41	13.16
P_E	kW	27.64	65.80	133.15	247.45	441.33
V	kn	3.65	4.86	5.93	6.70	7.10
R_T	kN	14.7	26.3	43.6	71.8	120.8
Np	rpm	198	265	338	427	542
P_B	kW	76	182	381	773	1595

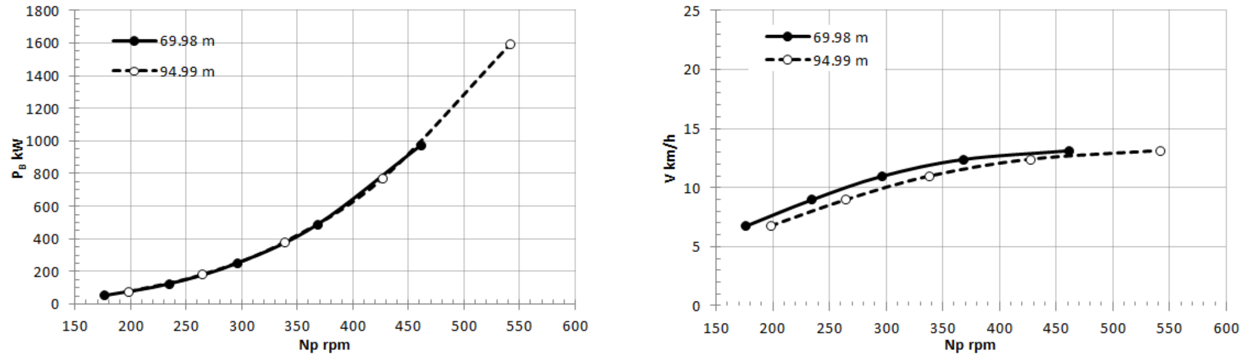


Figure 36 – Power requirements (propeller in nozzle) in shallow water (h = 3.5 m) – MV “Hendrik”

MV “RHEINLAND”

57.5 m - Deep water

V	km/h	9	12	15	18	21
P_E	kW	13.18	31.47	67.22	135.80	260.06
V	kn	4.86	6.48	8.10	9.72	11.34
R_T	kN	5.3	9.4	16.1	27.2	44.6
Np	rpm	296	394	511	654	823
P_B	kW	25	58	128	272	549

69 m - Deep water

V	km/h	9	12	15	18	21
P_E	kW	15.29	37.34	82.86	172.77	332.29
V	kn	4.86	6.48	8.10	9.72	11.34
R_T	kN	6.1	11.2	19.9	34.6	57.0
Np	rpm	313	423	557	722	912
P_B	kW	30	73	168	371	758

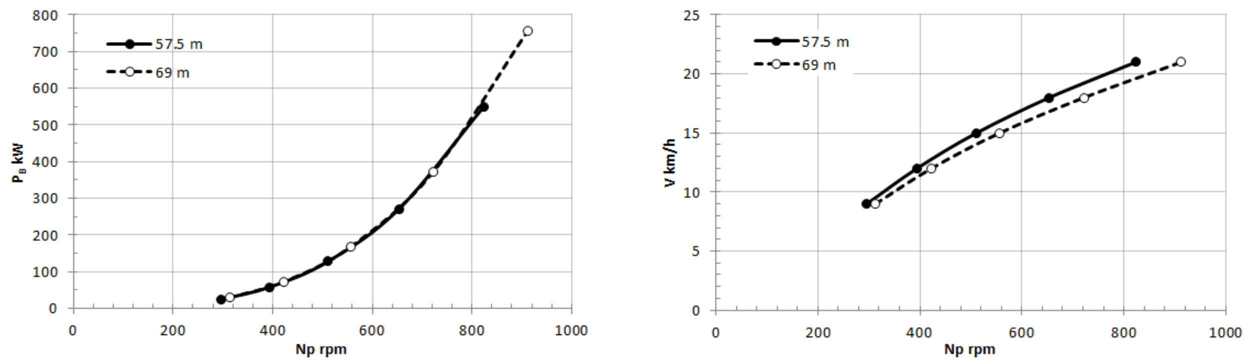


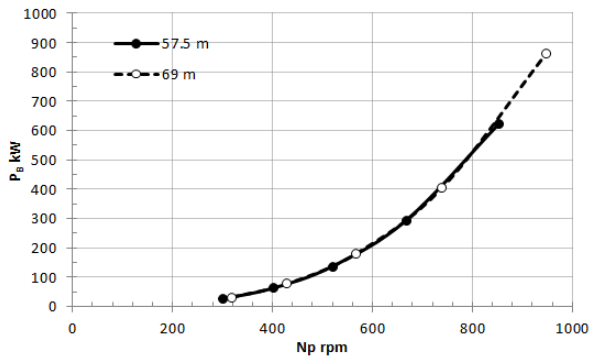
Figure 37 – Power requirements (propeller in nozzle) in deep water – MV “Rheinland”

57.5 m - h = 5.0 m

V	km/h	8.37	11.16	13.90	16.39	18.39
P_E	kW	13.18	31.47	67.22	135.80	260.06
V	kn	4.52	6.03	7.51	8.85	9.93
R_T	kN	5.7	10.2	17.4	29.8	50.9
Np	rpm	300	401	520	668	853
P_B	kW	26	63	137	295	623

69 m - h = 5.0 m

V	km/h	8.37	11.16	13.90	16.39	18.39
P_E	kW	13.18	31.47	67.22	135.80	260.06
V	kn	4.52	6.03	7.51	8.85	9.93
R_T	kN	5.7	10.1	17.4	29.8	50.9
Np	rpm	319	429	567	739	948
P_B	kW	32	77	180	405	864



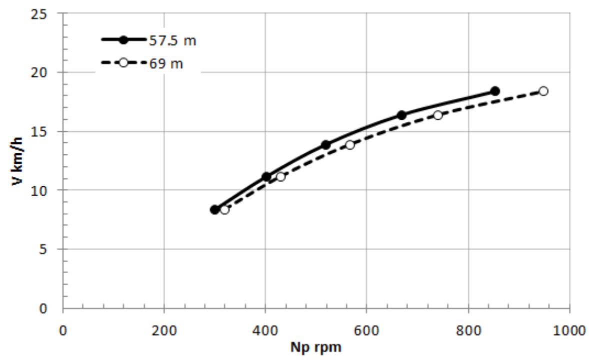


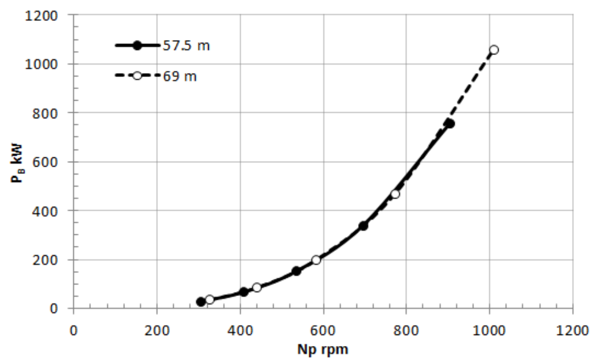
Figure 38 – Power requirements (propeller in nozzle) in shallow water (h = 5.0 m) – MV “Rheinland”

57.5 m - h = 3.5 m

V	km/h	7.66	10.18	12.48	14.19	15.24
P_E	kW	13.18	31.47	67.22	135.80	260.06
V	kn	4.13	5.50	6.74	7.67	8.23
R_T	kN	6.2	11.1	19.4	34.4	61.4
Np	rpm	306	409	534	695	904
P_B	kW	28	67	151	339	757

69 m - h = 3.5 m

V	km/h	7.66	10.19	12.49	14.21	15.25
P_E	kW	13.18	31.47	67.22	135.80	260.06
V	kn	4.14	5.50	6.74	7.67	8.24
R_T	kN	6.2	11.1	19.4	34.4	61.4
Np	rpm	326	440	583	772	1009
P_B	kW	34	85	200	469	1058



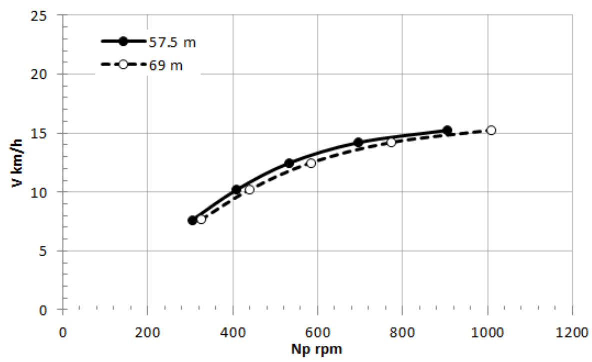


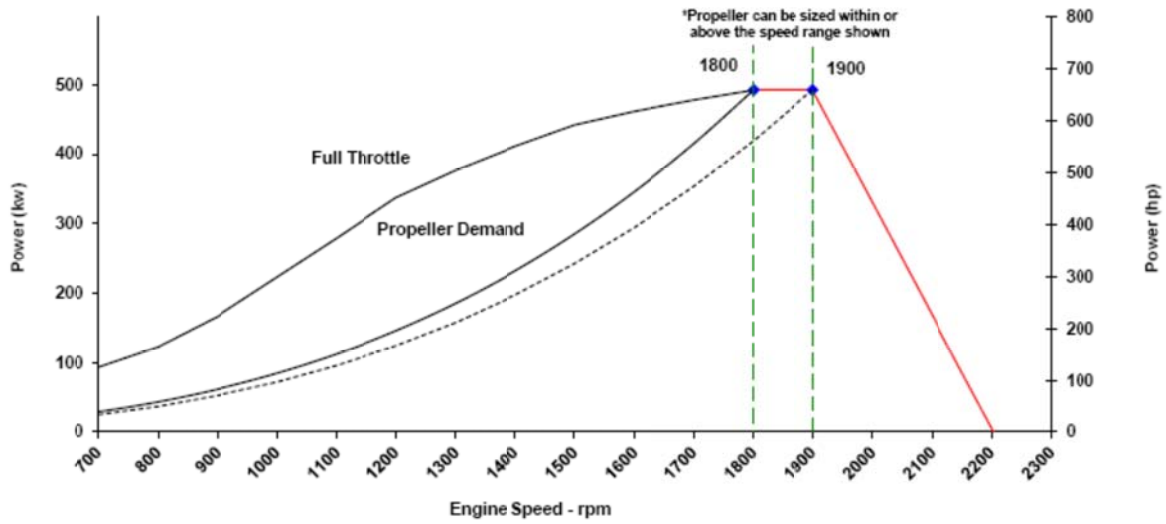
Figure 39 – Power requirements (propeller in nozzle) in shallow water (h = 3.5 m) – MV “Rheinland”

APPENDIX 3

Characteristics of selected diesel engines

MV "HENDRIK"

Main engine – CUMMINS QSK 19M (or similar)



* Cummins Full Throttle Requirements:

- Engine achieves or exceeds rated rpm at full throttle under any steady operating condition
- Engines in variable displacement boats (such as pushboats, tugboats, net draggers, etc.) achieve no less than 100 rpm below rated speed at full throttle during a dead push or bollard pull
- Engine achieves or exceeds rated rpm when accelerating from idle to full throttle

Rated Conditions: Ratings are based upon ISO 15550 reference conditions; air pressure of 100 kPa [29.612 in Hg], air temperature 25deg. C [77 deg. F] and 30% relative humidy. Power is in accordance with IMCI procedure. Member NMMA. Unless otherwise specified, tolerance on all values is +/-5%.

Full Throttle curve represents power at the crankshaft for mature gross engine performance corrected in accordance with ISO 15550. Propeller Curve represents approximate power demand from a typical propeller. Propeller Shaft Power is approximately 3% less than rated crankshaft power after typical reverse/reduction gear losses and may vary depending on the type of gear or propulsion system used.

Fuel Consumption is based on fuel of 35 deg. API gravity at 16 deg C [60 deg. F] having LHV of 42,780 kj/kg [18390 Btu/lb] and weighing 838.9 g/liter [7.001 lb/U.S. gal].

Continuous Rating (CON): Intended for continuous use in applications requiring uninterrupted service at full power. This rating is an ISO 15550 standard power rating.

Fuel System[1]

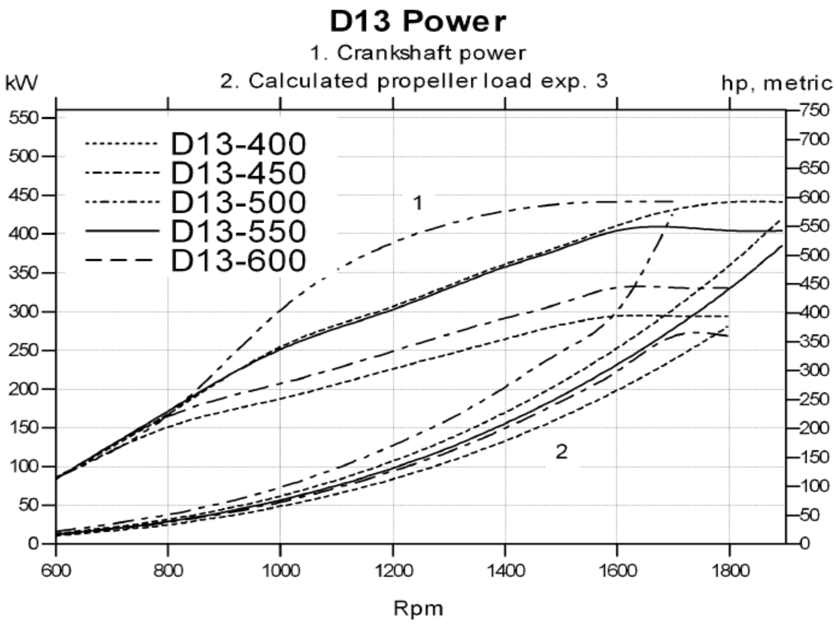
Avg. Fuel Consumption - ISO 8178 E3 Standard Test Cycle	l/hr [gal/hr]	94.9 [25.1]
Fuel Consumption at Rated Speed	l/hr [gal/hr]	126.0 [33.3]
Approximate Fuel Flow to Pump	l/hr [gal/hr]	366.8 [96.9]
Maximum Allowable Fuel Supply to Pump Temperature	°C [°F]	60.0 [140]
Approximate Fuel Flow Return to Tank	l/hr [gal/hr]	240.8 [63.6]
Approximate Fuel Return to Tank Temperature	°C [°F]	50.0 [122]
Maximum Heat Rejection to Drain Fuel	kW [Btu/min]	1.2 [70]

Emissions (in accordance with ISO 8178 Cycle E3)

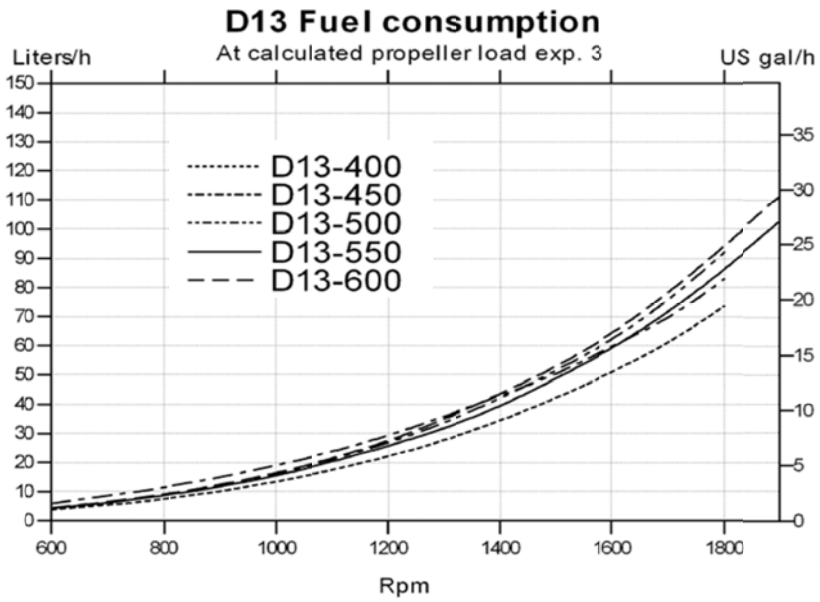
NOx (Oxides of Nitrogen)	g/kw·hr [g/hp·hr]	6.38 [4.76]
HC (Hydrocarbons)	g/kw·hr [g/hp·hr]	0.09 [0.07]
CO (Carbon Monoxide)	g/kw·hr [g/hp·hr]	1.51 [1.13]
PM (Particulate Matter)	g/kw·hr [g/hp·hr]	0.06 [0.04]

MV “RHEINLAND”

Main engine – Volvo Penta D13 MH (or similar)



Chosen model – D13-400



APPENDIX 4

Retrofitting costs*

THE COSTS OF THE EQUIPMENT FOR REPOWERING

Table 20 – Repowering costs for a needed power of 400 HP

Code	Description	No	Value in EUR (without VAT)	Value in EUR
D13MH	**VOLVO PENTA D13MH** **MARINE PROPULSION DIESEL ENGINE VOLVO PENTA TYPE D13MH:** 6 cylinders in line, power output (heavy duty rating) (P1): 400HP (294KW) @ 1800 rpm BV type approval certificate, CCNR2 certificate	1	48,760.00	48,760.00
DMT 150A	**Marine Reversing Gearbox D-I Industrial type** DMT 150H RED RATIO 2,51 / 3,08 : 1	1	6,240.00	6,240.00
EIAPP	**EIAPP CERTIFICATE**	1	1,250.00	1,250.00
RC2-C / R&D	**RIGID MOUNTS ROTACHOCK RC2-C / FLEXIBLE MOUNTS R&D FOR ENGINE MOUNTING**	2	76.00	152.00
RC2-C	**RIGID MOUNTS ROTACHOCK RC2-C FOR GEARBOX MOUNTING**	2	76.00	152.00
RC2-C	**R&D FLEXIBLE COUPLING**	1	594.00	594.00
RC2-C	**ONE KAPLAN DUCTED PROPELLER 1 RH:** four Bladed Approximately 900mm diameter, pitch ratio 1.15, DAR 0,7. Cast in nickel Aluminum Bronze supplied fully machined to suit shaft, fine disc finished and statically balanced.	1	17,500.00	17,500.00

	XL TYPE FIXED NOZZLE ONE TWIN SCREW SHIPSET of SHAFTING and STERNGEAR,Type DUPLEX F51 marine Grade high tensile steel Tail shaft 100mm diameter by approximately 5500 mm long complete with tapered half couplings to suit D-I DMT150 with a reduction gear of 2.51 / 3.08:1, all nuts and key. Heavy Duty Mild Steel Water lubricated sterntube assembly approximately 2000 mm long complete with LNF bearing fitted & forward packed gland assembly loose fitted BV PLAN APPROVAL			
TRANS	TRANSPORT	1	2,000.00	2,000.00
Total costs				***76,800.00***

THE COSTS OF THE MAN-HOURS AND MATERIALS FOR THE RE-POWERING 400HP INLAND VESSEL.

For an European shipyard (Romanian shipyard) the costs of the necessary man-hours and materials are:

Price = 156.000 EUR

Woks which have to be done:

- preparing the vessel for repowering: dismounting the equipment and degas the compartments;
- hull works, mounting and alignment the equipment, piping, mechanical and electrical works.

TOTAL COSTS FOR THE RE-POWERING OF THE INLAND VESSEL:

76800 + 156000 = ***232800 EUR***

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* Done by the University of Galati (UGAL) and Ship Design Group SRL (SDG), both from Romania

APPENDIX 5

Squat calculations

MV “HENDRIK”

- Method: *Huuska (1976)*

According to this method the squat of the ship can be estimated using following equation:

$$S_B = 2,4\frac{\nabla}{L_{PP}^2}\frac{Fr_h^2}{\sqrt{1-Fr_h^2}}K_S$$

where coefficient Ks is 1.

In case of water depth is 3.5m following results were obtained:

Length BP	m	67.30	73.30	79.30	85.3	92.3
Breadth	m	8.60	8.60	8.60	8.6	8.6
T	m	2.95	2.95	2.95	2.94	2.934
C_B	-	0.770	0.787	0.808	0.822	0.838
V km/h	3	-0.014	-0.013	-0.013	-0.012	-0.011
	6	-0.059	-0.055	-0.052	-0.049	-0.046
	9	-0.140	-0.132	-0.125	-0.118	-0.111
	12	-0.274	-0.257	-0.244	-0.230	-0.216
	15	-0.501	-0.470	-0.446	-0.420	-0.395

In case of water depth in 5.0m following results were obtained:

Length BP	m	67.30	73.30	79.30	85.3	92.3
Breadth	m	8.60	8.60	8.60	8.6	8.6
T	m	2.95	2.95	2.95	2.94	2.934
C_B	-	0.770	0.787	0.808	0.822	0.838
V km/h	3	-0.010	-0.009	-0.009	-0.008	-0.008
	6	-0.041	-0.038	-0.036	-0.034	-0.032
	9	-0.095	-0.089	-0.085	-0.080	-0.075
	12	-0.179	-0.168	-0.160	-0.151	-0.142
	15	-0.307	-0.288	-0.273	-0.257	-0.242

- Method: *Eryuzlu&Hausser (1978)*

According to this method the squat of the ship can be estimated using following equation:

$$S_{bE} = 0,113B\left(\frac{1}{h/T}\right)^{0,27} Fr_h^{1,8}$$

In case of water depth is 3.5m following results were obtained:

V	km/h	3	6	9	12	15
Smax	m	-0.03	-0.10	-0.20	-0.34	-0.50

In case of water depth is 5.0m following results were obtained:

V	km/h	3	6	9	12	15
Smax	m	-0.02	-0.06	-0.13	-0.22	-0.33

- Method: *Romisch (1989)*

According to this method the squat of the ship can be estimated using following equation:

$$S = C_V C_F K_{\Delta T} T,$$

where:
- *Cv* depends on critical speed:

$$C_V = 8\left(\frac{V}{V_{CR}}\right)^2\left(\left(\frac{V}{V_{CR}} - 0,05\right)^4 + 0,0625\right)$$

- *Vcr* can be determined by:

$$V_{CR} = 0,58\left(\frac{hL}{TB}\right)^{0,125}\sqrt{gh}$$

- C_F and $K_{\Delta T}$ are detrmined by:

$$C_F = \left(\frac{10C_B B}{L_{PP}}\right)^2$$

$$K_{\Delta T} = 0,155\sqrt{\frac{h}{T}}$$

In case of water depth is 3.5m following results were obtained:

Length BP	m	67.30	73.30	79.30	85.3	92.3
Breadth	m	8.60	8.60	8.60	8.6	8.6
T	m	2.95	2.95	2.95	2.94	2.934
CB	-	0.770	0.787	0.808	0.822	0.838
Vkr	m/s	4.490	4.538	4.583	4.627	4.674
CF	-	1.000	1.000	1.000	1.000	1.000
$K_{\Delta T}$	-	0.169	0.169	0.169	0.169	0.169
V km/h	3	-0.009	-0.008	-0.008	-0.008	-0.008
	6	-0.040	-0.039	-0.038	-0.037	-0.036
	9	-0.159	-0.152	-0.146	-0.140	-0.134
	12	-0.642	-0.606	-0.575	-0.546	-0.517
	15	-2.253	-2.117	-2.000	-1.889	-1.780

In case of water depth is 5.0m following results were obtained:

Length BP	m	67.30	73.30	79.30	85.3	92.3
Breadth	m	8.60	8.60	8.60	8.6	8.6
T	m	2.95	2.95	2.95	2.94	2.934
CB	-	0.770	0.787	0.808	0.822	0.838
Vkr	m/s	5.612	5.672	5.728	5.783	5.841
CF	-	1.000	1.000	1.000	1.000	1.000
$K_{\Delta T}$	-	0.202	0.202	0.202	0.202	0.202
V km/h	3	-0.007	-0.006	-0.006	-0.006	-0.006
	6	-0.028	-0.027	-0.027	-0.026	-0.025
	9	-0.082	-0.079	-0.077	-0.075	-0.072
	12	-0.252	-0.240	-0.230	-0.220	-0.210
	15	-0.768	-0.725	-0.688	-0.653	-0.619

- Method: ***Millward (1990, 1992)***

According to *Millward (1990)* the squat of the ship can be estimated using following equation:

$$S_{b_M} = 0.01 L_{pp}\left(15 C_B \frac{1}{L_{pp}/B} - 0.55\right)\frac{F_{nh}^2}{1-0.9F_{nh}}$$

According to *Millward (1992)*the squat of the ship can be estimated using following equation:

$$S_{b_{M2}} = 0.01L_{pp}\left(61.7C_B\frac{1}{L_{pp}/T} - 0.6\right)\frac{F_{nh}^2}{\sqrt{1-F_{nh}^2}}$$

In case of water depth is 3.5m following results were obtained:

Length BP	m	67.30	73.30	79.30	85.3	92.3
Breadth	m	8.60	8.60	8.60	8.6	8.6
T	m	2.95	2.95	2.95	2.94	2.934
CB		0.770	0.787	0.808	0.822	0.838
V km/h	3	-0.014	-0.014	-0.014	-0.014	-0.013
	6	-0.068	-0.067	-0.066	-0.064	-0.062
	9	-0.184	-0.181	-0.179	-0.175	-0.169
	12	-0.413	-0.406	-0.402	-0.392	-0.380
(1990)	15	-0.876	-0.860	-0.851	-0.830	-0.805
V km/h	3	-0.020	-0.020	-0.020	-0.020	-0.020
	6	-0.084	-0.084	-0.084	-0.083	-0.081
	9	-0.201	-0.200	-0.200	-0.197	-0.194
	12	-0.393	-0.391	-0.391	-0.385	-0.379
(1992)	15	-0.718	-0.714	-0.715	-0.704	-0.693

In case of water depth is 5.0m following results were obtained:

Length BP	m	67.30	73.30	79.30	85.3	92.3
Breadth	m	8.60	8.60	8.60	8.6	8.6
T	m	2.95	2.95	2.95	2.94	2.934
CB		0.770	0.787	0.808	0.822	0.838
V km/h	3	-0.010	-0.010	-0.010	-0.009	-0.009
	6	-0.045	-0.044	-0.044	-0.043	-0.041
	9	-0.117	-0.115	-0.114	-0.111	-0.108
	12	-0.247	-0.243	-0.240	-0.234	-0.227
	15	-0.475	-0.467	-0.462	-0.450	-0.437
V km/h	3	-0.014	-0.014	-0.014	-0.014	-0.014
	6	-0.058	-0.058	-0.058	-0.057	-0.056
	9	-0.136	-0.136	-0.136	-0.134	-0.131
	12	-0.257	-0.256	-0.256	-0.252	-0.248
	15	-0.440	-0.437	-0.438	-0.431	-0.424

MV “RHEINLAND”

Since equations that were used for calculations, according to selected methods, are explained in case of MV “Hendrik”, only results are presented here. All results are based on water depth of 3.5 m (5 m is deep enough from the squat viewpoint).

- Method: *Huuska (1976)*

Length BP	m	55.30	61.30	67.30
Breadth	m	6.35	6.35	6.34
T	m	2.43	2.43	2.42
CB	-	0.829	0.854	0.872
V km/h	3	-0.011	-0.011	-0.010
	6	-0.047	-0.044	-0.040
	9	-0.112	-0.104	-0.096
	12	-0.218	-0.203	-0.188
	15	-0.399	-0.371	-0.343

- Method: *Eryuzlu&Hausser (1978)*

V	km/h	3	6	9	12	15
Smax	m	-0.03	-0.09	-0.19	-0.32	-0.48

- Method: *Romisch (1989)*

Length BP	m	55.30	61.30	67.30
Breadth	m	6.35	6.35	6.34
T	m	2.43	2.43	2.42
CB	-	0.829	0.854	0.872
Vkr	m/s	4.662	4.723	4.782
CF	-	1.000	1.000	1.000
$K_{\Delta T}$	-	0.186	0.186	0.186
V km/h	3	-0.007	-0.007	-0.007
	6	-0.033	-0.032	-0.031
	9	-0.123	-0.117	-0.111
	12	-0.477	-0.446	-0.417
	15	-1.644	-1.526	-1.419

- Method: *Millward (1990, 1992)*

Length BP	m	55.30	61.30	67.30
Breadth	m	6.35	6.35	6.34
T	m	2.43	2.43	2.42
CB		0.829	0.854	0.872
V km/h	3	-0.011	-0.011	-0.011
	6	-0.053	-0.052	-0.050
	9	-0.143	-0.141	-0.136
	12	-0.322	-0.316	-0.304
	15	-0.682	-0.669	-0.645
V km/h	3	-0.019	-0.019	-0.018
	6	-0.077	-0.077	-0.076
	9	-0.183	-0.184	-0.181
	12	-0.359	-0.359	-0.353
	15	-0.655	-0.656	-0.646