МОРСЬКИЙ ТА ВНУТРІШНІЙ ВОДНИЙ ТРАНСПОРТ

OPTIMIZATION OF INTERCOOLING PARAMETERS
FOR CHARGED AIR IN MARINE DIESEL ENGINES

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Summary

Introduction. The efficiency of marine diesel engine power plants is primarily determined by the performance of their turbocharging systems, which must supply sufficient intake air pressure to the cylinders. At high compressor pressure ratios, nearly the entire exhaust-gas turbine power output is consumed by the compressor, leaving limited potential for waste-heat recovery or efficiency improvement. A promising method to reduce compressor power consumption is two-stage compression with intercooling, which increases air density, reduces compression work, and improves overall turbocharger efficiency. Deep intercooling enabled by waste-heat-driven ejector or absorption refrigeration systems is of particular interest. However, the optimal split of the total pressure ratio between the low- and high-pressure stages, as well as the required intercooler outlet temperature, remains to be fully defined for marine applications. Purpose. The purpose of this research is to evaluate the influence of intercooler depth and post-intercooler air temperature on the energy characteristics of a two-stage turbocharging system for marine diesel engines, and to determine the optimal pressure-ratio split ($\pi_{\kappa1}/\pi_{\kappa2}$) that minimizes compressor power consumption and maximizes turbine power availability for onboard use. Results. A thermodynamic analysis was performed for a two-stage compressor with various post-intercooler temperatures ($t_{ПО2}$ = 20–80°C) and ambient inlet temperatures (20 and 40°C). The results were compared with a baseline single-stage turbocharger (total pressure ratio = 4). The ratio of compressor powers ($N/N_{ПО}$) exhibits a distinct optimum at $\pi_{\kappa1}/\pi_{\kappa2} \approx$ 0.8–1.5, corresponding to a 5–15 % reduction in compressor power

*compared to the baseline. Deep intercooling to $t_{ПO2}$ = 20–40°C yields the most significant savings (12–15 %), although such temperatures require refrigeration beyond the capability of seawater cooling. Deeper cooling also shifts the optimal value of $\pi_{к1}/\pi_{к2}$ toward lower ratios. Temperature drops of 50–100°C across the heat exchangers were identified, providing design guidance for the steam generator and evaporator of waste-heat-driven refrigeration machines. The resulting increase in available turbine power enables it to be used either for electrical generation or to assist the main engine shaft power during cruising. **Conclusions**. The study confirms the effectiveness of two-stage turbocharging with intercooling in improving the energy efficiency of marine diesel engines. Optimal intercooling parameters and pressure ratio splits were identified, resulting in significant reductions in compressor work and freeing up turbine power for practical onboard applications. Deep intercooling yields the most considerable benefit but requires refrigeration-based cooling. The findings offer practical guidance for designing advanced turbocharging and heat-recovery refrigeration systems in modern marine propulsion plants.*

Key words: intercooling, marine diesel engine, turbocharging, pressure ratio, refrigeration system, waste-heat recovery, energy efficiency.

ОПТИМІЗАЦІЯ ПАРАМЕТРІВ ПРОМІЖНОГО ОХОЛОДЖЕННЯ ПОВІТРЯ НАДДУВУ В СУДНОВИХ ДИЗЕЛЬНИХ ДВИГУНАХ

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Анотація
Вступ. Підвищення ефективності суднових дизельних енергетичних установок значною мірою залежить від роботи системи турбонаддуву, яка забезпечує необхідний тиск повітря на впуску. За високих ступенів стискання компресор споживає практично всю потужність газової турбіни, що обмежує можливості рекуперації теплоти та зниження питомих витрат палива. Одним із найбільш перспективних методів зменшення роботи компресора є застосування двоступеневого стискання з проміжним охолодженням, яке знижує температуру робочого середовища, підвищує густину заряду та зменшує енергетичні витрати на стискання. Особливу увагу привертають схеми глибокого охолодження з використанням ежекторних або абсорбційних холодильних машин, що працюють від утилізованої теплоти відпрацьованих газів. Водночас

оптимальні параметри проміжного охолодження та співвідношення ступенів стискання між компресорними ступенями потребують додаткового аналізу. **Мета**. Метою роботи є визначення впливу ступеня та температури проміжного охолодження на енергетичні показники двоступеневої системи наддуву суднового дизельного двигуна, а також встановлення оптимального співвідношення ступенів стискання ($\pi_{к1}/\pi_{к2}$), що забезпечує мінімальне енергоспоживання компресора та максимальну доступну потужність газової турбіни для рекуперації. **Результати**. Проведено термодинамічний аналіз роботи двоступеневого компресора з проміжним охолодженням на різних температурах повітря після інтеркулера ($t_{ПО2}$ = 20–80°C) та температурі навколишнього середовища (20 та 40°C). Для порівняння використано одноступеневий компресор із загальним ступенем стискання $\pi_к$ = 4. Аналіз залежності N/NПО показав існування оптимального співвідношення $\pi_{к1}/\pi_{к2} \approx$ 0,8–1,5, за якого енергоспоживання компресора зменшується на 5–15 % порівняно з базовою схемою. Найбільший ефект досягається під час глибокого охолодження $t_{ПО2}$ = 20–40°C, що забезпечує зменшення споживаної потужності на 12–15 %. Показано, що для досягнення таких температур потрібне застосування холодильних машин, оскільки охолодження забортною водою є недостатнім. Додатково встановлено, що глибше охолодження зсуває оптимум $\pi_{к1}/\pi_{к2}$ у напрямку його зменшення. Визначено температурні перепади в теплообмінниках (50–100°C), необхідні для проєктування парогенератора та випарника у системах тепловикористовуючих холодильних машин. **Висновки**. Доведено доцільність застосування двоступеневого наддуву з проміжним охолодженням у суднових дизельних енергетичних установках. Встановлено оптимальні параметри, які мінімізують роботу компресора та підвищують загальну ефективність системи. Глибоке охолодження забезпечує найбільший енергетичний ефект, однак вимагає впровадження холодильних машин. Зменшення роботи компресора приводить до збільшення доступної потужності газової турбіни, яка може використовуватися як для електрогенерації, так і для підвищення корисної потужності головного двигуна під час руху. Отримані результати можуть бути використані під час проєктування інтегрованих систем наддуву та тепловикористовуючих холодильних машин у сучасних суднових енергетичних комплексах.

Ключові слова: *проміжне охолодження, наддув, судновий дизельний двигун, ступінь стискання, холодильна машина, теплова утилізація, енергетична ефективність.*

Introduction

Modern marine diesel engines commonly employ turbocharging compressors with relatively high-pressure ratios ($\pi_к \approx$ 2–4) to boost air intake pressure. This requires almost all the exhaust-gas-driven turbine's power output, effectively utilizing the entire enthalpy drop of the exhaust gas [1]. To improve engine efficiency and recover energy, it is necessary to reduce the compressor work and unload the turbine, thereby creating a power reserve (the difference between the turbine and compressor power) that can be redirected to the engine crankshaft or used to drive an electric generator [1]. A traditional method to reduce compressor work is *intercooling*, which involves cooling the boost air between compression

stages. Conventionally, this intercooling uses seawater; however, its cooling capacity is limited, and there are few onboard consumers of the heat removed [2]. Using the heat of compressed air directly in a steam power boiler is problematic, especially at part loads when the inlet air temperature drops [3]. One promising alternative is to cool the boost air using waste-heat-driven refrigeration cycles (e.g., ejector chillers) that utilize exhaust heat to produce refrigeration. The generated cold can be used to achieve deeper intercooling of the boost air (or even the inlet ambient air), thereby increasing the cylinder air charge and enabling higher fuel delivery and engine power [4].

Figure 1 schematically illustrates the two-stage turbocharging system with intermediate air cooling considered in this study. The system consists of two compressor stages connected in series – a low-pressure (LP) stage and a high-pressure (HP) stage – with an intercooler installed between them. Such a configuration may be realized either as a single turbocharger with a two-stage compressor or as two serially connected turbochargers; from a thermodynamic perspective, both arrangements are equivalent for the analysis of compressor power consumption.

Ambient air is compressed in the LP compressor to the pressure ratio $\pi_{\kappa1}$ and subsequently cooled in the intercooler to a prescribed after-intercooler temperature. The cooled air then enters the HP compressor, where it is compressed to the final pressure ratio $\pi_{\kappa2}$ before being supplied to the engine intake manifold. The overall pressure ratio of the system is defined as $\pi_{\kappa} = \pi_{\kappa1} \cdot \pi_{\kappa2}$.

The analysis is based on a steady-state thermodynamic model of two-stage compression with intermediate cooling. The total compressor pressure ratio π_{κ} is fixed according to engine air-supply requirements, while the pressure ratio split between the stages is varied by changing the ratio $\pi_{\kappa1}/\pi_{\kappa2}$.

The temperature after the first compression stage is determined assuming a polytropic compression process. After cooling in the intercooler, the air temperature is reduced to the specified after-intercooler value $t_{\text{ПО2}}$, which serves as the inlet temperature for the second compression stage. The outlet temperature of the HP compressor is then calculated using the same polytropic relations.

The investigated system represents a **single turbocharging unit with a two-stage compressor and intermediate air cooling between the stages**. The configuration includes a low-pressure compressor, an intercooler, and a high-pressure compressor arranged in series.
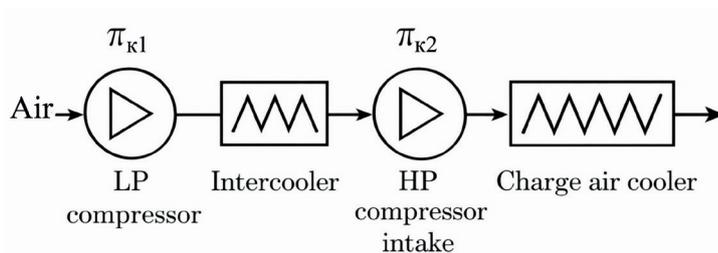

Figure 1. Schematic diagram of a two-stage turbocharging system with intermediate air cooling: LP compressor ($\pi_{\kappa1}$), intercooler, HP compressor ($\pi_{\kappa2}$), and engine intake

From a thermodynamic standpoint, this configuration is equivalent to a serial connection of two compressors within one turboaggregated system.

Figure 1 illustrates the adopted configuration and should be interpreted exclusively as a two-stage compressor with intermediate cooling.

Relevance to Marine Diesel Engines

The presented analysis is particularly relevant for marine diesel engines due to their specific operational characteristics. Marine propulsion and auxiliary engines typically operate at **constant rotational speed and near-constant power output** for prolonged periods, especially when driving fixed-pitch propellers or electrical generators.

Under such stable operating conditions, the turbocharging system can be optimized over a narrow, well-defined range of parameters. Additionally, marine engines are subject to **limitations in conventional seawater cooling capacity**, which restricts the achievable depth of intercooling. These constraints make advanced two-stage turbocharging systems with optimized intercooling especially attractive for marine applications.

Moreover, marine diesel engines increasingly operate at high boost pressure ratios, where compressor power consumption approaches the available turbine power. Therefore, any reduction in compressor work directly increases the available turbine power margin, which is of high practical importance for shipboard energy systems.

Justification of the Optimization Criterion

In this study, the optimization criterion was the minimization of **total compressor power consumption**. Both thermodynamic considerations and practical engine operation justify this choice.

Although different pressure-ratio splits result in different charge-air temperatures downstream of the intercooler and in the intake receiver, these temperature variations were explicitly accounted for in the thermodynamic model. Changes in air temperature and density at the receiver directly affect the inlet conditions of the high-pressure compressor and, consequently, its power consumption.

In the absence of a final aftercooler, the charge-air temperature supplied to the engine indeed varies with the pressure ratio distribution. However, reducing compressor work increases the available power of the exhaust gas turbine. For marine engines operating at constant speed and load, this released turbine power represents a direct energy benefit, either for mechanical assistance of the crankshaft or for onboard electricity generation.

Thus, minimizing the total compressor power is a physically meaningful and practically relevant optimization criterion for marine diesel engines with two-stage turbocharging and intermediate cooling.

Analytical Methodology

To determine the optimal intercooling parameters, we carried out calculations of the turbocharger power consumption as a function of the ratio $\pi_{\text{к}1}/\pi_{\text{к}2}$ of the low-pressure ($\pi_{\text{к}1}$) and high-pressure ($\pi_{\text{к}2}$) compressor stages under various conditions [5]. In the analysis, the intercooler outlet (after-intercooler) air temperature, $t_{\text{ПО}2}$, was varied (20, 40, 60, and 80°C), along with the ambient inlet temperature (tin = 20 and 40°C). The baseline case was defined as a single-stage turbocharger without intercooling (total pressure ratio = 4). The output parameter was the ratio of compressor powers, $N/N_{\text{ПО}}$, where N is the power required by the baseline compressor (no intercooling) and $N_{\text{ПО}}$ is the power required by the two-stage compressor with intercooling. The results are plotted

in Figure 2. In these plots, N (no intercooling) and $N_{\text{ПО}}$ (with intercooling) are shown as functions of the pressure ratio split $\pi_{\text{к1}}/\pi_{\text{к2}}$ at different $t_{\text{ПО2}}$ and inlet temperatures [5].

Mathematical Model and Governing Equations

The thermodynamic analysis of the two-stage turbocharging system was carried out using a steady-state model of polytropic air compression with intermediate cooling. Each compressor stage was assumed to operate under polytropic conditions.

For a polytropic compression process, the pressure–volume relationship is given by:

$$p_1 v_1^{\,n} = p_2 v_2^{\,n}$$

where n – is the polytropic exponent.

The specific work of compression for each stage is expressed as:

$$\omega_{pol} = \frac{n}{n-1} R T_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

where R – specific gas constant of air; T_1 – inlet air temperature to the compressor stage;
P_1 and P_2 – inlet and outlet pressures of the stage.

The compressor power consumption is calculated as:

$$N = \frac{\dot{m}\omega_{pol}}{\eta_p \eta_m}$$

where $\dot{m}$ – air mass flow rate; η_p – polytropic efficiency; η_m – mechanical efficiency.

The total compressor power of the two-stage system is determined as the sum of the power consumptions of the low-pressure (LP) and high-pressure (HP) stages. The overall pressure ratio is kept constant.

Results and Discussion

The current overall pressure ratio for marine engines is approximately 4. The results of the calculations presented below are provided for this specific pressure ratio. It should be noted that changes in the overall pressure ratio will lead to some variation in the results; however, these variations will be relatively minor and will generally correspond to the trends shown.

Figure 2 illustrates that for a turbocharged marine engine with intercooling, an optimal split of the pressure ratio exists between stages. Specifically, a ratio $\pi_{\text{к1}}/\pi_{\text{к2}}$ in the range 0.8–1.5 produces the maximum reduction in compressor power consumption [6]. This optimal split yields a 5–15 % decrease in required turbocharger power compared to the one-stage baseline. Moreover, deeper intercooling (lower $t_{\text{ПО2}}$) increases the magnitude of this power saving and shifts the optimal ratio toward lower values of $\pi_{\text{к1}}/\pi_{\text{к2}}$ [5; 7]. The most significant power reduction (over 12–15 %) is achieved when the compressed air is cooled to $t_{\text{ПО2}} = 20…40°C$. Such deep cooling is only achievable with mechanical or refrigeration cooling (beyond seawater alone). In these cases, the configuration of the ejector refrigeration system (driven by low-pressure steam) should include a high-pressure steam generator (power cycle of the refrigeration machine) to utilize the relatively high-temperature heat potential of the boost air, and an evaporator to cool the boost air to a low temperature $t_{\text{ПО2}} = 20…40°C$ between the compressor stages [5; 7].

When designing the heat exchangers of the heat-recovery refrigeration system (i.e., the high-pressure steam generator and low-pressure evaporator), the relevant temperature differences in the compressed air must be known. Depending on the cooling depth, the temperature drop $\Delta t_{\text{ПО}}$ varies approximately from 50°C to 100°C [8].
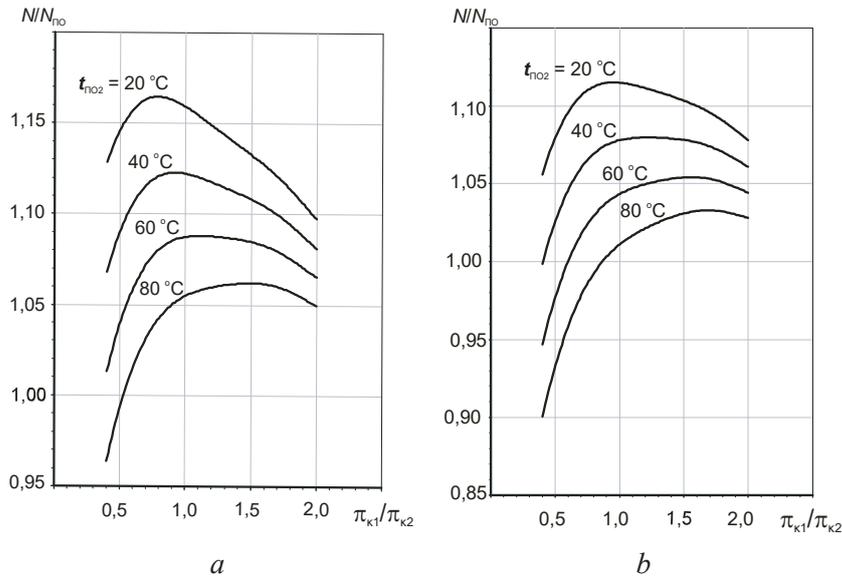

Figure 2. Dependence of the compressor power ratio $N/N_{\text{ПО}}$ on the ratio $\pi_{\kappa 1}/\pi_{\kappa 2}$ of the low-pressure ($\pi_{\kappa 1}$) and high-pressure ($\pi_{\kappa 2}$) compressor stage pressure ratios, for various post-intercooler temperatures ($t_{\text{ПО2}}$ = 20, 40, 60, and 80°C) and inlet air temperatures tin = 40°C (a) and tin = 20°C (b)
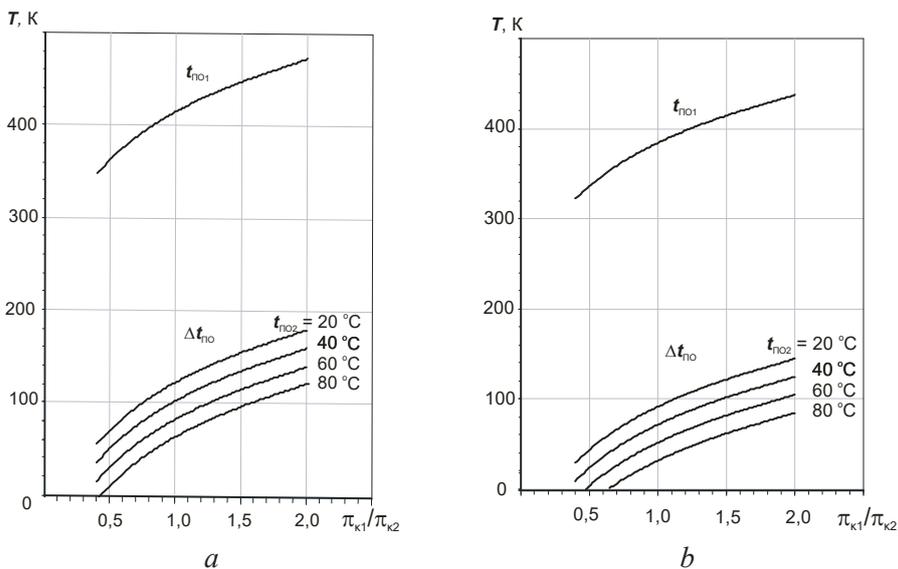

Figure 3. Dependence of the temperature after the first stage of cooling and after intercooling on the ratio $\pi_{\kappa 1}/\pi_{\kappa 2}$ of the pressure ratios of the low-pressure ($\pi_{\kappa 1}$) and high-pressure ($\pi_{\kappa 2}$) compressor stages at inlet air temperatures tin = 40°C (a) and tin = 20°C (b)

Importantly, for deep intercooling applications (either boost air or inlet air), it is inefficient to reject the intermediate-temperature heat (~40–60°C) through the refrigeration machine, because this yields very low ejector and thermal coefficients and consumes scarce low-temperature cooling capacity (evaporator discharge around 0–10°C) [9]. Instead, that intermediate heat is more appropriately removed by seawater. In practice, similar three-section intercoolers (steam–water systems) have been used on ships for many years. Still, their drawback is low efficiency or even infeasibility of the steam-generating (water-steam) section at part-load when exhaust temperatures fall [9]. The proposed heat-recovery circuit based on low-pressure steam is relatively effective even at partial engine loads [9; 10].

Overall, the intercooling system and heat-utilization circuit should be designed around the optimal pressure ratio split to maximize turbocharger power savings. In other words, the compressor stages should be sized so that $\pi_{\text{к1}}/\pi_{\text{к2}}$ is approximately 0.8–1.5 for optimal performance [7]. The reduction in compressor power frees up a portion of the power from the waste-heat recovery turbine, which can be used to generate electricity or to drive the main engine shaft during cruising. In summary, by selecting the optimal intercooling parameters, the engine's overall energy efficiency and output can be significantly improved.

Conclusions

1. Optimal Compression Split: For marine diesel engines with intercooling, there exists an optimal ratio of low-stage to high-stage pressure ratios ($\pi_{\text{к1}}/\pi_{\text{к2}}$) of 0.8–1.5. Using this ratio reduces the turbocharging compressor's power consumption by approximately 5–15 %.

2. Power Recovery and Use: The saved compressor power corresponds to additional power available from the gas turbine. This extra power can be utilized for onboard electrical generation or transmitted to the main engine shaft in cruising mode.

3. Intercooler-Refrigeration Design: The layout of the heat-recovery refrigeration system (e.g., ejector refrigeration) in the engine's gas–air path should be based on the identified optimal ratio. The placement of the steam generator and evaporator (between compressor stages) should be chosen to achieve the identified optimal pressure ratio split.

BIBLIOGRAPHY

1. Shtanko O., Litvinova M., Andrieiev A., Andrieieva M., Savchuk P. Building a technological model of the exhaust gas energy recovery device for the diesel engine on small-sized vessel. *Eastern-European Journal of Enterprise Technologies*. 2020. V. 1. № 8 (103). C. 35–42. DOI: https://doi.org/10.15587/1729-4061.2020.194938.

2. Radchenko R., Kornienko V., Radchenko M., Mikielewicz D., Andreev A., Kalinichenko I. Cooling intake air of marine engine with water-fuel emulsion combustion by ejector chiller. *Modern Power Systems and Units (MPSU 2021)* : Proceedings of the V International Scientific and Technical Conference, Kraków, Poland, May 19–21, 2021. *E3S Web of Conferences*. 2021. Vol. 323. Article 00031. 5 p. Published online 10 Nov 2021. DOI: https://doi:10.1051/e3sconf/202132300031.

3. Pyrysunko M., Radchenko A., Tkachenko V., Zubarev A., Andreev A. Marine diesel engine inlet air cooling by ejector chiller on the vessel route line / In: Advances in Design, Simulation and Manufacturing V. DSMIE 2022. Lecture Notes in Mechanical Engineering. Springer, Cham. 2022. C. 259–268. DOI: https://doi:10.1007/978-3-031-06044-1_25.

4. Sun Y., Sun P., Zhang Z., Zhang S., Zhao J., Mei N. Performance Prediction for a Marine Diesel Engine Waste Heat Absorption Refrigeration System. *Energies*. 2022. 15 (19). 7070. DOI: 10.3390/en15197070.

5. Tian W., Du D., Li J., Han Z., Yu W. Establishment of a two-stage turbocharging system model and analysis on influence rules of key parameters. *Energies*. 2020. 13 (8). 1953. DOI: https://doi.org/10.3390/en13081953.

6. Grönman A., Sallinen P., Honkatukia J., Backman J., Uusitalo A. Design and experiments of a two-stage intercooled electrically assisted turbocharger. *Energy Conversion and Management*. 2016. Vol. 111. Pp. 115–124. DOI: https://doi.org/10.1016/j.enconman.2015.12.055.

7. Watson N., Janota M. S. Turbocharging the Internal Combustion Engine. London, Bloomsbury Academic. 1982. DOI: https://doi.org/10.1007/978-1-349-04024-7.

8. Heim K. Existing and Future Demands on the Turbocharging of Modern Large Two-stroke Diesel Engines. Engineering, Environmental Science. 2014. URL: https://www.semanticscholar.org/paper/Existing-and-Future-Demands-on-the-Turbocharging-of-Heim/b31bcb22e187744ff24d153f5c3119c3c8f7004d

9. MAN Energy Solutions. Influence of ambient temperature conditions. Copenhagen SV, Denmark. 2023. URL: https://www.man-es.com/docs/default-source/marine/tools/5510-0074-03.pdf?sfvrsn=fa9e1cee_6

10. Wärtsilä Corporation. Combustion engine power plants: White Paper. Vaasa (Finland), 2021. *Wärtsilä Corporation*. URL: https://www.wartsila.com/docs/default-source/power-plants-documents/downloads/white-papers/general/wartsila-bwp-combustion-engine-power-plants.pdf

REFERENCES

1. Shtanko, O., Litvinova, M., Andrieiev, A., Andrieieva, M., Savchuk, P. (2020). Building a technological model of the exhaust gas energy recovery device for the diesel engine on a small-sized vessel. *Eastern-European Journal of Enterprise Technologies*. 1 (8 (103)), 35–42. DOI: https://doi.org/10.15587/1729-4061.2020.194938.

2. Radchenko, R., Kornienko, V., Radchenko, M., Mikielewicz, D., Andreev, A., Kalinichenko, I. (2021). Cooling intake air of marine engine with water-fuel emulsion combustion by ejector chiller. In M. Rerak & M. Majdak (Eds.). *Modern Power Systems and Units* : Proceedings of the V International Scientific and Technical Conference (MPSU 2021) (E3S Web of Conferences, Vol. 323, Article 00031). DOI: https://doi.org/10.1051/e3sconf/202132300031.

3. Pyrysunko, M., Radchenko, A., Tkachenko, V., Zubarev, A., & Andreev, A. (2022). Marine diesel engine inlet air cooling by ejector chiller on the vessel route line. In V. Ivanov, I. Pavlenko, O. Liaposhchenko, J. Machado, & M. Edl (Eds.). Advances in Design, Simulation and Manufacturing V: DSMIE 2022 (Lecture Notes in Mechanical Engineering, pp. 259–268). Springer. DOI: https://doi.org/10.1007/978-3-031-06044-1_25.

4. Sun, Y., Sun, P., Zhang, Z., Zhang, S., Zhao, J., & Mei, N. (2022). Performance prediction for a marine diesel engine waste heat absorption refrigeration system. *Energies*. 15 (19). 7070. DOI: 10.3390/en15197070.

5. Tian, W., Du, D., Li, J., Han, Z., & Yu, W. (2020). Establishment of a two-stage turbocharging system model and analysis on influence rules of key parameters. *Energies*. 1953. 13 (8). DOI: https://doi.org/10.3390/en13081953.

6. Grönman, A., Sallinen, P., Honkatukia, J., Backman, J., & Uusitalo, A. (2016). Design and experiments of a two-stage intercooled electrically assisted turbocharger. *Energy Conversion and Management*. Vol. 111. 115–124. DOI: https://doi.org/10.1016/j.enconman.2015.12.055.

7. Watson, N., Janota, M.S. (1982). Turbocharging the Internal Combustion Engine. London, Bloomsbury Academic. DOI: https://doi.org/10.1007/978-1-349-04024-7.

8. Heim, K. (2014). Existing and Future Demands on the Turbocharging of Modern Large Two-stroke Diesel Engines. Engineering, Environmental Science. URL: https://www.semanticscholar.org/paper/Existing-and-Future-Demands-on-the-Turbocharging-of-Heim/b31bcb22e187744ff24d153f5c3119c3c8f7004d

9. MAN Energy Solutions (2023). Influence of ambient temperature conditions. Copenhagen SV, Denmark. URL: https://www.man-es.com/docs/default-source/marine/tools/5510-0074-03.pdf?sfvrsn=fa9e1cee_6

10. Wärtsilä Corporation. Combustion engine power plants – White Paper. URL: https://www.wartsila.com/docs/default-source/power-plants-documents/downloads/white-papers/general/wartsila-bwp-combustion-engine-power-plants.pdf