PROCEEDINGS OF MOSES2019 CONFERENCE
2ND INTERNATIONAL CONFERENCE ON MODELLING AND OPTIMISATION OF SHIP ENERGY SYSTEMS
8-10 MAY 2019, GLASGOW, SCOTLAND, UNITED KINGDOM

MOSES2019-02023

A methodology for single turbocharger−marine engine matching

Panagiotis Mizythras[a*], Evangelos Boulougouris[a], and Gerasimos Theotokatos[a]

[a] Maritime Safety Research Centre, Department of Naval Architecture, Ocean and Marine Engineering,
University of Strathclyde, Glasgow, United Kingdom
* panayiotis.mizythras@strath.ac.uk

Abstract

The turbocharger is an essential component for the propulsion and auxiliary engines of the modern ships' power plants as it supplies the required air amount thus affecting the engine cylinders combustion process. In this respect, the matching of the marine engine with their turbocharging system is crucial for ensuring the engine efficiency as well as the propulsion systems response. In this paper, a new methodology consisting of three phases is proposed for facilitating the matching and selection process of a single turbocharging system with a two-stroke marine engine. The first phase included the estimation of the engine performance and the development of the compressor families' databases by employing a single engine cylinder zero-dimensional model and a parametric compressor tool, respectively. The second phase involves the compressor maps-engine matching checking and the identification of the compressor maps that satisfy the set requirements, whereas the third phase includes the turbine matching along with the selection of the optimal compressor and turbine to minimise the specific engine fuel consumption for a selected propeller curve. The derived results indicate that the developed method can identify an appropriate turbocharger that is possible to improve the engine fuel consumption by 2−4%.

Keywords: turbocharger matching, marine Diesel engine, modelling, compressor map parameterization.

1 INTRODUCTION

In the recent years, several improvements and developments have been performed in the turbocharged engines to improve the overall energy efficiency [1]. The turbocharging system is considered the best option with relatively low cost and complexity for improving the large marine engine efficiency and specific power output [2]. The aim of the engine-turbocharger matching procedure is to select the appropriate turbocharger unit including compressor and turbine, which will deliver the required air volumetric flow rate at the specified conditions (pressure, temperature) to the engine cylinders. Traditionally, the engine-turbocharger matching is performed by using simulation tools representing the engine as well as the turbocharger components. Although various modelling approached have been developed for the simulation of marine engines, compressor and turbine, the selection and matching of the engine-turbocharger is discussed mostly in the automotive applications [3], whereas very limited studies are available focusing on marine applications.

In the pertinent literature, the engine-turbocharging system matching is performed by investigating the compressor or turbine individually, depending on the engine flow and thermodynamic parameters requirements. An approach on the turbocharger-engine matching procedure was initially presented by Meier [4], whereas the various requirements for the most common turbocharged engine applications including marine applications were reviewed in [5].

An approach for engine-turbocharger matching in turbocompounded systems, which is based on the estimation of the compressor and turbine operating points taking into account the turbocharging system characteristics and the engine parameters, was presented in [6]. Based on this, an artificial neural network was developed for the matching and selection of fixed or a variable geometry compressor map family for a small-sized Diesel engine [7].

Various methodologies regarding the turbine matching to an existing engine were proposed by Pesiridis et al. [8] and Tancrez et al. [9]. In these approaches, an approximation model and existing turbocharger data were used to evaluate the engine performance. Similar models were presented in [10-12] for matching automotive engine with a two-stage turbocharging system.

The various modelling approaches for the prediction of the compressor and turbine performance can be categorised to data-driven models and physical models [5]. A review of the available physical models is presented in [13]. A physical 1-D turbocharger model coupled with a marine Diesel simulation model was reported in [14].

Considering the high computational cost of the physical models, data-driven models, which employ tabulated data and apply interpolation and extrapolation techniques, can be used for representing the turbocharger components. The first attempt to describe the compressor flow using a single cubic polynomial model was reported in [15]. Following the Moore-Greitzer's polynomial equation, several alternative approaches have been proposed [16, 17] for improving the compressor model accuracy. An alternative approach for the compressor map representation is by the application of an elliptic model [18-20], which provides better description of the constant speed curves. This methodology was tested in various applications on the effort to extrapolate the existing available compressor maps [21, 22]. Further development of the data-driven models included the description of the compressor families using a generalized parameterization method. The latter approach was initially developed for automotive industry in [23] and also employed for marine applications [24].

From the preceding literature review, it was inferred that the investigation of the matching process focuses mostly on the automotive applications, using existing data or investigating the performance of a specific component. Existing methodologies investigate the individual selection of either compressor or turbine taking into account the engine response for the estimation of the turbocharger components operation. It is deduced that there is not an automated procedure or a structured methodology that could be followed for the matching of a single turbocharging system to a marine engine. Moreover, the available matching procedures cannot be employed for making the optimal turbocharger systems selection considering a given engine operating profile.

In this study, a new methodology, which includes a number of simulation tools, is proposed for the selection and matching of a marine engine with its turbocharger. This methodology is implemented for the case study of a ocean-going vessel propulsion engine also considering typical engine operating profiles. Finally, the turbocharger optimal selection as well as the modularity of the developed methodology are discussed.

2 MARINE ENGINE-TURBOCHARGER MATCHING

During the design phase of a propulsion system, the selection of the turbocharging system is carried out by the engine manufacturer using the turbocharger components steady state performance maps provided by the turbocharger manufacturer. The main purpose of the proposed methodology is to provide an automated way for selecting the turbocharger system components for a marine engine. This is accomplished by developing and employing a number of computational tools and models. The proposed methodology includes the following three phases: (a) engine performance parameters and compressor maps database development; (b) compressors-engine matching check; and (c) Turbine selection and TC sorting. Each phase includes a number of steps, as shown in the flowchart presented in Fig. 1.

Considering the limited data that are available during the ship propulsion system design phase, computational tools were used for developing the engine performance parameters response surfaces and the compressors database. For the estimation of the engine performance parameters, a zero-dimensional (0D) single cylinder model was employed, whereas a compressor map parametric tool was used for the development of the compressor maps database. The 0D model allows the simulation of the cylinder performance by controlling its boundary conditions to represent the effect of various turbocharging systems [25]. The engine brake power, the thermodynamic properties of the exhaust gas as well as the air and exhaust gas mass flow rates are used for the engine-turbocharger matching considering the engine operation at steady state conditions. The developed 0D model is validated comparing the simulation results with the engine's performance data at the boundary conditions that engine was tested.

The data generation for the turbocharging system components is a more challenging task. The estimation of the compressor and the turbine curves may lead to numerous combinations, increasing the complexity of the overall methodology. Following the previous attempts that focused mainly on the matching only one of the turbocharging system components, the compressor component is selected as the component that is investigated in the second phase of the matching procedure. Although the turbine is the component that utilizes the engine cylinders exhaust gas waste heat, the compressor is included first due to its importance to the engine scavenging process. Thus, a database of compressor families is generated in this step.

For the development of a database with various compressor families, either physical or data-driven models can be employed, depending on the desired accuracy and the available data. Although the physical models that use fluid dynamic equations provide great accuracy, their application is considered insufficient for a simple estimation of compressor map at steady state conditions. On the contrary, the application of geometric representation approaches and parametric tools is considered as a more efficient method for the generation of the required compressors maps database. Additionally, in case that compressor maps are available from the manufacturer, they could be fed directly to the second phase of the proposed methodology. Considering that this process takes place at the initial design phase, a parametric tool is used in this study.

Usually, the parametric tools use interpolation and extrapolation techniques to represent the geometry of the compressor map constant rotational speed curves. The accuracy and the applicability of the method to sufficiently represent the operational range of different compressors depend on the selected techniques and the parameters that will be used. The initial purpose of these tools is the fast estimation of the operational point of the compressor map. In this case, the parametric tool should be modified accordingly to generate new compressor map. For this task, additional constrains should be defined to control the parameters that represent the compressor map, concerning the surge and choke limits, as well as the geometry of the generated compressor.

Having established the compressor map family and the engine response surface databases, the second phase of this methodology, which includes the matching check of the established databases, can be performed. During this phase, the generated compressors maps are tested individually considering the engine operation at various operating points. The main objective of this process is to check if the engine can provide the required power (estimated for the specific operating point) and the compressor can deliver the required air mass flow rate for the specified scavenge air receiver pressure. In case where the compressor cannot deliver the required air mass flow rate, the compressor is considered insufficient for the given operational profile and engine characteristics. Then, the process continues to the next compressor until a single compressor is found that satisfies the given conditions. The engine operating points at which the compressor matching process is performed are provided as input. These points can be initially estimated from the selected propulsion system performance at various vessel speeds.

During the compressor matching process, several constraints are considered for the normal operation of the system. The main boundary that is defined by the process is the operational range for each investigated compressor map, taking into account an offset factor in order to avoid the operation of the investigated compressor map close to its surge and choke limits. Moreover, this offset allows the operation of the compressor to the highest efficiency region, improving the performance of the overall turbocharging system. The second condition deals with the order of the operational points that the matching check is performed. The matching process starts from the operational point with the highest load demand. Thus, the pressure ratio that corresponds to this point can be set as the maximum pressure ratio limit for the evaluation of the next point.

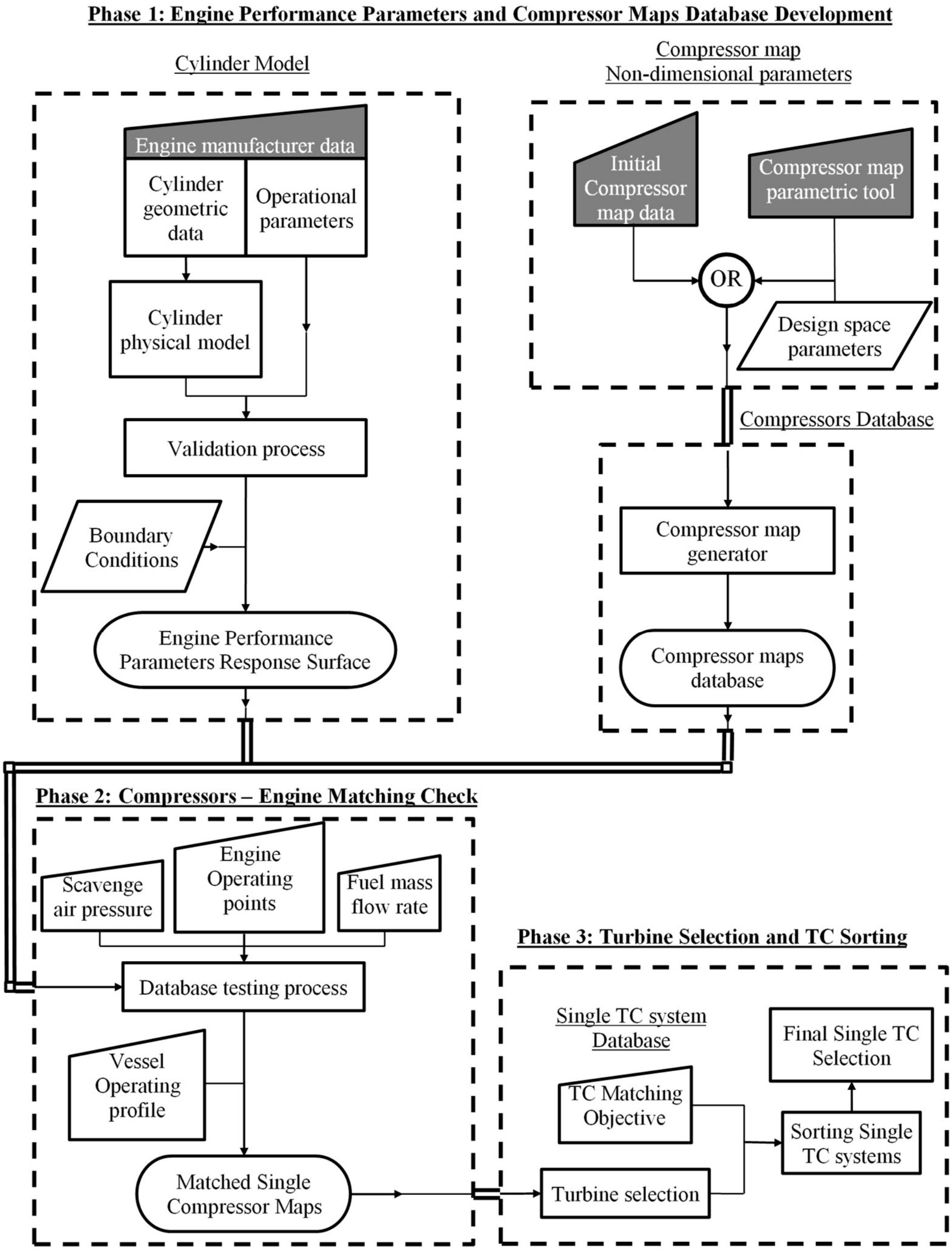

Fig. 1. Flowchart of the proposed methodology for the selection and matching of a turbocharger with a marine engine.

The third and final phase of the matching procedure includes the estimation of the turbine curves that are suitable for the matched compressor and marine engine as well as the selection of the single turbocharger (for the case where more than one solution is identified in the previous phase). The input parameters of this phase include the compressor required power and the rotational speed (also estimated form the previous phase) as well as the engine performance (estimated in the first phase). Thus, the turbine total-to-static isentropic efficiency and pressure ratio are predicted and the turbine geometric characteristics can be estimated.

The introduction of the operational points to the established methodology allows the selection of the optimum turbocharging system, depending on the objectives that will be defined during the design. The operational points are estimated for a given resistance curve that represent specific environmental and hull conditions, as well as for a specific propulsion system.

Considering the energy efficiency as one of the most important objectives during the design and selection of system components, the engine operational profile can be used for the estimation of the single turbocharging system that offers the greatest fuel efficiency. Estimating the fuel mass flow rate at different vessel speeds, the vessel annual fuel consumption is estimated by using operating profiles of existing vessels of similar size. Based on the estimated annual fuel consumption, the matched single turbocharging systems can be evaluated and the optimal turbocharger can be selected. Additionally, alternative objectives can be set, such as the engine response at low engine speeds or the optimisation of the turbocharging system at a specific operating point.

3 COMPRESSOR PARAMETRIC TOOL

The parametric tool is considered as the most efficient method for the description of a reference compressor map and the generation of compressor families. Herein, a similar approach to the elliptic model presented in in [23] and [24] is employed for the geometric approximation of the compressor map. The following equation was used for the estimation of the compressor constant speed curves:

$$PR = PR_{ISP} + \left(PR_{ZSP} - PR_{ISP}\right)\sqrt[n]{1 - \left(\frac{VFR - VFR_{ZSP}}{VFR_{ISP} - VFR_{ZSP}}\right)^{n}} \qquad (1)$$

where the PR and the VFR are the pressure ratio and the volumetric flow rate, respectively; ISP and ZSP correspond to the values on the infimum and zero slope points of the elliptic curve. The exponent of the applied elliptic model is modified in order to effectively approximate the elliptical curves curvature.

The polynomials that are selected for the estimation of the surge and the choke limits are different than the original method. In order to improve the accuracy and parameterization of the developed tool, a 5th order Bezier-Bernstein polynomial curve is selected. The distribution of the elliptic model exponents is described by using a 2nd order Fourier series. The selection of this approximation is preferred due to the different profiles that the exponent distribution may exhibit on different reference maps. In addition, the selection of the exponent depends on the selected edges of the ellipse. The isentropic coefficient is simulated using the approach presented in [22]. The process for the estimation of the parameters for a reference compressor map is presented in Fig. 2.

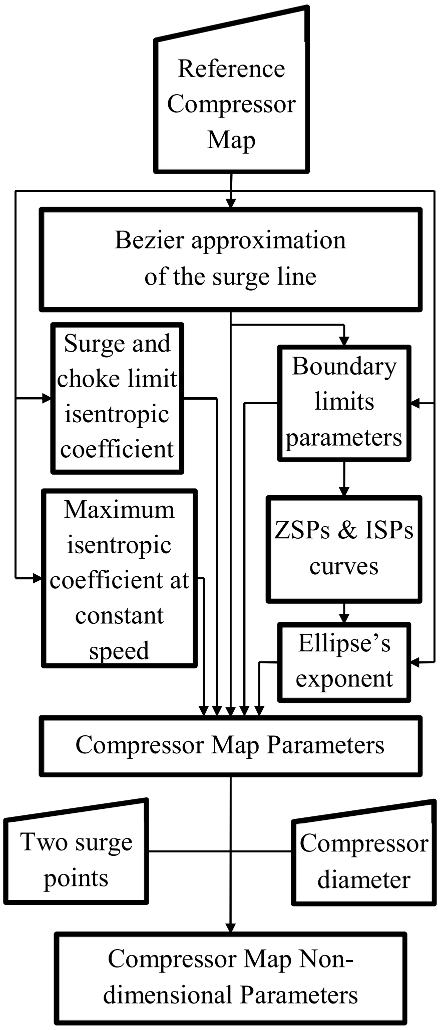

Fig. 2. Layout of the computational process for the parameterization of a given compressor map.

Using this method, 55 parameters are estimated, representing the overall steady state area of the compressor map. However, for the generation of the compressor families, the tool converts the estimated parameters to non-dimensional, using as reference two points of the compressor map surge line and the diameter of the compressor. Thus, the description of the given reference map is performed by using one set of non-dimensional and one set of dimensional parameters. The database of the compressors can be established by modifying either the dimensional or both sets of parameters. The modification of the compressor geometric characteristics as well as the pressure ratio and volumetric flow rate of the two surge line points will provide a fast generation of the new compressor maps, whilst a more detailed database of compressor maps can be developed by modifying the shape of the constant speed curves and map boundaries through the non-dimensional parameters.

4 CASE STUDY

The described methodology is used for the matching of a single stage turbocharging system with a marine two-stroke engine of an ocean-going tanker vessel. The specifications of the investigated marine engine are presented in Table 1. Based on the given geometric characteristics of the engine, the physical model proposed in [7] is used for the estimation of the selected engine performance. Thus, the engine air mass flow rate and brake power as well as the exhaust gas temperature and the composition are correlated as functions of the fuel mass flow rate, the scavenge air pressure, the exhaust receiver pressure and engine speed. The combustion parameters (i.e. valves and injection timing, heat release profile) of the selected engine are remained constant during the investigation. A comparison of the power and brake specific fuel oil consumption (BSFC), estimated by the developed 0D model, against the engine's shop trial test data at steady state conditions is presented in Table 2. The results show the great accuracy of the model to predict the engine performance at the shop trials boundary conditions.

For the generation of the compressor maps, only the set of the dimensional parameters set is modified. The PR and VFR values of the surge line points are modified, whereas the compressor diameter is selected taking into account the maximum volumetric rate of the surge line. The boundaries of a number of the generated compressor maps are presented in Fig. 3.

Table 1. Investigated engine specifications

Parameter	Value
Type	MAN 7S60 MC-C6
Bore	600 mm
Stroke	2292 mm
Maximum Brake Power	14300 kW
Maximum Speed	105 r/min

The operating points used in the matching process correspond to the calm water propeller curve that is approximated by using a third order polynomial that passes through the maximum continuous rating (MCR) point of the engine. The process indicates that only 31 out of the 144 totally generated maps are suitable to match with the investigated engine. The turbocharging system is selected by using as an optimisation objective the maximum engine efficiency at the 80% of the MCR engine load, assuming that this point corresponds to the most frequent engine operation. The parameter that is used for the sorting process of the matched turbochargers is the brake specific fuel consumption. A comparison of the reference brake specific fuel oil consumption (BSFC) values against the derived ones for the matched engine-single turbocharging system is presented in Fig. 4.

Table 2. Error percentage of 0D model results against engine's shop trials at various engine loads.

Engine Load	Power	BSFC
25%	4.47%	-3.47%
50%	1.21%	-1.91%
75%	-3.05%	3.15%
90%	-2.81%	3.39%
100%	-2.15%	1.94%

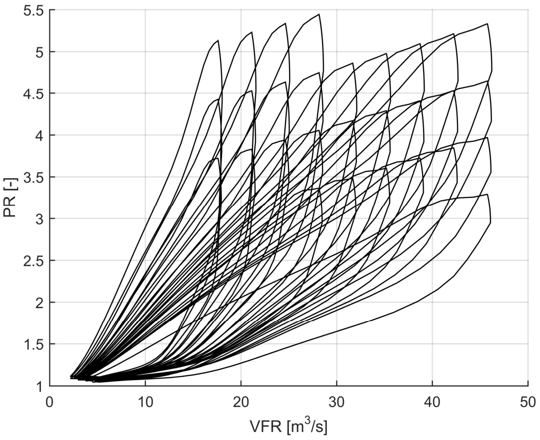

Fig. 3. Map boundaries from sample of the model generated compressor maps.

The investigation shows that the BSFC can be further reduced by selecting the appropriate turbocharger. Particularly, the simulation results show that the majority of the matched compressors improve the fuel efficiency of the selected engine at around 60% of the engine's MCR. However, setting as objective the selection of the turbocharger that allows the maximum fuel efficiency at 80% of the MCR, only one of these can be selected.

The compressor map that corresponds to the optimum selected turbocharging system is presented in Fig. 5, including the operational profile that corresponds to the investigated propeller curve.

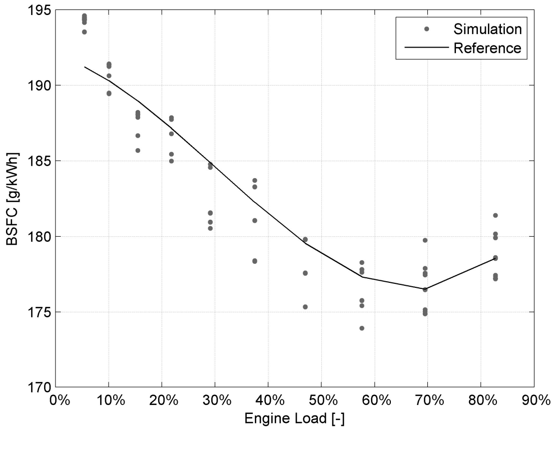

Fig. 4. Comparison of the BSFC between the reference engine and the matched engine-turbocharging system with a single turbocharger.

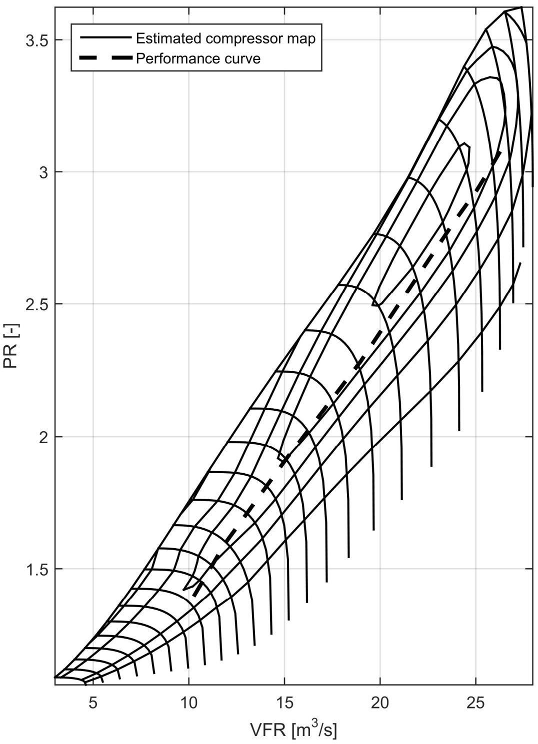

Fig. 5. Matched compressor map with superimposed operating points for the investigated engine operation.

5 CONCLUSIONS

In this paper, the matching procedure of a single turbocharging system with a marine engine was presented, taking into account the selected engine performance, the propulsion system configuration and the resistance curve of the vessel. Moreover, a parametric tool was developed for the approximation of any reference compressor map. The parameters of the reference map were used for the generation of compressor map families that are required for the purpose of the matching process.

The presented "three-phases" methodology allows the optimal matching and selection of a single turbocharger for a marine two-stroke Diesel engine, evaluating alternative turbocharging systems. Moreover, the development of a parametric compressor model that needs a limited number of input parameters to describe the compressor map allows the complete description of the entire steady state area of the compressor with increased accuracy independently of the compressor maps curves shape.

The modularity used in the first phase of the developed methodology allows the introduction of alternative physical and data-driven models or the selection of existing tools to estimate the engine performance parameter and the compressor map databases. Moreover, the proposed methodology can be used for the investigation of the turbocharging system performance during the initial phase of the design, where there are limited data available and a fast-computational process is required for the indication of the system that will match to the investigated engine.

Further improvements on the selected methodology are the investigation of alternative turbocharging system configurations, such as the matching of turbocharger connected in parallel, as well as the generation of compressor families by modifying the non-dimensional estimated parameters and the study of their effect to the engine performance. Additionally, alternative design objectives can be defined on the selection of the turbocharging system, introducing more details regarding the operational profile of the vessel or investigating the effect of the selected turbocharging system to the engine response at low engine speeds.

The matching and the selection of the turbocharging system are important for the evaluation of the overall ship performance and the selection of the limiters for the engine controlling system. Consequently, the described procedure, including the developed parametric compressor tool, can be considered as a guide to the designer for the detailed simulation and selection of the propulsion system engine and turbocharger components in steady state conditions.

ACKNOWLEDGEMENTS

This work was partially supported by the "HOLISHIP – Holistic Optimisation of Ship Design and Operation for Life Cycle" project that which was funded from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 689074. The work was also partially supported from DNV GL and RCCL, sponsors of the MSRC. The opinions expressed herein are those of the authors and do not reflect the views of EU, DNV GL and RCCL.

REFERENCES

[1] Kyrtatos A, Spahni M, Hensel S, Zuger R, Sudwoj G. The development of the modern low-speed two-stroke marine Diesel engine. In: Proceedings of 28th CIMAC World Congress on Combustion Engine (6-10 October 2016); 2016.

[2] Aghaali H, Angstrom H. A review of turbocompounding as a waste heat recovery system for internal combustion engines. Renewable and Sustainable Energy Reviews 2015. 49:813-24.

[3] Rakopoulos C, Giakoumis E. Diesel Engine Transient Operation - Principles of Operation and Simulation Analysis. Athens, Greece: Springer-Verlag London Limited; 2009.

[4] Meier E. Development of exhaust gas turbochargers and pressure charging systems for Diesel engines with high mean effective pressures. In: Proc. CIMAC (5-9 April 1973); 1973.

[5] Watson N, Janota M. Turbocharging the Internal Combustion Engine. 1st ed., London, UK: The MacMillan press Ltd.; 1982.

[6] Assanis D, Ekchian J, Frank R, Heywood H. A Computer Simulation of the Turbocharged Turbocompounded Diesel Engine System: A description of the Thermodynamic and heat transfer Models. U.S. Department of Energy, Cambridge. Massachussetts, US. 1985.

[7] Nelson S, Filipi Z, Assanis D. The use of Neural Nets for matching Fixed or Variable Geometry Compressors with Diesel Engines. J. Eng. Gas Turbines Power 2003. 125(2):572-79.

[8] Pesiridis A, Salim WI, Martinez-Botas R. Turbocharger matching methodology for improved exhaust energy recovery. In: 10th International Conference on Turbochargers and Turbocharging (15-12 May 2012); 2012. 203-218.

[9] Tancrez M, Galindo J, Guardiola C, Fajardo P, Varnier O. Turbine adapted maps for turbocharger engine matching. Experimental Thermal and Fluid Science 2011. 35(1):146-53.

[10] Liu Y, Zhuge W, Zhang Y, Zhang S, Zhang J, Huo X. A Matching Method for Two-Stage Turbocharging System. In: ASME Turbo Expo 2014: Turbine technical Conference and Exposition, Vols. Volume 1B: Marine; Microturbines, Turbochargers and Small Turbomachines; Steam Turbines (16-20 June 2014); 2014. 1-11.

[11] Liu R, Zhang Z, Dong S, Zhou G. High-Altitude Matching Characteristic of Regulated Two-Stage Turbocharger with Diesel Engine. In: ASME Turbo EXPO 2017: Turbomachinery Technical Conference and Exposition, Vols. Volume 8: Microturbines, Turbochargers and Small Turbomachines; Steam Turbines (26-30 June 2017); 2017. 1-10.

[12] Wu B, Han Z, Yu X, Zhang S, Nie X. A method for matching two-stage turbocharger system and its influence on engine performance. J. Eng. Gas Turbines and Power 2018. 1-18.

[13] Serrano J, Arnau F, Dolz V, Tiseira A, Cervello C. A model of turbocharger radial turbines appropriate to be used in zero- and one-dimensional gas dynamics codes for internal combustion engines modelling. Energy Conversion and Management 2008. 49(12):3729-45.

[14] Sakellaridis N, Raptotasios S, Antonopoulos S, Mavropoulos G, Hountalas D. Development and validation of a new turbocharger simulation methodology for marine two stroke diesel engine modelling and diagnostic applications. Energy 2015. 91:952-66.

[15] Moore F, Greitzer E. A theory of post stall transient in axial compression systems: Part I - Development of equations. ASME. Journal of Engineering for Gas Turbines and Power 1986. 108:68-76.

[16] de Jager B. Rotating stall and surge control: a survey. In: 24th IEEE Conference on Decision and Control (13-15 December 1995); 1995. 1857-62.

[17] Willems F, de Jager B. Modeling and control of compressor flow instabilities. IEEE Control Systems Magazine 1999. 19(5):8-18.

[18] Leufven O, Eriksson L. Time to surge concept and surge control for acceleration performance. IFAC Proceedings Volumes 2008. 41(2):2063-8.

[19] Tsoutsanis E, Meskin N, Benammar M, Khorasani K. A component map tuning method for performance prediction and diagnostics of gas turbine compressors. Applied Energy 2014. 135(15):572-85.

[20] Li X, Ying Y, Wang Y, Li J. A component map adaptation method for compressor modelling and diagnosis. Advances in Mechanical Engineering 2018. 10(3):1-13.

[21] el Hadef J, Colin G, Talon V, Chamaillard Y. New physics-based turbocharger data-maps extrapolation algorithms: Validation on a spark-ignited engine. IFAC Proceedings Volumes 2012. 45:30:213-20.

[22] Guan C, Theotokatos G, Zhou P, Chen H. Computational investigation of a large containership propulsion engine operation at slow steaming conditions. Applied Energy 2014. 130:370-83.

[23] Leufven O, Eriksson L. Surge and choke capable compressor model. IFAC Proceedings Volumes 2011. 44(1):10653-8.

[24] Llamas X, Eriksson L. Parameterizing compact and extensible compressor models using orthogonal distance minimization. ASME Journal Engineering Gas Turbines Power 2016. 139(1):1-10.

[25] Stiech G, Modelling Engine Spray and Combustion Processes, 1st ed., New York: Springer-Verlag Berlin Heidelberg, 2003.