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Efficiency analysis of a four-stroke marine engine

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Abstract. Conventional propulsion systems consisting of the main propulsion machine, transmission (axle line) and propeller fail to always meet all the conditions of flexibility, manoeuvrability and space requirements imposed on a modern naval propulsion system. The imposition of new, strict rules in shipbuilding and navigation has led to the emergence of new naval equipment, new propulsion systems that have changed the ship's arrangements for economic and efficiency reasons. The useful volume compared to the total volume of the ship is a good economic indicator that allows the analysis of the income and expenses of construction and operation of the ship. For example, following the analysis of the use of space on board passenger ships built in the last 50 years, the ratio between the volume intended for the propulsion installation and the total volume of the ship varies around an average of 11.3%, (between 8% and 17.5%, exceptionally reaching 22%).
Keywords. efficiency, propulsion, engine, four-stroke, passenger ship.

1. Introduction

The development of shipbuilding is closely linked to the evolution and improvement of propulsion systems. A naval propulsion system converts a primary form of energy into mechanical energy, which is transmitted to the propeller in order to overcome the ship's forward resistance and move it on the desired road at the required speed.

From an energy point of view, a naval propulsion system consists of the energy source: the main propulsion machine and the energy consumer: the propeller. Of the naval thrusters, the propeller responds best to current naval technology, being the most widely used and generally the most efficient naval thruster. The naval propulsion system has a decisive role in the realization of an economical and efficient ship. The assessment of a ship's efficiency is made taking into account economic criteria, functional safety criteria, comfort criteria for crew and passengers, etc.

The analysis of the ship - main propulsion - propeller system must be performed in the initial design phases, the type of propulsion system used must be chosen very early in the process of designing a ship, it having a strong impact on the design of the ship itself.

The choice of the ship's propulsion system involves the integration of a large number of elements in a functional space, involves the selection of components (main propulsion machine, transmission and engine), adjusting them by the constraints imposed by other elements, arranging them so as to the required system performance, a satisfactory configuration and an acceptable cost price are obtained. At the same time, the choice of propulsion system must reflect the operational profile of the ship, while analyzing the technical and economic performance of the ship's propulsion system, in order to reduce the specific cost of transport and increase operational safety. The parameters to be taken into account when choosing a propulsion system are:

- The cost of the initial investment;
- The specific cost of transport which depends on the specific fuel consumption as well as the number and level of remuneration of the crew serving the propulsion installation;
- Propulsion efficiency;
- Space related to the propulsion system;
- High operational safety and accessibility for control during operation.

2. Presentation of a passenger ship fitted with four-stroke marine engines

In the context of the growing concern both regionally and globally for sustainable development and the rational and responsible management of natural resources, the global market for cruise tourism is one of the most complex and dynamic sectors of the world economy. The choice of ships as tourist transport has been, since the beginning of the century, a tourist consumption option specific to the luxury demand segment. Of course, the existence of several quality classes within the same transport space also facilitated the access of tourists with lower incomes, although the rate paid for a boat cruise was quite high. The attraction of water travel as a support for leisure and not only as a possibility to access a tourist destination has stimulated the development and diversification of cruise arrangements. The fleet of ships in continuous development, the increase of transport safety, but especially the increase of the ship capacity and the diversification of the types of ships that offer conditions of comfort and Increased leisure activities have stimulated tourist demand for cruises.

The cruise market is today in a period of continuous development, the degree of use of ship space (calculated as the ratio between the number of passenger days and the number of potential passenger days) is over 80%, despite the increase in the number of companies operating cruises. The two largest markets for world cruises are the Caribbean basin, which accounts for about 28% of the world's market supply, and the Mediterranean basin, which accounts for about 15% of supply. The cruise tourism market has changed its image in recent years from a luxury market to a market and a mass offer, aimed at a wider and younger audience.

The first passenger-only ship was Prinzessin Victoria Luise, built by German designer Albert Ballin, manager of Hamburg-America Line (HAPAG), and launched on June 29, 1900. The ship was specially built for the purpose of to offer leisure trips at this time of year, in the Mediterranean and the Orient, when there were no passenger flights to cross the Atlantic due to unfavorable weather conditions. Princess Victoria Luise was designed to provide the best conditions for passengers, and the deck was designed for the warm climate the ship would pass through, avoiding the structures needed for liners crossing the North Atlantic. All 120 cabins of the ship were luxurious, and on board passengers could enjoy a library, a gym and even an obscure room dedicated to amateur photographers. Emperor Franz Joseph himself was envious after inspecting the ship, disappointed that it was longer than the royal yacht Hohenzollern.

The success of Victoria Luise's first voyage was highly publicized, so that several competing companies appeared with ships dedicated exclusively to holidays. For a long time, cruises were confused with navigation, most often with the crossing of the Atlantic Ocean in the Americas and vice versa. Over time, however, carriers have begun a blind race to attract customers by equipping vessels with objects, accessories and even luxury rooms for the more favored social classes. The most famous case of this kind is the well-known Titanic from 1912, which at the time of its launch was the largest cruise ship in the world. Now, he wouldn't even be in the top 50.

Undoubtedly, the year 2020 represented a not only favorable environment not only for CLIA members, but also for all branches of the economy. However, CLIA members are firmly convinced that they will be able to withstand all the obstacles that will arise, relying primarily on industry, which plans ahead and invests capital in the future, as evidenced by the numerous orders to build new ships. cruise until 2022, which will contribute to the revival of the economy.

The year 2019 was marked by the continued diversification and expansion of cruise operations. While the Caribbean, Alaska and Europe remained favorites, more and more cruise companies planned to step up their presence in other parts of the world, such as Asia, the Indian Ocean and Africa, the Amazon and Brazil, the Middle East and Arctic, including the islands of Newfoundland and Greenland.

The cruise ship MS "Monarch of the Seas" is the second ship in a series of three sister ships of the Sovereign class that were built for Royal Carribean International. Starting with 01.04.2013, it was sold to the company Pullmantur Cruises, which later became a subsidiary of RLCC. In the year of its launch, it was the largest passenger ship in the world, with a carrying capacity of 2,744 passengers. Their identifying features include long, steep bow areas, layered superstructures, masts and baskets adorned with Viking Crown sunbeds, terraced and rounded superstructures, and beautifully sculpted stern areas. The Monarch of the Seas has everything it needs to be compared to a 21st century ship, such as the Norwegian Epic, to see how much cruise ship architecture has evolved aesthetically over the years.

Figure 1: MS "Monarch of the Seas" in 1990, during construction

The main technical characteristics of the ship Monarch of the Seas are the following:
- Laid down: 31 July 1989;
- Launch: September 22, 1990;
- Maiden voyage: 11 November 1991;
- Call sign: 9HA3314;
- IMO number: 8819500;
- MMSI: 229415000;
- Port of registration: 1991 - 2004: Oslo, Norway; 2005 - 2013: Nassau, Bahamas; 2013 - 2020: Valletta, Malta;
- Deadweight: GT: 73,937 or NT: 47,505;
- Maximum length: 268.32 meters;
- Maximum width: 36 meters;
- Decks: 12;
- Energy system: four Wartsila-Pielstick type engines with a maximum combined power of 21,872 kW;
- Propulsion: 2 X propeller with adjustable pitch, 2 X bowthrusters;
- Cruising speed: 22 knots;
- Capacity: 2,744 passengers.

Figure 2: Monarch of the Seas passenger ship

3. Technical description of the engines onboard "Monarch of the Seas"

In June 1959, the first designed Wartsila diesel engine, the Wartsila Vasa 14 (with only three cylinders), was started for the first time. This small engine was so loved by the design team that their families visited the factory on Sunday just to see how it works. The first commercial engines, the six-cylinder Wartsila Vasa 614, were sold to Skandia for installation on the M/S Silja Line, which sailed between Finland and Sweden. In 1984, one of these engines was returned to Vaasa and can still be seen today in the Wartsila factory area.

The passenger ship "Monarch of the Seas" has in its energy system four engines from the Wartsila 32 range, model 9 L 32 installed on board the ship in collaboration with the French company Pielstick. Each engine develops a unit power of 7332 HP (5467 kW), giving the ship a total power of 29,328 hp. The engines are used to drive the propulsion system which has in its composition 2 propellers with adjustable pitch and 2 bowthrusters which give an extra maneuverability to the studied ship. Engines in the Wartsila 32 range (piston diameter reference value) have been the preferred choice of shipyards, operators and owners since the 1980's, with over 5100 engines delivered to the maritime market alone. Wartsila 32 is available in various construction variants with configurations from 6 to 16 cylinders and a developed power of between 3 and 9.3 MW at a rated speed of between 720 and 750 RPM. It has the best power efficiency and fuel economy in the class, and can be used in a wide range of operations. With proven reliability and low consumption of consumables, Wartsila 32 is the most efficient solution throughout the ship's life cycle, with the following advantages:

- Prolonged use in the maritime field;
- High reliability;
- High power density;
- Low fuel consumption over a wide range of loads;
- Works on HFO, MDO and liquid biofuels (including LNG).

The excellent flexibility of the fuel supply mode allows Wartsila 32 to operate on HFO, MDO and liquid biofuel, at a wide range of fuel viscosities, from 2.0 cSt to 730 cSt, for HFO, for example (at 50 °C / 122 °F). The engine is capable of running efficiently and economically on low-sulfur fuels (<0.1% S), making it suitable for operation in areas with controlled emission standards (SECA). The engine can also be equipped with an SCR catalyst, such as Wartsila NOR (nitrogen oxide reducer), which can reduce NOX emissions by up to 95%. This means that the engines already comply with IMO Tier III. The Wartsila 32 standard naturally complies with IMO Tier II regulations.

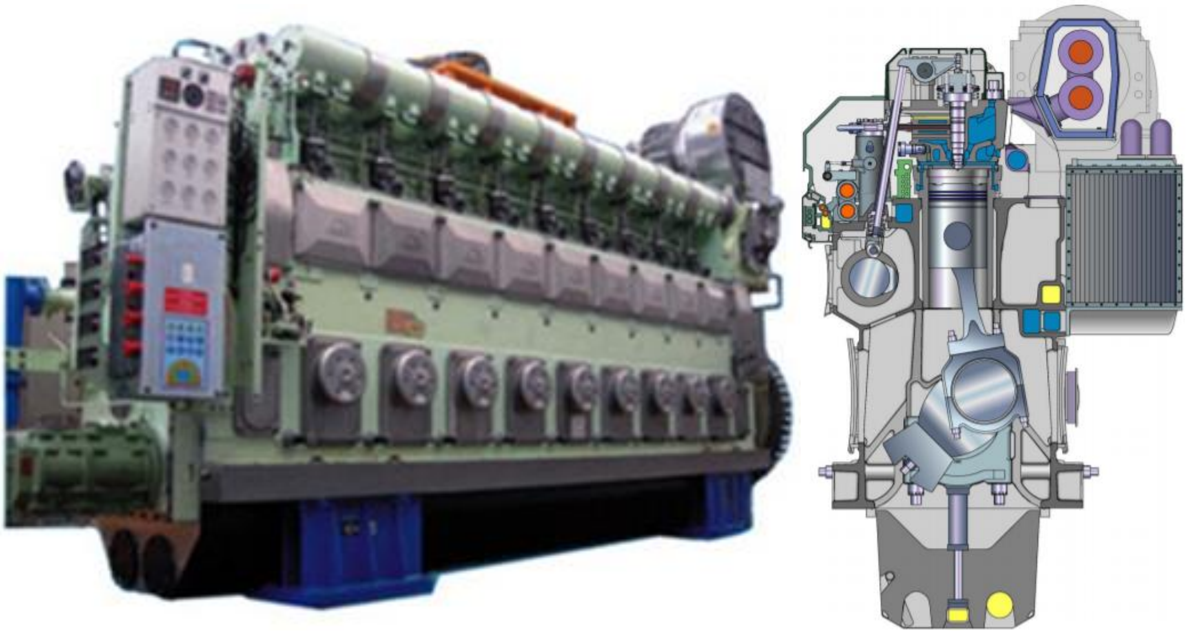

Figure 3: Wartsila 9L32 main engine onboard MS "Monarch of the Seas"

The main technical characteristics of the engine presented above are the following:
- Bore: 320 mm;
- Stroke: 400 mm;
- Piston displacement (cylinders): 32.2 liters per cylinder;
- Number of valves: 2 exhaust valves, 2 intake valves per cylinder head;
- Speed: 720 - 750 rpm;
- Average piston speed: 9.6 - 10 m/s;
- Dimensional characteristics:
- Power (as main engine): 7223 hp;
- Power (as auxiliary motor): 5040 kW (6050 kVA).

The main dimensional characteristics of the main engine Wartsila 9L32 on board the ship MS "Monarch" are the following:
- Length (with turbocharger): 6869 mm;
- Height (from crankshaft to tube blower cover): 2375 mm;
- Crankcase width: 880 mm;
- Total width: 2610;
- Length (without turbocharger): 5140 mm;
- Turbo-blowing length: 1650 mm;
- Weight: 49.2 tons.

The functional characteristics of the Wartsila 9L32 engine are:
- Average effective pressure: 2.9 MPa;
- Air flow at 100% load: 9.63 kg/s;
- Turbine blower air suction temperature: 45 ^{0}C;
- Aftercooler air temperature: 55 ^{0}C;
- Exhaust gas flow at 100% load: 9.45 kg/s;
- Exhaust gas temperatures at 100% load: 350 ^{0}C;
- Exhaust pipe diameter: 777 mm;
- Thermal balance:
    - o Cooling with cylinder water cylinder liners: 675 kW;
    - o Cooling with salt water sweeping air: 1152 kW;

o Fresh water cooling air sweep: 648 kW;
o Cooling oil lubrication: 612 kW;
o Radiation: 162 kW.

- Fuel pressure before injection: 700 kPa;
- Fuel pump capacity: 5.4 m^3/h;
- Specific fuel consumption at 100% load: 183.1 g/kWh;
- Lubrication pump capacity: 108 m^3/h;
- Specific fuel consumption at 100% load: 0.35 gKw;
- Capacity of the cooling pump with salt water: 85 m^3/h;
- Capacity of the fresh water cooling pump: 85 m^3/h;
- Launch air pressure: 30 bar.

4. Efficiency analysis of the four-stroke Wartsila 9L32 main engine

Analysis of the thermal efficiency of the Wartsila 9L32 engine on board the ship "Monarch of the Seas" will be carried out from the point of view of the verification of the design of the engine cooling and the endowment of the equipment. Additional information may reduce or eliminate the experience that must be achieved by reliable numerical analysis. This is of great interest in the advanced design of the engine and the analysis of its subsystems, such as the cylinder head, the engine jacket, the crankcase and the crankshaft. The state of boiling in the cooling mode is a common and visible phenomenon in many industrial applications, as well as in the engine cooling system, due to the high heat transfer criteria.

The use of computerized modeling of the interaction of the solid system with the fluid medium began in the 80's and the last century with the development of personal calculators. This type of modeling/simulation has received the right name for Computational Fluid Dynamics (CFD). The CFD is an instrument based on a computerized code (software) that uses the computational potential of modern calculators to simulate the behavior of a fluid system in a physical environment. Based on the elaboration of CFD codes, there is the apparatus of the mathematical equations, which describe the processes of heat transfer, the mass of fluid and the moment of the mass of the equator. It is important to mention that the use of CFD codes substantially helps to develop and market a product with a minimum of costs in a relatively short time. This is possible after simulating the processes on a real scale with the possibility of varying the functional parameters of the researched system.

In the case study, a fast, 9-cylinder, fast diesel engine is considered. The engine has a borehole of 320 mm, the piston stroke of 420 mm, and the cylinder is 32.68 dm^3. The engine power is 5836 kW, which operates at a constant speed of 750 rpm. The initial, a global model, with a six-cylinder block, was simulated with an adequate density of the general nodes, which ensures the accuracy of the results, together with a reasonable time. The most unfavorable operating conditions were studied for a set of temperature values of the wall and of the cooling water flow. A more detailed thermofluidic analysis was performed to refine the data for the weaker cylinder with a finer node mesh. The boundary conditions for entry and exit were obtained from the developed global model. The model of the engine coolant film covers the crankcase afferent area, the cylinder head cooling surface, the cylinder head cooling holes and the inlet pipe. A figure with the model of nodes afferent to a cylinder is presented in Figure 3. The CFX commercial code was used and run in stationary mode for more simulation sites. The numerical method in the CFX code is based on the discretization of the finite volume in the arrangement of the collated grid. Due to the low density of the steam in the cooled boiling regime, the movement of the phase of the dispersed steam follows the fluctuations in the liquid phase. As a result, turbulent stresses are modeled only for the liquid phase using the k - ε model, which is quite robust and simple.

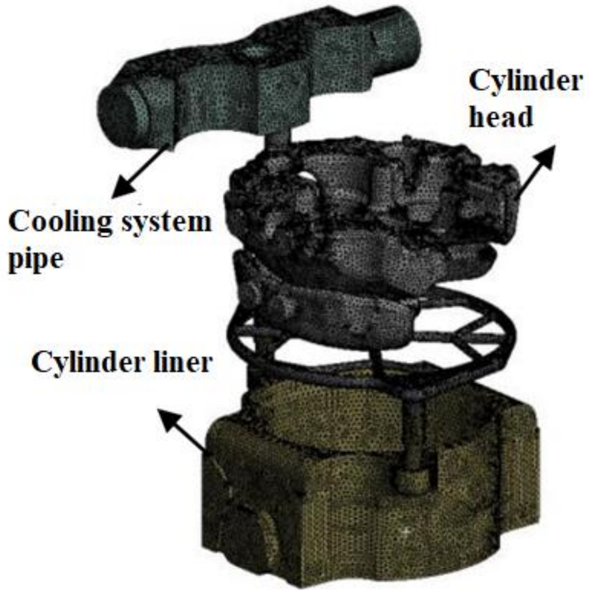

Figure 3: Design of the projected cooling system of the main engine cylinder Wartsila 9L32

This engine is designed for applications of the propulsion system, diesel engines and terrestrial energy applications. The worst case in terms of heat dissipation, water flow and pressure is relevant when the engine is running at 775 rpm and overloaded at 6000 rpm. The initial temperature of the wall showing the boundary zone was set at 100 degrees and subsequently modified during the coupled type calculation. The coolant was also at a static pressure of 3.2 bar and a temperature of 70 ^{0}C. The appropriate mass flow rate for the coolant is 3.82 kg/s, which also contains an addition of 30% ethylene glycol by volume as an antifreeze. The transport properties for the coolant samples are derived and validated for the current system by comparing the predictions with the available data.

The fluid in the vicinity of the wall region is analyzed by semi-empirical ratios for stable variable dependencies. These relationships are based on definite functions from a normal distance from the wall. In addition, it is important to take into account the dependence on the specified thickness of the boundary layer and the value on which the geometry and fineness of the fluid flow are known. As shown in the figure below, the fifth cylinder will be fed with the smallest amount of fluid flow and, consequently, will have a high temperature.

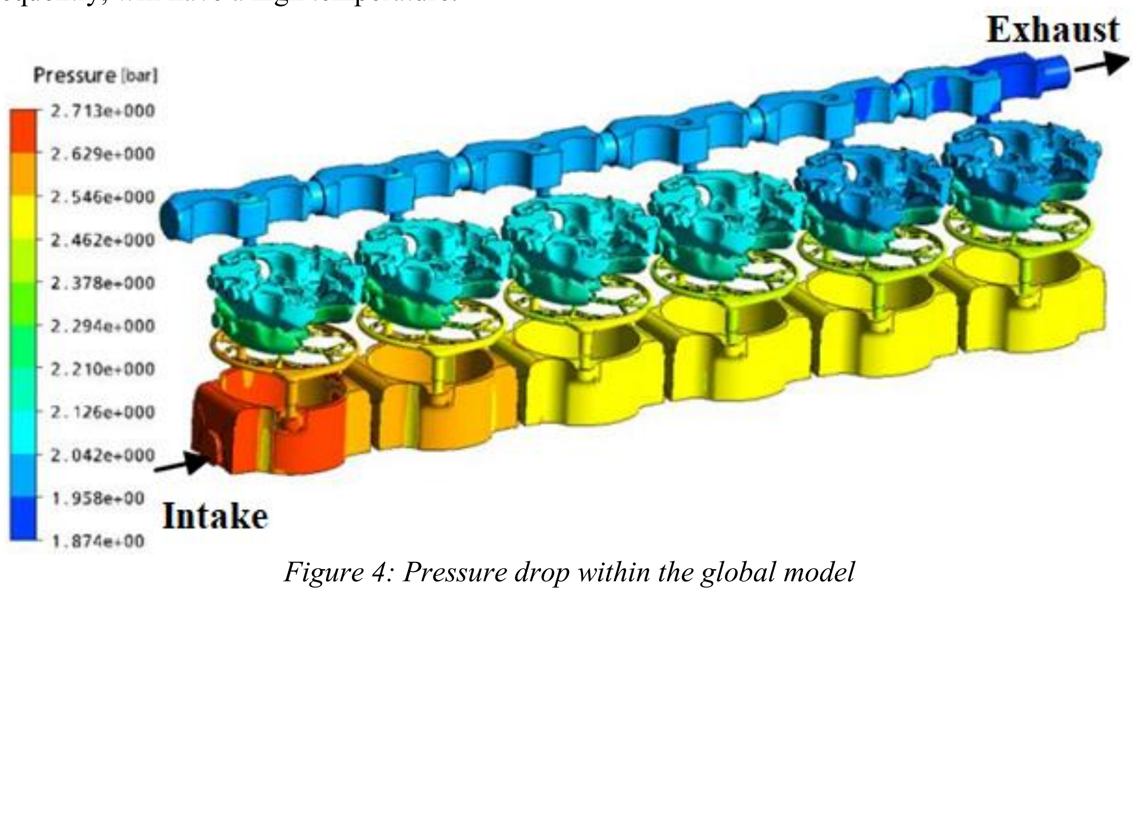

Figure 4: Pressure drop within the global model

As a result, cylinders 6 and 5 have the lowest cooling, due to the different structural geometry. The distribution of the coolant pressure in the diesel engine under study is shown in Figure 4. It is significant to mention how the pressure field is almost the same for all cylinders. It has been established that the pressure drop of approximately 0.5-0.6 bar occurs when the fluid flows from the cylinder liner jacket. It is obvious that the differential pressure level decreases with the pressure drop along the cooling passage. Trends similar to the pressure contour are expected and justified for the velocity currents shown in Figure 5. In other words, the water is accelerated in the cooling holes where the pressure drop is monitored.

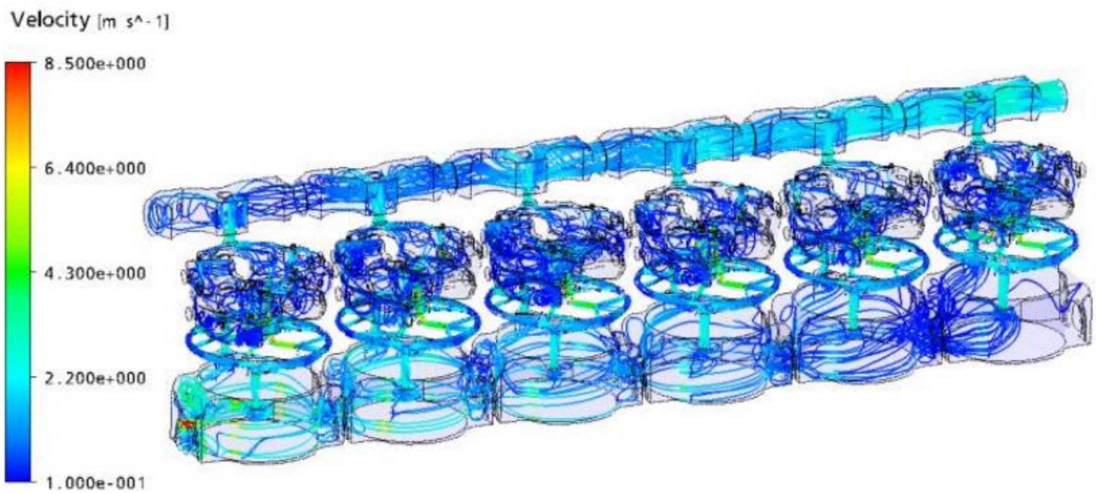

Figure 5: Velocity lines in the framework of the global model

The results indicate that the temperature at any point and the maximum temperature for the 6-cylinder cylinder is greater than that of the 5-cylinder in the case of the block in the case. In addition to this aspect, the asymmetric distribution of the 6th line of the temperature makes it on this cylinder, which is more critical, compared to the others. In the latter case, due to the structural inconsistency of the last cylinder, a more detailed analysis of the 6-cylinder cylinder is of vital importance. The aerodynamic path shown in Figure 6 shows a good circulation of the coolant in all passages with a maximum cooling fluid speed of 0.25 m/s and a maximum of 7.67 m/s and a maximum of 7.67 m/s and approximation of the evacuation orifice:

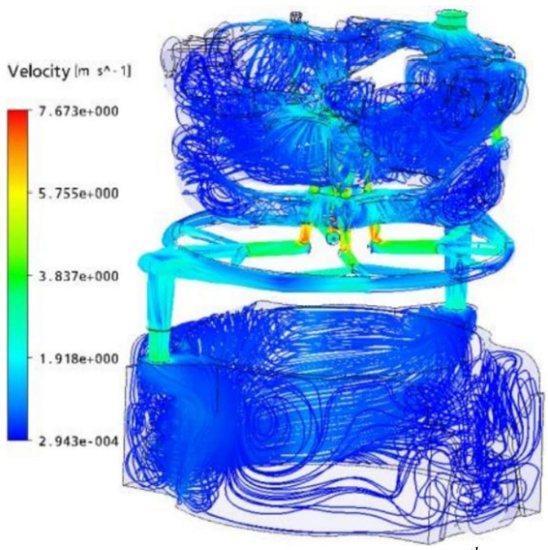

Figure 6: Velocity lines in the case of the 6th cylinder

Experimental data available for a nine-cylinder marine diesel engine but slightly different characteristics, in the power range 175 kW/450 rpm up to 6100 kW/1000 rpm were compared with the price. The CFD analysis is in accordance with the experimental data and the analysis of the case of cylinder 9 or of this engine is reported, in which the areas of the engine are similar to the sub-cooled one. The aerodynamic traces of the cylinder head show a very good circulation of water in all the passages, in figure 7, and the normalized distribution of the temperature of the cylinder is in the figure:

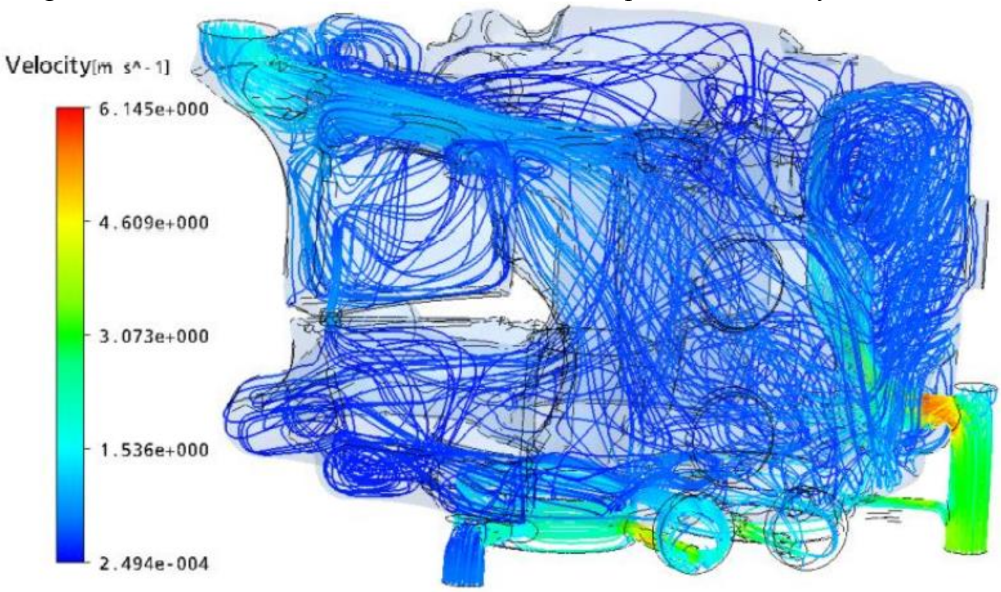

Figure 7: Velocity lines in the case of the 9th cylinder head

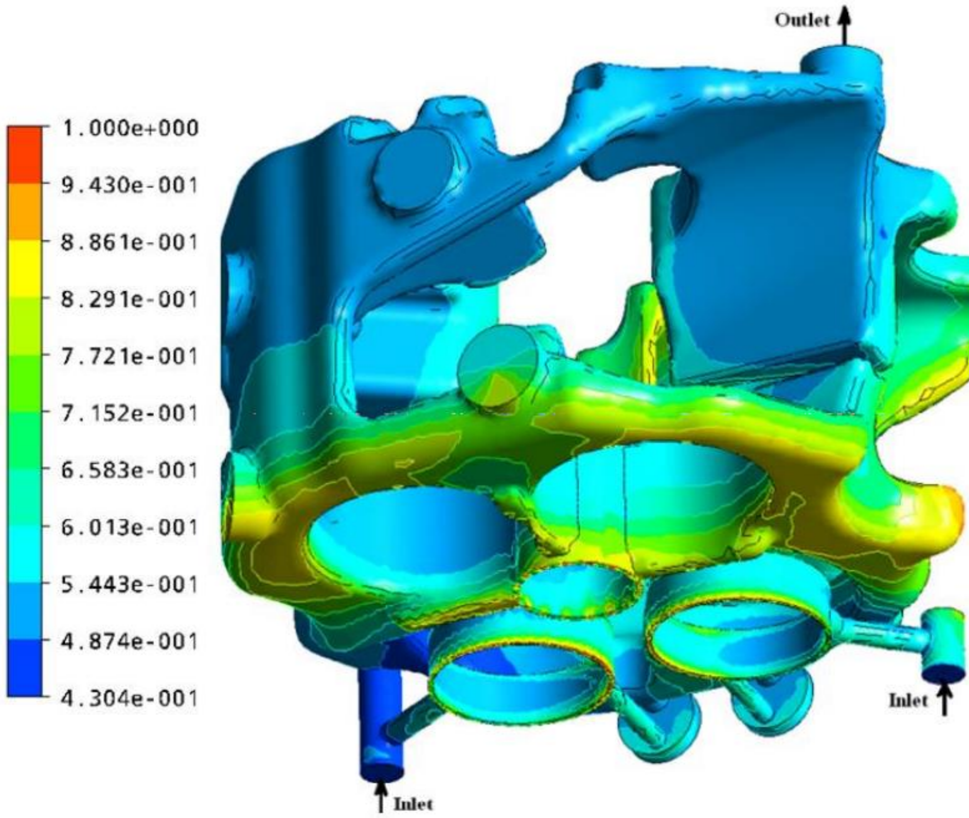

Figure 8: Temperature contours in the case of 9th cylinder head

The simulation results indicate that the cooling water temperature in the cylinder head area number nine of the main engine reaches 87 ^{0}C. Other values of the parameters monitored during the simulation, in accordance with the conditions specified when establishing the simulation environment (a maximum engine developing power of 6,000 kW and a constant speed of 775 rpm) are concentrated as follows:

- static suction pressure: 3.6 bar;
- coolant flow per discharge: 0.9 kg/s;
- suction coolant temperature: 81.4 ^{0}C - higher values are used than those calculated in the previous chapter (55 0C);
- coolant temperature on discharge: 86.2 ^{0}C - higher values than those calculated in the previous chapter are used (65 ^{0}C);
- static pressure on discharge: 3.41 bar;
- heat flow evacuated by cooling the cylinders: $5.5 \cdot 10^6$ kJ/h;
- heat flow evacuated for oil cooling: $4.23 \cdot 10^6$ kJ/h;
- heat flow evacuated by piston cooling: $1.98 \cdot 10^6$ kJ/h;
- heat flow evacuated by cooling the injectors: $6.20 \cdot 10^6$ kJ/h;
- heat flow corresponding to residual losses: $3.12 \cdot 10^6$ kJ/h;
- average temperature of the exhaust gases: Tev = 635.61 ^{0}K;
- useful thermal energy flow: $1{,}298 \cdot 10^7$ kJ/h.

5. Conclusions

In this study, an analysis of the engine efficiency is performed from the perspective of the cooling system. Thus, the analysis of the thermal efficiency of the Wartsila 9L32 engine on board the ship "Monarch of the Seas" was performed from the perspective of verifying the design of the engine cooling. It was essential to have the ability to accurately predict the rate of heat transfer in forced convection cooling mode under different pressure conditions and in different geometry configurations of an engine. In order to perform the simulation, a global simulation model was developed and the specific conditions were set out in detail. The main constructive elements on which the simulation focused were represented by the cooling holes of the cylinder heads, cylinder liners and cylinder heads. The main conclusions of the simulation can be summarized as follows:

- The results of the simulation performed demonstrate the capacity of the cooling model proposed in the design of the Wartsila 9L32 engine and at the same time ensure the accuracy of the results in a reasonable calculation time. So this approach can be used as a powerful tool in designing the concept for optimization and prediction of performance in the case of four-stroke naval engines used in propulsion systems;
- CFD calculations without regard to the cooling effect of subcooling can provide in the most efficient way an approximate estimate of the temperature distribution of the heated surface and the flow characteristics of the whole system, in particular on the surfaces of the cylinder heads, of the cooling holes in the cylinder heads, and on cylinder liners. The wall temperature in the regions where boiling has been activated can be reduced to 60;
- The boiling phenomenon has been activated where the heat flow is considerable while the flow is much lower. In this study, the wall of the cylinder liner, especially in the case of the 6th cylinder, and its outlet part of the cylinder head water film and the holes of the cooling pipe are the boiling regions activated in order to carry out a more efficient simulation;
- The results show that the effect of surface roughness on the heat transfer coefficient cannot be ignored and is worth investigating, especially in certain situations.

The table below summarizes the values obtained by calculating the thermal efficiency in and the values obtained by simulation in last chapter of this study:

Table 1: Comparison of results obtained by calculation and simulation

Parameter	Applied method - Calculus	Applied method - Simulation
Static suction pressure	3,1 bar	3,6 bar
Discharge of coolant on discharge	1 kg/s	0,9 kg/s
Suction coolant temperature	55 ^{0}C	81,4 ^{0}C
Discharge coolant temperature	65 ^{0}C	86,2 ^{0}C
Static discharge pressure	3,6 bar	3,41 bar
Heat flow evacuated by cooling the cylinders	$5{,}7 \cdot 10^6$ kJ/h	$5{,}5 \cdot 10^6$ kJ/h
Evacuated heat flow to cool the oil	$4{,}21 \cdot 10^6$ kJ/h	$4{,}23 \cdot 10^6$ kJ/h
The heat flow is evacuated by cooling the pistons	$2{,}08 \cdot 10^6$ kJ/h	$1{,}98 \cdot 10^6$ kJ/h
Heat flow evacuated by injector cooling	$6{,}21 \cdot 10^6$ kJ/h	$6{,}20 \cdot 10^6$ kJ/h
Heat flow corresponding to residual losses	$3{,}16 \cdot 10^6$ kJ/h	$3{,}12 \cdot 10^6$ kJ/h
Average exhaust gas temperature	650,61 ^{0}K	635,61 ^{0}K
Useful heat output	$1{,}302 \cdot 10^7$ kJ/h	$1{,}298 \cdot 10^7$ kJ/h

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