



**UNIVERSITY
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Literature review on charge air cooler heat transfer & cleaning systems and procedure in Wärtsilä medium speed engines for marine applications

Mechanical Engineering

Bachelor's thesis

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27.3.2026

Turku

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Bachelor's thesis

Subject: Mechanical Engineering

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Number of pages: 25 pages

Date: 27.3.2026

Keywords: Charge air cooler, heat exchanger, maintenance, condition, monitoring system, contamination, heatmetry, heat flux sensor.

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List of abbreviations

LP – Low pressure

HP – High pressure

CAC – Charge air cooler

FAT – Factory acceptance tests

rhs – Running hours

W46TS – Wärtsilä 46 Two stage turbocharging

1 Abstract

Tämä tutkielma antaa yleiskatsauksen Wärtsilän keskinopean W46TS moottorin ahtoilmajähdyttimen puhdistus- ja huoltojärjestelmiin. Työn tarkoitus on tunnistaa mahdollisia kehityskohteita sekä tarkastella ratkaisuja niiden toteutukselle. Tutkielma on alustava valmistelusuunnitelma ja toimii teoreettisena taustana tulevalle diplomityölle. Diplomityön tarkoituksena on tukea Wärtsilää huoltojärjestelmän kehittämisessä siten, että siitä tulee kustannus- ja aikaa säästävämpi sekä mahdollistaa samalla ahtoilmajähdyttimen käyttöiän pidentämisen. Nykyinen huoltosuunnitelma perustuu aiempien vuosien kokemukseen eikä selkeään ahtoilmajähdyttimen kunnon seurantaan. Siksi olemassa olevan seurantajärjestelmän toimivuus on arvioitava, jotta sitä voidaan hyödyntää huoltojärjestelmän kehittämisen tukena.

Ideaalitilanteessa ahtoilmajähdyttimen kuntoa seurataan jatkuvasti, jotta likaantumisen kehittyminen ja sen vaikutus ahtoilmajähdyttimen suorituskykyyn voidaan havaita ajoissa ja tarvittaviin toimenpiteisiin jää riittävästi aikaa. Tutkimuksen tehtävänä on määrittää ahtoilmajähdyttimen kuntoa parhaiten kuvaavat parametrit, selvittää mitkä niistä olisi todellisuudessaan mahdollista mitata tarvittavalla tarkkuudella ja verrata nykyiseen menetelmään. Tehtävän saavuttamiseksi ahtoilmajähdyttimen huoltoon liittyvä sisäinen dokumentaatio on tarkistettava ja sen hyödynnettävyys mahdollisten kehityskohteiden osalta arvioitava. Lisäksi työssä tulee tarkistella mittauksiin vaikuttavia keskeisimpiä tekijöitä sekä pyrkiä selvittämään ahtoilmajähdyttimen likaantumisprosessin kannalta merkittävimmät epäpuhtauksien lähteet.

The objective of this thesis is to overview Wärtsilä's medium speed W46TS (two-stage turbocharging) engine's charge air cooler (CAC) cleaning and maintaining systems, identify potential areas for development and review possible solutions for implementation. The research is preliminary preparational plan and considered as a part of theoretical background for future master's thesis. The purpose of future master's thesis is to support Wärtsilä in maintaining procedure development to be more cost and time efficient and to enable extension of CAC's exploitation time. Current maintenance plan is based on the experience of past years but not on clear monitoring of CAC's condition. Therefore, the functionality of current monitoring system is to be examined for its further supportive exploitation in development of maintaining procedure.

Ideally, the condition of CAC is to be monitored continuously to follow contamination progression. Thus, CAC's performance degradation caused by contamination can be detected on time and the time needed for corrective actions will be enough. Therefore, the goal is to determine parameters that ideally should be measured for reliable CAC's condition evaluation, identify what of the parameters could be measured in practice with needed accuracy and compare with currently used methods. To achieve the goal the internal documentation related to the maintaining procedure is to be reviewed and its usability is to be evaluated for potential further development. Additionally, major influencing factors affecting the measurements are to be reviewed and accounted. In terms of contamination process, the main sources of impurities are strived to identify.

2 Theoretical background

Generally, the charge air cooler (also called intercooler) is a type of heat exchanger used in internal combustion engines to transfer thermal energy between two fluids. In the vehicle and vessel engines it is used to cool down the air before the combustion chamber [1]. Consequently, the density of cooled air increases, which means its volume decreases.

$$\rho = \frac{m}{V} \quad (1)$$

Where ρ is density, m is mass and V is volume of the air

That allows to accommodate more air mass into the combustion chamber, which in turn increases engine power output, reduces fuel consumption and emissions [2].

From a scientific perspective the step-by-step compressing process is presented in three stage compressor's p-V diagram, see **Figure 1** [3].

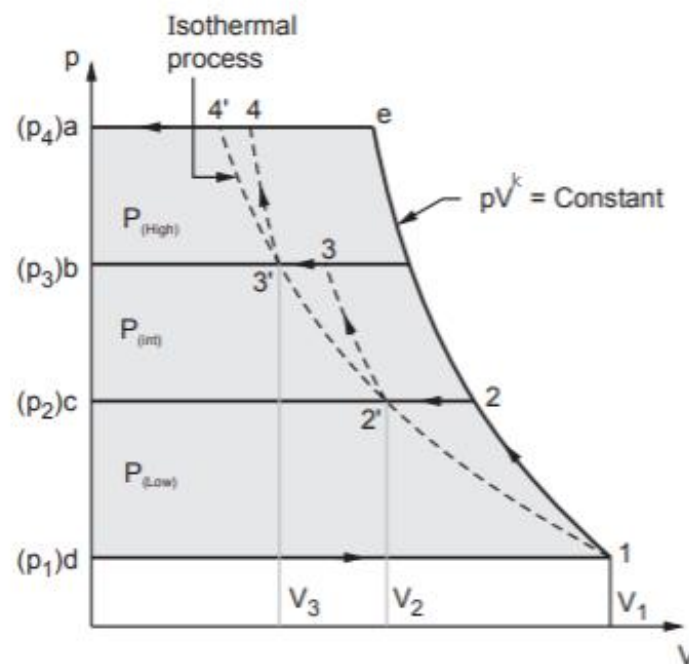


Figure 1. p-V for three stage compressor. (Modified from Laxmikant Dattatray Jathar et al. [3]. Copyright 2021 Laxmikant Dattatray Jathar, published by Technical Publication)

An ideal gas law describes accurate enough properties of the gas in the system. Thus, looking at the equation:

$$pV = RT \quad (2)$$

Where p is pressure, R is specific gas constant and T is temperature of the air (in kelvins)

It could be noticed that compression proceeds adiabatically. When pressure increases inside the compressor, the temperature will also increase, since R is a constant. The isothermal process is presented as an ideal compressing process (1-4'), where T is always a constant, when p is increasing. The final point (4') is presenting the final V of the gas reached with ideal compressing process. From the equation (2) this process is proven impossible. However, technically it is possible to complete artificially an isothermal process and reach almost the same final point (4) by cooling the gas.

Following the compression process from the beginning, starting from the step (1-2), where the air is compressed. Next step (2-2') is an isobaric process, where the air is cooled staying at the same pressure. At that point it could be noticed that with cooling down the temperature after the compression, the volume of the air is the same as it would be in ideal scenario. After repeating all the procedure with lower temperature (3-3') and higher pressure (2'-3) & (3'-4), the final point (4) represents the final V of the air that could be technically reached. The procedure could be theoretically repeated infinite number of times. However, practically it is impossible due to technical restrictions, such as material properties and machines' limited performance. That is also the reason why the final point (4') could not be reached.

Comparing the final points (4'), (4) with the (e), which represents the final volume if the air would be compressed without the cooling, it is noticeable that even though the point (4') is not reached, the difference between the points (4) and (e) is significant. The space between the points (4) and (e) is the difference in air volume that could be supplied into the combustion chamber. For example, burning 1 kilogram of diesel 14,5 kilograms of air is needed [4].

Usually, the charge air cooler is placed after the compressor, and before the combustion chamber, see **Figure 2**. For better efficiency, it is important to cool down the air as much as possible before supplying it to the chamber. Firstly, the air taken from

ambient passes through the compressor. There the air is compressed and also heated up. Heated air tends to expand therefore it must be cooled down. A charge air cooler is used to cool down the compressed air. Finally, when the air is compressed and cooled as much as possible, it is ready to be forwarded into the chamber.

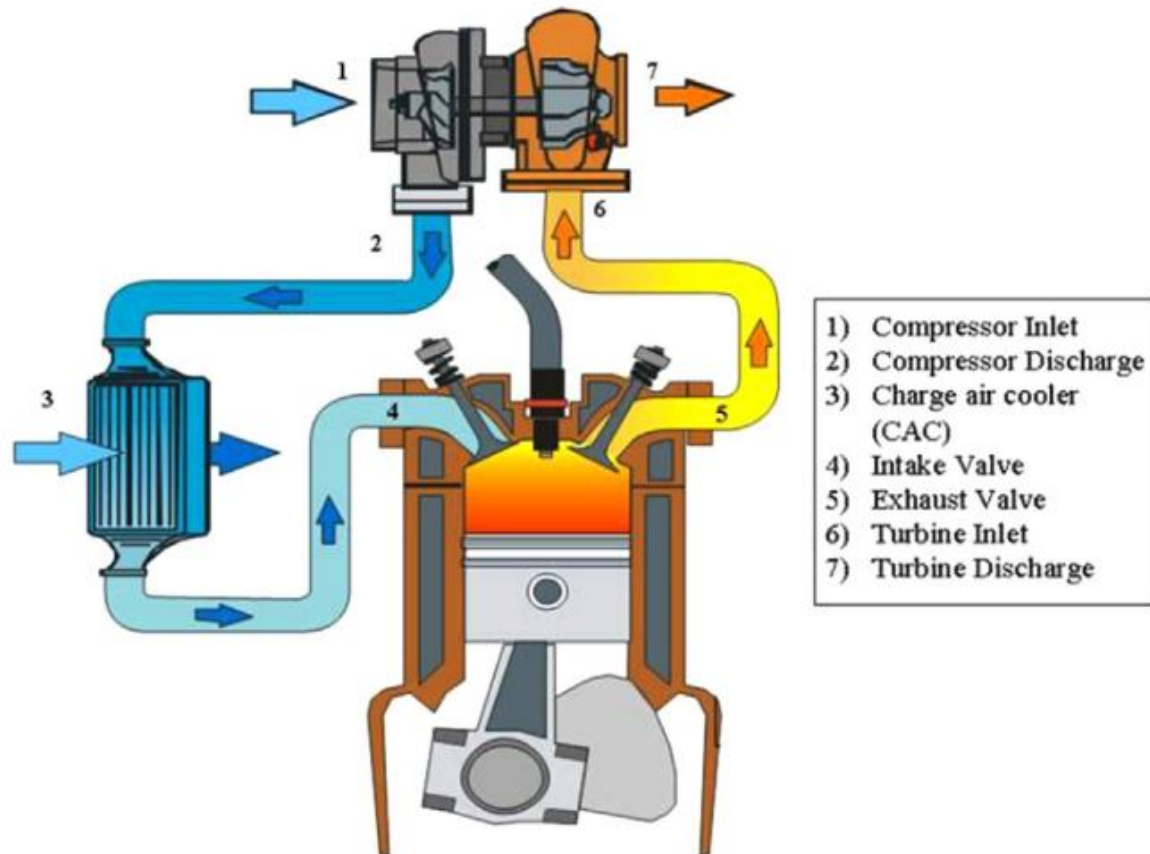


Figure 2. Schematic view of turbocharging. (Image reproduced with permission from [5]. Copyright 2014 Elsevier Ltd.)

In the research, five different engine setups were compared: naturally aspirated engine, turbocharged engine, turbocharged engine with intercooler, and two turbocharged engines with intercoolers with different pressure drop (pressure difference over the intercooler). It has been determined that an ideal intercooler inside the turbocharged engine could increase power output by 154%. For comparison, the same turbocharged engine without intercooler increases power output by 65% compared to naturally aspirated engine [6].

3 Technical overview

3.1 Operating principle of a two-stage turbocharging system

Wärtsilä's W46 two-stage turbocharging (TS) engines according to the name are equipped with two-stage turbocharging system, which also includes 2-stage charge air cooling system, see **Figure 3**.

CHARGE AIR AND EXHAUST GAS SYSTEM

Basic settings of 2-stage turbocharging

System components

- 01 Filter/silencer (optional)
- 02 LP compressor
- 03 LP charge air cooler
- 04 HP compressor
- 05 HP charge air cooler
- 06 Charge air receiver
- 07 Exhaust manifold
- 08 HP turbine
- 09 LP turbine
- 10 Air by-pass
- 11 Air wastegate
- 12 Exhaust wastegate

System connections

- A Air intake
- B Exhaust outlet

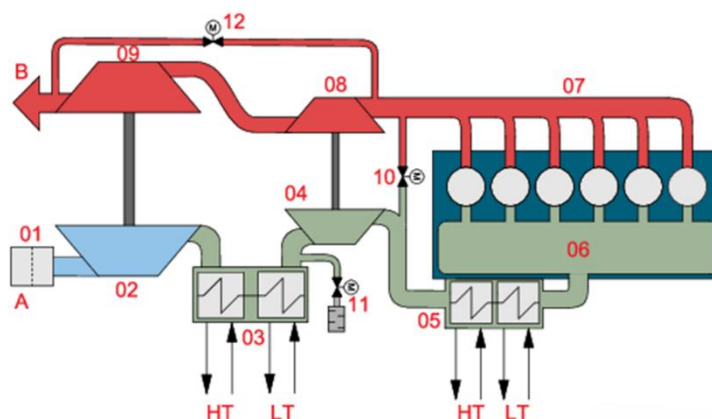


Figure 3 Charge air and exhaust gas system W46TS. (Image reproduced with permissions from Wärtsilä Oyj Abp. Copyright 2026 Wärtsilä Oyj Abp.)

This design structure saves fuel, decreases emissions and increases engine's power output (1300 kW/cyl.) compared to W46F and W46DF engines (1250 kW/cyl. and 1145 kW/cyl.) [7].

Going through the turbocharging structure, there are two compressors connected in series with two charge air coolers. From the air intake (A) air passes through the low pressure (LP) compressor (2), where it is compressed for the first time. After, compressed air is cooled down in the LP CAC (3). In the second stage the air is compressed in high pressure (HP) compressor (4) and cooled in HP CAC.

Additionally, 2-stage turbocharging system allows to use exhaust gases energy more efficiently. The gases pass through the HP and LP turbines (8 and 9) and drive the

connecting shafts between turbines and compressors. That assists in delivering charge air to the system.

3.2 CAC in W46TS engines

Charge air coolers as other heat exchangers are made up of a cooling water tubes and a fins in between, see **Figure 4** as a general reference of heat exchanger's structure.

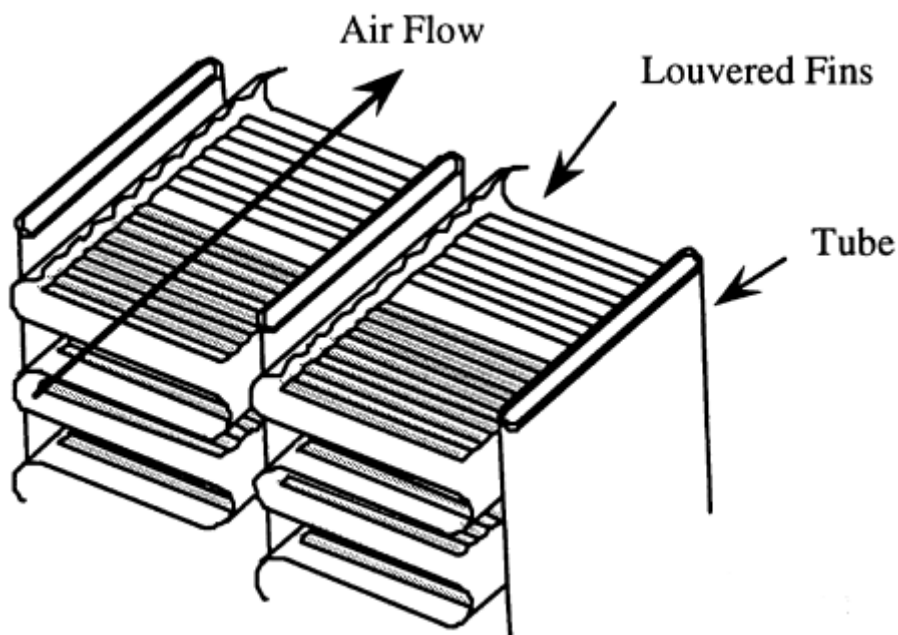


Figure 4. Schematic of louvered fin-and-tube heat exchanger. (Image modified and reproduced with permission from [8]. Copyright 1999 Elsevier Science Inc.)

The water tubes form a closed loop, so called water side with circulating coolant inside (glycol-based coolant with corrosion inhibitors) [9]. The fins between the pipes form a narrow channels the air passes through, also called air side. This structure allows it to cool down the air more efficiently. The air is distributed evenly through the fins; thus, amount of air that passes between the cooling water pipes is low enough to be cooled down to proper temperature. However, due to the space between the fins is narrow, the channels could be easily contaminated. Contaminated CAC could cause significant number of potential harms to the engine. For example, high cylinder peak pressure or knocking in several cylinders, high charge air temperature, low charge air or cooling water pressure [10]. Also, due to CAC contamination, air flow is restricted and

consequently pressure drop increased, which in turn decreases efficiency of turbocharger.

However, the most common is thermal overload for power system components. Due to the formed foulant deposit on the CAC surfaces, its cooling efficiency decreases which means the engine components could not be cooled enough, and their threshold values exceed. Thermal overload could cause thermal fatigue, components' deformation or heat cracks and each of these lead to fatal failure. [11]

3.3 Fouling sources

It could be noticed that only polluted CAC could affect significant amount of harms that in turn could potentially cause serious damage to the engine if not take preventive actions in time. Therefore, it is important to follow up the contamination of CAC or even better anticipate it.

With CAC contamination thermal conductivity decreases due to the formed foulant deposit on the surface. In turn, with decreased thermal conductivity, overall resistance to the heat flow increases, which depends on the thickness of foulant layer. That means the temperature emanating from the hot air distributes as shown on **Figure 5**.

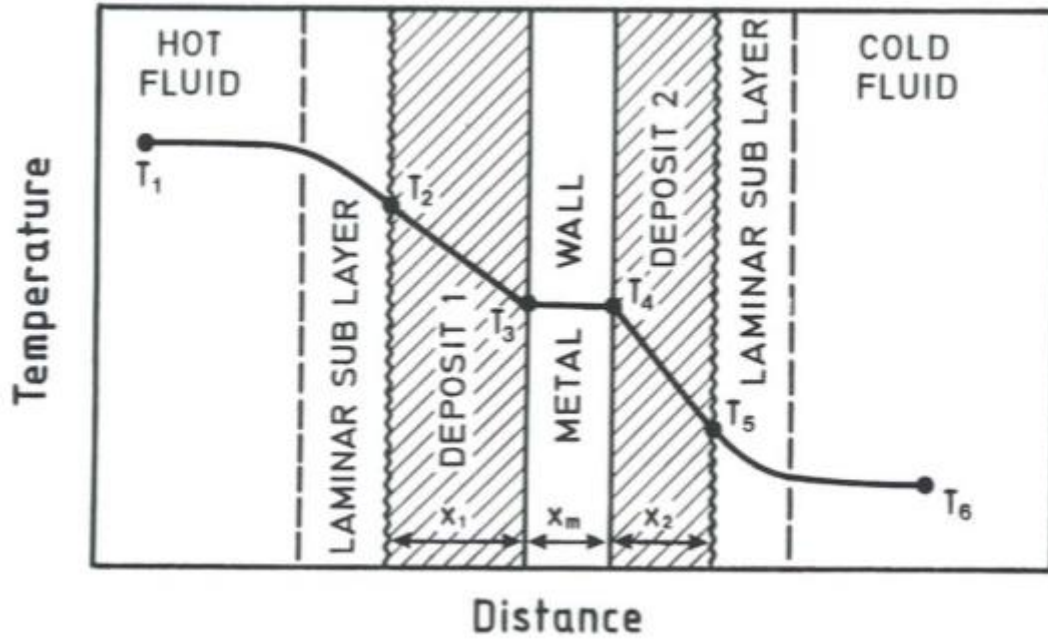


Figure 5. Temperature distribution across fouled heat exchanger surfaces. (Image reproduced with permission from [12]. Copyright 1995 Elsevier Science Inc.)

In practice that means the thermal energy is absorbed by a foulant deposit layers, consequently warmed layers are cooled down before the air could be cooled. As a result, cooling efficiency decreases. The resistance of foulant deposit could be calculated:

$$R = \frac{x}{\lambda} \quad (3)$$

where x is thickness of the deposit and λ is the thermal conductivity of the substance

Thus, the rate of heat transfer through the surface area could be calculated:

$$Q = \frac{A(T_1 - T_6)}{R_{total}} \quad (4)$$

Where A is a surface area, T_1 is initial temperature of the air, T_6 is final temperature and

$$R_{total} = \sum R \text{ is total resistance between the fluids}$$

However, CAC contaminates unevenly, since foulant deposit accumulates mostly in corners and concavities. Thus, it is difficult to calculate the total resistance or resistance at any area without information about amount of foulant. Therefore, the most

exposed to contamination areas needed to be defined. This is one of the objectives that will be completed as a part of future master's thesis.

There are several contamination sources, e.g. dust particles in the intake air, calcification, sulfur or oil mist from the exhaust gases [13]. Contamination sources could be split onto expected and unexpected sources. Preventative actions may differ depending on which type is in question. Difference between the sources is that for expected contamination is possible to prepare, while unexpected source could be unknown. For example, intake air condition could be considered as expected contamination source, therefore Wärtsilä threshold criteria for the intake air intake (highest permissible dust concentration at the turbocharger inlet after filtration is $0,5 \text{ mg/Nm}^3$ with particles above $5 \mu\text{m}$) [14].

Mostly expected contamination is followed precisely and maintained at regular intervals since there are clear preventative and maintaining instructions. There could be instructions for unexpected sources as well, however troubleshooting could take a certain time. In the situation when the contamination source is unknown, reaction time is extremely important. Logically, as sooner contamination can be recognized, there will be more time to react. Surely this amount of time is not enough for troubleshooting, however this time is needed for situation analyzing and preventing further system contamination.

Exhaust gases leakage is exemplary unexpected situation which could be caused by sealing defective condition, uneven surfaces of bellows and pipes or bellow breakdown. If the leakage sustains the gases will be recirculated into the CAC and contamination process will be extremely quick, therefore the alarm should be early enough to make needed preventative actions. To make possible an early alarm, the contamination monitoring mechanisms must be accurate enough with possibly minimal response time.

4 Current state analysis

4.1 Current monitoring methods for Wärtsilä's medium speed engine CAC

Current CAC condition monitoring method is measuring the pressure drop (Δp) over the CAC [15]. This method could not be called reliable due to its possible unsystematic results. The results mostly depend on the person, who and how the measurements were completed, what measuring device was utilized and how well it was calibrated.

Currently there are too many variables affecting the measurements. The measurements are completed at 100% load, however, at the same load percentage the power output could differ depending on operating environment, temperature and components' condition. Additionally, at 100% load the moving parts that generate pulsation e.g. pistons, air silencer or pumps also affect the results.

Another significant factor is how the measurement results were interpreted. Even though the measurements were completed by the same person, there could be differences in decisions such as measuring time, interference evaluating and determining the final Δp .

The pressure drop measured in factory acceptance tests (FAT) currently functions as a reference for further maintaining measurements. There are no exact nominal values defined due to the minor difference between the engines and setups. For every engine a performance manual is created with expected values for related engine. However, differences between the engines are minimal, thus for same engine setup and same fuel type, expected values differ insignificantly. In an ideal scenario, the values measured during the FAT must be compared with expected values in the engine performance manual. However, the manual is an extensive document, since there are presented all values from all systems in the engine. Therefore, in reality the engine is managed to be acceptable if the FAT values stay inside the alarm limits [16]. Since that, the values from the FAT are as a reference for further measurements.

4.2 Other methods and properties could be measured for monitoring

Currently the Δp is measured manually with differential pressure indicator as a part of 2000 hrs maintenance. Alternatively, pressure sensors are also available, and it is possible to install them into the measuring spots for manual device, see **Figure 6**.

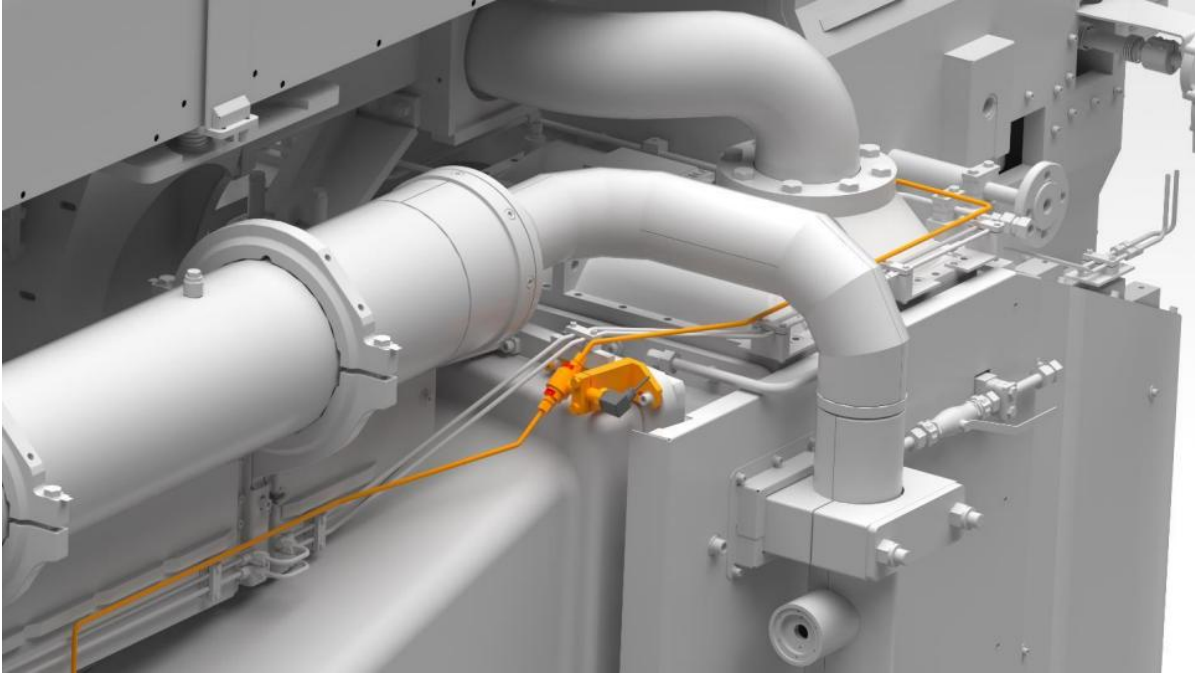


Figure 6. Wärtsilä Delta Pressure Sensor. (Image reproduced from [17] with permissions from Wärtsilä Oyj Abp. Copyright 2026 Wärtsilä Oyj Abp.)

By installing the sensors on the measuring spots for manual device means the manual indicator is simply replaced with sensors, which could be considered as improvement due to possibility of continuous measurements. However, that also means the measurement results do not significantly differ, since the measuring points are the same. Thus, the factors affecting the measurements are the same. Moreover, due to the sensors are susceptible to contamination, the results could differ for the worse. This may distort the overall assessment of system condition if sensor's data are relied upon without proper maintenance. However, currently the sensors are narrowly used in Wärtsilä's engines and none of W46TS engines has the pressure sensors in the setups.

Pressure sensors or even simple U-tube manometer would be a good option if the results are reliable. To achieve reliable results, the interferences must be minimized.

Reliable pressure sensors could possibly significantly improve and facilitate the monitoring quality of the CAC.

Temperature is another main parameter that could be utilized for monitoring. The intake manifold temperature is one of the key indicators of the CAC contamination [18]. Additionally, cooling water temperature could be also utilized as a part of CAC performance monitoring since it is measured continuously in W46TS engines. With CAC's air-side contamination the air could not be cooled enough due to increased resistance to heat flow [12]. That means the water supply temperature should be decreased to cool down the air. However, if contamination continues, so called pinch point comes up, when water supply temperature is at its minimum, but air temperature is still growing. Additionally, the water tubes are also subject to pollution or corrosion over time. Thus, cooling water side of the CAC needs to be taken into account as a part of CAC performance.

Generally, knowing that thermal energy always transfers from warmer substance to colder, the warmed substance could be cooled by decreasing temperature of colder substance or increasing its volume. Regarding the CAC, amount of cooling water could not be increased (due to the constant volume of the system); however, in addition to inlet temperature of cooling water the circulation speed could be adjusted for cooling efficiency. From equation (5) the heat transfer could be calculated:

$$q = c_p * \dot{m} * (T_{out} - T_{in}) \quad (5)$$

Where c_p is substance specific heat capacity of the, \dot{m} is mass flow rate of the substance and T_{out} & T_{in} are inlet and outlet temperatures (in kelvins) of the substance. The heat transfer between air and cooling water must be equal, thus with constant inlet cooling water temperature the mass flow ratio of cooling water could be calculated as follows:

$$c_{p_{water}} * \dot{m}_{water_1} * (T_{out_{water}} - T_{in_{water}}) = c_{p_{air}} * \dot{m}_{air} * (T_{out_{air,nominal}} - T_{in_{air}}) \quad (6)$$

Where $T_{out_{air,nominal}}$ is targeted temperature (in kelvins) of air when it leaves the system

$$c_{p_{water}} * \dot{m}_{water_2} * (T_{out_{water}} - T_{in_{water}}) = c_{p_{air}} * \dot{m}_{air} * (T_{out_{air,real}} - T_{in_{air}}) \quad (7)$$

Where $T_{out\,air,\,real}$ is the real temperature (in kelvins) of air when it leaves the system

$$\frac{\dot{m}_{water_1}}{\dot{m}_{water_2}} = \frac{T_{out\,air,\,nominal} - T_{in\,air}}{T_{out\,air,\,real} - T_{in\,air}} \quad (8)$$

With known mass flow ratio, the circulation speed can be adjusted to maintain a constant inlet temperature or if it has reached its minimum. The increased inlet speed could be calculated as follows if needed:

$$v = \frac{\dot{m} * \rho}{A} \quad (9)$$

Where ρ is density of the cooling water ($\rho_{water} = 1$) and A is cross-section area of the pipe

$$v_{water_2} = \frac{\frac{\dot{m}_{water_1}}{T_{out\,air,\,nominal} - T_{in\,air}}}{\frac{T_{out\,air,\,real} - T_{in\,air}}{A}} = \frac{\dot{m}_{water_1}}{(T_{out\,air,\,nominal} - T_{in\,air}) * (T_{out\,air,\,real} - T_{in\,air}) * A} \quad (10)$$

However, the lack of useful and reliable information about CAC's condition during the engine's operating time is the problem. Nowadays remote and digital monitoring are possible to integrate almost in every system of the engine, and the quality of the sensors is high enough to provide reliable information. Evidently, remote monitoring is time efficient and on a long distance also cost efficient. Currently on the market there are ready-made solutions for different types of heat exchangers provided by several companies. In these ready-made solutions widely used manners such as pressure and/or temperature following mechanisms with developed software are conveniently combined.

However, on the market there is available something more unique with high potential. Heat flux sensor measures heat flow between objects and gives exact value in 10 ns delay [19]. Compared to alternative measurement systems, the Heat Flux-sensor provides improved applicability due to its ability to be placed directly inside the CAC. That means it could measure heat fluxes directly between the surfaces thus avoiding

extra interferences. Additionally, the sensors could be placed in different spots inside the CAC thus it could be followed in what areas the CAC contaminates most. However, functionality and reliability of the sensor need to be ensured, since there is not yet practical experience in a like CAC operating environment. Additionally, excessive accuracy is unnecessary in CAC condition evaluation. Excessive accuracy could create interference that is intended to be avoided by reacting on even minimal differences therefore, additional tests will be completed as a part of future master's thesis.

Technology currently is narrowly used due to its novelty, uniqueness and obscurity. The sensor also could be potentially integrated and utilized in other systems, for example, detecting fuel/oil/gas leakages. To define how and where the sensor could be utilized additional tests and research are needed and will be also completed as a part of future master's thesis.

4.3 Maintaining methods for CAC

Currently there are two CAC maintaining intervals in the scheduled maintenance plan for W46TS [20] (2 000 running hours (rhs) and 48 000 rhs). Pressure difference over the CAC, which functions as a contamination indicator, is measured before and after the washing procedure as a part of 2 000 rhs maintenance [15].

According to the W46TS scheduled maintenance plan, the CAC washing procedure with Delta Cleaner is performed every 2 000 rhs [21]. The Wärtsilä Delta Cleaner is a system that enables in-situ cleaning of the CAC by injecting cleaning foam into the air side, eliminating the need for dismounting the unit [22], [23]. The purpose of washing procedure with Delta Cleaner is to keep the CAC at the same condition throughout lifetime, until the mechanical maintenance at 48 000 rhs. If the CAC contaminates significantly ($\Delta p \leq 1,5 \times$ measured value of new CAC), it could not be washed with Delta Cleaner to its functional condition. This fact highlights importance of monitoring CAC's condition. Currently, how precisely the CAC's condition is followed mostly depends on the customer-specific maintenance practices. The customer adjusts the intervals and decides how and when to maintain the CAC, since every vessel operates in different environment.

The operating environment is occasional for every vessel which is one of influential factors. Operating in different environments means different contamination speed for CACs. However, mentioned maintaining intervals are based on the experience and fixed in manuals for every vessel. Fixed maintaining interval could be considered as a safety factor if the interval is based on the worst possible operating environment. However, that means there are unnecessary costs. According to the W46TS maintenance plan and Wärtsilä's CAC maintaining instructions, the total lifetime maintaining costs for Delta Cleaner additives could be approximately calculated:

$$\frac{48\,000\text{ rhs}}{2\,000\text{ rhs}} * 1\,200\text{ €} = 28\,800\text{ €} \quad (11)$$

Considering that 1 200 € is approximate cost per bank for Delta Cleaner additives that could vary [25], the total cost could also vary. Even though, 24 000 € per 48 000 rhs (approximately ten years) could feel negligible, however, this is cost only per one bank.

Online monitoring system enables complete maintenance exactly in time when it is needed. Thus, maintaining intervals could be recalculated and redeveloped to be more flexible. In turn, that allows to recalculate the total lifetime of the CAC. Moreover, there could be integrated two separate monitoring systems to follow current contamination of CAC and its overall performance.

In addition to pressure and temperature for example, pH-value of the Delta Cleaner wastewater could be measured during the cleaning procedure and compared with the pH value of the cleaning foam. This could be a reliable supportive parameter to determine the cleanliness of the CAC after Delta Cleaner purify.

The 48 000 rhs mechanical maintenance is laborious process, which contains dismounting the CAC and chemical or ultrasonic cleaning [26]. The maintenance interval is also based on the experience, but not on any objective calculations. According to the Wärtsilä's mechanical maintenance instructions for CAC, it takes up to sixteen hours per one CAC to complete the procedure. In addition to mandatory costs, the engine is not operating for at least twelve hours. That correspondingly means the engine is out of operation and does not perform any value for that time.

5 Main results and discussion

The mechanical integrity of the engine requires that the CAC also be in good condition to ensure the performance specified for the engine. Therefore, reliable maintenance methods must be used. To achieve the best performance and avoid unnecessary costs, maintenance intervals should be determined based on monitoring data. The data should be sufficiently reliable and accurate to capture unexpected contaminants in time. Currently, there are few core problems in the CAC maintaining system:

1. There are a lot of variables in the system that affect CAC performance, such as: operating environment including intake air condition, fuel type and cooling water mixture intensity, crew's stance to importance of CAC condition, and also differences in measuring methods and devices.
2. The lack of remote monitoring system that provides reliable information about CAC's performance immediately. In addition to all variables already in the system, there are still risks of unexpected malfunctions. Manual monitoring could be more reliable than remote, however manual monitoring does not provide the information here and now. Moreover, manual monitoring is outdated as a main following method due to remote monitoring's time and cost efficiency. Nowadays remote-monitoring systems are accurate enough, selection on the market is wide and it is possible to integrate into the system without significant investments. With reliable manufacturers the quality of measurements and expected lifetime are not an obstacle. It is unreasonable to save on the high-quality monitoring systems in such expensive and high-tech engine.
3. Current instructions are inadequate and not user friendly. For most of experts in Wärtsilä entire CAC maintaining procedure could seem evident due to huge experience. However, for the beginner it will take a while to sort out the process. Moreover, some experts admit instructions being inadequate even though they are continuously involved in the instruction development process.

Currently if the $\Delta p \leq 1,5 \times \Delta p$ of the new CAC, it is considered as over contaminated. However, the contamination threshold is not specified in the

manuals as well as differential pressure indicators. Pressure difference is measured during the 2 000 rhs maintenance, but there are no additional supportive parameters measured to determine cleanliness of CAC.

The operating environment is one of the key factors affecting CAC's contamination. In different operating environments the estimated contamination time varies, however the maintenance intervals and total lifetime are fixed, which is illogical. The intervals are specified based on the experience, but not on the objective indicators. Even though the given intervals are only an assumption and more suggestion than a strict rule that assists the customer in assessing exact intervals, they could be defined in more detail in the manuals. Moreover, the maintaining intervals could be recalculated and redeveloped to be more flexible, vessel or environment-specific to avoid unnecessary costs by utilizing measured objective parameters. Thus, this could potentially increase customer responsibility to follow the CAC's condition due to the maintaining intervals will be mostly depending on their actions. Sub consequently the total lifetime of CAC could be potentially extended, which is evidently in the interests of Wärtsilä and vessel's owner.

However, the most cost efficient and definite manner is to integrate a remote monitoring system and predefine the Δp limit for maintenance with Delta Cleaner. In that case the maintenance will be based on the current state analysis and will not be fixed on 2 000 rhs. Thus, maintenance intervals would be dependent on measured value but not on the running hours and the CAC could be washed whenever it is needed. Additional supportive manual measurements still could be periodically completed to ensure that remote monitoring system is working properly.

6 Conclusion

Available internal documentation related to the W46TS engine's CAC maintenance was reviewed as a part of this thesis. Potential areas for improvement were found in the maintaining process such as lack of accurate, remote, continuous, cost and time efficient monitoring system for CAC current condition and overall performance, definition of most prone to contamination areas inside the CAC, rearrangement of the maintaining intervals and clarification of the manuals.

Possible solutions and improvement suggestions were proposed as follows: instead of utilizing manual pressure difference indicator to measure the Δp over the CAC, sensors could be installed for remote and continuous monitoring. Even though Wärtsilä has own pressure sensors, they could not be called reliable due to the sensors are designed to be installed on the spots for manual measuring. Thus, the same influencing factors affect the sensors' measurements as manual indicators measurements. Selection of the sensors and ready-made solutions on the market is wide enough; however, the heat flux sensor could be installed inside the CAC and thus heat transfer capacity could be measured directly avoiding unnecessary interferences. Additionally, most prone to contamination areas could be defined by installing several heat flux sensors in different spots. Minimal response time, high accuracy and possibility of internal installation make from the heat flux sensor a good option for remote monitoring system. However, its reliability, accuracy or possible excessive accuracy need to be tested in operating environment.

With continuous and accurate measurements, real exact contamination speed could be determined. Thus, exact threshold values for over contamination could be defined and based on this the maintaining intervals could be rearranged. Moreover, the maintenance with Delta Cleaner could be completed when it is needed, thus unnecessary costs could be avoided. Consequently, the exact total lifetime of CAC could be also followed, and CAC could be dismantled when it is needed, thus also avoiding unnecessary costs and saving valuable time.

Current definition of over contamination could be specified in the manuals as well as pressure difference indicators and measurements interpretation. This could assist the experts to complete the measurements similarly.

The objective of this thesis is successfully reached and as a result preliminary action plan for future master's thesis is created. This thesis is a part of the theoretical background for master's thesis and the research will continue. In master's thesis the heat flux sensor will be tested in real operating environment and its measurement accuracy will be compared with current monitoring systems and other possible options.

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