STYRELSEN FÖR

VINTERSJÖFARTSFORSKNING

WINTER NAVIGATION RESEARCH BOARD

Research Report No 127

Heinonen Teemu

RESEARCH ON MERCHANT VESSEL'S ABILITY TO PROVIDE SUFFICIENT THRUST AT LOW ICEBREAKING SPEEDS

Finnish Transport and Communications Agency

Finnish Transport Infrastructure Agency

Finland

Swedish Maritime Administration

Swedish Transport Agency

Sweden

Talvimerenkulun tutkimusraportit — Winter Navigation Research Reports
ISSN 2342-4303
ISBN 978-952-311-875-1

FOREWORD

In this report no 127, the Winter Navigation Research Board presents the results of research project Research on merchant vessel’s ability to provide sufficient thrust at low icebreaking speeds. The project investigated current day merchant vessel's ability to provide sufficient thrust in low speed winter navigation as intended by the Finnish-Swedish ice class rules.

The Winter Navigation Research Board warmly thanks Teemu Heinonen for this report.

Helsinki

August 2023

Ville Häyrynen

Finnish Transport and Communications Agency

Anders Dahl

Swedish Maritime Administration

Helena Orädd

Finnish Transport Infrastructure Agency

Stefan Eriksson

Swedish Transport Agency

Aker Arctic

AKER ARCTIC TECHNOLOGY INC REPORT

RESEARCH ON MERCHANT VESSEL'S ABILITY TO PROVIDE SUFFICIENT THRUST AT LOW ICEBREAKING SPEEDS

FOR

FINNISH TRANSPORT AND COMMUNICATIONS AGENCY

Name of document: Research on merchant vessel's ability to provide sufficient thrust at low icebreaking speeds			
Document Responsible: Heinonen Teemu		**Document Co-Author(s):**	
Document Reviewer: Saisto Ilkka		**Document Approver:** Leiviskä Topi	
Report number / Revision: K510 / B		**Status / Status Date:** Approved / 6.2.2023	
Client: Finnish Transport and Communications Agency / Lauri Kuuliala			
Revision remarks: A: initial version; B: WNRB comments implemented			

Summary:

This research is focused on the merchant vessel's ability to produce sufficient thrust at low icebreaking speeds. The objective is to investigate whether merchant vessels are able to produce such thrust as the Finnish-Swedish ice class rules assume and what could be situations in which the thrust or power of the merchant vessel is reduced. The main findings regarding the thrust capabilities are following:

- The FSICR assumptions give reasonable results in situations in which the full propulsion power is available (vessels with CP propellers and optimally functioning propulsion machinery).
- The propulsion power can be significantly reduced with FP propellers due to the torque limitations of the main engine. In these situations, the vessels do not deliver the thrust assumed by FSICR.
- PTI is very useful for vessels with FPP and the PTI can increase the available propulsion power at ice going speeds significantly.

It is feasible to consider changing the ice class rules in the future more into goal-oriented direction in which the goal for the merchant vessel is to have sufficient thrust to proceed at the required 5 knots speed in the designated ice conditions. The vessel's ability to produce the sufficient thrust is then demonstrated when the ice class is applied. Also, the actual thrust properties of the possible nozzles should be used instead of generic assumptions as the design targets of the nozzles differ. The functionality of CPP systems in ice is also discussed in the report. It is concluded that it is important that the crew of the merchant vessel has understanding how the full propulsion power is obtained without overloading the main engine. On the other hand, it is important that the possible automatic load control of the CPP is functioning properly in respect to the engine and propeller characteristics. However, more research is needed to better understand the phenomena related to automatic load control functionality.

Keywords: CP propeller (CPP); FSICR; Bollard pull; Net Thrust

Client reference: W22-7 STILS		**Project number:** 30851	**Language:** English
Pages, total: 50	**Attachments:** -	**Distribution list:** Traficom, Väylä, SMA	**Confidentiality:** Public

TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

A_e .... Expanded blade area
A_o .... Propeller disc area
B .... Breadth
D_p .... Propeller diameter
I .... Gear ratio
J .... Advance number
K_e .... Quality factor for bollard pull
K_P .... Delivered power coefficient
K_Q .... Torque coefficient
K_T .... Thrust coefficient
L_{pp} .... Length between perpendiculars
n .... Propeller revolutions
P .... Propulsion power
P_D .... Delivered power
Q .... Torque
R_{CH} .... Ice resistance in channel
R_T .... Total resistance
t .... Thrust deduction factor
T .... Thrust
T_{design} .... Design draft
T_{net} .... Net Thrust
T_{Pull} .... Bollard pull force
V .... Speed
V_{ow} .... Maximum open-water speed
$V_{service}$ .... Service speed in open water
w .... Wake fraction

ρ .... Water density

CP .... Controllable pitch
CPP .... Controllable pitch propeller
CSR .... Continuous service rating
DWT .... Deadweight
FP .... Fixed pitch
FPP .... Fixed pitch propeller
FSICR .... Finnish-Swedish ice class rules
MCR .... Maximum continuous rating
PTI .... Power take-in
PTO .... Power take-off
RPM .... Revolutions per minute
WNRB .... Winter Navigation Research Board

1 INTRODUCTION

Ice classed merchant vessel's ice-going capability is influenced by two factors: the vessel's ice resistance and the available thrust to overcome the resistance. The minimum power requirement of the Finnish-Swedish ice class rules (FSICR) is based on semi-empirical calculation methods both for the resistance and thrust to have a sufficient performance for the merchant vessel. As the current minimum power requirement has been in use for over 20 years, it is feasible to investigate how well the assumptions behind the requirement correlate to modern vessels. During the past 20 years the power to deadweight ratio of the ice classed merchant vessels has clearly reduced (Heinonen 2022). On the other hand, the vessel hullforms and propellers have become more optimized for open water. The energy efficiency and carbon intensity regulations will further reduce the engine powers in the future and therefore the margins between the required and installed power becomes smaller. As the margins are reduced, possible problems in the assumptions behind the minimum power requirement will have more influence on the functionality of the winter traffic system in the Baltic Sea.

This report focuses on the assumptions related to the thrust in the minimum power requirement. The ice resistance part of the minimum power requirement is not discussed. The objective is to investigate whether the merchant vessels are able to produce such thrust as the rules assume and what could be situations in which the thrust or power of the merchant vessel is reduced.

2 THEORY AND PROBLEM ASSESSEMENT

The background of the current Finnish-Swedish ice class rules minimum power requirement is described in Winter Navigation Research Board reports No. 52 (Riska et al., 1997) and No. 53 (Juva & Riska, 2002). In addition, the Winter Navigation Research Board report No. 67 (Riska, 2014) contains further discussion about the factors influencing the power requirement.

The target of the FSICR minimum power requirement is that the ice classed merchant vessels can keep 5 knots speed in designated brash ice channels. Therefore, according to the ice class rules the minimum propulsion power shall not be less than (Traficom 2021):

$$P_{min} = K_p \frac{\left({R_{CH}}/{1000}\right)^{3/2}}{D_P} \text{ [kW]} \qquad (1.)$$

The background of the formula (1.) is the bollard pull capability of the ship which is discussed in the next chapter.

2.1 BOLLARD PULL

The theory related to bollard pull of the vessel is described below. Formulas of propulsion power, total resistance, thrust and torque coefficients K_T and K_Q of the propeller are the basis when determining the bollard pull:

$$P_D = 2\pi Q n \qquad (2.)$$

$$R_T = T(1-t) \qquad (3.)$$

$$K_T = \frac{T}{\rho n^2 D^4} \qquad (4.)$$

$$K_Q = \frac{Q}{\rho n^2 D^5} \qquad (5.)$$

The bollard pull force can be determined by rearranging the formulas above into following format:

$$T_{Pull} = \frac{K_T}{{K_Q}^{2/3}} \sqrt[3]{\frac{\rho}{4\pi^2}} (P_D D_P)^{2/3} (1-t) \qquad (6.)$$

The formula (6.) is often shortened into following format:

$$T_{Pull} = K_e (P_D D_P)^{2/3}, \qquad (7.)$$

where $K_e = \frac{K_T}{{K_Q}^{2/3}} \sqrt[3]{\frac{\rho}{4\pi^2}} (1-t)$ (8.)

The factor K_e is called the quality factor for bollard pull goodness which represents the vessel’s ability to produce bollard pull force based on its propeller characteristics and hullform (thrust deduction). Higher K_e value means that the vessel is better in bollard pull situation and produces higher bollard pull force.

2.2 RELATION BETWEEN THE ICE RESISTANCE AND BOLLARD PULL

When the vessel is moving in ice, the ice resistance is assumed to be equal to the net thrust of the vessel ($T_{net} = R_{CH}$). The net thrust is the thrust that the vessel still has available when the thrust to overcome the open-water resistance has been taken into account. In construction of the FSICR the net thrust is calculated with empirical formula which has been derived based on typical K_T-curve (Riska et al. 1997):

$$T_{net} = \left[1 - \frac{1}{3}\frac{v}{v_{ow}} - \frac{2}{3}\left(\frac{v}{v_{ow}}\right)^2\right] \cdot T_{pull} \quad (9.)$$

The shape of the T_{net} -curve is parabolic and various sources have demonstrated that the net thrust curve calculated with formula (9.) has a good correlation to measurements in normal cases as can be seen in Figure 2-1.

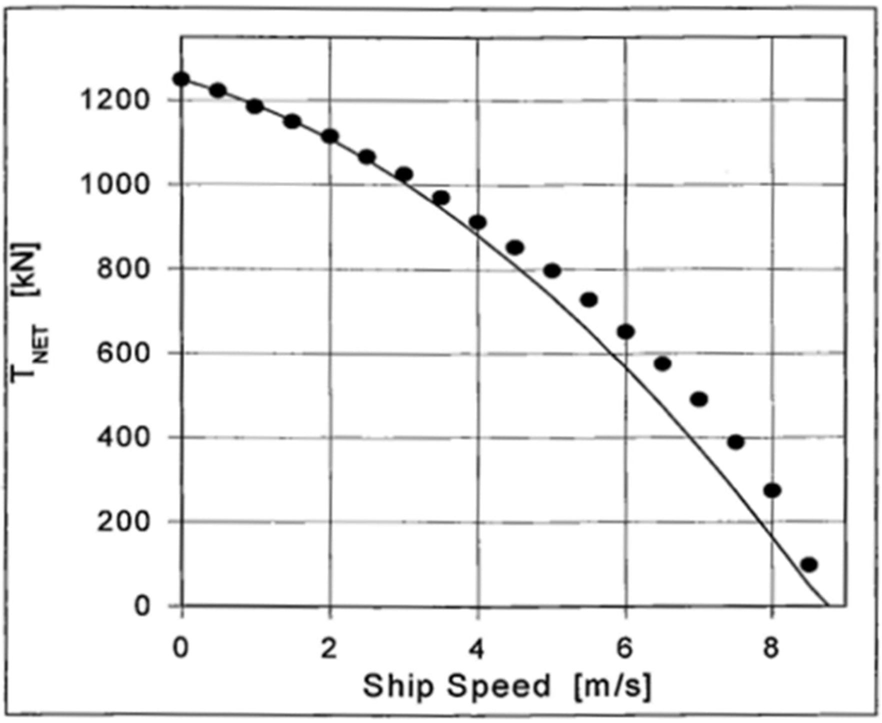

Figure 2-1: Correlation between calculated net thrust curve with formula (9.) (continuous curve) and measured net thrust values (dots) (Juva & Riska, 2002).

By assuming that the maximum open-water speed of the ice-going merchant vessel is 15 knots, the required net thrust at 5 knots speed can be approximated with formula (9.):

$$T_{net}(5kn) = \sim 0.8 \cdot T_{pull} \quad (10.)$$

Further, following can be written as the net thrust is assumed to be equal to the ice resistance:

$$R_{ch} = 0.8 \cdot T_{pull} \tag{11.}$$

The required power for the vessel to advance at 5 knots speed in ice can be determined by combining formulas (7.) and (11.):

$$P_D = \frac{1}{(0.8 \cdot K_e)^{3/2}} \frac{(R_{ch})^{3/2}}{D_P} \tag{12.}$$

The relation between formulas (12.) and (1.) is following:

$$K_p = \frac{1}{(0.8 \cdot K_e)^{3/2}} \tag{13.}$$

2.3 INFLUENCE OF THE PROPELLER TYPE TO THE VESSEL'S BOLLARD PULL CAPABILITY

Ice classed merchant vessel has typically a diesel-mechanical propulsion in which the main engine(s) is directly or via gears coupled to the propeller shaft. The main engines are typically 2- or 4-stroke diesel engines and the propellers are either fixed pitch (FP) or controllable pitch (CP) propellers. The propellers can be also ducted but this is somewhat rare for normal merchant vessels. However, ducted solutions have increased as a mean to fulfil energy efficiency regulations. The influence of the FP and CP propellers to the bollard pull capability of the vessel is discussed below while the influence of ducted propellers is discussed in 5.2.

It is notable that the formula (6.) does not contain torque nor propeller revolutions. It represents an ideal situation in which the vessel is able to fully absorb all available power to the propellers without any limitations. However, this is not the case if the propeller and the main engine are not properly matched for bollard pull situation and the propeller demands more torque at nominal RPM than the engine can provide.

The propulsion arrangement of a typical merchant vessel is optimized for good efficiency at the designed open-water speed in the designed operational conditions (loading condition, sea state, weather, fouling etc. are taken into account): the propeller is typically designed to provide best efficiency at the design speed and the main engine is designed to run with optimal load in order to optimize fuel consumption. Figure 2-2 presents a schematic example of the propeller (power) demand curve and operational range of the engine. In principle, the propeller curve should cross the MCR point of the engine. The propeller curve shifts to left when the propeller's power demand increases (for example in bollard pull situation) and to right when the power demand decreases. For a typical merchant vessel, the propeller is heavy-running in bollard pull situation and the propeller curve is shifted to left. Otherwise, the propeller would be light-running at normal operating speeds in open-water and the vessel cannot utilize the power of the engine due to the RPM limitation of the main engine. On the other hand, the heavy-running propeller curve can cross the torque limit of the engine and the propeller does not achieve nominal RPM and full power in bollard pull situation. As the propeller RPM is reduced due to the torque limitation of the engine, both the propulsion power and bollard pull force are also reduced.

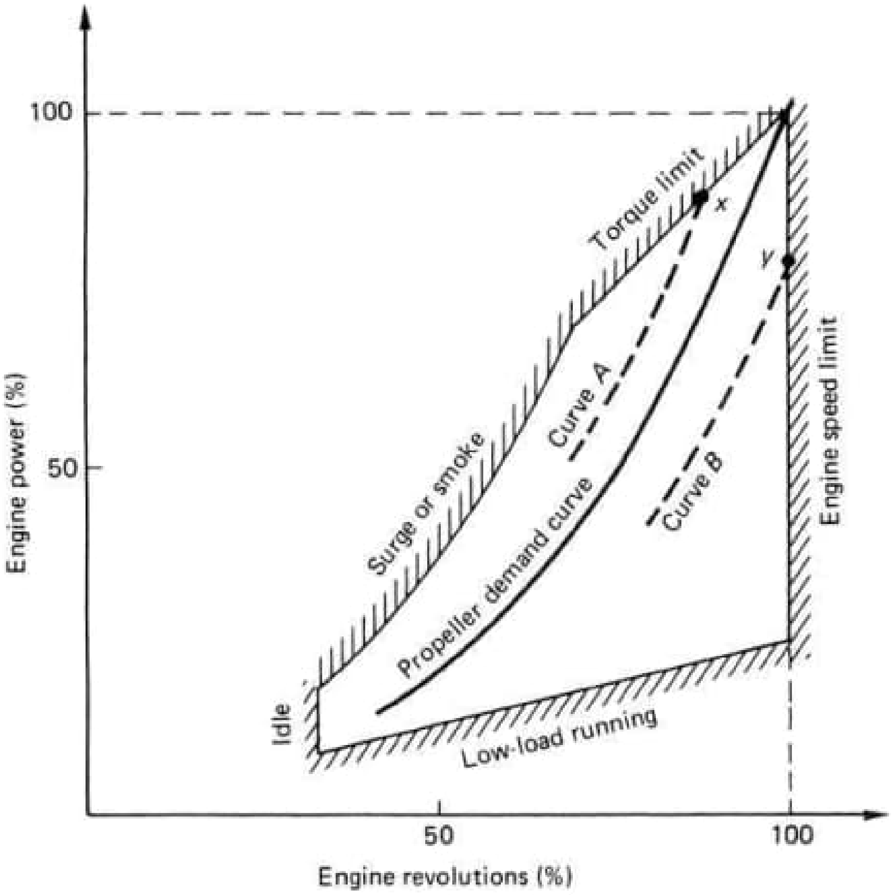

Figure 2-2: A schematic example of the propeller curves and the operating range of the engine (Carlton, 2007). The curve A demonstrates heavy-running curve while curve B is light-running.

Figure 2-3 presents a schematic example of the operational range of the main engine and propeller curves for CP propeller with different pitches. As the propeller pitch can be varied, it is possible to adjust the loading of the propeller so that the propeller curve matches with the propeller design point. Therefore, similar reduction of propulsion power and bollard pull force which is observed with FPP can be avoided with CPP if the pitch is adjusted correctly. As the normal operating condition of the merchant vessel is in open-water, the design pitch normally corresponds to somewhat high open-water speeds and the propeller with the design pitch is heavy-running in bollard pull condition. Therefore, it is not possible to achieve full bollard pull capability with the design pitch and the pitch must be reduced in bollard pull condition. As the propeller blade is turned off from the design pitch, the blade profile is distorted (Figure 2-4). The distortion of the blade profile reduces the efficiency of the propeller and it also cavitates more easily (Matusiak, 2005). However, the benefits in the torque capabilities should compensate for the lower efficiency when compared to FP propeller.

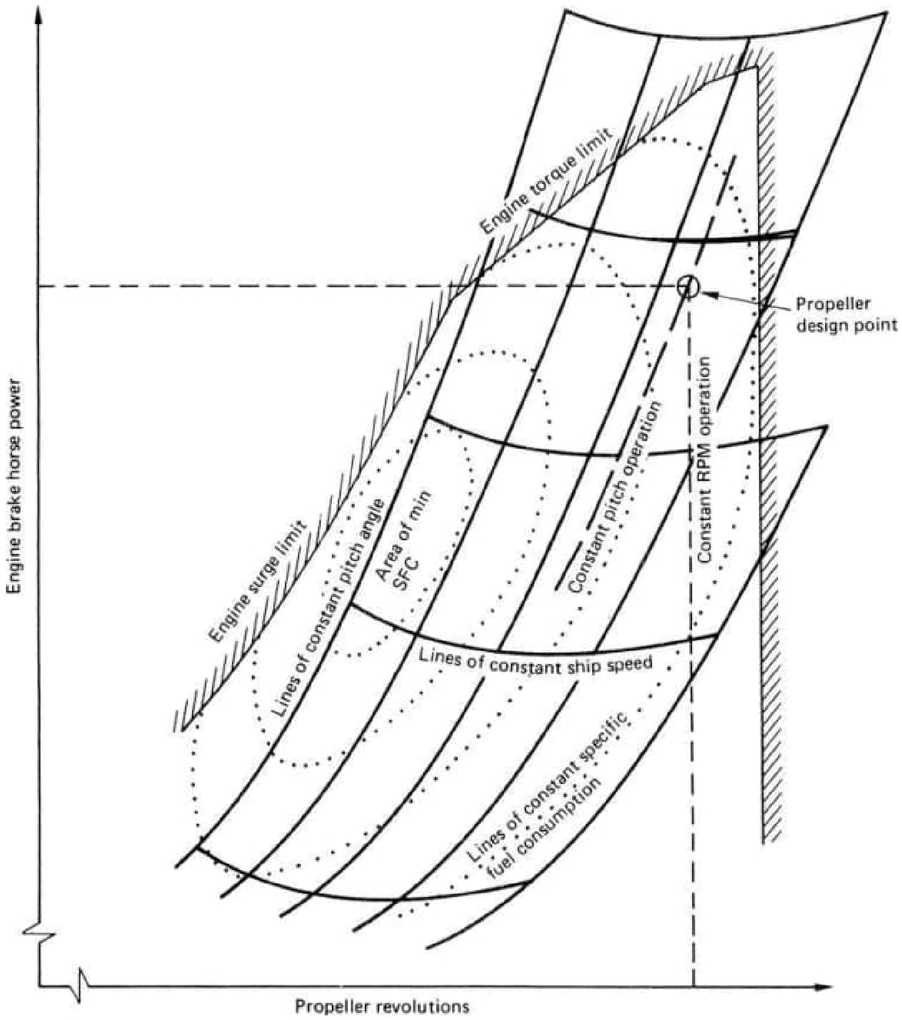

Figure 2-3: A schematic example of the propeller curves with different pitches and the operating range of the engine for vessel with CP propeller (Carlton, 2007).

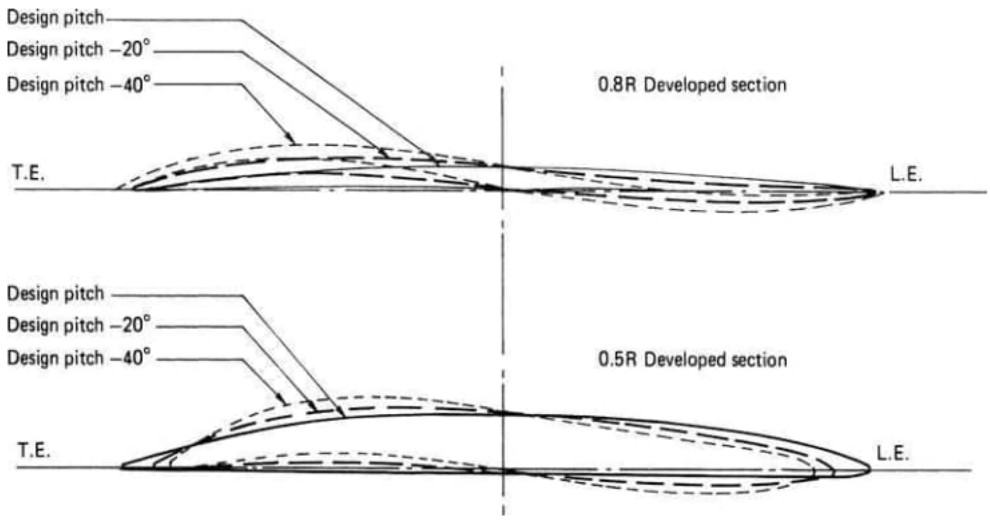

Figure 2-4: Section distortion due to changes of pitch angle (Carlton, 2007).

2.3.1 POWER TAKE-IN (PTI)

Different kind of hybrid propulsion solutions have gained popularity in recent years. One particularly attractive system for an ice-going merchant vessel is PTO/PTI system. In this kind of system there is a combination of shaft generator/electric motor installed to the propeller shaft or to the reduction gear before the shaft (Figure 2-5). In open-water and in light ice conditions the system is in PTO-mode and running as a shaft generator producing electricity to the vessel. In more difficult ice conditions, the electricity is produced with auxiliary diesel-generators and the system is running in PTI-mode as an additional electrical motor/booster. This kind of solution provides the possibility to reduce the power/size of the main engine to match the needs of operation in open water. The electric booster motor will produce the additional power needed in ice.

The torque capabilities of an electrical motor are very good as the full nominal torque is available immediately at low RPM. A schematic example of the torque and power behavior of an electric motor is presented in Figure 2-6. At low RPM the torque is constantly at full nominal value until the nominal maximum power is achieved. If the RPM is further increased, the torque starts to drop while the power stays constant.

As the power of the electric motor is added to the propeller shaft, the RPM of the shaft increases. The torque capabilities of a diesel-engine depend on the engine RPM as can be seen from Figure 2-2. As the PTI-booster increases the shaft RPM, the torque capabilities of the main diesel engine are also improved, and the propeller RPM is further increased. Therefore, it can be concluded that the PTI-booster motor is very useful in respect of the vessel's bollard pull capability and therefore to the overall ice-going capability of the vessel. Whether the PTI-system will completely prevent possible power and thrust reductions related to FPP, depends on the PTI system features. Influencing factors are the maximum power and torque levels of the PTI motor. If the maximum torque is low, the full power of the PTI is not available at low icebreaking speeds when the main engine needs the most assistance.

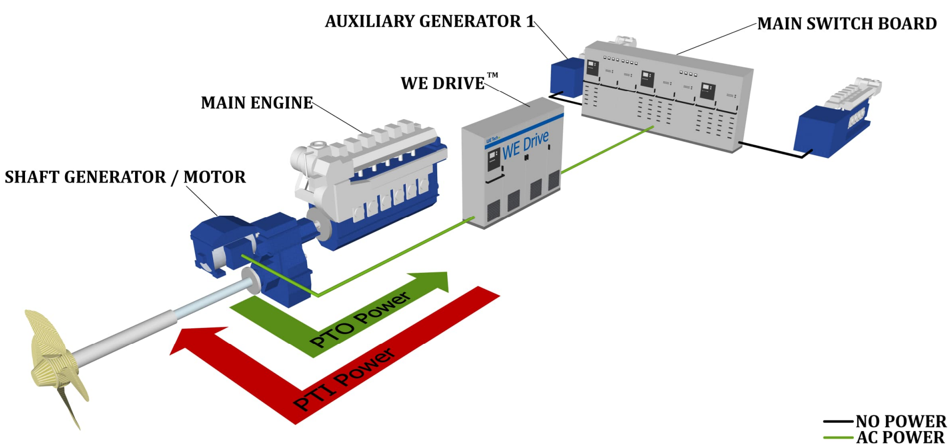

Figure 2-5: A schematic presentation of PTO/PTI system on a medium-speed 4-stroke machinery (www.wetech.fi). On a medium-speed solution the system is often installed to the reduction gear while the low-speed 2-stroke engines can have the system also installed directly to the propeller shaft.

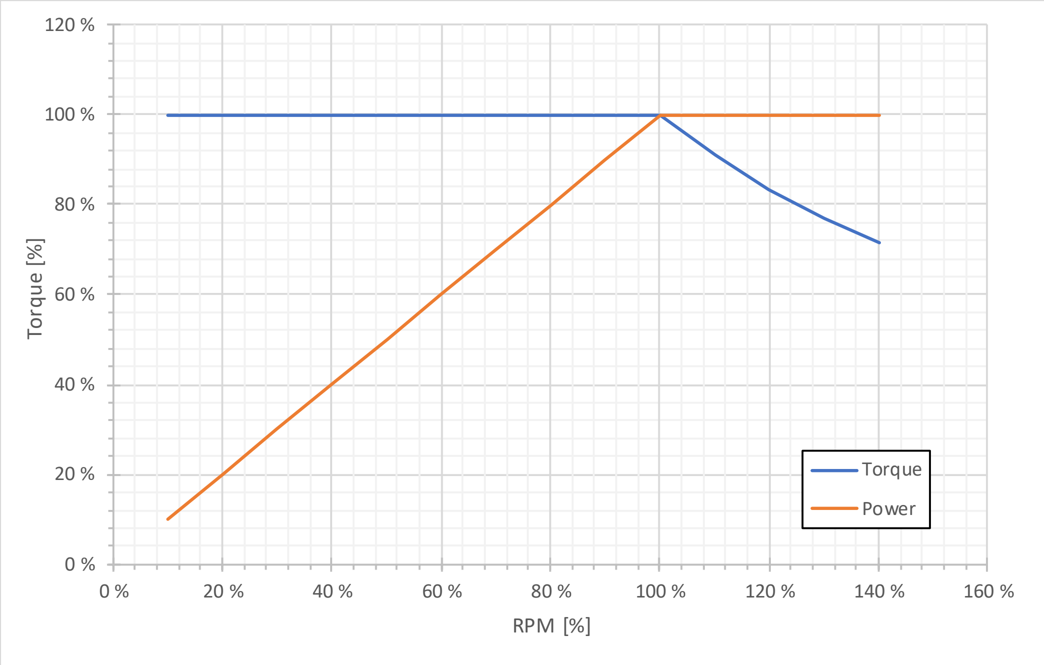

Figure 2-6: A schematic presentation of the torque and power of an electric motor. The 100% RPM level refers to the RPM level in which the full power is available.

2.4 K_E AND FINNISH-SWEDISH ICE CLASS RULES

Table 2-1 presents different values of the K_e according to the Finnish-Swedish ice class rules for vessels with CP-propellers. The values of K_e are initially presented by Loly Tsoy in 1983 (Tsoy, 1983). The origin of the values is not mentioned in Tsoy's article but most likely the values are at least partly empirical and possibly originate from data which has been obtained from icebreakers. There is no information whether the values are initially for CP or FP propellers.

Table 2-1: Different values for K_e for vessels with CPP according to FSICR.

	Single screw	**Twin-screw**	**Triple screw**
K_e	0.78	0.98	1.12

The values in Table 2-1 are for CP propellers. The torque limitations related to FP propellers have been acknowledged in the FSICR and the K_e values for vessels with FP propellers are multiplied with factor of 0.9 (Table 2-2). The origin of this factor is unknown but it is assumed to be at least partly empirical (Juva & Riska, 2002). However, it has been considered that the performance drop could be even bigger than the factor of 0.9 indicates (Riska, 2014).

Table 2-2: Different values for K_e to vessels with FPP according to FSICR.

	Single screw	**Twin-screw**	**Triple screw**
K_e	0.702	0.882	1.008

As a reference, J. Tornblad has presented following values for K_e (Tornblad, 1983):

- Ferries: 0.86
- Tugboats: 0.90

Based on the values of Tornblad, the values of FSICR seem to be somewhat reasonable for a merchant vessel which is not designed for bollard pull unlike a tugboat.

The formula (8.) presents the theoretical formulation for the quality constant K_e of bollard pull and does not take the possible torque limitations into account. On the other hand, the values presented in Table 2-1 are empirical and therefore contain the effects of possible torque limitations within the values itself. However, as the values are most likely based on relatively old data and possibly from icebreakers which are optimized for good bollard pull capability and also often equipped with electric propulsion engines with good torque capabilities, it is reasonable to consider how well the values represent modern merchant vessels.

In WRNB report No. 53 the values of K_e have been compared to databank of different vessels found from public sources. However, as described in the WRNB report No. 53, the bollard pull capability is normally considered as a relevant value only for icebreakers, offshore vessels and tugboats and it is not normally measured for normal merchant vessels with relatively low ice class. Therefore, it is difficult to find any actual measured bollard pull data for normal merchant vessels. Majority of the reference vessels presented in the databank of the WNRB report No. 53 are tugboats, icebreakers or icebreaking cargo ships with relatively high ice class: i.e. vessels which are probably not as particularly representative of modern ice classed merchant vessel needing icebreaking assistance.

In addition, it should be also noted that the bollard pull force is often considered as somewhat sensitive data which is not normally publicly reported even though it could have been measured. Similar analogy can be seen also for other parameters of ships, for example speed data: the actual measured trial speed is seldomly publicly informed. Instead, a design speed or similar reference value can be informed. The possible difference between the public and actual values adds uncertainty to the validation of the K_e. Finally, it should be noted that almost half of the vessels used in the databank of the WNRB Report No. 53 are from reference by Dick and Laframboise (1989). In this reference the bollard pull value has been specifically mentioned as a value which contains missing information and possible missing information is filled with calculated values. Basically, this means that the calculated values have been validated with other calculated values.

2.5 VALUES INFLUENCING THE K_E COEFFICIENT

The K_e is dependent on following factors related to the vessel:

- Thrust coefficient K_T
- Torque coefficient K_Q
- Thrust deduction t

The thrust and torque coefficients are related to the propeller while the thrust deduction is mainly influenced by the aft ship shape and rudder arrangement. In bollard pull situation the thrust deduction can be assumed to be within few percentages for typical merchant vessels. Figure 2-7 shows the influence of thrust deduction to K_e in situation in which 5% thrust deduction would result $K_e = 0.78$. It can be seen that one percentage point change in thrust deduction results into approximately 1% change in the value of K_e.

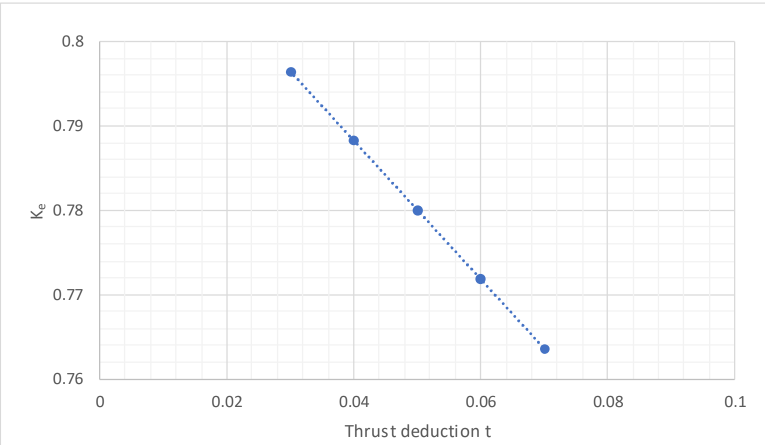

Figure 2-7: Influence of thrust deduction to coefficient K_e.

The influence of the propeller parameters is discussed below. When investigating the propeller parameters, it is important to understand that the parameters are linked to each other and changes in one parameter often means changes to other parameters. The main engine and the nominal RPM range of the engine typically sets the limits for the possible changes of the propeller parameters. For example, if the propeller diameter is increased, the pitch is typically reduced in order keep the engine RPM and load on same level. Variation of the main engine and its parameters gives more freedom for the propeller design.

The K_e is dependent on the ratio of thrust and torque coefficients which are related to the geometry of the propeller, mainly pitch and blade area-ratio. Juva and Riska (2002) investigated the influence of the propeller pitch to K_e with different blade area-ratios for Wageningen B-series propellers (Figure 2-8). It can be seen that increasing pitch has a negative impact on the K_e while the influence of blade area ratio depends on the pitch. On the other hand, a larger pitch improves the open water efficiency of the propeller as can be seen from Figure 2-9. Propeller with larger pitch needs more torque which means that the RPM of the propeller drops if the pitch is increased, and other propeller parameters are kept unchanged. This could favor the use of low-speed two-stroke engines which often have a smaller specific fuel consumption when compared medium-speed 4-stroke engines (Häkkinen, 2006).

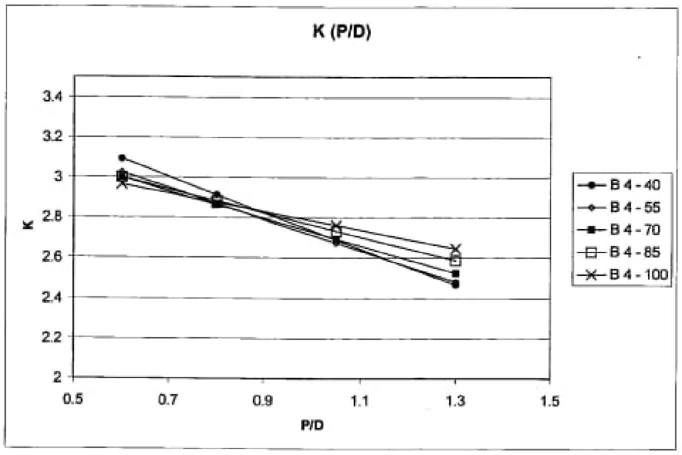

Figure 2-8: The influence of propeller pitch to coefficient K_e for FPP (Juva & Riska, 2002).

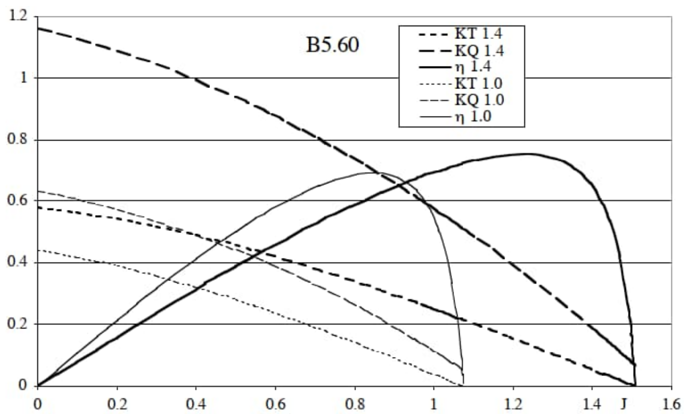

Figure 2-9: Open-water characteristics for a propeller with two different pitches (Matusiak, 2005).

Even though the propeller diameter is not directly influencing the K_e, it is a significant variable as the minimum power requirement (equation (1.)) is inversely proportional to the propeller diameter. In addition, the propeller efficiency can often be improved by increasing the propeller diameter (Figure 2-10). Therefore, increasing propeller diameter is an attractive method to increase the efficiency of the merchant vessel and to reduce the power of the main engine. As the larger propeller requires more torque, the propeller RPM is decreased if other propeller parameters are kept unchanged. This could favor the use of low-speed engines with small specific consumption. Engine manufacturer MAN has estimated that in future the ice-classed vessels could have 10-12% larger propeller diameters driven with ultra long stoke 2-stroke engines improving the total efficiency (MAN, 2013).

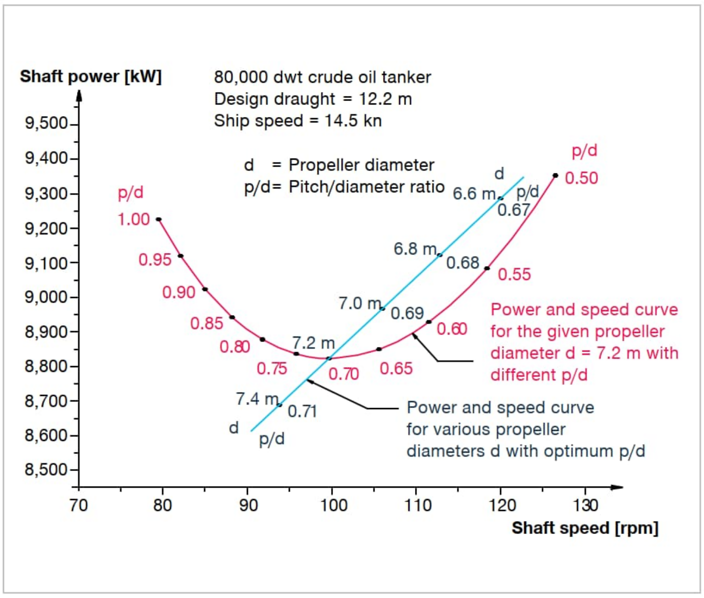

Figure 2-10: Example of influence of propeller diameter and pitch (MAN, 2018).

Even though the propeller diameter does not directly influence K_e, it influences K_e indirectly via other propeller parameters which will change as the diameter changes. Juva and Riska (2002) also investigated the influence of propeller diameter to the K_e (Figure 2-11). It can be seen that increasing diameter has a negative influence on the K_e.

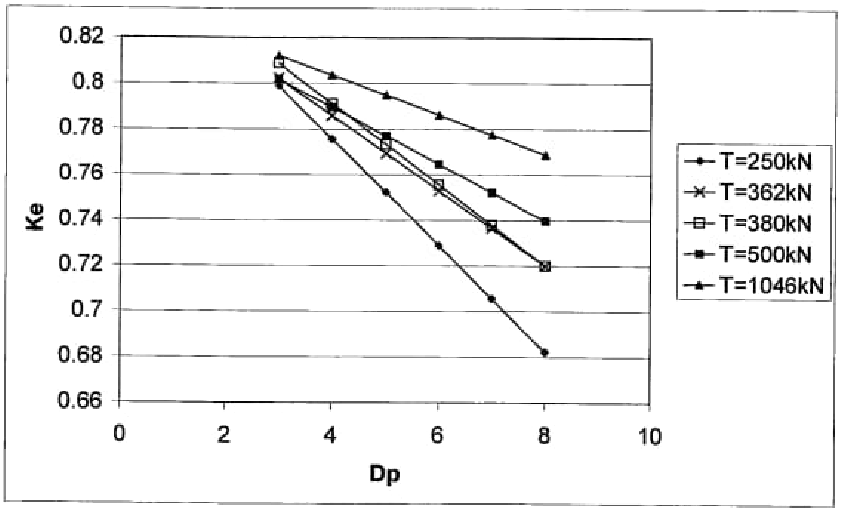

Figure 2-11: The influence of propeller diameter to K_e for FPP (Juva & Riska, 2002).

2.6 PROBLEM ASSESMENT

The merchant vessel's ability to proceed in ice conditions is greatly influenced by its bollard pull capability. The bollard pull quality factor K_e is key factor related to the bollard pull capability of the vessel. The FSICR uses values of K_e which are based on old data from vessels which are not necessarily particularly representative to modern ice-classed merchant vessels needing icebreaker assistance. In addition, it has already been considered in the previous WNRB report No. 53 that the influence of FPP can be larger than the rules assume. Therefore, this report focuses to investigate how well the K_e -values presented in FSICR correlate to actual values which ice-classed merchant vessels could have based on their propeller and engine characteristics. As concluded in the previous chapters, it is very difficult or basically impossible to validate the K_e value for modern merchant vessels based on actual measured full-scale data as bollard pull tests are not conducted for normal merchant vessels. Therefore, it is necessary to do the investigation based on calculated values. In this report the bollard pull force and propulsion power will be calculated for different vessels based on the propeller and engine data and compared to values which are calculated based on the assumptions of the FSICR.

It should be also noted that if the bollard pull force and propulsion power of the vessel are restricted due to torque limitation, the shape of the net thrust curve will differ from the parabolic shape presented in Figure 2-1. The propeller loading becomes lighter as the speed of the vessel increases which means that the propulsion power increases as the vessel starts to move. As the propulsion power increases with the ship speed, the assumption of equation (10.) is not anymore valid and the shape of the actual net thrust curve is different. Therefore, the vessel's thrust and propulsion power at 5 knots speed are also investigated and compared to the values calculated with the assumptions of the FSCIR.

Finally, the influence of a PTI system is also investigated in this report. It is not totally clear how the PTI should be taken into account when calculating the minimum propulsion power according to the FSICR. Can the vessel be assumed to perform similar to a vessel which has fully electric propulsion?

As a summary, following topics will be investigated in this report:

- Calculation of bollard pull force and propulsion power based on propeller and engine data for different type of vessels with different characteristics. Following parameters will be varied (discussed more in chapter 3):
    - Propeller type (FPP/CPP)
    - Propeller diameter
    - Propeller pitch and design RPM
    - Engine type (2-stroke low speed/4-stroke medium speed)
    - PTI
    - Number of propellers
- Calculation of net thrust force and propulsion power at 5 knots speed based on propeller and engine data for different type of vessels with different characteristics using same parameters as in the bollard pull force calculation.

- Comparison of the calculated bollard pull and net thrust forces and propulsion powers to values based on FSICR assumptions
- Investigation of other possible scenarios in which the vessel's propulsion power and bollard pull force are reduced/limited:
    - Functionality and operation of the CPP system in ice
    - Propellers in nozzle
    - Influence of alternative fuels

3 ANALYSIS METHOD

The vessels' ability produce bollard pull force is investigated by creating example cases. Three different example ship-types are investigated:

- General cargo ship, 5000 DWT
  - Most common ship type and vessel size at the northern Baltic Sea
- Large bulk carrier, 97000 DWT
  - Clearly larger comparison with relatively low power to deadweight ratio
- Container vessel, 13000 DWT
  - More powerful ship-type than the other two

All investigated vessels are assumed to have IA ice class which is the most common ice class operating at northern Baltic Sea throughout the whole winter under icebreaker assistance. The main particulars of each vessel are presented in Table 3-1 to Table 3-3.

The different ship-types are chosen so that they would give information about the influence of the vessel size and power level to the vessel's ability to produce bollard pull. The 5000 DWT general cargo ship is the most common ship-type operating at northern Baltic Sea during wintertime and can be considered as a reference case. The other ship types are chosen so that there is one case which is clearly larger but with relatively low power level (bulk carrier) and one ship-type (container ship) which has higher power to deadweight ratio but is still normally built to IA ice class and assumed to need icebreaker assistance. The Ro-Ro cargo and passenger ships are also powerful, but these vessels are already so powerful that they are often built to IA Super ice class and seldomly need icebreaker assistance.

Even though the parameters of the vessels are chosen to be realistic and representative for each ship-type, it should be noted that the absolute values of different parameters are irrelevant for the analysis. The main idea is to investigate difference between the bollard pull capability based on the actual propulsion characteristics of the vessel and according to the assumptions of FSICR. As described in the previous chapters, the bollard pull capability of the vessel is mainly dependent on propeller characteristics and propulsion power. Therefore, the influence of the absolute main dimensions is insignificant as long as the propulsion characteristics are somewhat reasonable for the corresponding ship-type.

The vessel's ability to produce bollard pull and net thrust is investigated by varying following parameters:

- Propeller type (FPP/CPP)
- Propeller diameter
- Propeller pitch and design RPM
- Engine type (2-stroke low speed/4-stroke medium speed)
- PTI
- Number of propellers

Each parameter is discussed in the following subchapters. A summary of the varied parameters is presented in Table 3-4. The actual values of the varied parameters are presented in Appendix 1.

Table 3-1: Main particulars for the general cargo ship.

DWT [ton]	5000
L_{PP} [m]	90
B [m]	15.2
T_{design} [m]	5.9
$V_{service}$ [kn]	12
P_D [kW]	2625
$D_{P,1}$ [m]	3.3
$D_{P,2}$ [m]	3.6

Table 3-2: Main particulars for the bulk carrier.

DWT [ton]	97000
L_{PP} [m]	230.5
B [m]	38.0
T_{design} [m]	13.5
$V_{service}$ [kn]	14.5
P_D [kW]	15000
$D_{P,1}$ [m]	7.1
$D_{P,2}$ [m]	7.7

Table 3-3: Main particulars for the container ship.

DWT [ton]	13000
L_{PP} [m]	140
B [m]	22.7
T_{design} [m]	7.8
$V_{service}$ [kn]	18.5
P_D [kW]	9070-9760
$D_{P,1}$ [m]	5.5
$D_{P,2}$ [m]	6.0
$D_{P,3}$ [m]	3.9
$D_{P,4}$ [m]	4.25

Table 3-4: Summary of varied parameters. The propeller blade areas have been constant for each ship-type. The numbering in the subscripts refer to different values for each ship-type and the values differ between different ship-types.

Vessel type	FPP/CPP	Propeller No.	2-/4-stroke	PTI	D_p	RPM	P/D
General cargo	FPP	1	4	no	$D_{p,1}$	n_1	P/D_1
General cargo	FPP	1	4	no	$D_{p,2}$	n_1	P/D_2
General cargo	FPP	1	4	no	$D_{p,2}$	n_2	P/D_1
General cargo	FPP	1	4	Yes	$D_{p,1}$	n_1	P/D_1
General cargo	FPP	1	4	Yes	$D_{p,2}$	n_1	P/D_2
General cargo	FPP	1	4	Yes	$D_{p,2}$	n_2	P/D_1
General cargo	CPP	1	4	no	$D_{p,1}$	n_1	P/D_1
General cargo	CPP	1	4	no	$D_{p,2}$	n_1	P/D_2
General cargo	CPP	1	4	no	$D_{p,2}$	n_2	P/D_3
General cargo	CPP	1	4	Yes	$D_{p,1}$	n_1	P/D_4
General cargo	CPP	1	4	Yes	$D_{p,2}$	n_1	P/D_5
General cargo	CPP	1	4	Yes	$D_{p,2}$	n_2	P/D_6
Bulker	FPP	1	2	no	$D_{p,1}$	n_1	P/D_1
Bulker	FPP	1	2	no	$D_{p,2}$	n_1	P/D_2
Bulker	FPP	1	2	no	$D_{p,2}$	n_2	P/D_1
Bulker	FPP	1	2	Yes	$D_{p,1}$	n_1	P/D_1
Bulker	FPP	1	2	Yes	$D_{p,2}$	n_1	P/D_2
Bulker	CPP	1	2	no	$D_{p,1}$	n_1	P/D_1
Bulker	CPP	1	2	no	$D_{p,2}$	n_1	P/D_2
Bulker	CPP	1	2	no	$D_{p,2}$	n_2	P/D_3
Bulker	CPP	1	2	Yes	$D_{p,1}$	n_1	P/D_4
Bulker	CPP	1	2	Yes	$D_{p,2}$	n_1	P/D_5
Container	FPP	1	2	no	$D_{p,1}$	n_1	P/D_1
Container	FPP	1	2	no	$D_{p,2}$	n_1	P/D_2
Container	FPP	1	2	no	$D_{p,2}$	n_2	P/D_3
Container	CPP	1	2	no	$D_{p,1}$	n_1	P/D_1
Container	CPP	1	2	no	$D_{p,2}$	n_1	P/D_2
Container	CPP	1	2	no	$D_{p,2}$	n_2	P/D_3
Container	CPP	1	4	no	$D_{p,1}$	n_3	P/D_4
Container	CPP	1	4	no	$D_{p,2}$	n_3	P/D_5
Container	CPP	2	4	no	$D_{p,3}$	n_4	P/D_6
Container	CPP	2	4	no	$D_{p,4}$	n_4	P/D_7

3.1 PROPELLER CHARACTERISTICS

The selection of propellers and different propeller parameters which are varied in the analysis are discussed in the following subchapters.

3.2 PROPELLER TYPE

The influence of propeller type is investigated by calculating the bollard pull and net thrust values both for FPP and CPP solutions. The comparison between CPP and FPP is mainly related to 2-stroke engines as having a FPP in a 4-stroke engine can be considered as somewhat unconventional and possibly unpractical solution. However, the comparison of FPP and CPP with 4-stroke main engine is done for the general cargo vessels as an example. For the container ship it is not possible to reasonably match the FP propeller and 4-stroke engine due to the high speed and propulsion power. Therefore, only the CPP solution is investigated for the container ship with 4-stroke main engine alternative.

The design and calculation process with CP propellers is discussed in more detail in chapter 3.5.

3.2.1 DESIGN PRINCIPLES

The propeller for each vessel is designed based on the open-water requirements which is a common practice for merchant vessels. The target is to minimize the needed propulsion power at the service speed. The required thrust/open-water resistance for each ship type at the open-water service speed is estimated by using the Holtrop 84 method. The propeller characteristics (diameter, pitch, area ratio, RPM) are chosen in a way that the propeller delivers the required thrust. The required propulsion power at the service speed (continuous service rating, CSR) is calculated based on the propeller characteristics and used in the selection of the main engine (Table 3-5). The propellers are assumed to have fixed pitch when the CSR is calculated.

Table 3-5: Required propulsion powers in open water at the service speed.

Ship type	$V_{service}$ [kn]	CSR [kW]
General cargo ship	12	1525
Bulk carrier	14.5	9630
Container ship (2-stroke, small propeller)	18.5	8065
Container ship (2-stroke, large propeller)	18.5	7700
Container ship (2-stroke, large propeller, low RPM)	18.5	7805
Container ship (4-stroke)	18.5	7950

For the analysis of this research, the propeller open-water curves are produced based on the Wageningen B-screw propeller series for the FP propellers (Oosterveld & van Oossanen, 1975). The number of blades is assumed to be 4 for all cases. Cavitation is not considered in the propeller selection.

3.2.2 BLADE AREA RATIO

The blade area ratio $\frac{A_e}{A_o}$ of the propellers is chosen to be representative for the corresponding ship-type (service speed and power level). The blade area ratio is kept the same for all propeller variants for each ship-type.

Following blade area ratios used in the analysis:

- General cargo ship: 0.50
- Bulk carrier: 0.50
- Container ship: 0.55

3.2.3 PROPELLER DIAMETER AND NUMBER OF PROPELLERS

The used propeller sizes are presented in Table 3-1 - Table 3-3. As presented in the previous chapters, increasing propeller diameter can be an attractive solution to reduce the propulsion power. Therefore, the propeller diameter is varied in order to investigate the influence of the propeller diameter to the vessels' ability to produce bollard pull. The propeller diameters are chosen so that there are two different size alternatives for each ship type: one diameter represents a somewhat typical value for such a vessel while the other one is approximately 10% larger. Whether the chosen propellers can actually fit into the example vessels is not considered. The two different propeller diameters are referred as small ($D_{p,1}$) and large ($D_{p,2}$) in the analysis and results.

The selected ship types are typically single propeller vessels and therefore the analysis focus on single screw solutions. Typical twin-screw vessels at the northern Baltic Sea are RoRo-cargo and passenger vessels which have high propulsion power in relation to their draft. However, these vessels are not included in the analysis as they normally have IA Super ice class. The influence of the number of propellers is investigated with the container vessel which the most probable alternative of the selected ship types to have two propellers.

The propeller diameter for the twin-screw container vessel is calculated with following formula to have the same power per propeller disk area as the single screw vessel:

$$D_{p,2} = \frac{D_{p,1}}{\sqrt{2}} \qquad (14.)$$

To simplify, only the propeller size has been changed when the single screw container vessel is converted to twin-screw vessel. The thrust deductions, wake fractions etc. are kept the same.

3.2.4 ROTATION SPEED AND PITCH

Generally, there are three different FP propeller variants for each ship type. The design RPM (the RPM which produces the required thrust in open water at the service speed) and propeller pitch are chosen with following method:

- Propeller variant #1, small propeller ($D_{p,1}$):
  - The design RPM and propeller pitch are chosen to minimize the propulsion power with $D_{p,1}$.
- Propeller variant #2, large propeller ($D_{p,2}$):
  - The design RPM is kept the same as for the variant #1. The pitch is reduced to obtain the required thrust and similar propulsion power as with variant #1
- Propeller variant #3, large propeller ($D_{p,2}$):
  - The pitch is the same as for the variant #1. The RPM is reduced to obtain the required thrust and similar propulsion power as with other variants

The above variation of RPM, pitch and propeller diameter is considered to demonstrate the influences of the pitch and propeller diameter changes to the thrust capabilities of the vessel. Both pitch and propeller diameter are important factors when optimizing the propulsion power of the vessel.

For the container ship the variation has been done slightly differently as there are both 2-stroke and 4-stroke engine variants. For 2-stroke engines there are three different propeller variants:

- Propeller variant #1, large propeller ($D_{p,2}$):
  - The design RPM and propeller pitch are chosen to minimize the propulsion power with $D_{p,2}$
- Propeller variant #2, small propeller ($D_{p,1}$):
  - The design RPM is kept the same as for the variant #1. The pitch is increased to obtain the required thrust.
  - The pitch is relatively high and the power consumption is increased.
- Propeller variant #3, 2-stroke engine, large propeller ($D_{p,2}$):
  - The propeller diameter is the same as for the variant #1. The pitch is between the variants #1 and #2 as the propeller RPM is reduced as much as possible with the selected engine.

For 4-stroke engines there are two different propeller variants both for the single screw and twin-screw versions. The selection of engines is done for both with similar method:

- Propeller variant #1, small propeller ($D_{p,1}$):
  - The design RPM and propeller pitch are chosen to minimize the propulsion power with $D_{p,1}$.
- Propeller variant #2, large propeller ($D_{p,2}$):
  - The design RPM is kept the same as for the variant #1. The pitch is reduced to obtain the required thrust and similar propulsion power as with variant #1

3.3 ENGINE SELECTION

The power levels informed for each ship-type in Table 3-1 to Table 3-3 represent the maximum installed power and the engines are selected based on this power level. Different ship-types use typically different type of engines based on the size of the vessel. Following engine types are used in the analysis:

- General cargo ship, 5000 DWT: 4-stroke engine with reduction gear
- Bulk carrier, 97000 DWT: directly coupled 2-stroke engine
- Container ship, 13000 DWT: both 4-stroke and 2-stroke variants

The used engines for different ship-types are presented in Table 3-6. All engines are assumed to run on MDO. The possible influences of alternative fuels are discussed in chapter 5.3.

The required CSRs for different vessels are presented in Table 3-5. The engines are matched to the investigated propellers so that the engines produce the CSR at reasonable load. The same CSR has been used for general cargo ships and bulk carriers for all different propeller alternatives as the changes in the propulsion power have been small. For container ship, there has been bigger difference between the propellers and therefore the CSR is varied. As the design RPMs of different propellers has varied, the 2-stroke engines are matched to the propellers by derating the engine while the 4-stroke engines are matched by adjusting the gear-ratios. The different gear ratios and design RPMs are presented in Appendix 1.

To simplify, the delivered power is assumed to be the same as the installed power (MCR) in the analysis. The losses occurring in the shaft bearings and possible gears are not taken into account.

Table 3-6: Summary of the used engines for different ship types.

Ship type	Engine make and model	MCR [kW]	Stroke-type	PTI [kW]	P_D [kW]
General cargo ship	Wärtsilä 7L25A	2625	4	0	2625
General cargo ship	Wärtsilä 6L25A	2040	4	585	2625
Bulk carrier	MAN 7S60	15000	2	0	15000
Bulk carrier	MAN 5S60	10700	2	4300	15000
Container ship	MAN 6S50	9070 - 9490	2	0	9070 - 9490
Container ship	Wärtsilä 16V31	9760	4	0	9760
Container ship with two shaftlines	2 * Wärtsilä 8V31	2 * 4880	4	0	9760

3.3.1 PTI

The influence of PTI is investigated with general cargo ships and bulk carriers. The open-water performance is seldomly the determinative factor for the power level of slow steaming merchant vessels. The ice-classed vessels typically have more power installed than the open-water performance alone would require due to the FSICR minimum power requirement. Therefore, it is possible to also have alternatives with PTI in which the size of the main engine is reduced to better match the requirements in open water.

For container ships the somewhat high open-water speed is typically the determinative factor for the power level and there is no need to install additional power due to the ice class requirements. Therefore, PTI is not feasible solution for container ships and it is not investigated with container ships.

The power level of the PTI is the estimated difference between the required power level in open-water and in ice. Possible losses in the gears are disregarded. In addition, it is not considered whether the power level of the PTI is reasonable in respect of the need for auxiliary engines in the vessel. For variants with PTI, the power level of the main engine size is reduced by reducing the number of cylinders to keep the characteristics of the main engine otherwise somewhat unchanged.

The maximum torque of the PTI is determined based on the maximum RPM of the main engine. It assumed that the full power of the PTI is obtained with the maximum RPM of the main engine and the torque is constant at lower RPM. For general cargo ship there are two alternatives as the gear-ratio has been varied.

Table 3-7: Summary of the PTI characteristics.

Ship type	PTI [kW]	Max. RPM	Q_{max} [kNm]
General cargo ship	585	176.5	31.7
General cargo ship	585	150.0	37.2
Bulk carrier	4300	93.8	437.8

3.4 CALCULATION OF BOLLARD PULL AND NET THRUST

The bollard pull and the net thrust at 5 knots speed are calculated by determining the intersection of the propeller curves and engine layout (see Figure 2-2). The delivered thrust and required torque of the propeller are calculated with the propeller open water curves while the available torque of the main engine is based on the engine layout of each selected engine. The layouts have been manually extended to lower RPM levels when necessary. The 100% load curve of the engines has been used when determining the intersections of the propeller curves and engine layouts (Figure 3-1). There is also an overload curve available but the 100% load is used in the analysis as the overload curve is only for short-term operation. However, it should be noted that in principle the vessels are able to produce more power for a very short-term operation.

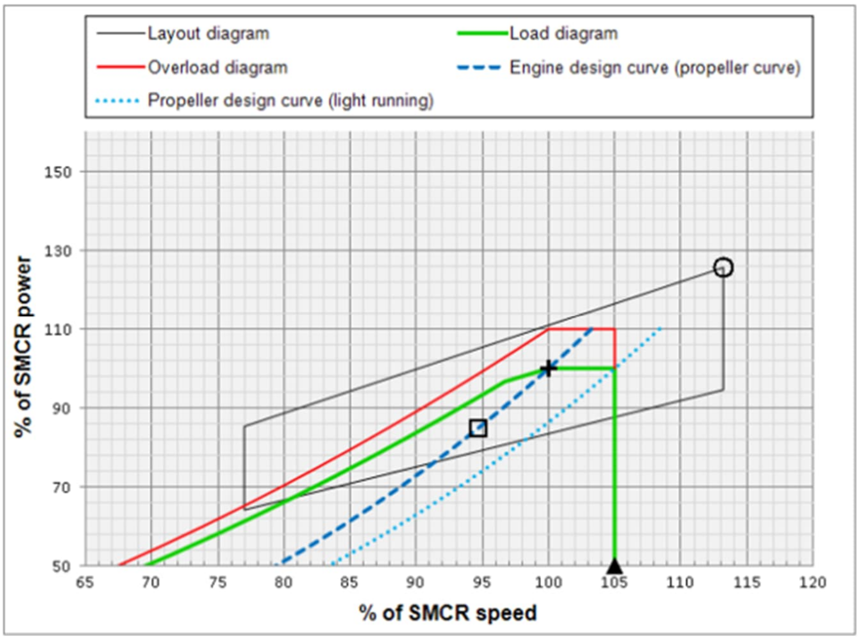

Figure 3-1: The 100% load diagram (green) is used when the torque capability of the main engine is used. The overload diagram (red) is only for very short-term operation. Image from MAN CEAS engine calculation tool.

Summary of the thrust deductions and wake fractions used in the calculations are presented in Table 3-8. A constant 5% thrust deduction is assumed for all ship types in bollard pull. The wake fraction is assumed to be constant throughout the whole speed range except w=0 in bollard pull.

Table 3-8: Summary of the used thrust deductions and wake fractions.

Ship type	$t_{0\ kn}$	$t_{5\ kn}$	w
General cargo ship	0.05	0.144	0.27
Bulk carrier	0.05	0.15	0.34
Container ship	0.05	0.12	0.20

Once the bollard pull force has been calculated, the quality factor for bollard pull K_e is calculated based on the equation (7.) (the installed power used as propulsion power):

$$K_e = \frac{T_{Pull}}{(P_D D_P)^{2/3}}, \qquad (15.)$$

The bollard pull and net thrust values which are calculated based on the actual propeller and engine characteristics are compared to the values which are calculated based on the assumptions of the FSICR. Using the assumption of the FSICR, the bollard pull force is calculated with equation (7.) and the values for K_e are taken from Table 2-1 and Table 2-2. According to the FSICR, the net thrust at 5 knots speed is calculated with equation (10.).

3.5 CONTROLLABLE PITCH PROPELLERS

The design and calculation process for CPPs is slightly different than with the FPPs. For CP propellers the calculation process is more complicated as there are only very few standard propeller series for CP propellers and the public references are somewhat old. The open water characteristics of controllable pitch propeller series have been largely neglected in the open literature (Carlton, 2007). In the analysis of this report, also the CP propellers are also designed/calculated by using the Wageningen B-screw propeller series as there are no feasible public propeller series for CPP. The design and calculation process for CPPs is following:

- The same main engines and engine layouts are used as with the FPP variants. Also, the propeller diameters and blade area ratios are kept the same.
- The propeller is assumed to rotate at shaft RPM corresponding the maximum RPM of the main engine.
- The propeller pitch is chosen so that the P_D at the maximum RPM is the same as the MCR.
- The thrust is calculated using the propeller open water curve. As the CPPs have larger hub than FPPs and the blade profile is distorted (Figure 2-4), the calculated thrust is reduced by 3%.

4 RESULTS

The results of the analysis are presented individually for each different propulsion arrangement in following subchapters. The calculated propulsion power and thrust based on the actual propeller and engine parameters (referred as calculated values in the results) are compared to values which are calculated based on the assumptions of the FSCIR (referred as FSICR values) and the ratios between the calculated and FSCIR values are presented in the results. The influence of different parameters to the vessel performance at low icebreaking speeds is discussed in chapter 4.5.

When investigating the comparisons of the K_e -value, it should be noted that the full installed propulsion power is used in the calculation of the K_e. The possible reductions of propulsion power are taken into account in the value of K_e. The comparison of propulsion power is used to present what is the actual propulsion power of the vessel at low speed and how much the power is reduced due to torque limitation of the main engine.

The detail results with all propeller and engine parameters are presented in Appendix 1.

4.1 FIXED PITCH PROPELLERS

As described in chapter 3.2.4, there are three fixed pitch propeller variants: two variants with same design RPM but varying diameter and pitch, and one variant with large diameter but smaller design RPM. These variants are referred as $D_{p1,n1}$; $D_{p2,n1}$ (“high” RPM variants) and $D_{p2,n2}$ (“low” RPM variant).

Summary of the results with FPP vessels is presented in Table 4-1. It can be seen that the main engines are not able to rotate the open water optimized fixed pitch propellers with full power at low icebreaking speeds. The propulsion power is reduced in all investigated cases and therefore the vessels are not delivering the thrust which the FSICR assumes based on the installed propulsion power and propeller diameter. In all cases the propulsion power is increased as the speed of the vessel is increased to 5 knots from the bollard pull situation. This is expected but it means that the net thrust curve does not have similar shape as presented in Figure 2-1. As the propulsion power is increased, the difference between the calculated and FSICR net thrusts is decreasing when compared to the difference observed in bollard pull.

Table 4-1: Summary of the bollard pull and 5 knots net thrust results with FPP variants.

			Bollard pull								5 knots speed					
			Propulsion power [kW]			Bollard pull force [kN]			K_e		Propulsion power [kW]			Net thrust [kN]		
Vessel type	D_p	RPM	Installed	Calculated	Ratio	FSICR	Calculated	Ratio	FSICR	Calculated	Installed	Calculated	Ratio	FSICR	Calculated	Ratio
General cargo	$D_{p,1}$	n_1	2 625	99	4 %	296	38	13 %	0.702	0.090	2 625	588	22 %	237	78	33 %
General cargo	$D_{p,2}$	n_1	2 625	82	3 %	314	37	12 %	0.702	0.082	2 625	499	19 %	251	72	29 %
General cargo	$D_{p,2}$	n_2	2 625	110	4 %	314	43	14 %	0.702	0.096	2 625	876	33 %	251	117	47 %
Bulker	$D_{p,1}$	n_1	15 000	6 905	46 %	1577	1093	69 %	0.702	0.486	15 000	8 749	58 %	1262	967	77 %
Bulker	$D_{p,2}$	n_1	15 000	6 122	41 %	1665	1091	66 %	0.702	0.460	15 000	8 071	54 %	1332	969	73 %
Bulker	$D_{p,2}$	n_2	15 000	6 872	46 %	1665	1150	69 %	0.702	0.485	15 000	8 832	59 %	1332	1 027	77 %
Container	$D_{p,1}$	n_1	9 490	3 139	33 %	980	479	49 %	0.702	0.343	9 490	4 170	44 %	784	463	59 %
Container	$D_{p,2}$	n_1	9 070	2 399	26 %	1008	454	45 %	0.702	0.316	9 070	3 415	38 %	806	443	55 %
Container	$D_{p,2}$	n_2	9 260	2 626	28 %	1022	465	45 %	0.702	0.319	9 260	3 649	39 %	818	454	55 %

The general cargo ship has difficulties to rotate the selected propellers in bollard pull. However, results with the general cargo ship should be viewed carefully. The load diagrams of the selected 4-stroke engines have similar shape as the propeller curves and therefore the intersection between the propeller curve and engine layout is not as clear as it is with the 2-stroke engines. A somewhat small change in the propeller parameters could mean that the full power is available. In addition, the possibility for short-term overload would improve the situation. Finally, it should be noted that the 4-stroke engine is not well suited for a fixed pitch propeller due to the need for a reverse gear.

A comparison between the different propeller variants is presented in Figure 4-1. The differences between the variants are relatively small but it can be seen that the performance at low speed is decreased when the propeller diameter is increased but the design RPM is kept the same (pitch reduced). The performance is improved when the design RPM has been reduced (pitch increased). This is most likely related to the fact that the torque capabilities of the main engine are improved as it is derated (2-stroke) or the gear-ratio is increased (4-stroke).

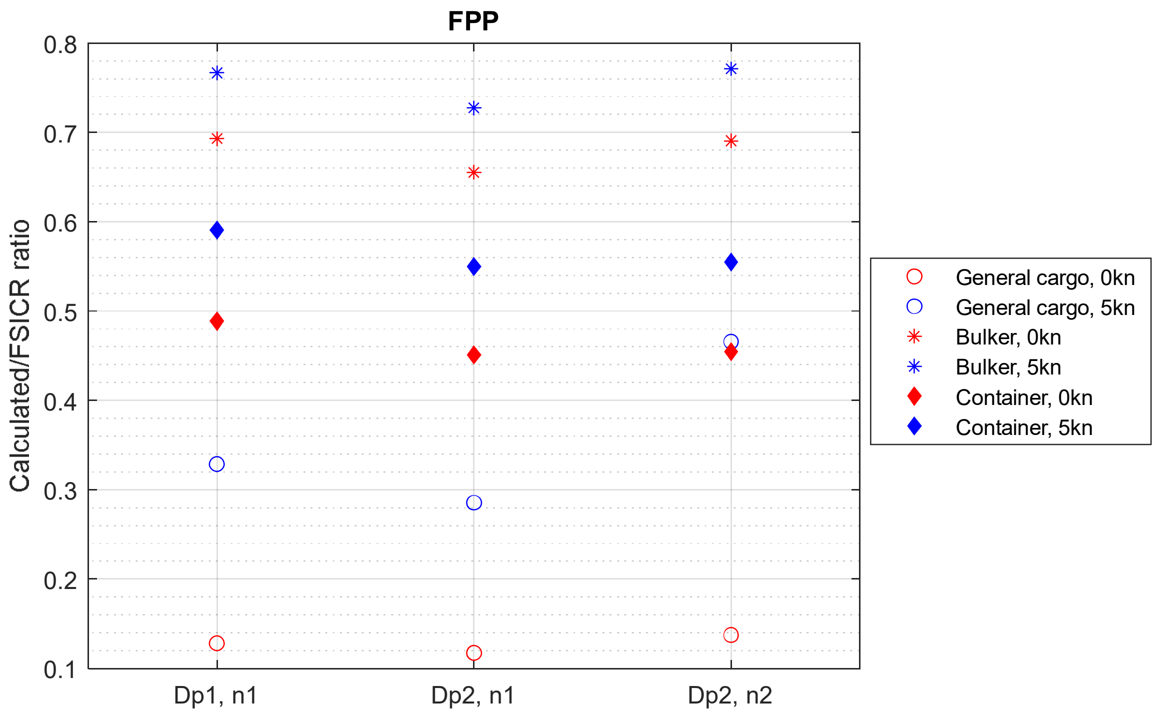

Figure 4-1: Ratio between the bollard pull and net thrust forces for different FPP propeller variants.

4.2 FIXED PITCH PROPELLERS WITH PTI

The propeller variants and the total installed propulsion power for vessels with PTI are the same as for the vessels without the PTI in chapter 4.1. Summary of the results is presented in Table 4-2. It is not totally obvious how the PTI with FPP is to be taken into account in the FSICR as the K_e -values of the FSICR are for conventional propulsion systems. In the analysis the K_e -value of 0.78 (for CPP or electric propulsion) is used when calculating the FSICR thrust values.

Table 4-2: Summary of the bollard pull and 5 knots net thrust results with FPP + PTI variants.

			Bollard pull								5 knots speed					
			Propulsion power [kW]			Bollard pull force [kN]			K_e		Propulsion power [kW]			Net thrust [kN]		
Vessel type	D_p	RPM	Installed	Calculated	Ratio	FSICR	Calculated	Ratio	FSICR	Calculated	Installed	Calculated	Ratio	FSICR	Calculated	Ratio
General cargo	$D_{p,1}$	n_1	2 625	1 760	67 %	329	259	79 %	0.780	0.614	2 625	2 518	96 %	263	254	97 %
General cargo	$D_{p,2}$	n_1	2 625	1 397	53 %	349	244	70 %	0.780	0.545	2 625	2 621	100 %	279	283	102 %
General cargo	$D_{p,2}$	n_2	2 625	2 269	86 %	349	325	93 %	0.780	0.727	2 625	2 362	90 %	279	256	92 %
Bulker	$D_{p,1}$	n_1	15 000	13 738	92 %	1753	1729	99 %	0.780	0.769	15 000	14 996	100 %	1402	1 447	103 %
Bulker	$D_{p,2}$	n_1	15 000	12 630	84 %	1850	1768	96 %	0.780	0.745	15 000	14 736	98 %	1480	1 526	103 %

Based on the results the PTIs clearly improves the vessels' thrust at low speeds. However, it should be noted that the PTI does not automatically mean that full power is available as can be seen from the results. Generally, the high propeller load at bollard pull limits the RPM which reduces the propulsion power at zero speed but almost full power is achieved when the speed of the vessel has increased from zero to 5 knots.

The general cargo vessels give interesting demonstration of the influence of the design point of the PTI system. The "high" RPM variants ($P_{d1,\,n1}$ & $P_{d2,\,n1}$) have clearly reduced propulsion power in bollard pull while the "low" RPM variant ($P_{d2,\,n2}$) can achieve almost full power in bollard pull. The "low" speed variant propeller is designed for low RPM by increasing the gear ratio which improves the torque capabilities of the main engine. In addition, the PTI is designed for low RPM which increases the maximum torque of the PTI motor. Therefore, the bollard pull capability is clearly higher when compared to the other general cargo variants. However, when the speed of the vessel is increased to 5 knots, propulsion power of the "low" RPM variant is reduced because the maximum RPM of the main engine is reached. Also, for the $P_{d1,\,n1}$ variant (general cargo vessel) the propulsion power is reduced at 5 knots speed as the maximum RPM is reached. Therefore, the variant which has the highest bollard pull force has the lowest net thrust at 5 knots speed. On the other hand, the variant which has the lowest bollard pull delivers the highest net thrust at 5 knots speed. This is a good example how the design point of the PTI is an important factor when considering the benefits of the PTI with FPP.

A comparison between the different propeller variants is presented in Figure 4-2. The RPM limitations makes the comparison more unclear when compared to Figure 4-1.

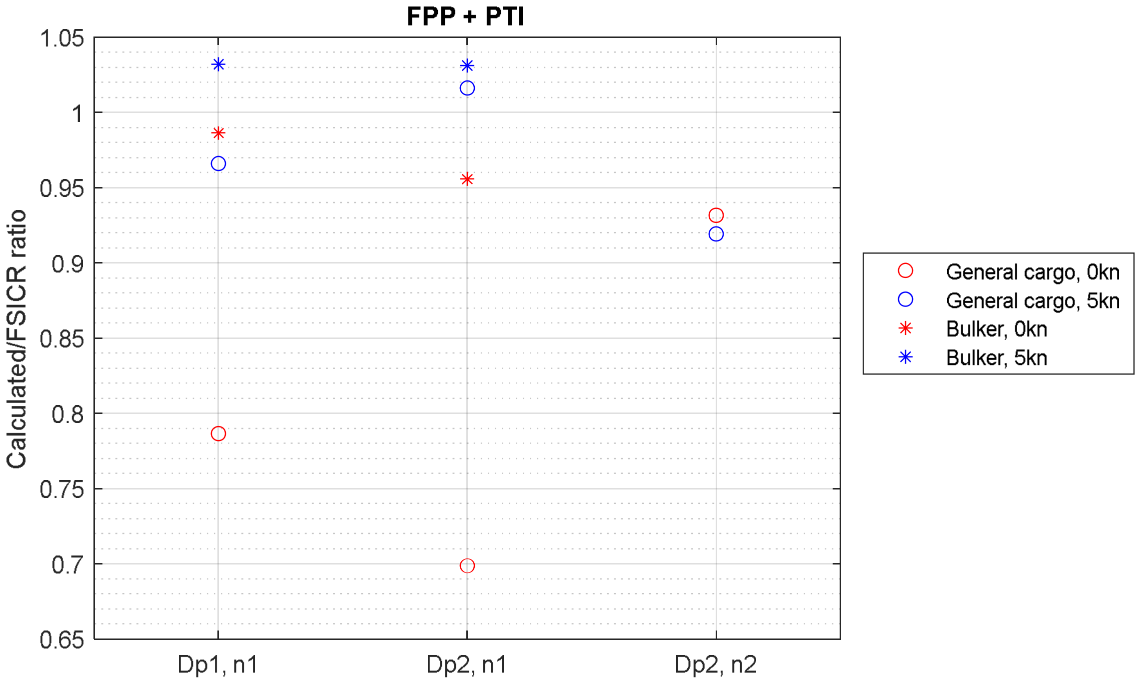

Figure 4-2: Ratio between the bollard pull and net thrust forces for different FPP + PTI propeller variants.

4.3 CONTROLLABLE PITCH PROPELLERS

For general cargo ships, bulk carriers and container ships with 2-stroke engines the propeller diameters and the main engines are the same for CPP variants as for the FPP variants. For container ships with 4-stroke engines there are no FPP variants as described in chapter 3.2.4. The results with CP propellers are presented in Table 4-3. It can be seen that the calculated bollard pulls and net thrusts are very close to the values obtained with FSICR assumptions. Also, for the 2-shaftline version the results are well in-line. It can be concluded that when the propulsion power is not limited, the assumptions of the FSICR give good results. There are few percentage point differences between the calculated and FSICR thrust values, but it should be noted that the values are of the same magnitude and there are no similar clear differences as there are with the vessels which have FPP only. The few percentage point differences in the thrust values can be explained by differences in the propeller designs.

A comparison between the different propeller variants is presented in Figure 4-3. There are no clear trends, and the observed differences between the variants are smaller than with vessels with FPP and FPP + PTI.

Table 4-3: Summary of the bollard pull and 5 knots net thrust results with FPP + PTI variants.

			Bollard pull								5 knots speed					
			Propulsion power [kW]			Bollard pull force [kN]			K_e		Propulsion power [kW]			Net thrust [kN]		
Vessel type	D_p	RPM	Installed	Calculated	Ratio	FSICR	Calculated	Ratio	FSICR	Calculated	Installed	Calculated	Ratio	FSICR	Calculated	Ratio
General cargo	$D_{p,1}$	n_1	2 625	2 625	100 %	329	336	102 %	0.780	0.795	2 625	2 625	100 %	263	256	97 %
General cargo	$D_{p,2}$	n_1	2 625	2 625	100 %	349	364	104 %	0.780	0.815	2 625	2 625	100 %	279	275	99 %
General cargo	$D_{p,2}$	n_2	2 625	2 625	100 %	349	355	102 %	0.780	0.793	2 625	2 625	100 %	279	270	97 %
Bulker	$D_{p,1}$	n_1	15 000	15 000	100 %	1753	1829	104 %	0.780	0.814	15 000	15 000	100 %	1402	1 422	101 %
Bulker	$D_{p,2}$	n_1	15 000	15 000	100 %	1850	1919	104 %	0.780	0.809	15 000	15 000	100 %	1480	1 476	100 %
Bulker	$D_{p,2}$	n_2	15 000	15 000	100 %	1850	1931	104 %	0.780	0.814	15 000	15 000	100 %	1480	1 497	101 %
Container 2-stroke	$D_{p,1}$	n_1	9 490	9 490	100 %	1089	1079	99 %	0.780	0.773	9 490	9 490	100 %	872	881	101 %
Container 2-stroke	$D_{p,2}$	n_1	9 490	9 070	105 %	1154	1157	100 %	0.780	0.782	9 490	9 070	96 %	924	930	101 %
Container 2-stroke	$D_{p,2}$	n_2	9 260	9 260	100 %	1136	1152	101 %	0.780	0.791	9 260	9 260	100 %	909	932	103 %
Container 4-stroke	$D_{p,1}$	n_3	9 760	9 760	100 %	1110	1154	104 %	0.780	0.811	9 760	9 760	100 %	888	930	105 %
Container 4-stroke	$D_{p,2}$	n_3	9 760	9 760	100 %	1176	1174	100 %	0.780	0.779	9 760	9 760	100 %	941	931	99 %
Container 2 shaftlines	$D_{p,3}$	n_4	9 760	9 760	100 %	1109	1140	103 %	0.980	1.008	9 760	9 760	100 %	887	892	101 %
Container 2 shaftlines	$D_{p,4}$	n_4	9 760	9 760	100 %	1174	1226	104 %	0.980	1.023	9 760	9 760	100 %	939	950	101 %

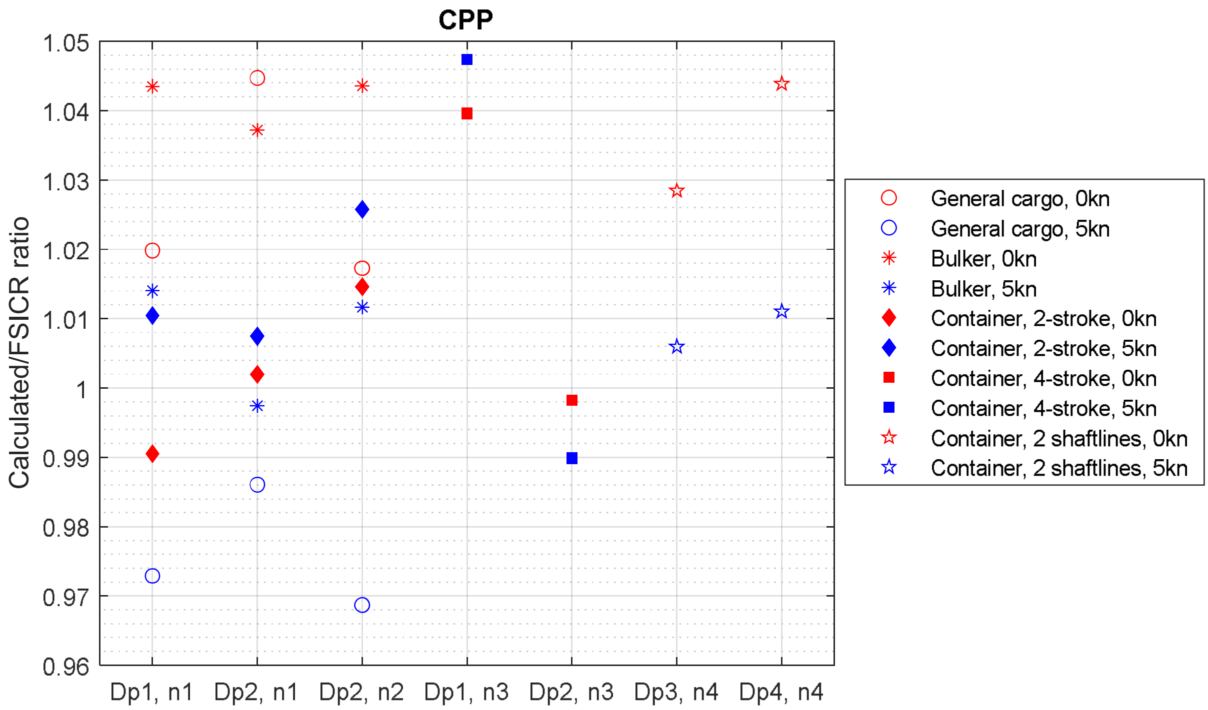

Figure 4-3: Ratio between the bollard pull and net thrust forces for different CPP propeller variants. Note the scale of the y-axis when compared to previous figures.

4.4 CONTROLLABLE PITCH PROPELLERS WITH PTI

For CPP + PTI variants, the main engines, PTIs and propeller diameters are the same as for the FPP + PTI variants (chapter 4.2). The propeller pitch and RPM are different. When compared to variants with CPP without PTI (chapter 4.3), the total installed power, propeller diameters and propeller RPM are the same. The main engines are different and the propeller pitch can be larger as the PTI improves the torque capability of the machinery.

The results for CPP + PTI variants are presented in Table 4-4. When compared to the FPP + PTI variants (Table 4-2) it can be seen that the thrust capabilities are improved as the full propulsion power is constantly available due to CPP. When compared to the CPP alone (Table 4-3), the CPP + PTI variants have developed approximately 1% less thrust. The larger pitch propellers of the CPP + PTI variants have lower $\frac{K_T}{K_Q{}^{2/3}}$ ratio when compared to propellers of the CPP only variants. This explains the small difference between the two different propulsion alternatives. The calculated thrusts are close to the values which are obtained with the assumptions of the FSICR as is the case also with vessels with CPP only.

A comparison between the different propeller variants is presented in Figure 4-4. The smallest pitch propellers have performed the best, but the differences are small.

Table 4-4: Summary of the bollard pull and 5 knots net thrust results with CPP + PTI variants.

			Bollard pull								5 knots speed					
			Propulsion power [kW]			Bollard pull force [kN]			K_e		Propulsion power [kW]			Net thrust [kN]		
Vessel type	D_p	RPM	Installed	Calculated	Ratio	FSICR	Calculated	Ratio	FSICR	Calculated	Installed	Calculated	Ratio	FSICR	Calculated	Ratio
General cargo	$D_{p,1}$	n_1	2 625	2 625	100 %	329	331	101 %	0.780	0.784	2 625	2 625	100 %	263	253	96 %
General cargo	$D_{p,2}$	n_1	2 625	2 625	100 %	349	363	104 %	0.780	0.811	2 625	2 625	100 %	279	275	98 %
General cargo	$D_{p,2}$	n_2	2 625	2 625	100 %	349	348	100 %	0.780	0.779	2 625	2 625	100 %	279	266	95 %
Bulker	$D_{p,1}$	n_1	15 000	15 000	100 %	1753	1795	102 %	0.780	0.799	15 000	15 000	100 %	1402	1 401	100 %
Bulker	$D_{p,2}$	n_1	15 000	15 000	100 %	1850	1933	105 %	0.780	0.815	15 000	15 000	100 %	1480	1 498	101 %

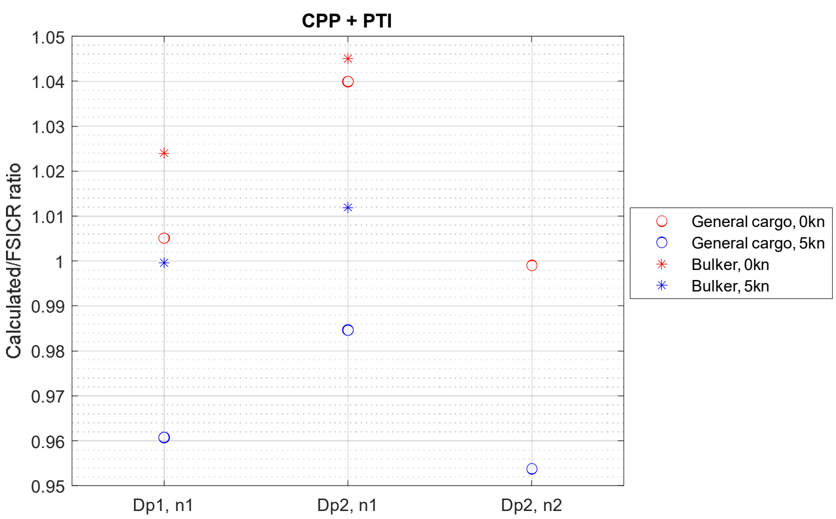

Figure 4-4: Ratio between the bollard pull and net thrust forces for different CPP + PTI propeller variants. Note the scale of the y-axis when compared to previous figures.

4.5 INFLUENCE OF DIFFERENT PARAMETERS

Based on the findings presented in the previous subchapters, it can be concluded that the FSICR assumptions give reasonable results when the full propulsion power is available. However, if the propulsion power is reduced due torque/RPM limits (mainly related to FPP), the FSICR assumes too high net thrust values. The difference between the calculated and FSICR values vary between different ship-types and therefore it is not possible to give a general value for the difference between the calculated and FSICR thrusts. The propeller parameters (diameter, pitch, design RPM) has been varied within different ship-types and the influence of different parameters was investigated in Figure 4-1 to Figure 4-4. It is not possible to make clear conclusions how variation of certain propeller parameter influences to the vessels ability to produce thrust at low speeds as the main engine characteristics has a major role regarding the vessel's ability to produce thrust (at low speed). The most important aspect regarding the thrust capability is the matching of the main engine and propeller.

One method to investigate the difference between the calculated and FSICR thrust values is to compare the torque demand of the propeller to the available torque of the main engine. This can be done by calculating a torque coefficient K_Q also for the main engine with formula (5.):

$$K_{Q,m} = \frac{Q}{\rho n^2 D^5},$$

where n is maximum RPM of the engine and Q is the maximum torque of the engine.

The $K_{Q,p}$ for the propeller is obtained from the propeller open water curves. The relation between the engine's and propeller's torque coefficients can be used to investigate the difference between the calculated and FSICR thrusts (Figure 4-5). The difference between the calculated and FCICR thrusts increases when the propeller torque demand increases in relation to the main engine's torque capabilities.

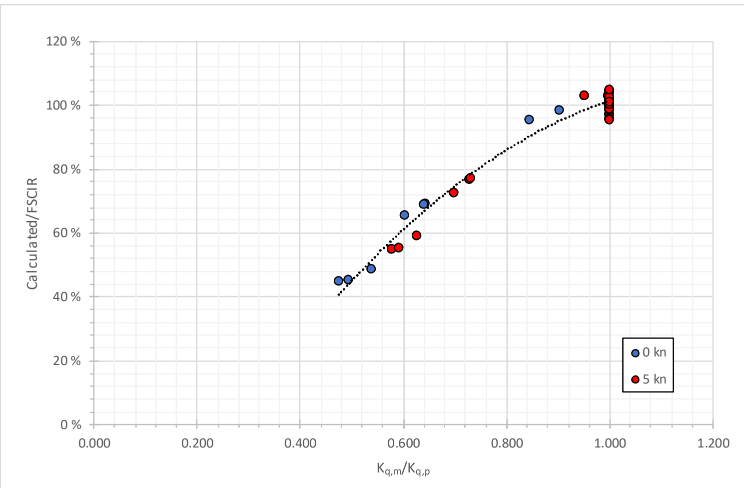

Figure 4-5: Comparison of the torque capability of the engine and torque demand of the propeller to the difference of calculated/FSICR thrust values. With CPP the torque ratio of the engine and propeller is 1. The general cargo vessels with FPP are disregarded from the figure.

4.6 TAKING THE ACTUAL PROPELLER AND ENGINE CHARACTERISTICS INTO ACCOUNT IN THE FSICR

Currently the FSICR is using the minimum power requirement to ensure sufficient ice-going capability for the ice-classed merchant vessels. However, the minimum power requirement does not take the real propeller and engine characteristics into account. As the actual thrust is the determinative factor regarding to the vessel's performance in ice (instead of the installed power), it could be feasible to change the rule requirements more into goal-oriented direction in which the goal is that the merchant vessel shall have a sufficient thrust to maintain 5 knots speed in designated brash ice channels. The required thrust can be calculated with the rule resistance formula or obtained with ice model tests. As the thrust of the vessel is linked both to the propeller and to the main engine, there is no straightforward simple calculation method which can be used to determine the actual bollard pull force or net thrust at 5 knots speed. However, the vessel's ability to produce the needed thrust can be determined relatively easily based on the propeller open water curve, vessel's thrust deduction factor and engine layout (Figure 4-6). Similar tools are already used in the open-water design of the vessels and could be relatively easily expanded to ice operation. When the ice class is being applied, the propeller curve with engine layout could be one mandatory document needed to demonstrate that sufficient thrust is available. The thrust deduction factor could be either set by the rule or obtained from the open water model tests.

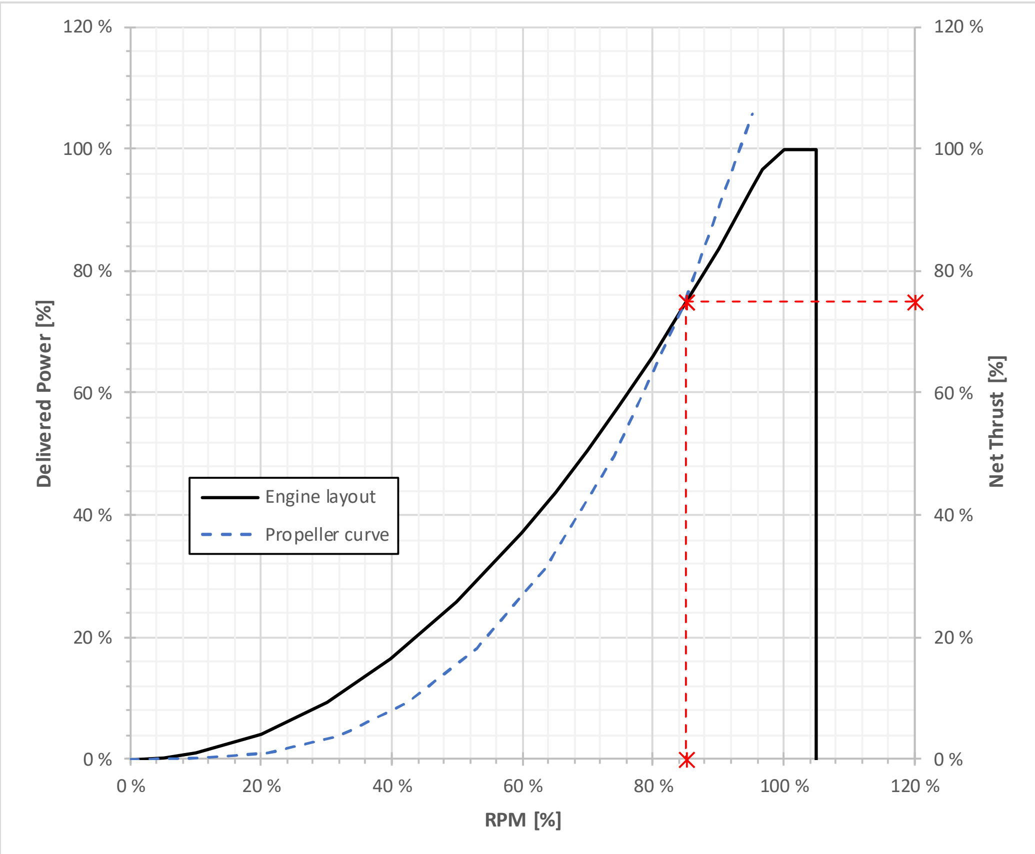

Figure 4-6: A schematic example of the propeller curve and the engine layout (based on delivered power). The thrust information linked to the propeller curve can be used to determine the actual thrust of the vessel at bollard pull or at 5 knots speed.

5 OTHER POSSIBLE SCENARIOS INFLUENCING THE PROPULSION POWER AND THE THRUST OF THE VESSEL

Other possible scenarios influencing the propulsion power and the thrust of the vessel are discussed in the following subchapters. The objective is to present possible scenarios in which the actual performance of the vessel differs from assumptions of the FSICR as possible future research topics.

5.1 FUNCTIONALITY OF THE CPP-SYSTEM IN ICE

As presented in Figure 2-3, a vessel with CP propeller can utilize full propulsion power when the propeller pitch is set correctly. However, if the pitch is set incorrectly, the propulsion power will be reduced and maximum possible thrust is not available. If the pitch is too small, the propulsion power is limited due to RPM limit of the main engine. If the pitch is too large, the propulsion power is reduced due to torque limitations of the main engine. The pitch setting is influenced both by the controls of the captain and the vessel automation (propulsion load control).

In order to understand what could be situations in which the full propulsion power (and thrust) is not available, it is important to understand how the CPP systems are designed to work and how they are operated. This is based on discussions and interviews with CPP system suppliers and crews of vessels with CP propellers. It should be noted that the functionality of the propulsion control system is a combination of the CPP and main engine. As there are several different CPP suppliers and several different engine manufacturers with several different engine models, there also numerous different combinations how the propulsion control system works. Therefore, the observations of this chapter are to be considered as general remarks to give information about the CPP systems' functionality in ice in relation to the vessel performance. The objective is to identify possible topics for future research. Below is a description of the basic principle of a simplified CPP-system without any influence of possible load control automation. The idea is to understand the relation between the propulsion power and the pitch controls.

Typically, a constant RPM mode is used when the vessels with CPP are operating in difficult ice conditions. In this mode the RPM is fixed to constant value (e.g. maximum RPM) and the pitch and propulsion power varies. The constant RPM is feasible solution when operating in ice as the inertia of the propulsion train is utilized and there is no need to use energy for inertial forces if the propulsion power is changed. A common method is that the control lever position sets the target pitch (the pitch is constant in normal conditions). Typically, the pitch varies linearly based on the lever position: zero pitch is obtained with zero position of the lever, maximum pitch is obtained with maximum position of the lever (full ahead). As both the RPM and pitch are constant at each lever position, the propulsion power varies based on the propeller loading (ice conditions and speed of the vessel). As described in previous sections, the pitch has to be set to correct setting in order to obtain the full propulsion power. In bollard pull condition or at low icebreaking speeds, this basically means that the pitch must be reduced from the design pitch which is related to the open-water speeds of the vessel. This can be somewhat unintuitive for the helmsman as the "full ahead"-setting of the control lever does not produce full propulsion power and thrust as the propeller is heavy-running with the maximum pitch: instead, the lever must be pulled back to reduce pitch. While this is most likely a clear procedure for a crew which is constantly operating in ice, it is possible that a crew which is operating in ice conditions for the first time does not realize the unintuitive relation between the control lever and propulsion power. Therefore, it is important that the issue addressed by the pilots and in the instructions which the icebreaker gives to the merchant vessel. It could be also useful that the bollard pull pitch has been defined and the information of the bollard pull pitch is available for example in the pilot card.

The behavior of the propulsion power and thrust in bollard pull in relation to the lever position is demonstrated in Figure 5-1 and Figure 5-2. The data is based on the bulk carrier example ship-type with 15 MW main engine and 7.1 m propeller. The pitch is varied linearly with each lever position between zero pitch and the open water design pitch with lever position 10. Once the maximum torque of the main engine is reached, the propulsion power and thrust are reduced.

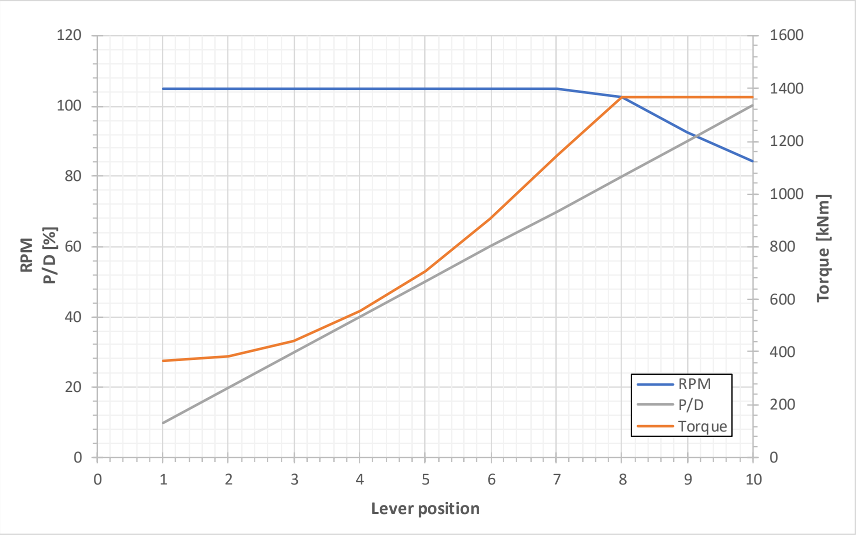

Figure 5-1: Relation of the pitch, RPM and torque in bollard pull for the bulk carrier.

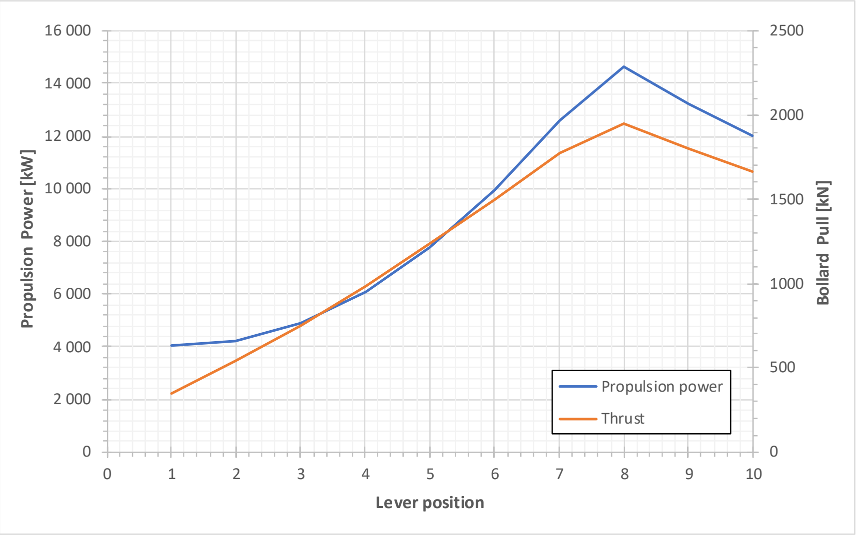

Figure 5-2: Relation of the power and thrust in bollard pull for the 15 MW bulk carrier.

The main engine is overloaded if the pitch setting is too large and the propeller demands more torque than the engine is capable to provide. This will result that the RPM of the main engine starts to drop. Therefore, there is typically a load control automation which will automatically reduce the propeller pitch in order to reduce the loading of the engine back to acceptable level. Automatic pitch control can be considered generally as somewhat challenging to regulate in ice: the ice conditions vary and affect the loading of the propeller and the loading changes in ice can be somewhat rapid. In addition, the automatic pitch control should be matched to the behavior of the main engine which is not necessarily straightforward as there are several different engine manufacturers and models. Interviews with crews indicated that in some cases the automatic loading control behavior is not optimal in ice. The automatic pitch reduction used to avoid engine overloading can be too rapid meaning that the main engine could obtain overspeed which is then compensated for example by limiting the charge air pressure of the engine. This decreases the propulsion power and thrust and the risk for getting stuck is increased as the speed of the vessel decreases and dynamic friction changes to static.

The actions of the crew and the behavior of the automatic load control system seem to be the main factors related to availability of full propulsion power and maximum thrust in ice with vessel with CPP. The crew must actively operate the vessel (correct position of the control lever) in order have full power available without overloading the engine. However, if the engine is overloaded, the automatic loading control should behave in such manner that the propulsion power is not excessively reduced. To have better understanding of the phenomena related to thrust and power limitations in ice due to loading of the CPP, a separate research program would be needed in which the behavior of different systems is investigated in actual ice conditions.

5.2 PROPELLER IN NOZZLE

A nozzle can be used to increase the thrust of the vessel and therefore nozzles are common solution for example in tugboats. The nozzle can be used also to improve the propulsion efficiency at service speeds and therefore nozzles are sometimes installed also to normal merchant vessels which are operating in open water. The influence of the nozzles is investigated in the guidelines of the FSICR (Traficom 2019). The guidelines suggest that 30% thrust increase can be expected from the nozzle when compared to normal open propeller with same diameter. The propulsion power can be therefore reduced to approximately 70% when compared to similar vessel with open propellers. Therefore, a nozzle is an attractive solution for ice-classed merchant vessel to reduce the propulsion power.

However, it should be noted that the nozzles can be installed to the merchant vessels based also on other requirements than the thrust or propulsion efficiency. Noise and vibration, improved wake and cavitation properties are other possible criteria favoring the use of a nozzle. Also, a nozzle for a merchant vessel which is optimized for speeds above 10 knots is designed based on different criteria than a nozzle for a tugboat which is designed for good bollard pull capability. The thrust properties of nozzles which are designed based on different criteria could vary. Therefore, the assumption of generic 30% thrust increase presented in FSICR should be viewed carefully.

The possible clogging of the nozzle with ice is also one factor to consider regarding the ice-going performance of the vessel with nozzles. The clogging of the nozzle will result considerable performance drop and heavy vibrations (Lindroos & Björkestam, 1986). Also, a partial clogging can cause severe vibrations which will require the vessel to stop and clear the nozzle even though the performance drop itself would not be as significant. The probability of clogging is influenced by the ice conditions (piece size) in relation to the propeller diameter, depth in which the propeller is installed, stern geometry and possible appendages and vessel speed and propeller loading (Björkestam, 1985). Basically, the clogging occurs when the ice piece is so big that it can get stuck against the nozzle (Figure 5-3). Therefore, a smaller propeller is more likely to get clogged. The ice-classed merchant vessels are mainly operating in pre-broken channels where likelihood to meet such big ice pieces is quite small. However, it should be noted that probability of clogging increases in difficult ice conditions where the maximum thrust of the vessel is critical. Generally, in difficult spots there is more ice and thicker ice which will increase the probability of clogging. In addition, the speed of the vessel is decreased and the propulsion power is high at difficult spots. Both factors will increase the probability of clogging as the propeller suction is intensified and ice is sucked to the propeller from larger area. Even though the nozzle generally improves the vessel's thrust in ice, a vessel with small diameter propeller especially operating at ballast draught could get the nozzle clogged in difficult ice conditions where the maximum thrust would be needed.

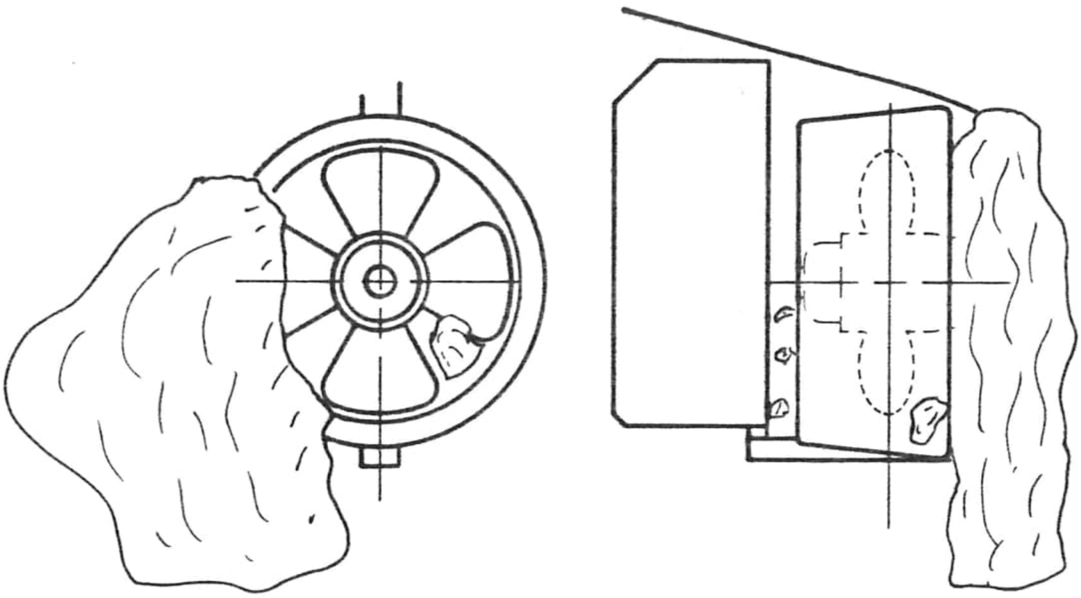

Figure 5-3: A typical clogging event (Lindroos & Björkestam, 1986).

The nozzle is an attractive solution to reduce propulsion power of an ice-classed merchant vessel. However, if the nozzle is used to reduce the propulsion power, it is recommended that the ice class rules require that the actual thrust properties in bollard pull condition and at low icebreaking speeds are determined instead of using general assumptions. In addition, the nozzle's tendency for clogging should be also investigated/demonstrated.

5.3 ALTERNATIVE FUELS

Generally, the influence of using alternative fuels (gas, methanol, ammonia) for ice-going capability of the merchant vessels is expected to be somewhat small. Possible impacts are briefly discussed in this chapter. However, it should be noted that the influence of alternative fuels is somewhat out of the focus of this project. Therefore, a separate research project is proposed if the topic is wanted to be investigated further. In addition, it should be noted the applications with methanol and ammonia are still under development and not all data is yet fully available.

In relation to operation in ice, probably the most significant difference between the engines running with alternative fuels is the slower loading capacity of the engine when compared to running with diesel (Figure 5-4). The slower loading capacity means that power changes in the propulsion take more time which can be relevant in some cases when operating in varying ice conditions. The crew of the merchant vessel must anticipate their actions more when operating with gas than with diesel to keep the vessel moving. For example, if there is a challenging ridged part ahead, the propulsion power should be increased beforehand to ensure that the full power is available when the vessel enters the challenging area. If the power is increased when the vessel is already at the difficult part, there is a risk that the vessel stops before the full power is available and then it is more challenging to get the vessel moving again as the static friction increases the vessel's resistance.

Other topic worth mentioning is the narrower operating range of the engine with alternative fuels than with diesel. An example of this is presented in Figure 5-5 where it is visible that the overload limit with gas is lower than with diesel. Basically, this means that the torque capabilities of the engine are reduced with gas compared to diesel when the engine is running at off-design point (for example bollard pull situation with fixed pitch propeller). However, the dual-fuel engines are typically designed to automatically to switch back to diesel if the loading exceeds the engine's capacity. Therefore, there are no differences in the torque capabilities of the modern dual-fuel engines compared to similar diesel engines. On the other hand, switching back to gas after the engine has been tripped to diesel takes some time. This could potentially to lead to situations in which the crew operates the merchant vessel somewhat carefully to avoid over-loading the engine. This could result that the full capabilities of the vessel are not used in ice.

It should be noted that the torque capabilities of the dual-fuel engines do not differ from regular diesel engines due to the possibility of running the engine with diesel. However, in case there would be a mono-fuel engines in the future, the situation would be different. Generally, the engines using alternative fuels have a narrower operating range which can reduce the performance at off-design points (which icebreaking at low speed can be often considered). Therefore, it is advisable to follow the development of the alternative fuels and engines using them.

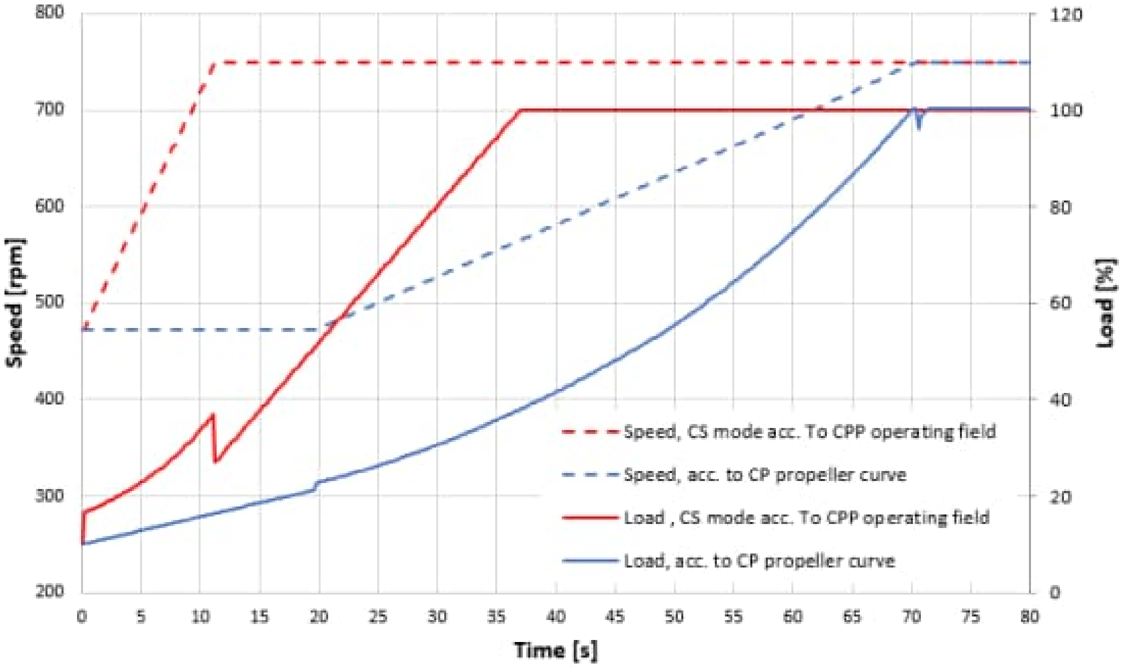

Fig 2-4 **Gas mode** 1) 2)

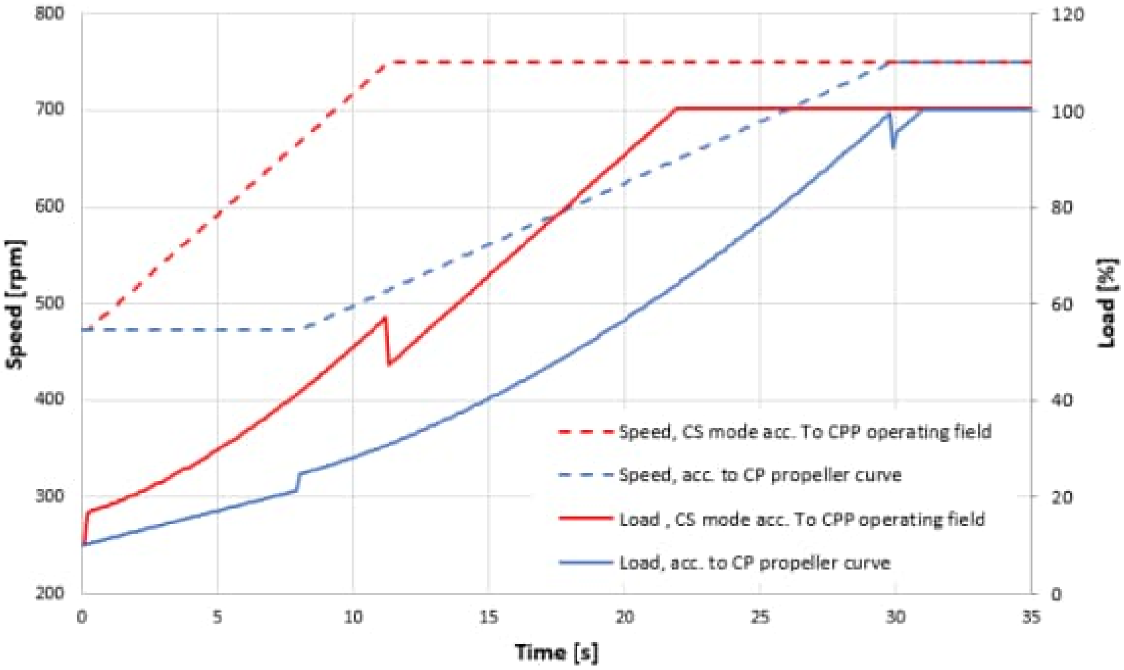

Fig 2-5 **Diesel mode** 1) 2)

Figure 5-4: Loading capacity of Wärtsilä 31DF engine both in gas and diesel modes (Wärtsilä, 2020 [1]).

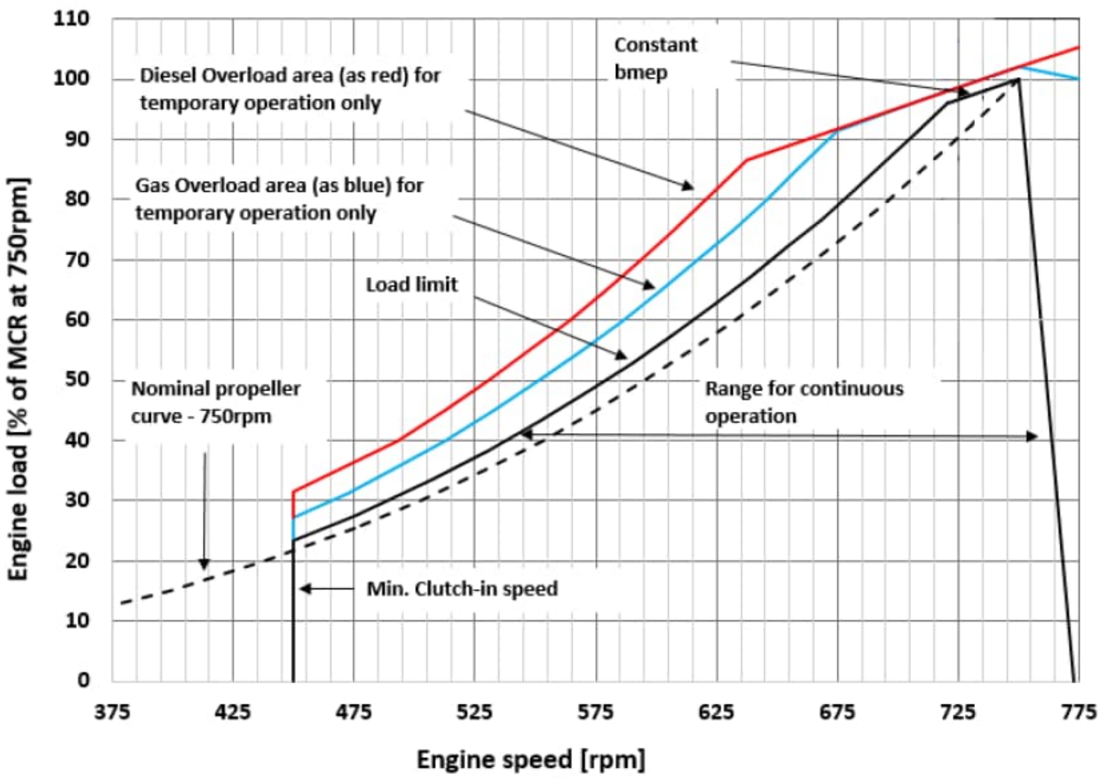

Figure 5-5: Operating range of the Wärtsilä 34DF engine. The overload limit is smaller in gas mode than with diesel (Wärtsilä, 2020 [2]).

6 CONCLUSIONS

This research focused on the merchant vessel's ability to produce sufficient thrust at low icebreaking speeds. The thrust of the vessels has been calculated based on actual propeller and engine characteristics and compared to values which are calculated based on the assumptions of the FSICR. The main findings regarding the thrust capabilities are following:

- The FSICR assumptions give reasonable results in situations in which the full propulsion power is available (vessels with CP propellers and optimally functioning propulsion machinery).
- The propulsion power can be significantly reduced with FP propellers due to the torque limitations of the main engine. In these situations, the vessels do not deliver the thrust assumed by FSICR.
- PTI is very useful for vessels with FPP and the PTI can increase the available propulsion power at ice going speeds significantly. However, it should be noted that the PTI does not necessarily mean that the full propulsion power is available at low speeds. The design point of the PTI system is important for vessels with FPP.
- PTI does not seem to provide additional performance gain for vessels with CPP when compared to a CPP vessel without PTI with same propulsion power.

The research demonstrated that the difference between the actual thrust and the thrust assumed by FSICR can be significant with vessels with fixed pitch propellers. However, it is not a simple topic how this should be taken into account as the difference has been present since the current version of the minimum power requirement has been in force. A requirement to have more thrust at low speeds with FPP could result into relatively big changes to the vessels with potentially negative impacts to their energy-efficiency in open water. PTIs are one possible part of the solution.

For CPPs the FSICR assumptions and the FSICR minimum power requirement gives reasonable results. However, it should be noted that FSICR assumes that the propulsion machinery is functioning optimally. This means that the propeller pitch is correctly set and automatic load control system is functioning optimally. The CPP does not automatically mean that the full propulsion power is available.

Generally, the propulsion powers are reducing due to the emission regulations and therefore the margins in vessels' ice-going capability are decreasing. Therefore, it is feasible to consider changing the ice class rules in the future to more goal-oriented direction in which the goal for the merchant vessel is to have sufficient thrust to proceed at the required 5 knots speed in the designated ice conditions. The vessel's ability to produce the sufficient thrust is then demonstrated when the ice class is applied. This can be done with somewhat simple engine layouts and propeller open water curves. This would be feasible also for CPP vessels for which the FSICR assumptions seemed to work relatively well. As the vessels' ability to produce net thrust depends on its engine and propeller characteristics, it is important to note that different results can be obtained with different propeller and engine combinations. The search to reduce propulsion power and to improve propulsive efficiency can result that in the future the propeller profiles differ from the ones which are the basis of the analysis of this report and therefore the thrust properties at low-speed overload situation can be different.

In addition, other situations in which the vessel performs differently than the FSICR assume were also investigated in the report. The focus was on situations in which the vessels' propulsion power or thrust would be limited. The main findings regarding the functionality of the CPP system in ice are following:

- It is important that the crew of the merchant vessel has understanding how the full propulsion power is obtained with vessel with CPP without overloading the engine. The bollard pull pitch should be defined and the corresponding control setting could be informed in the pilot cards.
- The functionality of the automatic load control of the CPP system in ice should be further investigated. There are indications that the systems are not always working optimally in ice and the power and thrust can be excessively reduced. The extent of the problem, possible causes and possible solutions should be objectives of the future study.

Propellers in nozzles were also discussed in the report. A nozzle is an attractive method to reduce the propulsion power of the ice-classed merchant vessel. However, as the design targets of the nozzles differ, it is suggested that the actual thrust properties of the vessel with nozzle are demonstrated instead of using generic assumptions of the thrust increase. In addition, the possible clogging of the nozzle should be also considered.

Finally, the influence of alternative fuels was briefly discussed in the report. The main findings are following:

- The loading capacity of the engine is slower when using alternative fuels. The crew operating the vessel must anticipate their maneuvers in ice more.
- Main engines running on alternative fuels have narrower operating range than main engines running on diesel. This does not limit the performance when dual-fuel engines are used as the engine can switch back to diesel when overloaded.
    - The situation can be different if monofuel engines are available in the future
    - The crew can try to avoid a situation in which the engine is tripped back to diesel and not fully utilizing the power of the vessel in ice.

7 REFERENCES

Björkestam, H. 1985. *En jämförande undersökning av dyspropellerns och den öppna propellerns egenskaper I isförhållanden.* Master's Thesis. Helsinki University of Technology.

Carlton, J. 2007. *Marine propellers and propulsion.* Second Edition. ISBN: 978-07506-8150-6

Dick R. A., Laframboise J. E., 1989. *An empirical review of the design and performance of icebreakers*. Marine Technology, Vol. 26, No. 2, April 1989, pp 145-159.

Heinonen, T. 2022. *EEDI and the need for icebreaker assistance II.* Winter Navigation Research Board research report No. 118.

Häkkinen, P. 2006. *Laivan koneistot.* Helsinki University of Technology Ship Laboratory. Report M-179. Tenth Edition.

Juva, M., Riska, K. 2002. *On the power requirement in the Finnish-Swedish Ice class rules.* Winter Navigation Research Board research report No. 53

Lindroos, H., Björkestäm, H. 1986. *Hydrodynamic loads developed during ice-clogging of a propeller nozzle and means to prevent the clogging.* Proceedings of the Polartech '86. The international Offshore and Navigation Conference and Exhibition, Helsinki, Finland, pp. 1061-1092

Matusiak, J. 2005. *Laivan propulsio.* Helsinki University of Technology Ship Laboratory. Report M-176. Sixth Edition.

MAN. 2018. *Basic principles of ship propulsion.* Publication 5510-0004-04, MAN Energy Solutions. Copenhagen.

MAN. 2013. *Ice classed ships – Main Engines.* Publication 5510-0140-00, MAN Energy Solutions. Denmark.

Oosterveld, M.W.C., van Oossanen, P. 1975. *Further computer-analyzed data of the Wageningen B-screw Series.* International Shipbuilding progress Vol. 22

Riska, K. 2014. *Factors influencing the power requirement in the Finnish-Swedish ice class rules.* Winter Navigation Research Board research report No. 67.

Riska, K., Wilhelmson, M., Englund, K., Leiviskä, T., 1997. *Performance of merchant vessels in ice in the Baltic.* Winter Navigation Research Board research report No. 52.

Tornblad J. 1985. *Fartygspropellrar och fartygs framdrift.* Marinlaboratoriet KaMeWa AB Kristinehamn, R-370 S.

Traficom, 2019. *Guidelines for the application of the 2017 Finnish-Swedish ice class rules.* TRAFI/708629/03.04.01.01/2018 Helsinki, 8 January 2019

Traficom, 2021. *Ice Class Regulations and the Application Thereof.* TRAFICOM/68863/03.04.01.00/2021

Tsoy, L. G., 1983. *Modelling of vessel's movement in a channel broken up by icebreaker.* POAC '83. Proceedings Vol. 2. Helsinki, Finland 5-9 April 1983, VTT Symposium 28, pages 654-663

Wärtsilä [1] , *Wärtsilä 31DF Project guide*, 2020

Wärtsilä [2], *Wärtsilä 34DF Project guide,* 2020

APPENDIX 1: DETAIL RESULTS

	Propeller information							Engine information						Bollard pull									5 knots speed						
															Propulsion power [kW]			Bollard pull force [kN]			K_e			Propulsion power [kW]			Net thrust [kN]		
Vessel type	FPP/ CPP	Propeller No.	D_p [m]	Design RPM	A_e/A_o	$P/D_{0\,kn}$	$P/D_{5\,kn}$	Engine	2-/4 -stroke	MCR [kW]	PTI [kW]	Max RPM	i	$RPM_{0\,kn}$	Installed	Calculated	Ratio	FSICR	Calculated	Ratio	FSICR	Calculated	$RPM_{5\,kn}$	Installed	Calculated	Ratio	FSICR	Calculated	Ratio
General cargo	FPP	1	3.30	166.1	0.50	0.857	0.857	Wärtsilä 7L25A	4	2 625	0	185.2	5.4	57.6	2 625	99	4 %	296	38	13 %	0.702	0.090	112.1	2 625	588	22 %	237	78	33 %
General cargo	FPP	1	3.60	166.1	0.50	0.695	0.695	Wärtsilä 7L25A	4	2 625	0	185.2	5.4	53.2	2 625	82	3 %	314	37	12 %	0.702	0.082	106.0	2 625	499	19 %	251	72	29 %
General cargo	FPP	1	3.60	144.4	0.50	0.857	0.857	Wärtsilä 7L25A	4	2 625	0	158.7	6.3	51.6	2 625	110	4 %	314	43	14 %	0.702	0.096	110.1	2 625	876	33 %	251	117	47 %
General cargo	FPP	1	3.30	166.1	0.50	0.857	0.857	Wärtsilä 6L25A	4	2 040	585	176.5	5.1	150.5	2 625	1 760	67 %	329	259	79 %	0.780	0.614	176.5	2 625	2 518	96 %	263	254	97 %
General cargo	FPP	1	3.60	166.1	0.50	0.695	0.695	Wärtsilä 6L25A	4	2 040	585	176.5	5.1	136.7	2 625	1 397	53 %	349	244	70 %	0.780	0.545	176.5	2 625	2 621	100 %	279	283	102 %
General cargo	FPP	1	3.60	144.4	0.50	0.857	0.857	Wärtsilä 6L25A	4	2 040	585	150.0	6.0	141.6	2 625	2 269	86 %	349	325	93 %	0.780	0.727	150.0	2 625	2 362	90 %	279	256	92 %
General cargo	CPP	1	3.30	185.2	0.50	0.758	0.810	Wärtsilä 7L25A	4	2 625	0	185.2	5.4	185.2	2 625	2 625	100 %	329	336	102 %	0.780	0.795	185.2	2 625	2 625	100 %	263	256	97 %
General cargo	CPP	1	3.60	185.2	0.50	0.590	0.642	Wärtsilä 7L25A	4	2 625	0	185.2	5.4	185.2	2 625	2 625	100 %	349	364	104 %	0.780	0.815	185.2	2 625	2 625	100 %	279	275	99 %
General cargo	CPP	1	3.60	158.7	0.50	0.769	0.826	Wärtsilä 7L25A	4	2 625	0	158.7	6.3	158.7	2 625	2 625	100 %	349	355	102 %	0.780	0.793	158.7	2 625	2 625	100 %	279	270	97 %
General cargo	CPP	1	3.30	176.5	0.50	0.820	0.875	Wärtsilä 6L25A	4	2 040	585	176.5	5.1	176.5	2 625	2 625	100 %	329	331	101 %	0.780	0.784	176.5	2 625	2 625	100 %	263	253	96 %
General cargo	CPP	1	3.60	176.5	0.50	0.643	0.695	Wärtsilä 6L25A	4	2 040	585	176.5	5.1	176.5	2 625	2 625	100 %	349	363	104 %	0.780	0.811	176.5	2 625	2 625	100 %	279	275	98 %
General cargo	CPP	1	3.60	150.0	0.50	0.844	0.903	Wärtsilä 6L25A	4	2 040	585	150.0	6.0	150.0	2 625	2 625	100 %	349	348	100 %	0.780	0.779	150.0	2 625	2 625	100 %	279	266	95 %
Bulker	FPP	1	7.10	90.6	0.50	0.782	0.782	MAN 7S60	2	15 000	0	105.0	1.0	70.0	15 000	6 905	46 %	1577	1093	69 %	0.702	0.486	78.9	15 000	8 749	58 %	1262	967	77 %
Bulker	FPP	1	7.70	90.6	0.50	0.645	0.645	MAN 7S60	2	15 000	0	105.0	1.0	65.8	15 000	6 122	41 %	1665	1091	66 %	0.702	0.460	75.7	15 000	8 071	54 %	1332	969	73 %
Bulker	FPP	1	7.70	79.2	0.50	0.782	0.782	MAN 7S60	2	15 000	0	91.8	1.0	61.0	15 000	6 872	46 %	1665	1150	69 %	0.702	0.485	69.3	15 000	8 832	59 %	1332	1 027	77 %
Bulker	FPP	1	7.10	90.6	0.50	0.782	0.782	MAN 5S60	2	10 700	4300	93.8	1.0	88.0	15 000	13 738	92 %	1753	1729	99 %	0.780	0.769	93.7	15 000	14 996	100 %	1402	1 447	103 %
Bulker	FPP	1	7.70	90.6	0.50	0.645	0.645	MAN 5S60	2	10 700	4300	93.8	1.0	83.8	15 000	12 630	84 %	1850	1768	96 %	0.780	0.745	91.7	15 000	14 736	98 %	1480	1 526	103 %
Bulker	CPP	1	7.10	105.0	0.50	0.608	0.648	MAN 7S60	2	15 000	0	105.0	1.0	105.0	15 000	15 000	100 %	1753	1829	104 %	0.780	0.814	105.0	15 000	15 000	100 %	1402	1 422	101 %
Bulker	CPP	1	7.70	105.0	0.50	0.471	0.511	MAN 7S60	2	15 000	0	105.0	1.0	105.0	15 000	15 000	100 %	1850	1919	104 %	0.780	0.809	105.0	15 000	15 000	100 %	1480	1 476	100 %
Bulker	CPP	1	7.70	91.8	0.50	0.607	0.649	MAN 7S60	2	15 000	0	91.8	1.0	91.8	15 000	15 000	100 %	1850	1931	104 %	0.780	0.814	91.8	15 000	15 000	100 %	1480	1 497	101 %
Bulker	CPP	1	7.10	93.8	0.50	0.738	0.781	MAN 5S60	2	10 700	4300	93.8	1.0	93.8	15 000	15 000	100 %	1753	1795	102 %	0.780	0.799	93.8	15 000	15 000	100 %	1402	1 401	100 %
Bulker	CPP	1	7.70	93.8	0.50	0.584	0.626	MAN 5S60	2	10 700	4300	93.8	1.0	93.8	15 000	15 000	100 %	1850	1933	105 %	0.780	0.815	93.8	15 000	15 000	100 %	1480	1 498	101 %
Container	FPP	1	5.50	104.5	0.55	1.213	1.213	MAN 6S50	2	9 490	0	110.3	1.0	62.0	9 490	3 139	33 %	980	479	49 %	0.702	0.343	71.8	9 490	4 170	44 %	784	463	59 %
Container	FPP	1	6.00	104.5	0.55	0.999	0.999	MAN 6S50	2	9 070	0	110.4	1.0	55.3	9 070	2 399	26 %	1008	454	45 %	0.702	0.316	66.4	9 070	3 415	38 %	806	443	55 %
Container	FPP	1	6.00	96.6	0.55	1.120	1.120	MAN 6S50	2	9 260	0	102.2	1.0	53.1	9 260	2 626	28 %	1022	465	45 %	0.702	0.319	62.9	9 260	3 649	39 %	818	454	55 %
Container	CPP	1	5.50	110.3	0.55	0.870	0.929	MAN 6S50	2	9 490	0	110.3	1.0	110.3	9 490	9 490	100 %	1089	1079	99 %	0.780	0.773	110.3	9 490	9 490	100 %	872	881	101 %
Container	CPP	1	6.00	110.4	0.55	0.670	0.727	MAN 6S50	2	9 070	0	110.4	1.0	110.4	9 490	9 070	105 %	1154	1157	100 %	0.780	0.782	110.4	9 490	9 070	96 %	924	930	101 %
Container	CPP	1	6.00	102.2	0.55	0.769	0.829	MAN 6S50	2	9 260	0	102.2	1.0	102.2	9 260	9 260	100 %	1136	1152	101 %	0.780	0.791	102.2	9 260	9 260	100 %	909	932	103 %
Container	CPP	1	5.50	150.00	0.55	0.527	0.576	Wärtsilä 16V31	4	9 760	0	150.0	5.0	150.0	9 760	9 760	100 %	1110	1154	104 %	0.780	0.811	150.0	9 760	9 760	100 %	888	930	105 %
Container	CPP	1	6.00	150.00	0.55	0.392	0.442	Wärtsilä 16V31	4	9 760	0	150.0	5.0	150.0	9 760	9 760	100 %	1176	1174	100 %	0.780	0.779	150.0	9 760	9 760	100 %	941	931	99 %
Container	CPP	2	3.90	177.21	0.55	0.713	0.767	Wärtsilä 8V31	4	4 880	0	177.2	4.2	177.2	9 760	9 760	100 %	1109	1140	103 %	0.980	1.008	177.2	9 760	9 760	100 %	887	892	101 %
Container	CPP	2	4.25	177.21	0.55	0.559	0.611	Wärtsilä 8V31	4	4 880	0	177.2	4.2	177.2	9 760	9 760	100 %	1174	1226	104 %	0.980	1.023	177.2	9 760	9 760	100 %	939	950	101 %