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ENGINE AUXILIARY SYSTEM GUIDELINE: COOLING SYSTEMS

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VAASAN AMMATTIKORKEAKOULU
Kone- ja tuotantotekniikan koulutusohjelma

TIIVISTELMÄ

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Lopputyö tehtiin Wärtsilän Technical Services –organisaatiolle. Toimeksiantona oli koota olemassa olevien yrityksen sisäisten dokumenttien, kirjallisuuslähteiden ja yrityksen jäähdytysjärjestelmäasiantuntijoiden haastattelujen pohjalta ohje koskien jäähdytysjärjestelmää yhtenä 4-tahtimoottorien apujärjestelmistä. Ohjeen tuli kattaa sekä voimalaitos- että merimoottori-installaatiot koskien Wärtsilän tällä hetkellä tuotannossa olevia 4-tahtimoottoreita.

Ohjeessa on kuvattu jäähdytysjärjestelmän merkitys moottorien toiminnalle, tyypillisimmät jäähdytysjärjestelmävariaatiot sekä yhtäläisyydet ja eroavaisuudet voimalaitos- ja merimoottori-installaatioiden välillä. Ohjeessa on niin ikään esitelty lyhyesti jäähdytysjärjestelmän komponentit ja kuvattu suljetun nestekierron järjestelmän dynamiikkaa lämpötilojen, paineiden ja tilavuusvirtojen kautta. Lisäksi ohjeessa kerrotaan jäähdytysveden käsittelystä ja vaadittavista ylläpitotoimenpiteistä ruostumis- ja pinnoitteenkertymisongelmien estämiseksi. Osana ohjeen kokoamista luettiin ja analysoitiin myös Technical Services –osaston tietokannoista löytyvät jäähdytysjärjestelmiä koskevat raportit ja koottiin tiedot tyypillisistä kenttäongelmista.

Wärtsilän 4-tahtimoottoreiden jäähdytysjärjestelmä on moottorin toiminnan kannalta tärkeä apujärjestelmä, joka suojaa moottoria kuumuuden aiheuttamilta vaurioilta ja joka ohjatessaan mm. ahtoilman lämpötilaa vaikuttaa suoraan moottorin suoritusarvoihin. Jäähdytysjärjestelmästä on olemassa lukuisia eri variaatioita ja järjestelmän lopullinen valinta tehdäänkin projektikohtaisesti asiakkaan vaatimukset huomioiden. Tyypilliset kenttäongelmat liittyvät järjestelmän tasapainottamiseen ja puutteellisen ylläpidon aiheuttamien ongelmien ratkomiseen.

Avainsanat jäähdytysjärjestelmä, 4-tahtimoottori, kenttäraportti

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ABSTRACT

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The thesis was done for Wärtsilä Technical Services organization. The assignment was to consolidate a guideline for cooling systems as an engine auxiliary system covering the Wärtsilä 4-stroke engines currently in production. The guideline was to include information considering both marine and power plants installations. The sources of information were internal documentation from Wärtsilä, literature review and discussions with Wärtsilä cooling system experts.

The guideline includes information on the impacts of the cooling system, on engine operations, on typical cooling system configurations as well as on the differences and similarities in cooling systems between marine and power plan installations. Furthermore, the components included in the cooling system and the dynamics of a closed circuit system with constant fluid circulation are shortly presented in the guideline. The cooling water quality requirements and related maintenance activities are also presented in the guideline as the cooling water quality has a direct impact on the performance of the cooling system via corrosion, fouling and deposit formation processes. Finally, the Services reports related to cooling systems were reviewed and analyzed to include information of typical issues on cooling systems to the guideline.

The cooling systems of the Wärtsilä 4-stroke engines have an essential impact on the engine operations as they protect the engine from the thermal damages and impact the performance of the engine e.g. by controlling the charge air temperature. The cooling system configuration for each installation is selected based on the ambient conditions, water availability, engine type, financial criteria and customer preferences. Typical issues in the field are related to system balancing and to the consequences of insufficient cooling system maintenance practices.

Keywords Cooling system, 4-stroke engine, field report

TABLE OF CONTENTS

TIIVISTELMÄ

ABSTRACT

LIST OF ABBREVIATIONS

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DF	Dual fuel engine (gas or diesel as fuel)
CAC	Charge air cooler
CHP	Combined heat and power
EAM	Engine auxiliary module
HFO	Heavy fuel oil
LFO	Light fuel oil
LO	Lube / lubricating oil
HE	Heat exchanger
HR	Heat recovery
HT	High temperature
LT	Low temperature
MC	Mixed cooling
PLC	Programmable Logic Controller
PP	Power Plants
SP	Ship Power
SG	Spark ignited engine (gas as fuel)
TCV	Temperature control valve
VFD	Variable frequency drive
WOIS	Wärtsilä Operator Interface System
WWCU	Wärtsilä Water Conditioning Unit

1 INTRODUCTION

This thesis is made for Engine Auxiliary Systems -team in Wärtsilä Technical Services, 4-Stroke Engines organization. The purpose of this thesis was to gather and structure existing information about engine cooling systems into one guideline that is to be used by Technical Services personnel as a training material and as a means of troubleshooting cooling system cases. The sources of information for the thesis are:

- Wärtsilä Power Plants, Ship Power and R&D design handbooks, functional descriptions and other relevant documentation on cooling systems
- Wärtsilä Technical Services reports
- Wärtsilä R&D laboratory test reports
- Literature and research review
- Interviews of Wärtsilä cooling system experts

1.1 Wärtsilä as a Company

Wärtsilä is a global company operating in both marine and power plant business areas offering its customers complete lifecycle power solutions. Wärtsilä was established in 1834. Today Wärtsilä serves customers throughout the lifecycle of the products providing services from the initial building phase all the way to operations and maintenance of the power solutions and renewal of existing power solutions. Wärtsilä aims for the optimum environmental and economic performance of the vessels and power plants of its customers by focusing on technological innovation and total efficiency. /36/

Wärtsilä operated in nearly 70 countries around the world and employed approximately 17,700 people in 2014. The headquarters of the company are located in Helsinki, Finland and the stock of the company is quoted in NASDAQ OMX Helsinki. In 2014 Wärtsilä net sales was EUR 4,779 million. Wärtsilä operates through three business lines: Ship Power serves the customers in marine and oil & gas businesses, Power Plants focuses on flexible base load power plants operating on various gaseous and liquid fuels and Services provides life cycle services for both marine and power plant customers. /36/

Technical Services is a department in Services providing technical support for customers and Wärtsilä internal stakeholders throughout the lifecycle of products and solutions. Technical Services is also responsible for developing and maintaining technical knowledge and expertise. An additional task for the department is to analyse field experience and enable product improvement based on field feedback. The consolidated guideline as a thesis work is well aligned with the responsibility areas of Technical Services. /25/

1.2 Thesis Limitations

This thesis focuses on the cooling systems of those 4-stroke engines that are currently in production in Wärtsilä and does not deal with upon cooling systems on other engine products. The guideline covers the entire engine cooling system including sub-systems and components both on and off the engine. Additionally, the guideline takes into account the typical marine installations as well as typical power plants installations within Wärtsilä scope of delivery.

2 ENGINE COOLING SYSTEM

In this chapter the purpose, the main functionalities and typical configurations of the cooling system are explained. Furthermore, the impacts of cooling system on engine performance and operations are described.

2.1 Cooling Systems on Wärtsilä 4-Stroke Engines

On Wärtsilä 4-stroke engines the main purpose of the cooling system is to remove the heat from the engine generated in the combustion process. In addition, the cooling system maintains the charge air and lubricating oil temperatures at nominal values. A secondary function for the system is to preheat the engine block during operating breaks. /16/; /22/

Indirect cooling is used on Wärtsilä 4-stroke engines, meaning that the heat is released to a closed coolant circuit instead of releasing the heat directly to cooling air without using a cooling agent /30, p. 309/. In the cooling system the cooling water is circulated through the heat sources of the engine. The heat is conducted to the cooling water and the circulating motion carries the heat away from the heat sources. The cooling system also includes a method to remove the heat load from the operating cycle to the environment. For example radiators, cooling towers, central coolers and box coolers are used for this purpose. /16/; /22/

In most cases the cooling system consists of two separate cycles that are referred to as primary cycle and secondary cycle. The primary cycle is always a closed cycle that circulates the cooling water in the heat sources and is cooled down by a heat exchanger. Treated fresh water is used in all Wärtsilä 4-stroke engines as a cooling agent on primary cycle and glycol is used as an additive to prevent freezing when operating in cold conditions. The heat exchanger in the primary cycle serves as a connection for the heat to transfer to the secondary cycle which then takes care of the heat disposal. There are also applications where the heat exchanger in the primary cycle serves directly as a heat exposal method, e.g. when using radiators. /16/; /22/

In Wärtsilä applications the cooling system configurations used are water/water cooling with a semi-open secondary cycle, water/water cooling with an open secondary cycle or air/water cooling where the secondary cycle is cooled down by air flow. The cooling system with cooling towers is an example of water/water cooling with a semi-open secondary cycle (Figure 1). This configuration is used in power plant applications and the cooling effect is based on evaporation. The cooling system with a central cooler using sea water in the secondary cycle is an example of a water/water cooling with an open secondary cycle (Figure 2). This configuration is the most common cooling system used on marine applications and can be used also in power plants. The cooling system with radiators is an example of air/water cooling (Figure 3). This configuration is the most common configuration in power plant applications. /16/; /22/; /30, pp. 311-312/

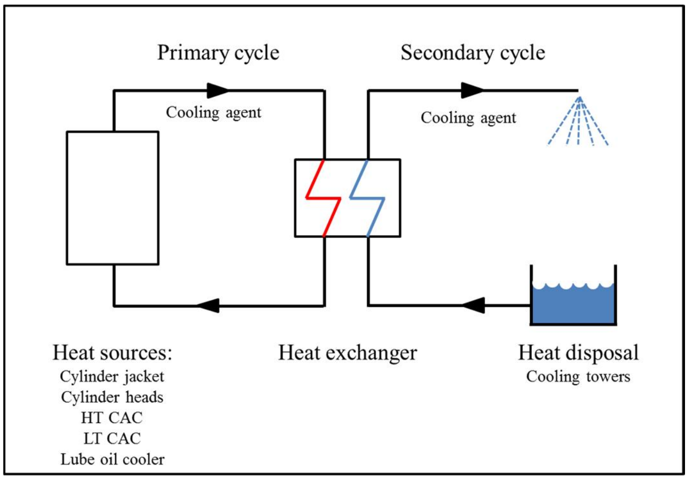


Figure 1. Operating principle of water/water cooling system with semi-open secondary cycle /16/; /22/; /30/

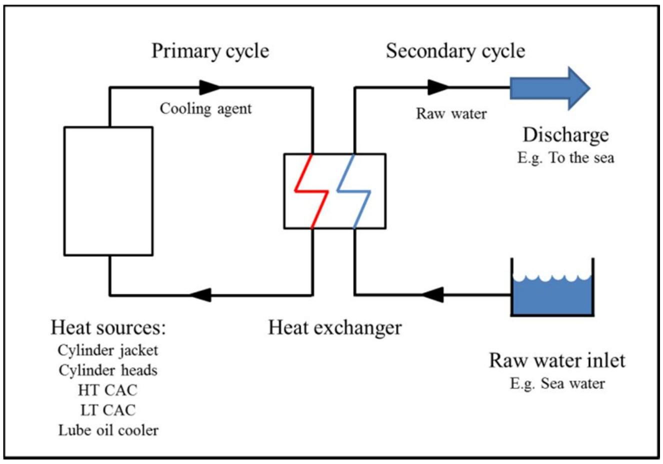


Figure 2. Operating principle of water/water cooling system with open secondary cycle /16/; /22/; /30/

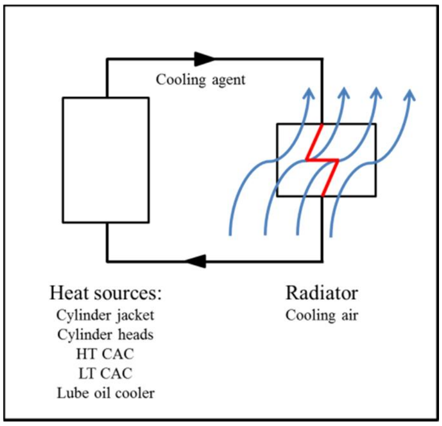


Figure 3. Operating principle of air/water cooling system /16/;/30/

Cooling system removes heat from the following heat sources of the engine:

- Engine jacket i.e. cylinder liners and cylinder heads
- Charge air
- Lubricating (lube) oil. /16/ /22/

A typical cooling system includes the following components and sub-systems:

- Maintenance tank and maintenance pump

- Expansion tank (a.k.a. expansion vessel)
- LT and HT circulation pumps
    - Stand-by pumps required in marine single main engine installations
- Temperature control valves (TCV)
    - LT and HT TCV:s in minimum
    - Heat recovery (HR) TCV added if HR included in the installation
- Charge air cooler (CAC) either in one or two stages
- Lubrication oil cooler (LOC) – considered to be part of lubricating oil system
- Pre-heater system: electrical or steam heater and pump
- Cooling water channels inside the engine jacket
- Heat disposal system:
    - Raw water cooling: central cooler, raw water pump, suction strainer or sea water filtering system, optional TCV
    - Radiators, optional variable frequency drives (FVD)
    - Cooling tower system: central cooler, cooling towers, circulation pump
- Heat recovery system (optional, e.g. evaporator)
- Required piping and pressure/flow regulation components (throttle valves, lenses, orifices)
- Air and dirt separator (optional).

Further details of the function of each component or sub-system are explained in Chapter 3 Cooling system components. /16/; /22/; /14/

The primary cycle of the cooling system can be either a one-circuit / mixed circuit system or split into two separate circuits: high temperature (HT) circuit and low temperature (LT) circuit. Different terminology is used in Ship Power compared to Power Plants when it comes to different variations of the primary cycle:

1-circuit mixed cooling system (PP)

A typical Power Plants cooling system has a 1-circuit mixed cooling in the primary cycle: cooling water flows through the LT charge air cooler, lube oil cooler and

HT charge air cooler. After that a required amount of LT cooling water mixes with HT cooling water that circulates through the engine jacket i.e. only the jacket cooling is included in the HT circuit. The HT outlet temperature controls the mixing ratio. The rest of the LT cooling water is mixed with HT outlet water prior to continuing to the radiators. /16/; /24/

2-circuit system (PP)

Power Plants uses the term 2-circuit system when referring to a primary cycle where the LT circuit includes LT CAC and LO cooler and HT circuit includes HT CAC and engine jacket. 2-circuit systems sometimes have fully separate LT and HT circuits all the way to the heat disposal method (radiators) meaning that LT and HT circuits do not mix at all. /16/; /24/

1-circuit system (SP)

According to Ship Power terminology a 1-circuit system is a system where LT and HT cooling waters are mixed on the engine. This version is used e.g. on Auxpac-engines and also called combined LT/HT circuit. /22/; /25/

2-circuit system (SP)

Ship Power defines that a cooling system is divided into two separate circuits when referring to a system where LT and HT cooling waters mix off the engine. In these Ship Power systems the flow of the cooling water is similar to Power Plants 2-circuit systems, i.e. the LT circuit includes LT CAC and LO cooler and the HT circuit includes the engine jacket and HT CAC. In Ship Power a 2-circuit system with fully separate LT and HT circuits all the way to the central cooler is called the split LT / HT system. /22/; /25/

The cooling system set-ups also differ when it comes to the location of certain components. For example, the lube oil cooler can be located either on or off the engine and the locations of the thermostatic valves depend on the fuel used on the installation. Further details of the cooling system set-ups are defined in Chapters 2.3 and 2.4. /22/; /25/

2.2 Impacts of Cooling System on Engine Operations

The heat balance of a diesel engine is shown in Figure 4. Approximately 46 % of the energy included in the fuel is transformed to work as shaft output and represents the engine efficiency. The remaining 54 % is heat lost to exhaust gas, cooling and radiation. Even though cooling can be seen as a parasitic loss on the engine, the cooling system serves many purposes both related to protecting the engine and affecting the performance of the engine. /25/

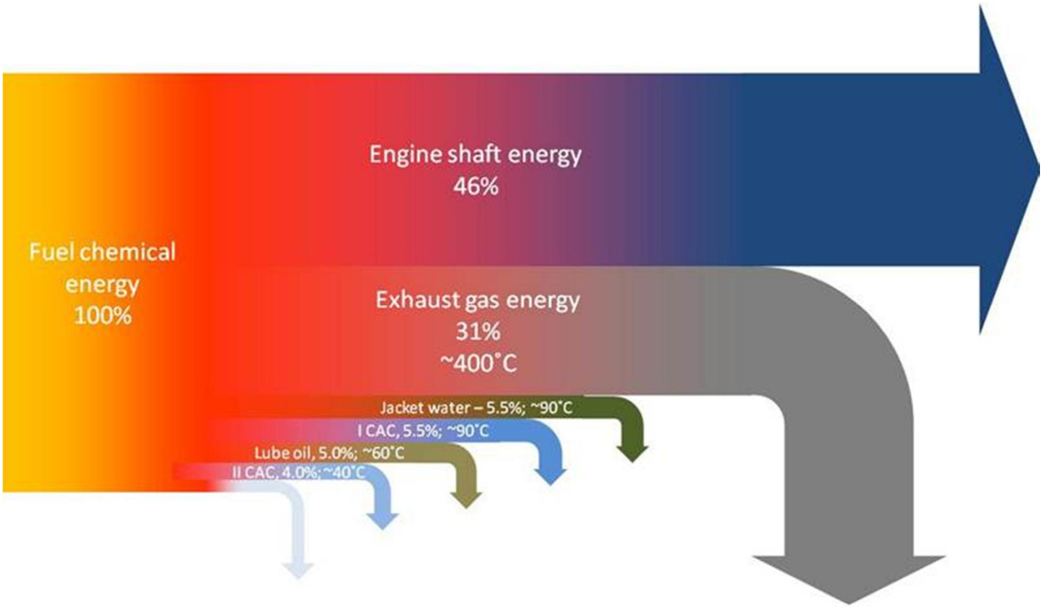


Figure 4. Heat balance of a diesel engine as a Sankey diagram /25/

The heat reduction provided by the cooling system is needed to protect the engine components from thermal overload and breakdown. During combustion the peak temperatures of the combustion gas in the combustion chamber can reach over 2000 ºC whereas the limits for materials used for the cylinder head, valves, pistons and other components in the engine are at significantly lower values. Allowing the temperature to rise in continuous operations would naturally result in a breakdown. /29, p. 15/; /10, p. 211/

The cooling system maintains the temperature of the charge air at a desired level. Charge air temperature has impact on the combustion process. Turbocharging increases the pressure of the charge air. According to the equations of state and ideal gas equation the pressure increase also increases the temperature of the charge air, thus reducing the air density. When the charge air is cooled down the density is increased and the same volumetric amount of air includes more oxygen. A higher amount of oxygen in the combustion process enables to mix more fuel to the same volumetric amount of air resulting in higher power and allows also the tuning of the emission levels. /53, pp. 499-501/; /28/

The cooling system maintains also lube oil temperature at nominal level. In addition to the main task of lubricating the engine the lube oil system also protects the engine parts from corrosion and removes heat from the engine. The temperature of the lube oil is affecting the viscosity of the oil: too big of a temperature increase would eventually have impact on the lubricating capability of the oil. E.g. higher temperature leads to oil film becoming too thin in the bearing leading to overheating and possible damage. Maintaining the temperature of the lube oil at the correct level ensures the right level of heat transfer away from the engine through the lube oil system. So while the lube oil system participates in the cooling of the engine and that way carries partly the same task as cooling system, the lube oil is also cooled down through the cooling system. /16/; /22/; /33, p. 370/

Pre-heating functionality in the cooling system is used to warm up the engine prior to the start and to maintain the engine temperature during operating breaks enabling a faster loading of the engine. Without pre-heating the temperature differences in the engine during the start-up would require the engine loading to be done slowly and more carefully. HT pre-heating is used in most applications but in cold ambient conditions LT pre-heating is needed as well to ensure the minimum intake air temperature. Pre-heating also prevents certain fuels from solidifying in the engine (e.g. HFO/LBF) and ensures that the conditions in the cooling system stay unfavorable to cold corrosion. Cold corrosion is defined in further detail in Chapter 3.2.2. /16/; /22/; /25/

2.3 Typical Power Plant Cooling System Description

Power plants are built in various ambient conditions, thus Wärtsilä is offering multiple options for the cooling system configuration. The maximum and minimum ambient temperatures, ambient humidity and availability of cooling water affect the selection of the cooling system. Radiators are the most common method in power plants to remove heat from the cooling system to the environment. Additional methods used are cooling towers and raw water cooling. Power plant cooling systems are engine specific: each engine has an individual system that is not connected to the cooling systems of the other engines on the same plant. /16/; /25/

The cooling systems in power plant applications can be either one-circuit or two-circuit systems. In one-circuit systems LT CAC, LO cooler and HT CAC are connected to the LT circuit and only the engine jacket is connected to the HT circuit. In two-circuit cooling systems the LT circuit includes LT CAC and LOC and the HT circuit has both the engine jacket and HT CAC connected to it. Two-circuit systems can have fully separate piping for the LT and HT circuits all the way to the heat disposal method, i.e. radiators. In one-circuit mixed cooling systems the LT and HT circuits connect prior to the radiators. A typical 1-circuit mixed cooling system for the power plant is shown in Figure 5. The cooling system configuration is selected according to the ambient conditions and the power plant type: the 1-circuit system gives usually a better engine performance and is used in electricity generation whereas the 2-circuit system is used in combined heat and power applications with cooling system heat recovery. The 2-stage CAC is used basically in all power plants applications. /16/; /19/;/25/

In a typical power plant 1-circuit mixed cooling system the cooling water flows first through the LT charge air cooler (LT CAC) and continues then through the lube oil (LO) cooler and high temperature charge air cooler (HT CAC). After the HT CAC the cooling water mixes with HT-circuit cooling water: part of the water flows through the engine jacket and part of the water continues directly to the radiators after being mixed with HT outlet water. The temperature valves maintain the cooling water temperature at the LT CAC inlet and at the HT cooling water outlet after the engine jacket. /16/;/25/

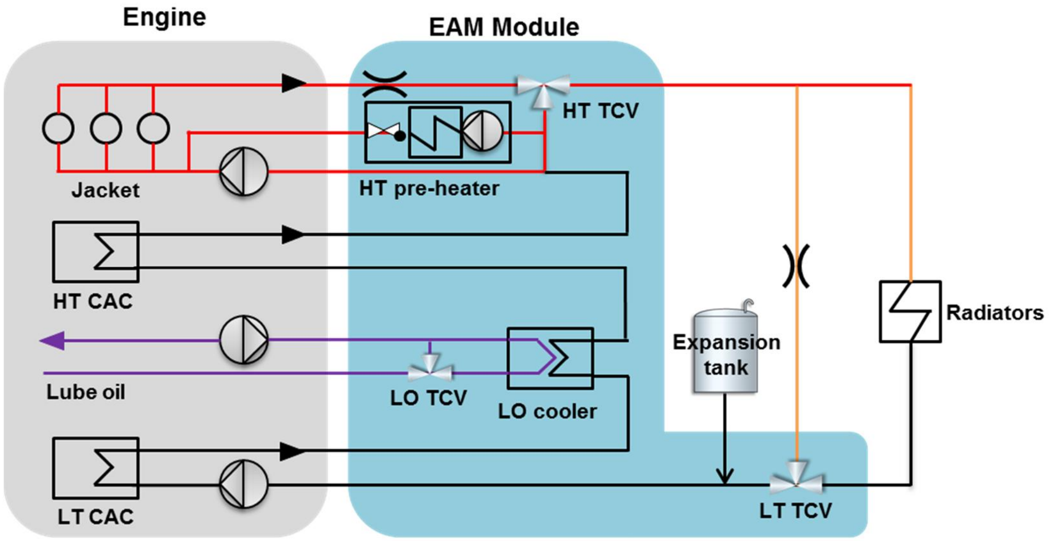


Figure 5. Typical power plants cooling system (1-circuit mixed cooling with radiators, W50) /16/

Commonly used variations of power plants cooling systems are listed below:

- 1-circuit or 2-circuit cooling system (Figure 6.)
- Heat disposal method: radiator, cooling tower, raw water cooling (see Chapter 4.3. Heat disposal systems)
- When operating in cold conditions 1-circuit cooling systems can be equipped with a jacket cooler (Figure 7) and 2-circuit systems with a dump cooler. These variations enable running without glycol in the HT circuit thus reducing the need for derating since glycol has inferior heat transfer capabilities compared to water.
- LT pre-heater as an option in addition to the HT pre-heater: required for 1-circuit SG and DF engine cooling systems where both charge air coolers are connected to the LT circuit and when intake air temperature is below 5 °C (arctic set-up to ensure high enough charge air temperature).

- Heat recovery system as an option, used in combined heat and power installations
- Charge air dew point control as an option: required for tropical conditions and other ambient conditions with high relative humidity and diurnal temperature changes. A control system functionality that adjusts the charge air temperature in real time in order to stay above the dew point and to prevent the humidity in the charge air from condensing to water. Dew point control is explained in Chapter 3.1.3.
- The components of the cooling system that are not installed on the engine can be installed either in the engine auxiliary module (EAM module, Figure 8) or separately on the site but the EAM module is used in most of the installations. /14/; /16; /19/; /24/; /25/

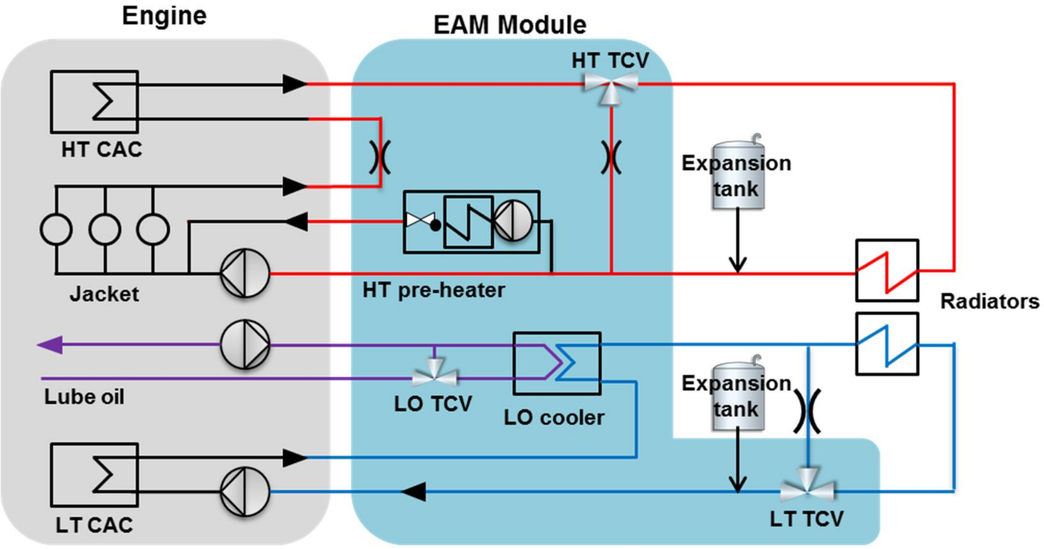


Figure 6. 2-circuit cooling system with engine jacket and HT CAC in the HT circuit /27/

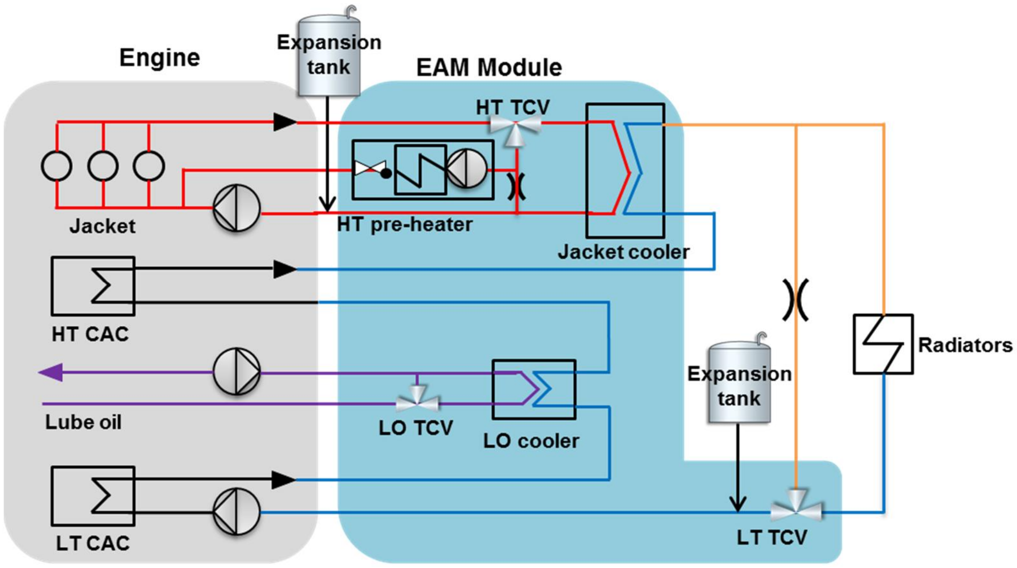


Figure 7. 1-circuit mixed cooling system with jacket cooler /16/

On typical power plant installations the LT and HT pumps and charge air coolers are installed on the engine. The lube oil cooler is installed on the engine on the smaller end of the product portfolio (W20, W32 and W34) and off the engine on the larger engines (W46, W50). If the LO cooler is not on the engine, it is located on the EAM module. The temperature control valves and the pre-heating unit are usually located on the engine auxiliary module i.e. off the engine. /14/;/16/; /25/ /

Figure 8. Engine auxiliary module for W32-engine /40/

The temperature control valves (TCV) in power plant installations can be installed either on the engine inlet (mixing mode) or outlet (diverting mode). If the engine is equipped with the EAM module, the thermostatic valves are externally actuated globe type valves included in the EAM. Also self-actuated wax element thermostatic valves (installed on engine, typically used in diesel fuel applications) and externally actuated rotary plug valves are used as TCV:s in power plant installations. Externally actuated valves have to be selected when more detailed temperature control is needed, meaning on SG and DF engines and / or when the heat recovery process is used but in practice externally actuated TCV:s are installed in all power plant installations. Further details of the temperature control valves are explained in Chapter 4.4.1. /14/

2.4 Typical Marine Cooling System Description

The cooling systems in marine applications are usually systems with a central cooler and raw water cooling. There is plenty of cooling water available in the sea, thus the secondary cycle typically uses sea water as a coolant and the excess heat from the cooling system is released to the sea. The secondary cycle is an open cycle. Box coolers and keel coolers are alternative heat release methods used in marine applications. Cooling systems on ships are often combined for multiple engines on the ship: engines located in the same engine room are connected to the same central cooler. Due to classification society requirements the redundancy of all systems on board needs to be ensured, thus there are duplicates or back-up pieces available for many of the components of the cooling system on ships. /22/; /25/; /27/

The on-engine cooling system is usually split into two circuits: the LT charge air cooler and lube oil cooler connected to the LT circle and the HT charge air cooler and engine jacket cooling connected to the HT circle. There are temperature control valves located on the engine in both the LT output and HT output pipes controlling whether the cooling water flows back to the respective cooling circle or whether it continues towards the central cooler. Additionally, there is a heat recovery temperature control valve that controls whether HT water flows back to the HT cooling circle after the evaporator or continues via the LT piping to the central cooler. A typical cooling system for marine application is presented in Figure 9. /22/; /25/

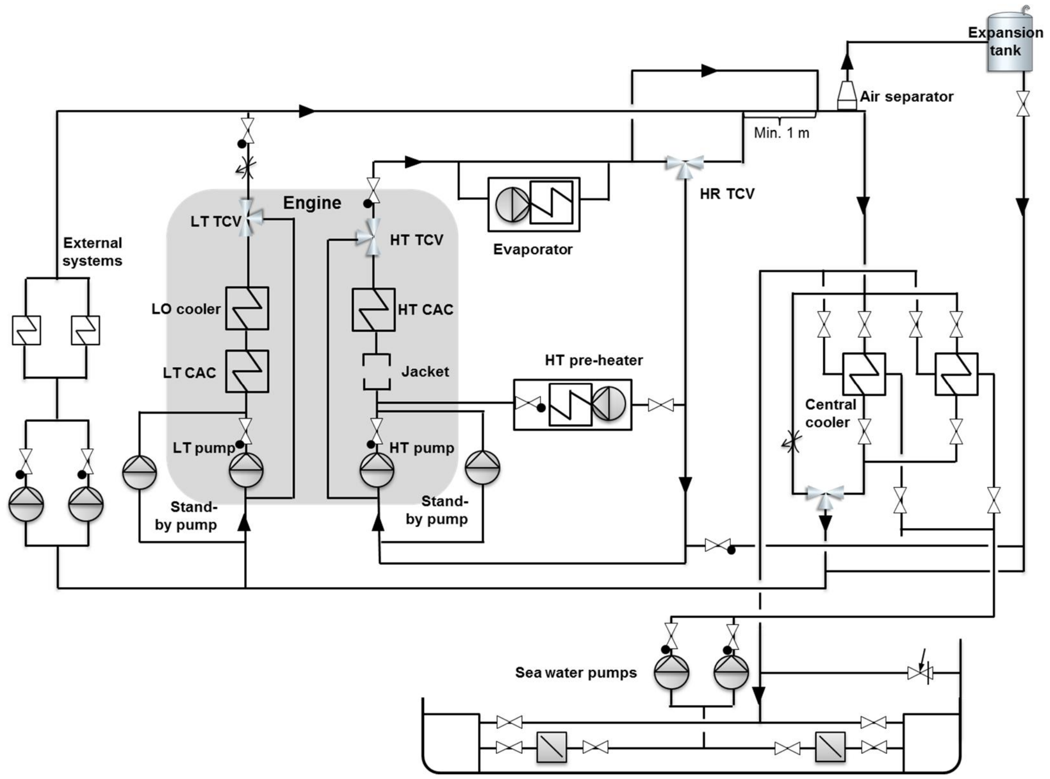


Figure 9. Typical marine cooling system configuration: Single W32 engine with heat recovery /8/

Common variations available of the cooling system for marine applications are:

- Circuits: LT and HT circuits are typically separate on the engine but combined in the external system. A variation of “pure 2-circuit system” with fully separated LT and HT circuits all the way to the central cooler exist.
- Heat disposal method: sea water cooling with the central cooler (see further details in Chapter 4.3.3 Raw water cooling), box cooler or keel cooler
- Charge air cooler installed either as one stage or two-stage.
- Temperature control valves can be located either on the engine or off the

engine depending on the engine type and control needs. The DF-engines require a more careful temperature control than diesel engines. Therefore, externally actuated TCV:s are used on DF operated engines. Externally actuated TCV:s are typically installed off the engine. Wax element thermostatic valves are used on HFO engines and usually installed on the engine.

- LT and HT circulating pumps can be installed either on the engine or off the engine. If installed on the engine, the pumps are engine driven centrifugal pumps. If installed off the engine, the pumps are driven by electrical motors. Engine driven pumps are used in the majority of installations.
- Cooling system can have an evaporator for generating fresh water or heat exchanger for pre-heating water prior to the boiler as heat recovery systems.
- Cooling of external systems: cooling system can cool generator, gearbox, propeller and fuel with LT water. /22/; /25/; /27/

In marine applications the classification societies refer to arctic, normal or tropical ambient conditions. Arctic conditions require special arrangements from the configuration of the cooling system for two charge air temperature related reasons:

- Cold intake air has a higher density compared to warm air. At high engine loads the turbocharger is able to increase the flow of air to the engine in such amounts that there is a risk of increased firing pressure peaks in the cylinder as well as a risk of turbocharger surging. The surging of the turbocharger means an unstable operation with temporary interruptions in the air flow and it typically occurs when there is a high pressure compared to the flow.
- During starting and at low engine loads the cold intake air does not warm up sufficiently in the turbocharging and instead of giving out heat in the charge air cooler the air is taking heat from the LT circuit and causing a theoretical risk of freezing. /22/; /27/

To avoid the risk of turbocharger surging the turbocharger mapping is paid attention to: higher margins are used in relation to the surge line. To limit the peak firing pressure in the cylinders air waste gates are used to bleed off air from the charge air system and thus to reduce the pressure when needed. To ensure that the charge air is warm enough when fed to the engine the LT system is equipped with an additional LT water heater and LT charge air cooler is used also to heat the combustion air. Warm LT water is also circulated when the engine is stopped to ensure there is heat available for starting the engine. Furthermore, the engine room is built in such a way that it is possible to take the combustion air from the engine room during the start-up or that there are electric heaters installed to warm up the intake air. The temperature of the HT cooling water system is ensured by removing the HT CAC and using the 1-stage CAC instead. /22/

If a vessel is used in tropical conditions the central cooler has to be dimensioned for small temperature approach. Additionally, the charge air cooling has to be done in two stages to provide sufficient cooling capacity. LT TCV set point in tropical conditions is dropped from the usual 38 ºC to 35 ºC to ensure there is some margin available and the central cooler is dimensioned for 32 °C. /22/; /25/; /27/

Heat disposal methods in marine installations use the naturally available cold mass for cooling: sea water. Sea water cooling with a central cooler is the most common heat disposal method in marine applications (see Chapters 4.2.1 and 4.3.3). The box cooler and keel cooler are optional heat disposal methods. They are heat exchangers installed on the ship’s hull under the waterline. The keel cooler is a structure built on the surface of the hull whereas the box cooler is integrated in the hull (Figure 10). Out of these two options the box cooler (Figure 11) is used more often than the keel cooler and has become increasingly common in the recent times e.g. in offshore vessels. Both heat disposal methods are connected to the cooling water circuit of the engine. The coolant circulates through the cooler, a tubed construction providing required surface area for warm pipe connection with colder sea water. During the flow the heat is transferred from the coolant to the sea water and the cooled down fluid continues circulation back to the heat sources. /22/; /25/; /27/

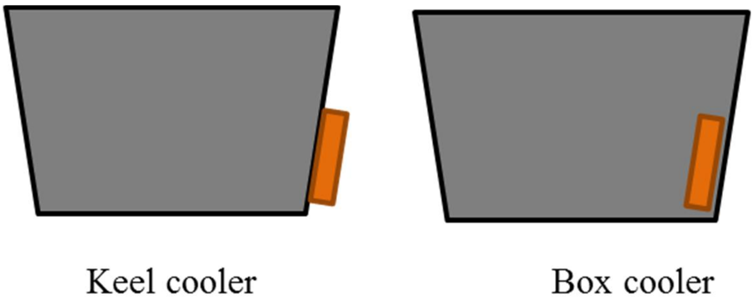


Figure 10. Keel cooler and box cooler mounting on the ship's hull /22/

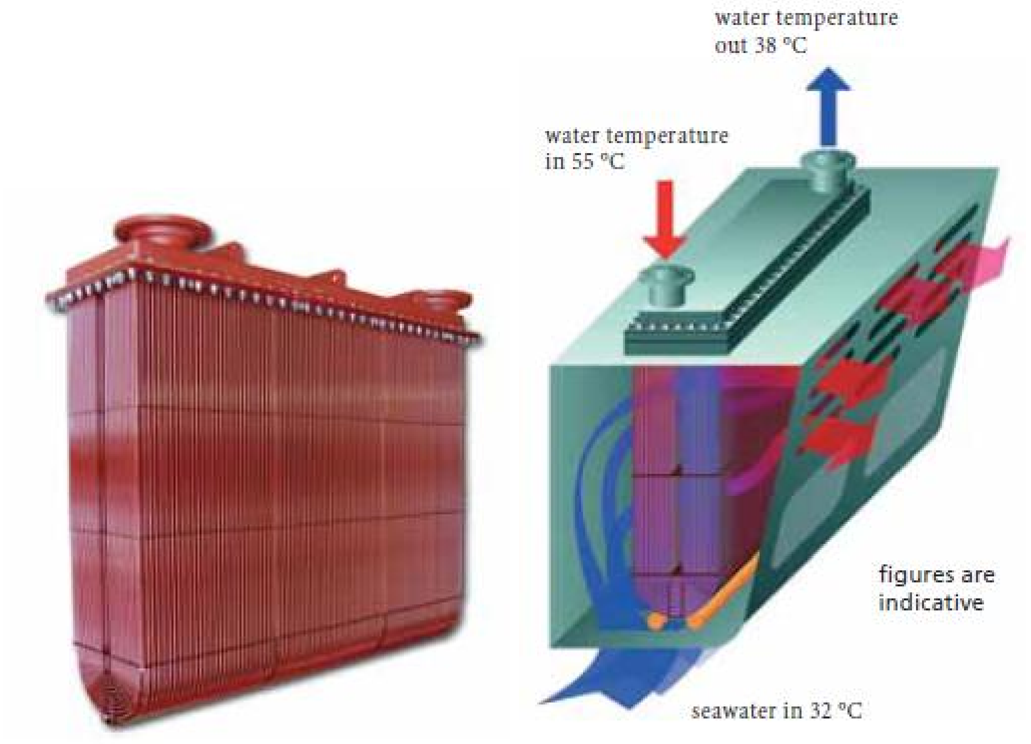


Figure 11. Box cooleer tubed structure and installation on the ship's hull /5, 3/

With a keel cooler or box cooler there is no need to set up the sea water system inside the ship's hull, which increases the reliability of the vessel. Sea water has a corrosive effect and sea water piping and components are therefore exposed to the high risk of corrosion related issues. The cooling efficiency of both keel coolers and box coolers is sensitive to the movements of the ship. If the ship is staying still, the cooling impact can get very low as the sea water is not moving around the tube structure. /23/; /25/; /27/

As the box coolers are located in sea water and provide a warm environment they can easily attract marine fouling. Therefore, ICAF (impressed current anti-fouling) system is recommended to be used. In this system anodes of copper are installed under the box cooler and constant current is led to the anodes to dissolve copper to the sea water. Copper creates a toxic environment for marine growth and thus prevents fouling. /22/; /27/

3 ESSENTIAL PARAMETERS

Temperatures and cooling system temperature control functions, pressure, flow and parameters related to cooling water quality are presented in this chapter. Cooling system controls the charge air temperature, provides the cooling energy for the lube oil cooler and has an impact on the heat balance of the engine via cooling the engine jacket. As the cooling system is a heat exchange system running in a closed circuit and operating on fluid, the cooling water temperature and temperature changes, the flow of the coolant and pressure of the coolant indicate how well the process works. The cooling water quality is affecting the system in the long run via slower processes, such as corrosion, fouling and deposit formation. /9/; /25/

3.1 Temperature and Temperature Control

The Celsius temperature scale is used in Wärtsilä to measure temperatures. In cooling systems there are three main temperature measurement points:

1. Charge air temperature to the cylinders (LT circuit)
2. Jacket cooling water outlet temperature and temperature change over the engine (HT circuit)
3. Temperature at the engine inlet for lube oil (part of the lube oil system).

If there is a heat recovery (HR) system on the HT-circuit of the engine, there is a separate temperature control and an additional TCV linked to HR. The temperatures presented in engine technical data are shown in Table 1 by using two engines as examples. /19/

Table 1. Technical data related to temperatures on W20 and W50DF engines /44, 25/ /41, 11/

	W20	**W50DF**	**W50DF**
		Gas mode	**Diesel mode**
Combustion air system	°C		
Temperature after air cooler	Covered		
HT Cooling water system			
Temperature before cylinder, approx.			
Temperature after charge air cooler, nom.			
LT Cooling water system			
Temperature before engine, max.			
Temperature before engine, min.			
Lubricating oil system			
Temperature before bearings, nom.			

3.1.1 LT Water Temperature Control

The LT cooling water circuit controls the charge air temperature to the cylinders. The lower the charge air temperature the more air it is possible to include to the burning process leading to improved combustion and efficiency and lower emission levels. However, too low of a temperature combined to the high pressure of the charge air and possibly high ambient humidity may cause the charge air temperature to drop below the dew point and lead to condensation. The impact of pressure and ambient humidity on the dew point is shown in Figure 12. The increased pressure caused by turbocharging increases the dew point. Water droplets in the combustion air have negative effects on the combustion process and condensed water also increases the risk of water stroke. /19/

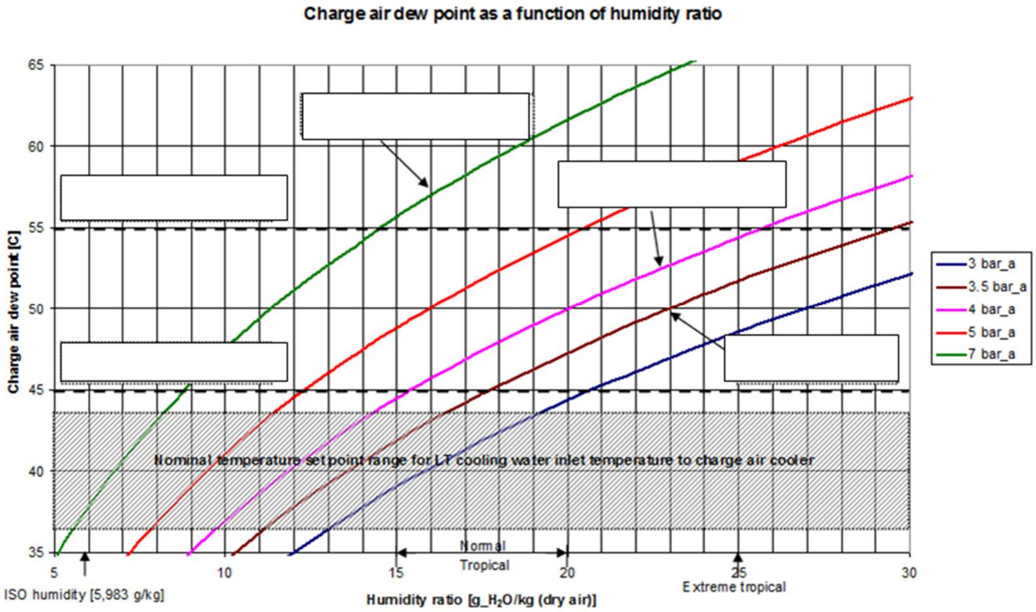


Figure 12. Charge air dew point temperatures as a function of ambient humidity ratio and charge air pressure /19/

The charge air temperature is measured at air receiver and adjusted by changing the temperature of the LT water. The temperature control valve is usually installed at the LT circuit engine inlet in power plant applications (Figure 13). In marine applications the temperature control valve is often located on the engine after the LT CAC and LOC as presented in Figure 9. Configurations with the LT TCV located at the engine inlet after the central cooler or at the engine outlet off the engine, between the LT CAC and LOC (in set-ups where LOC is off the engine) are also available. The set point for LT water temperature that is used to control the LT TCV varies respectively depending on the location of TCV. The set point is the lowest when the TCV is at the engine inlet and highest when it is after all cooling equipment. The LT circuit temperature control range depends on the capacity of the primary cooling equipment (e.g. radiators or central cooler) and the capacity of the lube oil cooler. The capacity of the heat disposal equipment i.e. upstream side dictates how low temperatures can be reached in the LT circuit in the first place. The capacity of the lube oil cooler which is usually included in the same circuit with the LT CAC on the downstream side defines how high temperatures can be used while still staying below the LO engine inlet temp limits. /19/

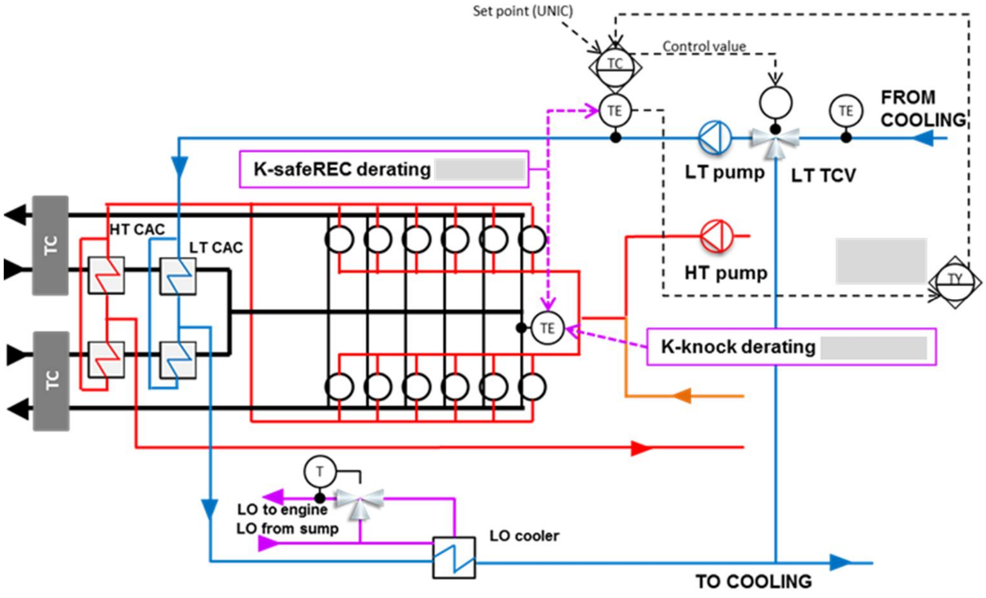


Figure 13. Gas and DF engine LT-circuit temperature control and measurement points and derating rules for power plant installations /19/

In diesel engines the control target is to keep the charge air temperature at nominal (or desired) level and thus the aim is also to keep the LT water inlet temperature on constant level. In gas engines and DF engines running in gas mode the LT inlet water temperature is changing according to the load: the lower the load the higher the LT inlet temperature is set as a target value. Gas engine ignition is more sensitive to the temperatures and heat balance of the engine: on low loads a higher CA temperature helps to ensure the ignition and on high loads the lower CA temperature helps to prevent knocking. The difference in control logic is shown in Figure 14. /19/; /28/

Covered

Covered

Figure 14. The difference in control logic between gas engines and diesel engines on power plant installations /19/; /24/

Gas and diesel engines differ in temperature control when it comes to load reduction or derating rules. In power plant engines the following rules apply. As gas engines are more prone to knock and more sensitive to temperature changes in combustion process they are derated according to the charge air inlet temperature to cylinders (K_{knock}). The derating level is installation specific and depends on multiple factors, such as methane number of the gas fuel, ambient conditions and emission/performance tuning. Diesel engines are derated according to high LT water inlet temperature (K_2 derating). In addition, the control system follows the ΔT between LT water inlet temp and CA temp for both gas engines and diesel engines($K_{safeREC}$ derating). Diesel engine derating rules are shown in Figure 15. /19/

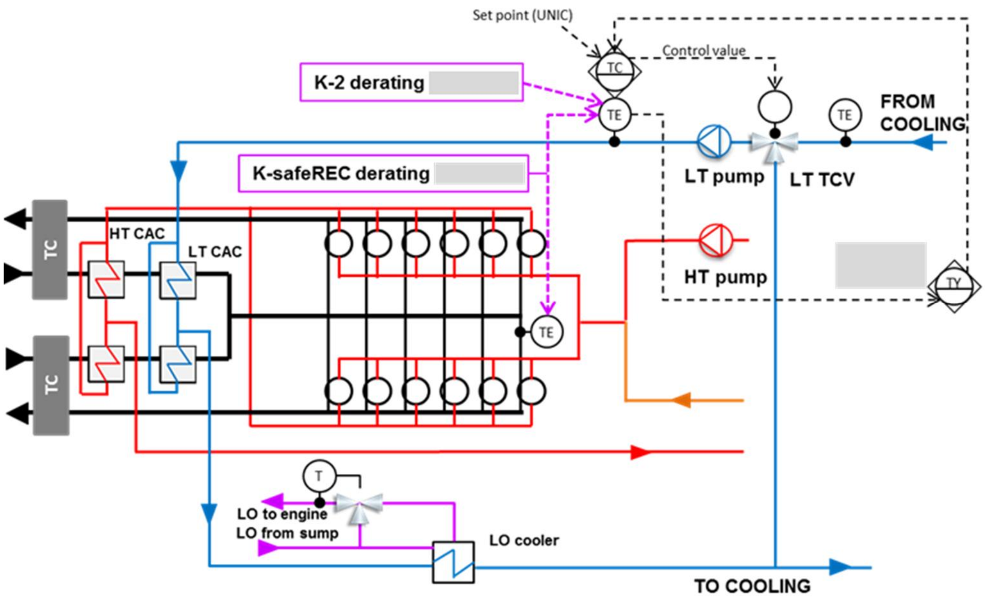


Figure 15. Diesel engine LT-circuit LT-circuit temperature control and measurement points and derating rules /19/

The diesel engine load reduction in marine installations follows different rules compared to power plants. LT water temperatures are not used for triggering load reductions in marine installations directly. Increased LT temperature does generate an alarm in the control system but does not lead to load reduction. Increased CA temperature and LO temperature at the engine inlet on the other hand reflect the performance of the LT circuit and lead to load reduction on both marine and power plant installations. High CA temperature will also trigger a shut down. For example, the CA temperature load reduction limit for marine main engines is already the shut-down limit for power plant engines. /20, 9, 15-16, 22/

Marine DF-installations use CA temperature at the engine inlet as a trigger for load reductions if the temperature is increased enough. The difference compared to power plant installations is that marine DF engines first trip to diesel fuel and continue running with the diesel process on higher CA temperatures before taking load reduction to use. /39, 40/

Note: The CA temperature on marine W34DF engines is load dependent as shown in Figure 16. On low loads the heat energy in the combustion is lower and higher CA temperature can be utilized to ensure good combustion and on time ignition. On high loads low CA temperature is required for preventing knock. /8/; /28/

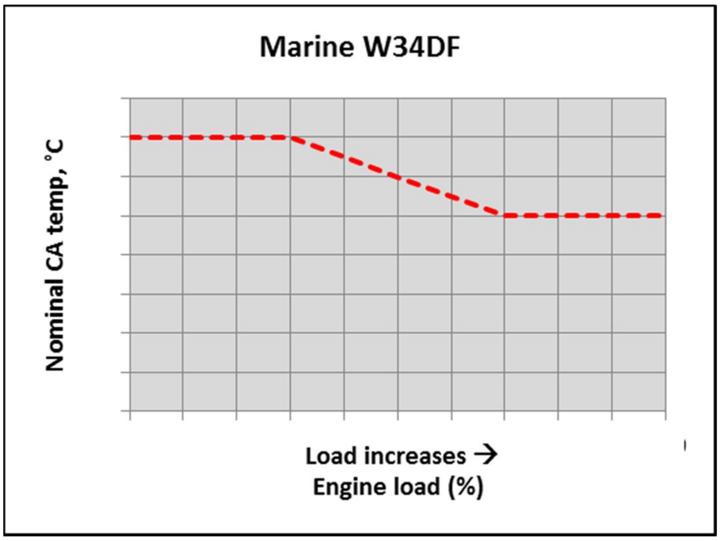


Figure 16. Nominal CA temperature on different engine loads for W34DF marine installations /8/

3.1.2 HT Cooling Water Temperature Control

Jacket cooling water outlet temperature is followed up to ensure that the heat load for the hot engine components does not exceed the safety values on both marine and power plant installations. /19/; /20/, /39/

In marine and power plant installations diesel, DF and SG engines have a similar control approach with each other but there are differences in the temperature measurement points depending on whether the HT circuit has both the engine jacket and HT CAC connected to it (i.e. 2-circuit system in PP terminology, Figure 17.) or only the engine jacket connected to it (i.e. 1-circuit system in PP terminology, Figure 18). If the HT circuit includes both the engine jacket and HT

CAC, the set point is higher than if the HT circuit includes only the engine jacket. /19/

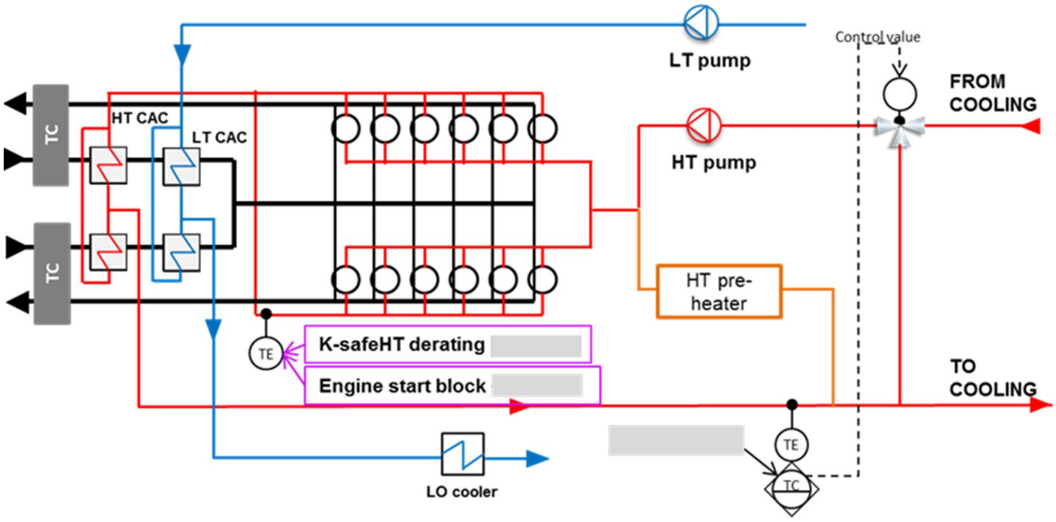


Figure 17. HT-circuit temperature control, measurement points and derating rules in 2-circuit cooling systems, power plants installation /19/

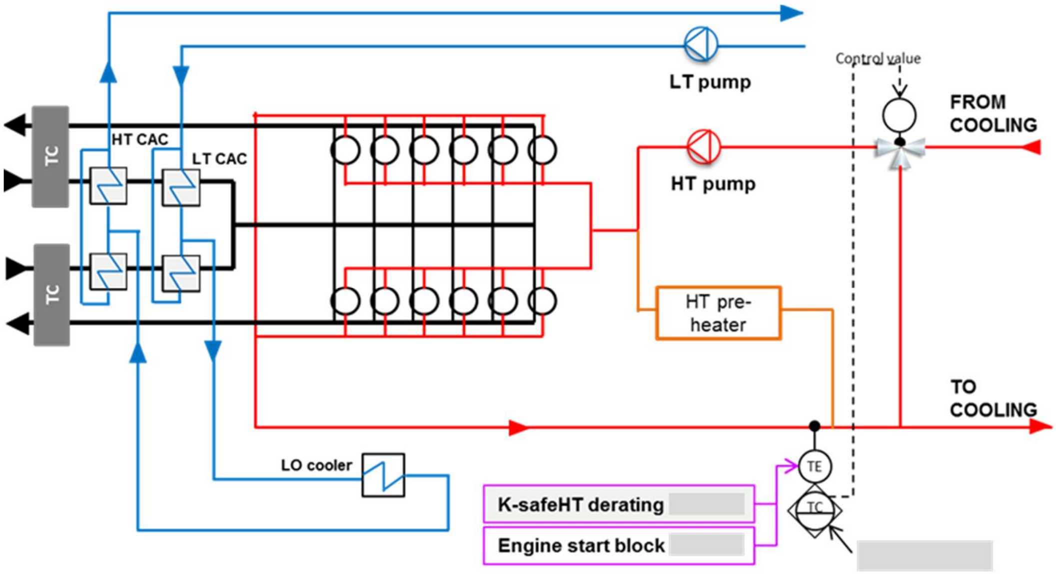


Figure 18. HT-circuit temperature control, measurement points and derating rules in 1-circuit cooling system, power plants installation /19/

HT cooling water temperature has alarm limit, load reduction limit and shut down limit defined to prevent the overheating of the engine. The nominal pre-heating temperature for the HT circuit is defined. The engine does not start if the HT cooling water temperature is below a specific value (lower than the nominal pre-heating temp). If HT temperatue is between these values, the engine is not allowed to run on full load (K_{safeHT} derating). /19/

If there is a heat recovery (HR) system included in the HT circuit, an additional TCV is typically used after the heat recovery equipment to ensure maximum efficiency for HR. In power plant applications both temperature control valves are controlled with the same temperature controller using a so called split-range arrangement (Figure 19). The temperature range allowed by the temperature controller is split into areas that enable the following variations considering the TCV positions:

- 1st TCV directs the full flow back to engine (HT circuit too cold for heat recovery or other cooling)
- 1st TCV allows partial or full flow to HR system but 2nd TCV directs the flow back to the engine (HR system cools the HT coolant sufficiently, HR system maximum heat recovery capacity not in use)
- 1st TCV directs full flow through HR and 2nd TCV directs part or full flow to primary cooling equipment (HR system maximum capacity in use and additional cooling needed). /8/; /19/

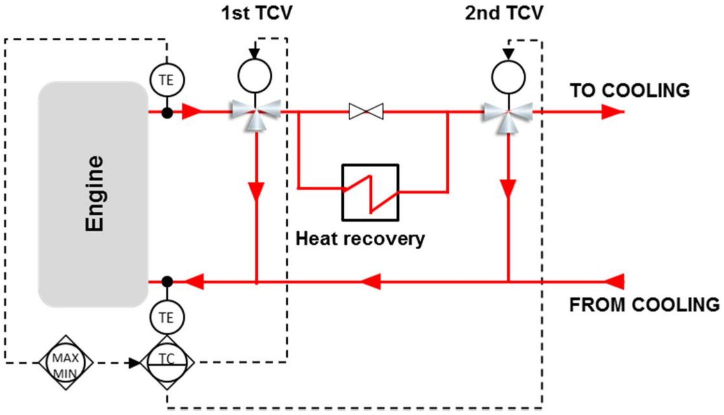


Figure 19. Heat recovery, additional TCV and related temperature measurement points in a 2-circuit cooling system, power plant installation /19/

To make the control of HT circuit with HR more stable and faster the temperature is measured in two locations: engine inlet and engine outlet. In power plant installations the control system utilizes the engine inlet temperature and the temperature change over the engine to prevent fluctuations and overshooting in controlling. /19/

3.1.3 Dew Point Control

As described in Chapter 3.1.1 the ambient (relative) humidity and the high pressure of the charge air increase the dew point of water vapor in the charge air. Since the temperature and thus the relative humidity in engine operating site may have significant diurnal or annual variations, control functionality is available to take the ambient humidity into account and to adjust the charge air temperature and LT water inlet temperature set points accordingly. /19, 12-13/

When the humidity of the air condenses to water, energy is released. The energy released in condensing is higher than the energy released when humid air is cooling down. Thus the temperature change in the LT water cooling the charge air with condensation happening means that LT water is heating up significantly but the charge air temperature is not dropping in the same proportion. On the other hand, the presence of **water vapor** in gaseous form in the charge air has positive impacts on the combustion process: suitable level of humidity in charge air helps to maintain the NO_x emissions and exhaust gas temperatures under control and ensures high enough combustion air mass flow. These are an additional reason to apply dew point control and ensure the cooling process on the engine remains efficient. /19, 13/

The dew point control functionality combines ambient humidity measurement from the site done with one common sensor to the engine specific charge air pressure measurement and calculates the dew point. The LT water inlet temperature is set slightly below the dew point to make sure that dew point is not reached. The control is run on real time and thus the set point is adjusted within allowable levels whenever the ambient relative humidity changes. /19/

3.1.4 Temperature Approach and Pinch

Temperature approach and pinch are synonyms used with heat exchangers referring to the cooling capacity of the heat exchangers: the smaller the temperature difference in primary and secondary circuits is (or circuit to be cooled and circuit taking care of the cooling) the higher the cooling capacity in the heat exchangers. The temperature approach is calculated with the following formula:

$$\text{Temperature approach} = \Delta T = T_{\text{he pri out}} - T_{\text{he sec in}} \tag{1}$$

Where $T_{\text{he pri out}}$ = Temperature of the primary circuit fluid after it leaves the heat exchanger and $T_{\text{he sec in}}$ = Temperature of the secondary circuit fluid when it enters the heat exchanger. The calculation principle for temperature approach is illustrated in Figure 20. /17, 3/

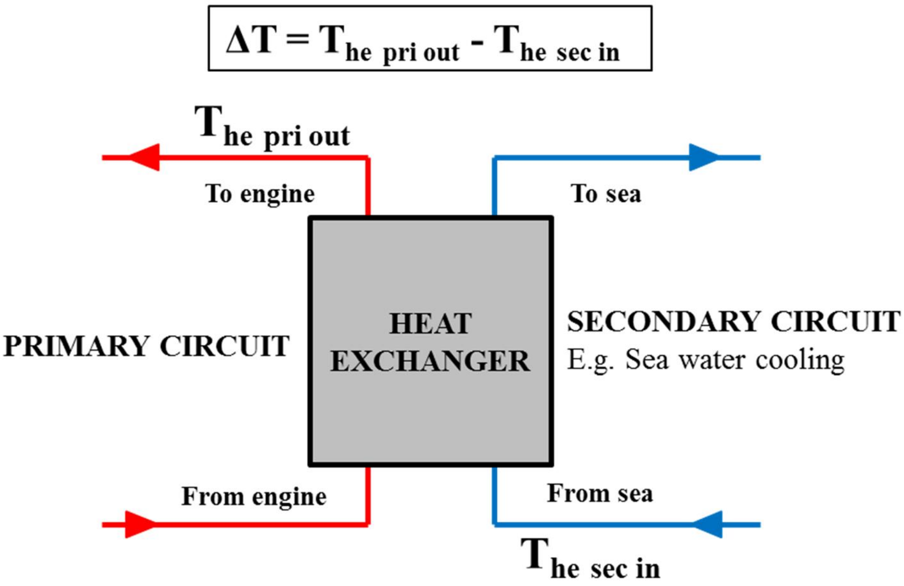


Figure 20. Temperature approach /13, 5/

For radiators the temperature approach is the ΔT between the coolant outlet temperature when it leaves the radiators and the ambient air temperature as ambient air is used to absorb the heat from the coolant. In central coolers the temperature approach is the temperature difference between the primary circuit coolant outlet temperature from the central cooler and the secondary circuit inlet temperature to the central cooler. In cooling towers the temperature approach is the temperature difference between the cooling tower water outlet temperature and wet bulb temperature of the ambient air. (Note: in cooling tower systems the temperature control comes into play in two locations: first on the cooling tower itself and secondly at the central cooler that connects the heat flow from the engine to the central coolers.) Further details of the temperature approach or pinch for each heat disposal method are defined in Chapter 4.3. /13, 5/; /15, 5/; /17, 3/

In all cooling systems the temperature approach or pinch is usually higher for diesel engines than for gas and DF engines (gas mode). Engines operating in the gas mode require a lower charge air temperature since they are more prone to knocking than diesel engines. In gas engines the fuel is pre-mixed to the intake air and inserted to cylinders though inlet valves whereas in diesel process the fuel is sprayed through the injection nozzle at the desired time. Knocking means that the burning process starts at a random air / fuel pocket inside the cylinder in addition to starting at the desired, optimal location. During knocking there is more than one combustion front inside the cylinder which leads to significantly higher cylinder pressure compared to normal combustion and can cause severe damage. The probability of knocking is increased if there is higher pressure, higher temperature or longer time for the air / fuel mixture to be affected to: conditions that apply more easily with pre-mixed fuels inserted through inlet valves than diesel fuel injected through the injection nozzle. /28/

The higher temperature approach with diesel engines compared to SG and DF engines means that the heat disposal method used can be off lower capacity. E.g. if using radiators, less radiators or smaller radiators can be selected for a diesel engine compared to a gas engine. /25/

3.2 Flow

In cooling systems the flow is a parameter linked to the pump performance. Volume flow defines the volume of cooling water pumped during a given period of time. The unit used in Wärtsilä for the volume flow is m^3/h. The circulation of the cooling water – namely the flow – carries the heat away from the heat sources and ensures sufficient de-aerating of the cooling water. Too low a flow leads to too low heat transfer but also to reduced de-aerating. The impacts of excess air in the cooling water are described in Chapter 2.5.4. As the flow is generated with engine driven centrifugal pumps in Wärtsilä 4-stroke engines, the flow is linked to the pressure: the higher the pressure in the system, the lower the flow and vice versa when using the same pump. See an example of a pump curve in Figure 21 showing the connection with delivery head (or pressure) and flow. /25/; /32/

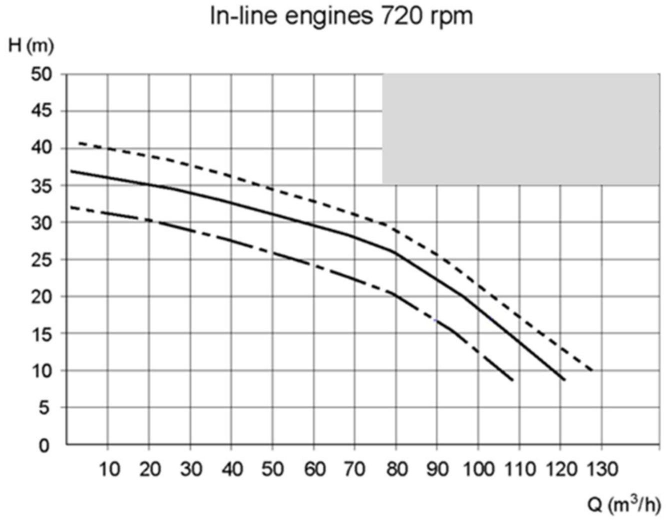


Figure 21. Example of a pump curve for engine driven centrifugal pump /41 p. 103/

Engine specific flow values depend on the size of the engine: the larger the engine, the higher the heat load and the volume of the cooling system leading to a higher flow is needed. The nominal flow values for each engine are defined in the technical data and they vary in the range of 20 m^3/h (W20) - 400 m^3/h (W50DF). The nominal flow is defined for LT and HT circuits separately but the values are in many cases the same as mixed cooling systems have a combined flow at some parts of the system. In 2-circuit systems with fully separate LT and HT circuits the flow requirement for the HT pump can be significantly lower than the flow requirement for the LT pump due to the lower volume of the HT circuit compared to the LT circuit. Flow and water volume related technical data with some examples is shown in table 2. /25/; /41, 11/ ;/44, 25/

Table 2. The cooling system flow information from technical data with examples /41, 11/; /44, 25/

	WL20	**W50DF**
High temperature cooling system		
Capacity of engine driven pump, nom. m^3/h	Covered	
Water volume of the engine, m^3		
Low temperature cooling system		
Capacity of engine driven pump, nom. m^3/h		
*) depending on the rpm		

The flow in the cooling water circuits is not used as engine controlling parameter as such and therefore it is not measured or shown in the engine control systems as a process value on continuous basis in typical Wärtsilä installations. However, the flow is often measured during troubleshooting to see how close to the nominal or design value the flow is since it has an impact on the heat transfer of cooling systems. The temperature changes are linked to the flow levels: if the temperature increase (ΔT) over the engine is higher than the nominal value, the flow in the system is usually lower than designed. /25/

3.3 Pressure

Pressure describes the amount of force per unit area. The unit used for pressure in Wärtsilä cooling systems is kPa. In Wärtsilä installations the cooling water pressure is measured and it is linked to an alarm limit but not to derating limit or shut down limit. /25/;/34, 99/

The pressure in the cooling water circuits affects the boiling point of the coolant: the higher the pressure, the higher the boiling point (Figure 22). The nominal pressures in Wärtsilä 4-stroke engine cooling systems vary between 200 - 480 kPa (Note: as 1 bar = 100 kPa, the respective range in bars is 2 – 4,8 bar) meaning that the boiling point in the cooling systems in higher than in atmospheric pressure. This protects the engine since boiling coolant has lower capacity to absorb heat due to the air bubbles. /25/; /41, 11/; /44, 25/; /50/

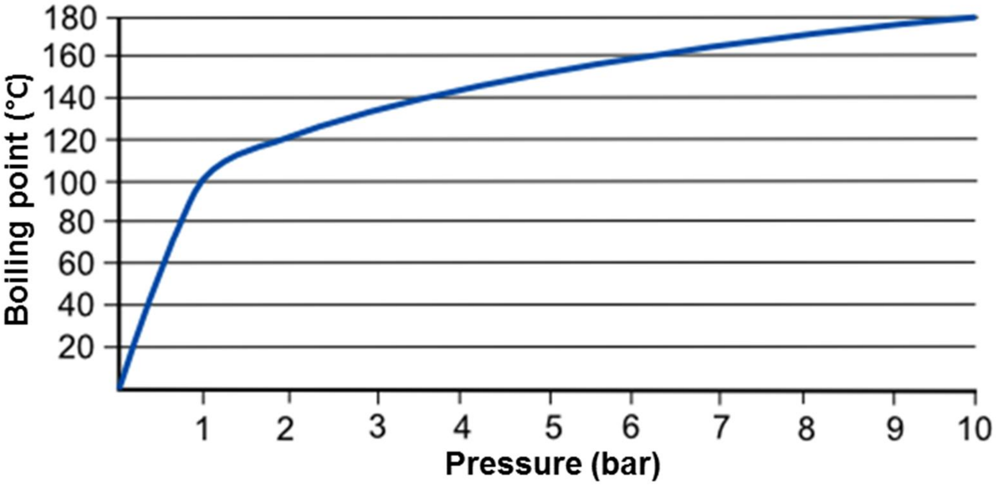


Figure 22. The boiling point of water as a function of pressure /50/

Cavitation is another thermodynamic process linked to pressure and pumps. Cavitation is the formation of small air bubbles or other vapor cavities in a liquid. Boiling occurs when the temperature of the liquid rises to the boiling point whereas cavitation occurs when the pressure drops below the vapor pressure required for maintaining the liquid form. Cavitation is linked to the temperature as the vapor pressure of a fluid increases when the temperature increases. This means that the higher the temperature the higher pressure is needed to avoid cavitation (see Figure 23). There are conditions enabling cavitation when the pressure in the system drops locally below the water vapor pressure curve. /49/; /8/

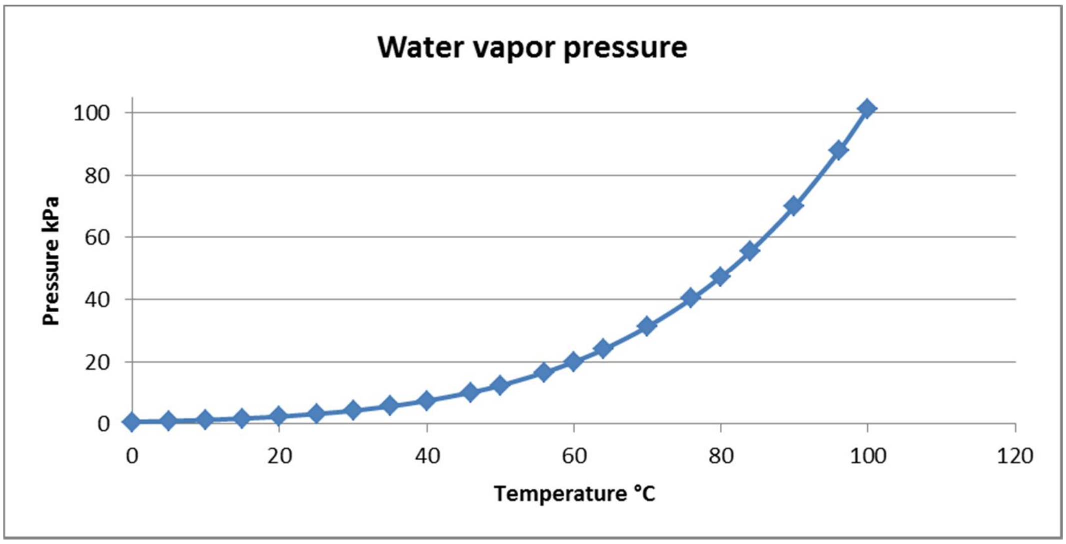


Figure 23. The impact of temperature on the vapor pressure of water /51/

In cooling systems there are conditions that enable cavitation especially in circulating pumps and control valves. Cavitation has to be avoided as the air bubbles or voids that form when low enough vapor pressure is reached implode once the pressure becomes higher again. The implosions have high energy and can cause significant damage to components. The static pressure provided by the expansion tanks is needed for the protecting the pumps from cavitation: the pressure is therefore at all times higher than the water vapor pressure. In addition, the components are located on the cool side of heat exchangers whenever it is possible. /49/; /8/

Pressure as such is an unwanted phenomenon as it puts requirements for the mechanical strength of the cooling systems. However, as the pressure represents the capability of the fluid to do work, it is necessary to maintain high enough pressure to make sure the coolant will move through the entire cooling system with sufficient velocity. The pressure and thus also the velocity of the coolant drops due to the friction in the system and some of the components have significant pressure drops related to them (e.g. central cooler). The pressures defined in the technical data with reference values from small bore and large bore sizes are presented in Table 3. /25/

Table 3. The cooling system pressures defined in engine technical data and example values /44, 25/; /41, 11/

	W20	**W50DF**
High temperature cooling system	kPa	
Pressure at engine, after pump, nom.	Covered	
Pressure at engine, after pump, max.		
Pressure drop over engine, total		
Pressure drop in external system, max.		
Pressure from expansion tank		
Low temperature cooling system		
Pressure at engine, after pump, nom.		
Pressure at engine, after pump, max.		
Pressure drop over charge air cooler		
Pressure drop over oil cooler		
Pressure drop in external system, max.		
Pressure from expansion tank		

Static pressure that the table refers to is the static pressure provided by the expansion tank height. The system has some built-in tolerances to allow for different set-ups of external equipment to be connected to the cooling system (e.g. gear box cooling) and to enable a different installation height for the expansion tank. The flow and the pressure in the system can be controlled with throttles / orifices. An orifice will increase the pressure in the system and reduce the flow. Orifices are needed in parallel pipes to balance pressure drops. E.g. if there is a by-pass pipe next to a central cooler there needs to be an orifice with the same pressure drop in the by-pass line. /25/; /8/

3.4 Parameters Related to Cooling Water

The chemical parameters followed up related to the cooling water are pH and hardness. The pH of the cooling water has to be followed up on a regular basis during engine operations and the hardness of the cooling water has to be checked 2-4 times per year. pH and hardness (°dH) are also checked from the raw water that is treated with additives to be used as cooling water. /9/

pH indicates the acidity or alkalinity of the fluid. pH value affects the corrosive impact of the cooling water: the lower the pH, the more acidic the cooling water is and the higher the corrosive effect. Nitrites are typically used as corrosion inhibitors in Wärtsilä installations. The required concentration of the nitrites in order to provide the highest possible protection against corrosion depends on multiple factors, such as temperature, chloride and sulphate content and pH, thus providing an additional reason for ensuring that the pH levels are within the acceptable levels. In Wärtsilä installations the pH limits are 6,5 – 8,5 for the raw water and 8 – 11 for the cooling water. /9/

The hardness of the water indicates the mineral content of the water. The recommended value for raw water hardness is <10 °dH (German degree, unit selected for Wärtsilä use) which correlates with 178 mg/l of $CaCo_3$. Suitable levels of calcium and magnesium compounds in the cooling water cause a thin, corrosion protective layer to form on the heat exchanging surfaces of the cooling system. If the water is soft (close to 0 °dH), it has the ability to dissolve oxygen and carbon dioxide from the air, thus leading to a low pH and a high corrosive effect. Too high hardness increases the deposit formation and will eventually affect the heat transferring properties of the system. /9/

4 COOLING SYSTEM COMPONENTS

The components required in typical cooling systems are presented in this chapter. Components are grouped according to how they are located in the overall system, i.e. if they are mounted on the engine, part of the external systems off the engine or can be either or.

4.1 Components “On Engine”

Components that are usually located on the engine are LT and HT pumps, LT and HT charge air coolers, and the engine components included in the cooling system, namely the engine jacket and the cylinder head. /16/; /25/

4.1.1 LT and HT Circulating Pumps

Cooling system LT and HT pumps are usually engine driven, centrifugal pumps that are located at the free end of the engine (Figure 24). The purpose of the LT and HT pumps is to circulate the cooling water through the heat sources and that way enable the cooling water to carry the heat load away from the heat sources to be disposed. The capacity of a pump is defined as volume flow (m^3/h). /16/; /22/ /25/

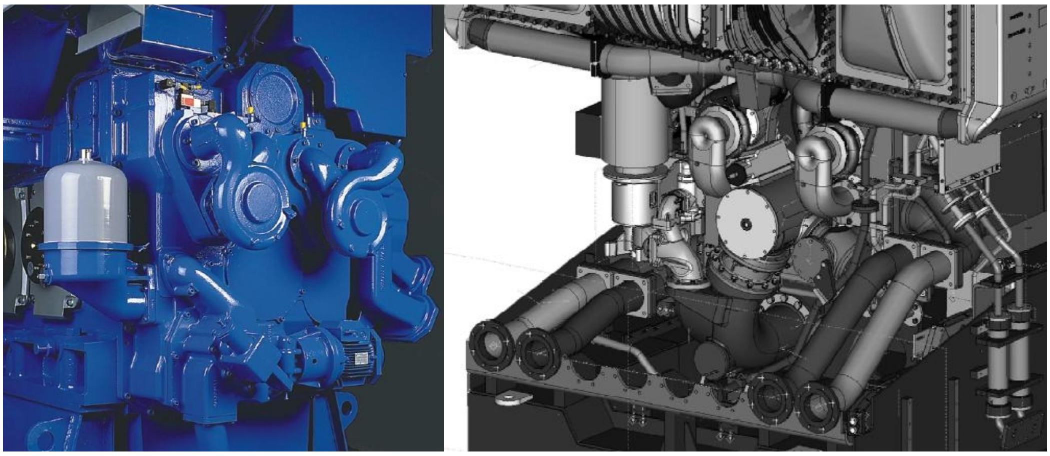


Figure 24. Cooling water circulation pumps located on the engine free end: L-engine on the left and V-engine on the right /46, 14; 37/

The centrifugal pump converts the mechanical energy given by the engine to hydrodynamic energy of the cooling water with a rotating impeller. At the same time the pump increases the pressure of the cooling water. The pressure difference between the pump inlet and outlet drives the fluid through the circuit the pump is connected to. The cooling water inlet is located close to the rotating axis at the center of the impeller. The velocity and pressure of the cooling water are increased due to the centrifugal force as the water flows towards the outer rim of the impeller while the impeller rotates. Cooling water exits the pump with an increased velocity and pressure along the blades of the impeller. The structure of a centrifugal pump driven by an electric motor is presented in Figure 25. /35, p. 11/

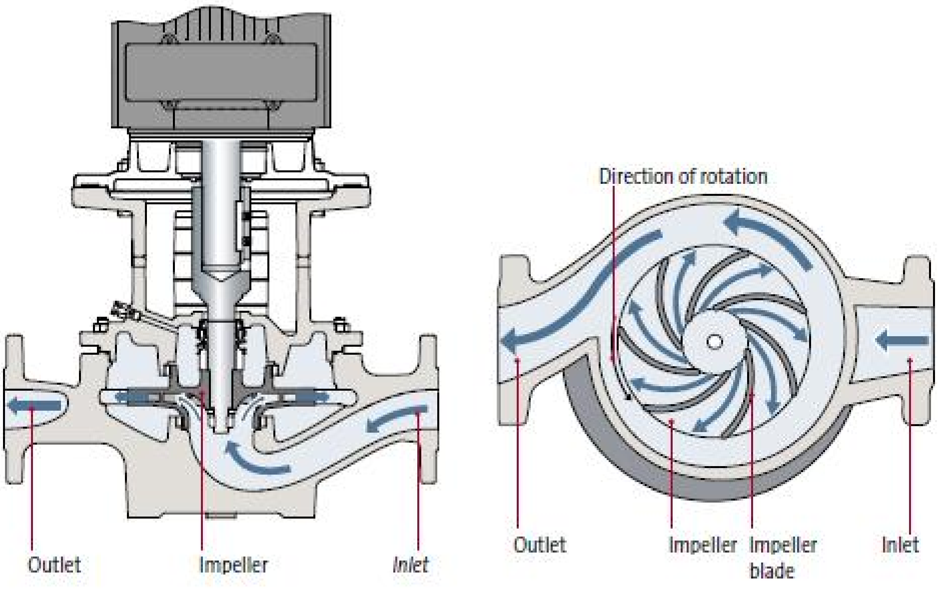


Figure 25. Structure of a centrifugal pump (electric motor driven) /35/

In centrifugal pumps the pump performance is presented with a pump curve showing the dependency between the delivery head and the flow of the pump on a defined rotating speed. An example of a QH pump curve is shown in Figure 18 (Q = volume flow, H = delivery head). The same pump type is typically available with

2-4 different impeller sizes to enable different performance. The larger the impeller, the higher up the pump curve is on the graph. The pPump curve can also include information on the required net positive suction head (NPSH), power requirements of the pump and efficiency of the pump (shown as so called mussel curve). NPSH and power requirement have own scales marked on the graph. Further detailed pump curve is shown in Figure 26. /11, 3-4/

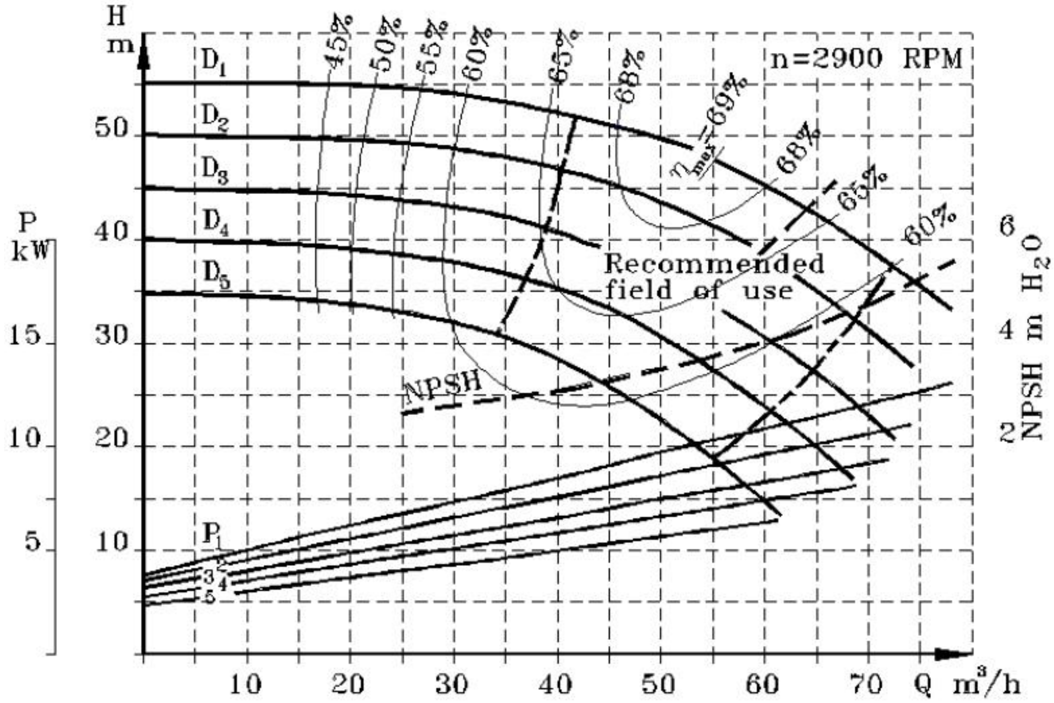


Figure 26. Pump curve including performance curve for 5 different impeller sizes (D1-D5, D1 referring to the largest impeller), NPSH, power requirements for each impeller size (P1-P5) and efficiency (η) as mussel curve /11, 3/

Wärtsilä 4-stroke engines are available as both constant speed and variable speed versions. For example, the W32 engine operating range is 300-750 rpm. In engine driven pumps the rotating speed of the pump is directly proportional to the rotating speed of the engine with a fixed transmission ratio. The rotating speed of the pump affects both the flow of the pump and the delivery head of the pump in a similar way as impeller size: if rotating speed is reduced, the whole pump curve moves downwards on the chart as shown in Figure 27. /35, 38; 53/; /41, 8/

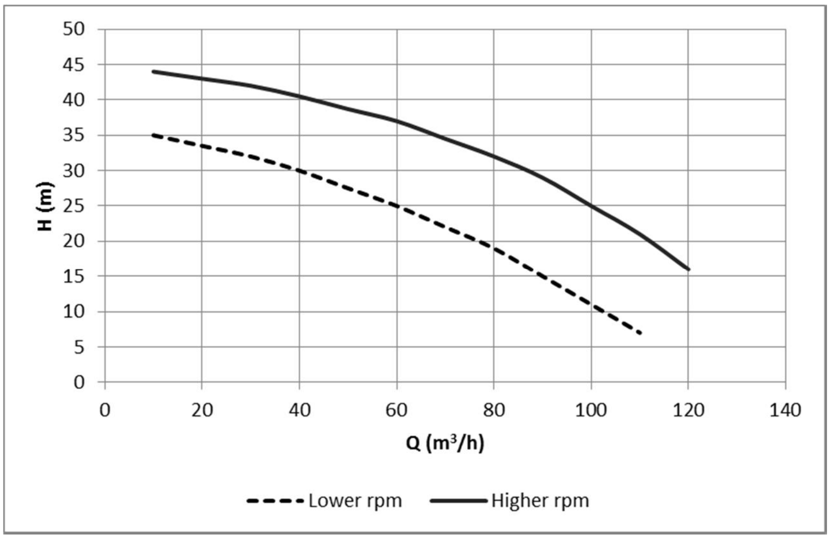


Figure 27. Example of the impact of rotating speed on pump performance /41, 103/

In variable speed engines the pumps are dimensioned so that the pump produces the required flow also for the lower engine speeds. When the engine driven pump can no longer provide the required pressure, the electrical motor driven stand-by pumps are switched on (classification society requirement on marine single main engine installations). A cooling system equipped with stand-by pumps is shown in Figure 9. The impacts of connecting pumps in parallel and in series are shown in Figure 28. /25/; /35, 50-51/

LT and HT circulating pumps pump treated fresh water with corrosion inhibitors included in it. The operating pressure and the temperature of the fluid are relatively low. Therefore, grey cast iron (e.g. GJL-200) can be used as a material for pressure housing, bearing housing and impeller. The shaft of the pump is typically made of duplex stainless steel (e.g. AISI 329). /11, 13/

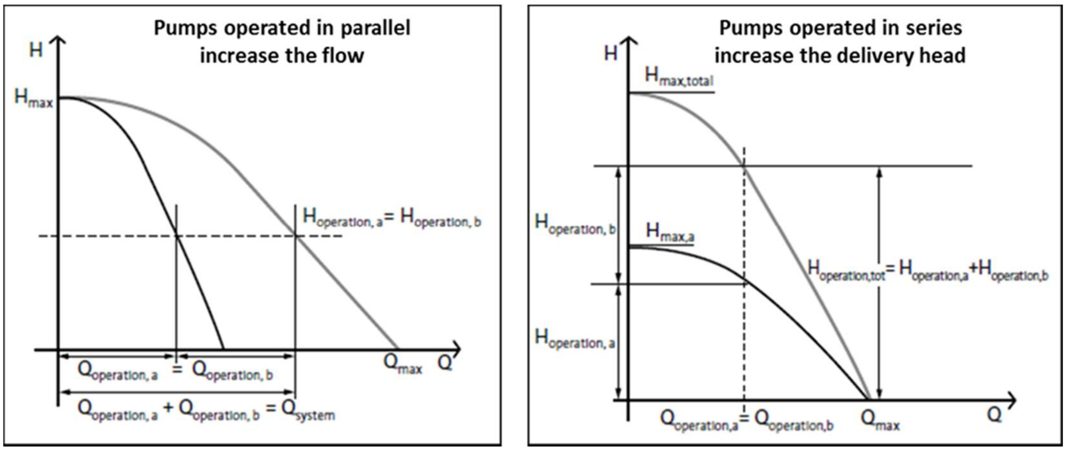


Figure 28. Impact on the pump performance when connecting pumps in parallel or in series /35, 50-51/

4.1.2 Charge Air Cooler (1-stage / 2-stage)

The charge air cooler (CAC) is a heat exchanger that cools the charge air before it is fed into cylinders. The reason for cooling of the intake air is explained in Chapter 2.2. The charge air cooler is part of the turbocharging and air cooling module. The components of the module and the location of the module on the engine are shown in Figure 29. The components of the module are:

1. Compressor
2. Turbine
3. Charge air cooler
4. Air receiver
5. Water separator. /16/; /22/ /25/ /43/

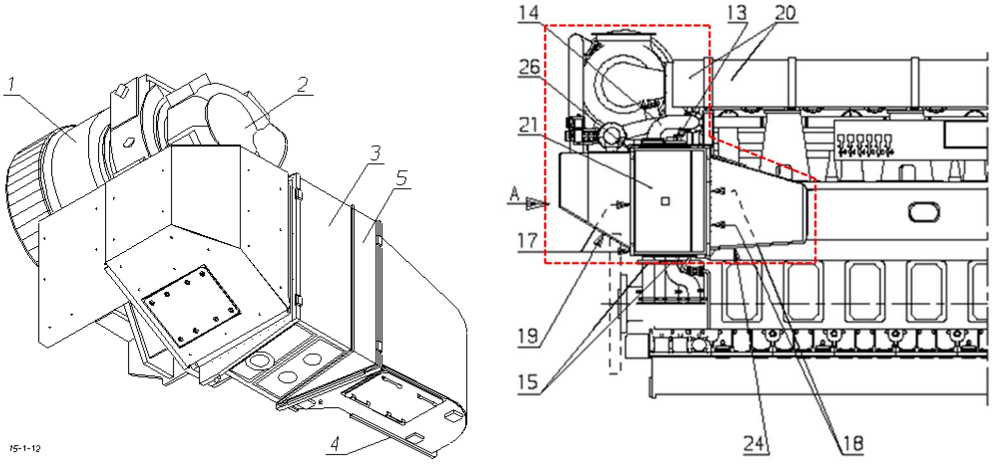


Figure 29. Turbocharging and air cooling module and location of the module on the engine /43, 15-0143-00/

In a charge air cooler the cooling water flows through finned tubes in a box through which the charge air is blown. When air passes the finned tubes, the heat from the air is conducted to the cooling water, thus cooling down the air and warming up the water. As the CAC cools down the inlet air after the turbocharger, the CAC is mounted on the engine at the same end as the turbocharger (either free end or driving end). The structure of the charge air cooler is shown in Figure 30. The components are listed in Table 4. /12/

The water separator or water mist collector separates water droplets from the cooled air to prevent droplets from entering the receiver or further to the air inlet channels. If the removal of water in CAC does not work properly, there is a risk of water accumulating in the receiver and in the worst case ending up to cylinders during operations and causing a water stroke. Droplets of water in the intake air increase the corrosion risk in the receiver and inlet channels and can cause damages to inlet valves. The water separator is not used in all engines as a default. However, there is always water drainage in the CAC unit, either embedded in the water separator or in the CAC itself at the air side. /19, 13/; /12, 17/

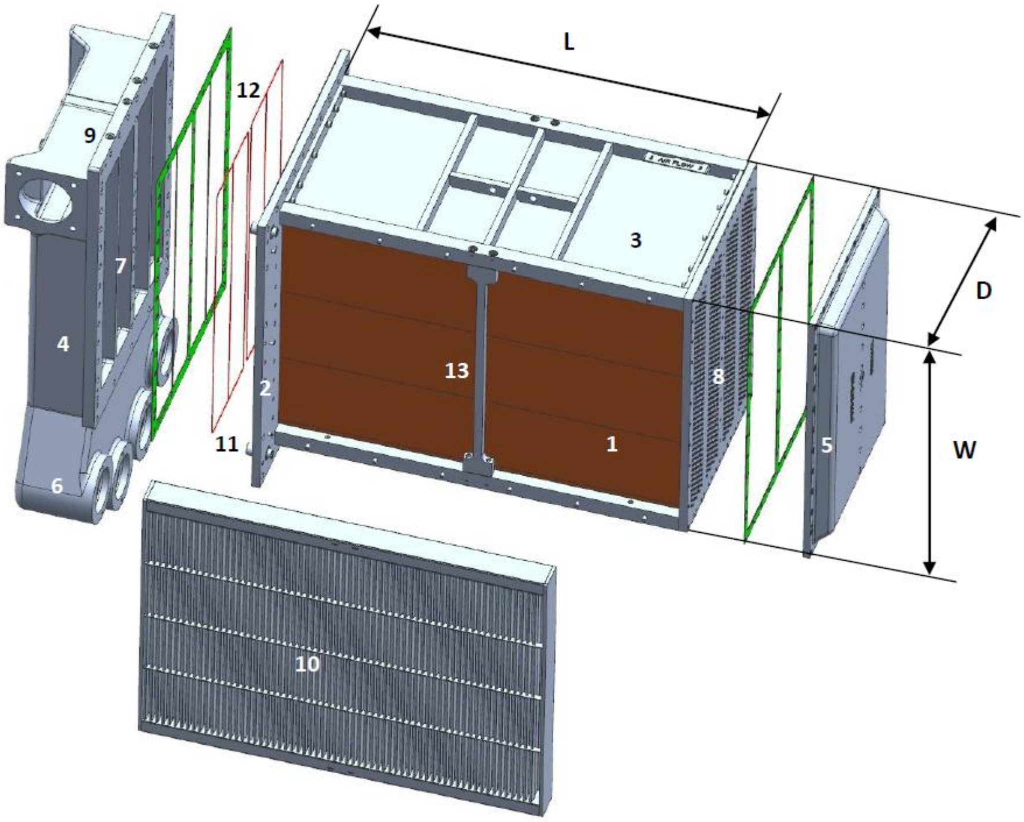


Figure 30. Charge air cooler explosion to components (W50DF) /12, 4/

Table 4. Component list related to charge air cooler (figure 27)

No	Component name	No	Component name	No	Component name
1	Tube bundle	6	Water connections	10	Water mist collector (WMC)
2	Front tube plate	7	Water chambers	11	Water drain
3	Side cover	8	Rear tube plate	12	Gaskets (O ring or flat gasket)
4	Water cover (front)	9	Air vent	13	Tie bar support
5	Water reverse cover				

The materials of the charge air cooler must withstand high temperatures without the strength or chemical structure being compromised. As treated fresh water is the coolant circulating in most of the charge air coolers, corrosion is typically not an issue on the water side. On the air side the side members and tube plates need to be corrosion resistant enough to tolerate the condensation drops from the CAC. Coatings are typically used for corrosion protection on the air side. The materials used in the charge air coolers are e.g. aluminum brass or copper-nickel for tubes, copper-nickel for tube plates, copper for fins, steel for side covers and steel or nodular cast iron for housing. /12, 20-21/

Charge air cooling is done either in one stage or two stages in Wärtsilä 4-stroke engines. If there are two CAC:s in the same system, they are assembled as one unit but connected to different cooling water circuits (HT and LT). The HT CAC is located at the turbocharger side of the CAC unit and the LT CAC on the cooler side i.e. further away from the turbochargers. In 1-stage charge air cooling systems the CAC is located in the LT circuit as the first heat exchanger after the LT pump, followed by the LO cooler. In 2-stage charge air cooling systems the LT CAC is located on the LT circuit after the LT pump in a similar way as in 1-stage CAC systems and the HT CAC is located in the HT circuit after the engine jacket cooling. /16/; /22/; /25/

Nowadays practically all power plant applications use 2-stage charge air cooling. In marine applications both 1-stage charge air cooling and 2-stage charge air cooling are used, while 2-stage cooling is more common. The benefit of splitting the charge air cooling to LT and HT CAC is that there is more heat energy available at the HT system at high loads which gives an increased efficiency if there are heat recovery systems connected to the cooling system (e.g. combined heat and power installations, installations with evaporator). The disadvantages of 2-stage charge air cooling are linked to low load situations and cold ambient conditions: the HT water can be cooled too much especially in the arctic conditions and there is limited heat capacity available for heat recovery. /16/; /27/; /22/; /24/

4.1.3 Engine Jacket and Cylinder Head

Cooling water circulates through the engine jacket and cylinder head in order to remove heat from the hot parts of the engine. The water channels in the engine are shown in Figure 29.

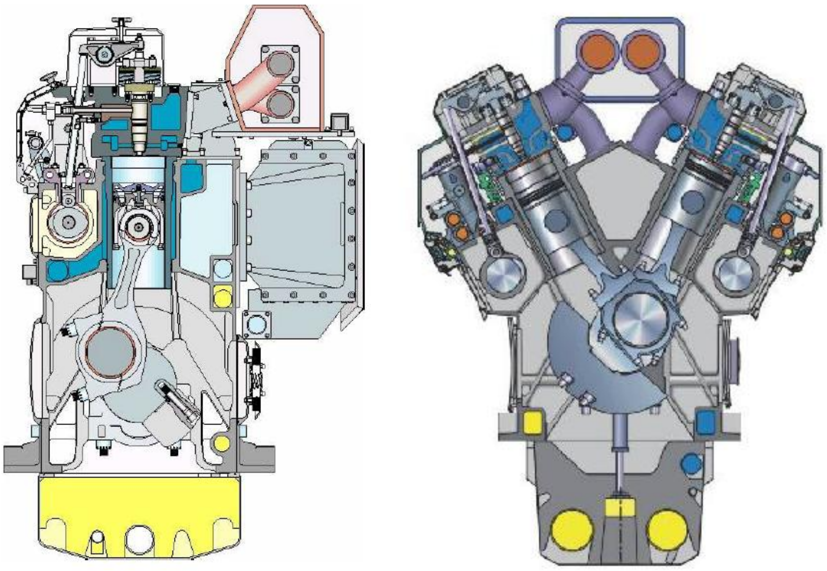


Figure 29. Cross-sections of L and V engine configurations; cooling water channels marked with dark blue /46/

4.2 Components "Off Engine"

Components and systems that are usually installed off the engine are the heat disposal systems, such as radiators or raw water cooling, central cooler, pre-heater unit, expansion vessel, maintenance tank and heat exchangers for heat recovery or evaporator. Additionally, there are a number of pumps in the external systems, e.g. pump for maintenance tank, stand-by pumps in variable speed installations and pumps in cooling tower systems. /16/; /22/; /25/

4.2.1 Central cooler

The central cooler (Figure 31.) serves as a heat transfer media to release heat from the primary circuit to the secondary circuit. Central coolers are used in both marine and power plant installations operating on raw water cooling. Additionally, central coolers are used in power plant cooling tower systems installations. /13, 2/; /22/

The gasket plate heat exchangers are the most common type of HE used as central cooler in Wärtsilä installations. In a gasket plate heat exchanger a selected number of thin plates are installed on a steel frame. The hot and cold fluid flow in parallel sections and heat transfer takes place through the thin metal wall. The heat transfer capacity of a gasket plate heat exchanger can be adjusted by adding or removing plates on the frame. The cooler can also be disassembled for cleaning up purposes. There are also brazed and welded plate heat exchangers available but they are not commonly used as central coolers due to higher cost and limitations in cleaning up. /13, 2/;/38/

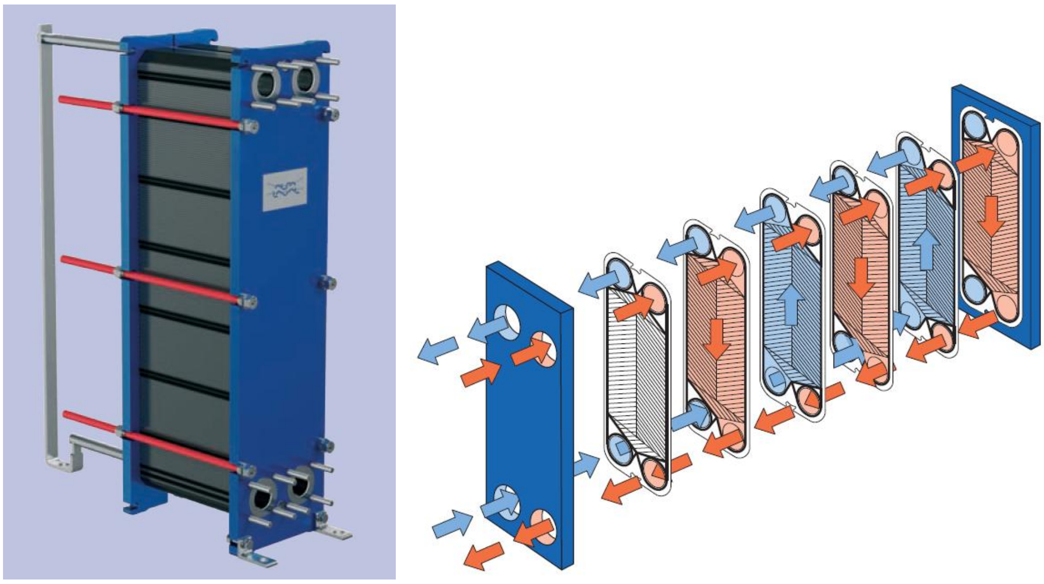


Figure 31. Plate heat exchanger type central cooler and the flow principle inside the cooler /38/

The plates in the central cooler are corrugated to ensure a turbulent flow. Corrugation also increases the strength of the plates against differential pressure. Central coolers typically have a high pressure drop due to turbulent flow but as a trade-off there is a high heat transfer efficiency meaning small temperature approach. The counter-current flow of hot and cold fluids is often used as it is the most efficient from the heat transfer point of view. /13, 3/

The frame of the central cooler is usually made of steel and nitrile is used as gasket material. Stainless steel ALSI 316 is typically used as plate material in central cooler is for fresh water applications. Titanium is used in sea water applications as it is not sensitive to corrosion. The thinner the plate is, the better the heat transfer capabilities are. On the other hand, the plates need to withstand manual cleaning to remove fouling and deposits from the central coolers. /13, 3/

The raw water side of the central cooler is exposed to biological material and other impurities that can lead to fouling (e.g. algae) or deposit formation. On the hot side of the central cooler there is a risk for precipitation of calcium carbonate i.e. scaling. Since the scaling tendency is directly linked to the temperature of the coolant, it is important to ensure a sufficient flow through the central cooler and that way reduce the risk of temperature increase leading to scaling. The efficiency of the central cooler has a direct impact on the efficiency of the cooling system and therefore the central cooler has to be cleaned up based on the need to maintain its capacity. The correct cooling water treatment and keeping temperatures in central cooler on a low level also ensure a good functionality of the cooler. /13, 3/

The temperature approach on central coolers is calculated as ΔT between the primary circuit out of the central cooler and the secondary circuit into the central cooler (see Figure 18). Temperature approach is used as the dimensioning data on power plant installations. In marine installations there is at times plenty of cooling capability available through the sea water and therefore the target is not always to aim for the smallest possible temperature approach. Instead the central cooler is dimensioned to compensate for a high pressure loss in the other parts of the cooling circuit with a smaller pressure loss (correlating with higher temperature approach) in the central cooler. In marine installations the dimensioning is not done based on the temperature approach: instead a desired LT temperature for cooling water is used (for example 30 °C) as a reference and the capacity of central cooler needed depends on the temperature of the sea water in the areas where the ship is aimed at. /27/; /13, 3/

The dimensioning of a central cooler depends on the amount of engines connected to it. In marine installations there is typically one central cooler per engine room. In Power plant cooling tower system and raw water system installations there is typically one central cooler for each engine located in the engine hall next to engine auxiliary module. /24/; /13, 5/

4.2.2 Pre-heater

The purpose of the pre-heater is to warm up the cooling water prior to engine start-ups to enable faster loading and maintain the cooling water temperature during down times to reduce cold corrosion and to prevent the fuel from solidifying in the engine piping. The pre-heater (Figure 38) consists of electric motor driven circulating pump, heating unit and necessary shut-off, safety and non-return valves. The heater can operate either on electricity, steam or thermal oil. The safety valve is needed for releasing excess pressure if heating generates too much pressure in the system. The pre-heater can be sold as separate components or as a ready-made unit. In power plants applications the pre-heater is included to the EAM module whenever the engine is equipped with the module. /22/; /14, 6/

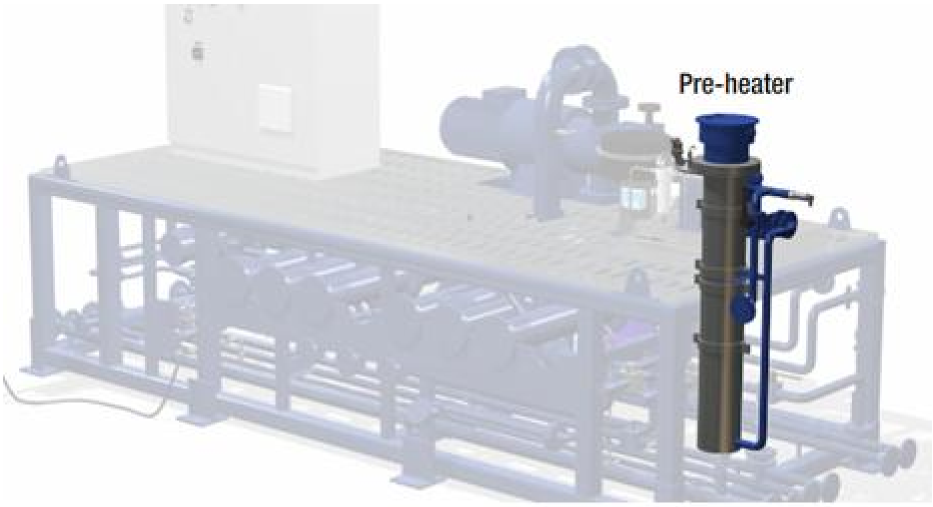


Figure 38. Pre-heater installed on the engine auxiliary module /14/

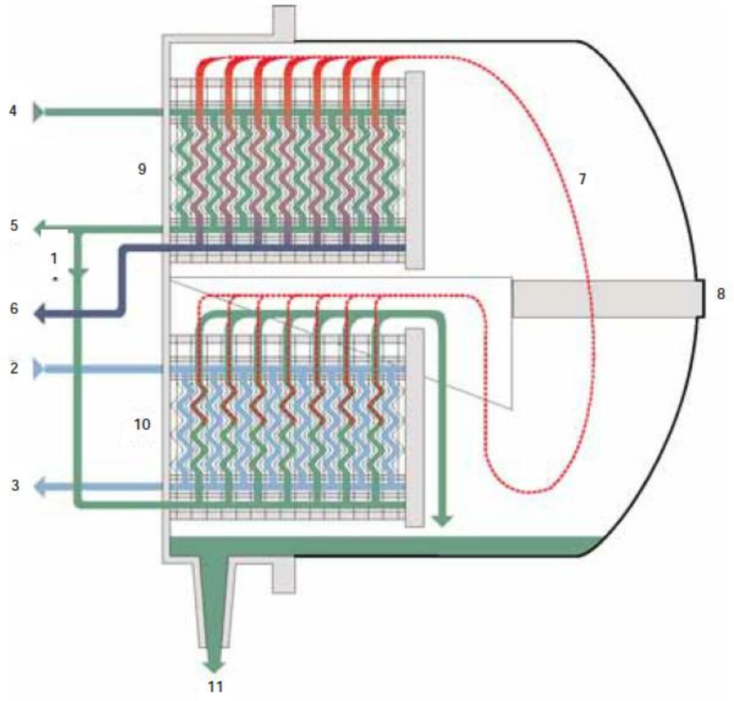
The capacity required from the pre-heater depends on the engine size: the larger the engine, the higher the volume of the cooling water and the cold mass of the engine and the more heating capacity is required. The heating capacity is given either as an absolute value (e.g. 40 kW) or as a value per cylinder (e.g. 6 kW/cyl). In both marine and power plant installations there is also a need from time to time to keep the stopped engines warm. The pre-heating value required for keeping a hot engine warm is approximately half of the overall heating value. /22/; /14, 8/

4.2.3 Heat Recovery Systems

In marine installations there are two basic types of heat recovery systems connected with cooling system: evaporators for generating fresh water and usage of heat energy from the cooling system for the boiler water pre-heating. Power plants that generate both electricity and heat (CHP, combined heat and power) can utilize heat from the HT circuit for heat generation. /27/; / 41/

The evaporator (or fresh water generator, see Figure 39) uses vacuum distillation process to convert sea water into process water and domestic water. The heat needed in the system is taken from the HT circuit. An additional feed pump is needed in variable speed engines. The cross-section of an evaporator is shown in Figure 40. As the changes from liquid to gaseous state take place in a vacuum of 85-95 % the evaporation takes place already at the temperature of 40 – 60 ºC. The higher the temperature available from the HT circuit is, the higher the capacity of the evaporator is. If the HT circuit heat is used in marine installations for pre-heating the boiler water, a heat exchanger is needed for transferring the heat. The target with this set-up is overall energy consumption optimization on the vessel. /37/

Figure 39. Two different evaporator models used on marine applications /37/



1	Seawater feed
2	Heating medium in
3	Heating medium out
4	Seawater cooling in
5	Seawater cooling out
6	Freshwater out
7	Evaporated steam
8	Demister
9	Condenser
10	Evaporator
11	Brine out

Figure 40. Cross-section of an evaporator /37/

In power plant CHP installations additional heat exchangers are used to capture heat from cooling system as shown in Figure 41. The heat energy can be used for generating hot water for district heating, process steam or even chilling out water.

More efficient heat recovery is possible in cooling systems with separate LT and HT circuits. In the concept presented below heat is taken from the HT circuit, LT circuit and LO circuit to maximize the district heat generation. As each CHP installation is individual when it comes to the electricity price and district heat price the optimization of these systems is done based on financial criteria case by case. /24/; /6/

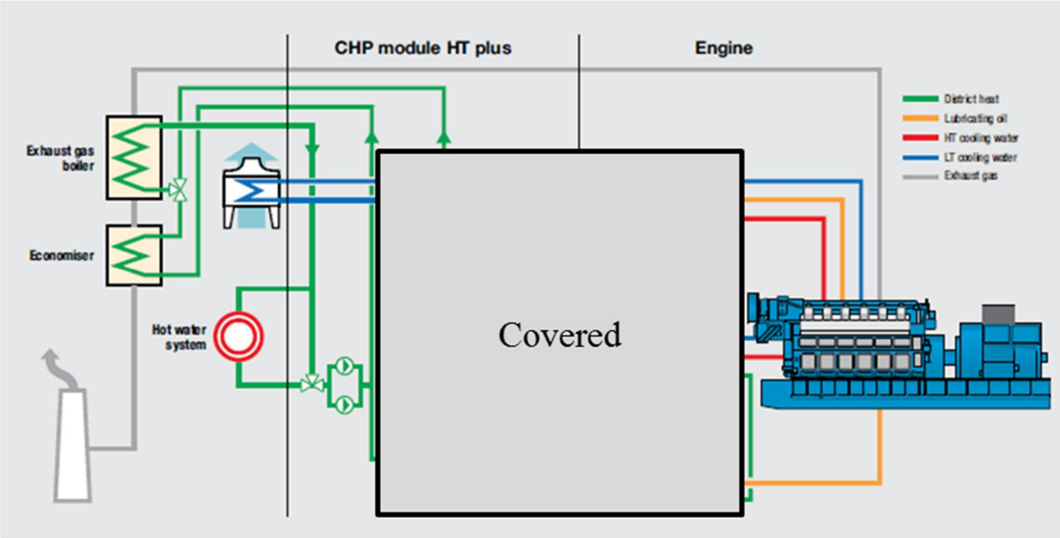


Figure 41. Hot water generation for district heating applications in Power Plants /6/

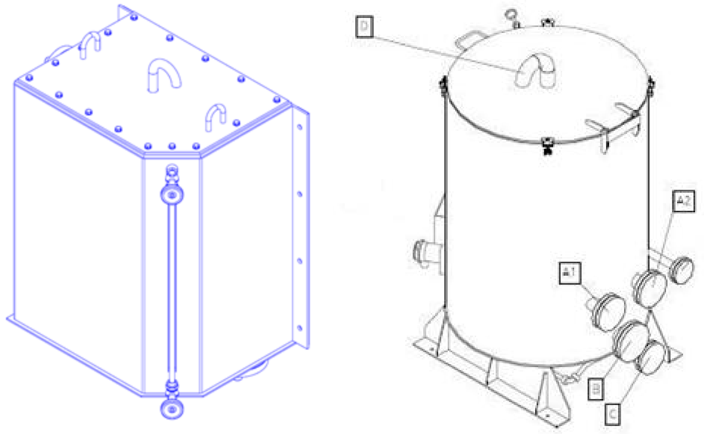
4.2.4 Expansion Vessel

The purpose of the expansion vessel is to compensate for the thermal expansion of the coolant. The temperature of the cooling water affects the volume of the liquid and as the temperature of the cooling water in the system varies, an expansion tank is required. Additionally, the expansion tank is used to ensure there is no cavitation in the system pumps by controlling the net positive suction head (NPSH) by placing the expansion tank at the correct level above the LT and HT pumps.

Open type expansion vessels also take care of de-aeration in the cooling system. /22/; /14, 16/

Each cooling water circuit requires an own expansion vessel meaning that if there is a 2-circuit system with no mixing of LT and HT cooling water, there needs to be two expansion vessels on the engine. In Power Plants applications the expansion vessels are typically engine specific, whereas in Ship Power installations the same expansion vessels can be used by more than one engine. There are two different designs of the expansion vessel: open and closed. The open type is more common and the closed type is not recommended to be used unless necessary. /22/ /14/

The open expansion vessel is a tank with the volume of 5 -10 % of system volume. As air venting takes place in the open type expansion vessels the de-aeration pipes lead to the expansion vessel. To avoid air pockets forming in the vent pipes the pipes need to have an upward slope towards the expansion tank. The balance pipe down from the expansion vessel is dimensioned according to the number of vent pipes so that the flow velocity in the balance pipe stays between 1-1,5 m/s. The expansion tank is located at the highest point of the cooling system, typically 7-15 meters above the LT and HT pumps to create sufficient inlet pressure for the pumps in order to avoid cavitation. An open type expansion vessel with typical connections is shown in Figure 42. /22/; /14, 17-21/; /8/



A1, A2	Venting pipe connections
B	Make up pipe connection
C	Drain and overflow
D	Air venting

Figure 42. Open expansion vessels for Ship Power and Power Plants installations /14, 17/ /8/

The expansion vessel is connected to the LT and HT circuits of the system and the flow that goes through the expansion vessel is bypassing the heat disposal on the system (e.g. radiators or central cooler). Thus, the fluid from the expansion vessel is warmer than the fluid from the heat disposal and the flow through the expansion vessel has to be regulated. For this reason 5 mm orifices are used in the vent pipe connections. /25/; /14, 16/

The closed expansion tank is a pressurized tank divided into an air section and a fluid section by a flexible membrane. When the tank is empty the membrane moves and the air takes over the entire tank. When the coolant enters the tank, the air section becomes smaller and the pressure is increased due to compressed air. This means that the higher the temperature in the cooling system is, the higher the volume of the coolant is and the higher the pressure in the tank becomes. The closed expansion tank requires separate de-aeration tank to be used as the air venting is not taking place through the expansion tank. The benefit of using a closed expansion tank is that the system is not in contact with air which makes the system less prone to corrosion. As a whole the closed expansion vessel is more complex and sensitive solution compared to the open expansion tank and therefore not commonly used. /14, 20-21/

4.2.5 Maintenance Tank

The maintenance tank (also called drain tank) is used when the cooling system needs to be emptied from the cooling water for service purposes: water is drained from the cooling system to the maintenance tank and once necessary actions are taken, it is pumped back to the system. The maintenance tank is also used to mix additives to the water to ensure a proper mixing and even quality of the coolant. The maintenance tank is usually common for multiple engines and installed as close to the engine(s) and as low as possible to enable draining the coolant to the tank without additional pumping. If glycol is used in the LT circuit but not in the HT circuit, there needs to be a separate maintenance tank for the LT and HT circuits in order to not mix the coolant including glycol with one not including it. /14, 3/

The maintenance tank is dimensioned according to the cooling system volume of an individual engine as the tank is used for one engine at a time. The following formula can be used when defining the size for the tank: /14, 4/;/22/

$$V_{tank} = \text{Covered} \qquad (2)$$

Where V_{tank}: Maintenance tank volume [m^3]
V_{wv}: Water volume of the engine type [m^3]
A: Pipe cross-section area [m^2]
L: Piping length [m]
V_{ce}: Cooling equipment volume
xxx: Rest volume in maintenance tank

4.2.6 Air and Dirt Separators

Even though the open expansion tank and air venting pipes take care of the deaeration of the system, there can be a need for improved removal of entrained air. An additional air separator is recommended in the marine installations. The air separator is shown in Figure 43. Air is entrained to the cooling water on the hot surfaces of the system. The air bubbles tend to accumulate in the areas with low flow and have a negative impact on the heat transfer of the coolant. Air separators should be installed at the highest point of the system on the hot side before the central coolers. The typical installation point is directly after the connection point of the LT and HT circuits in mixed cooling systems (see Figure 9). If LT and HT circuits are fully separate, the air separators should be installed directly after the HT water outlet on the engine and directly after the LT water outlet on the engine. /8/

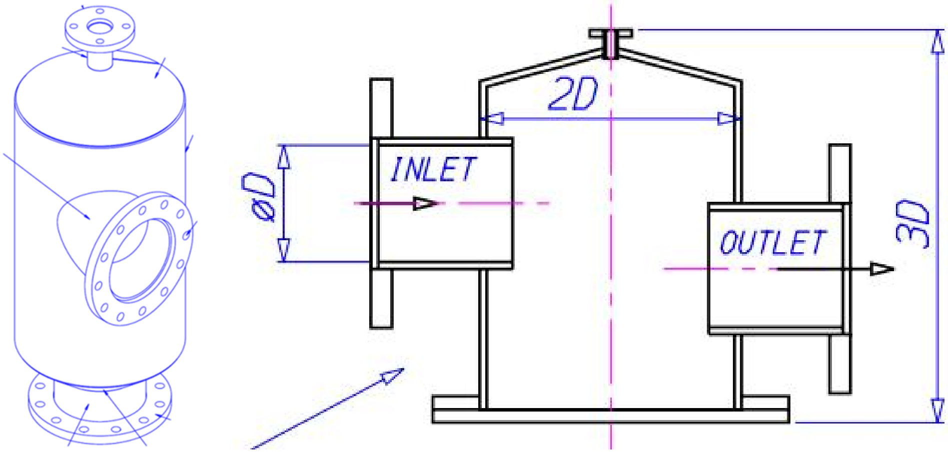
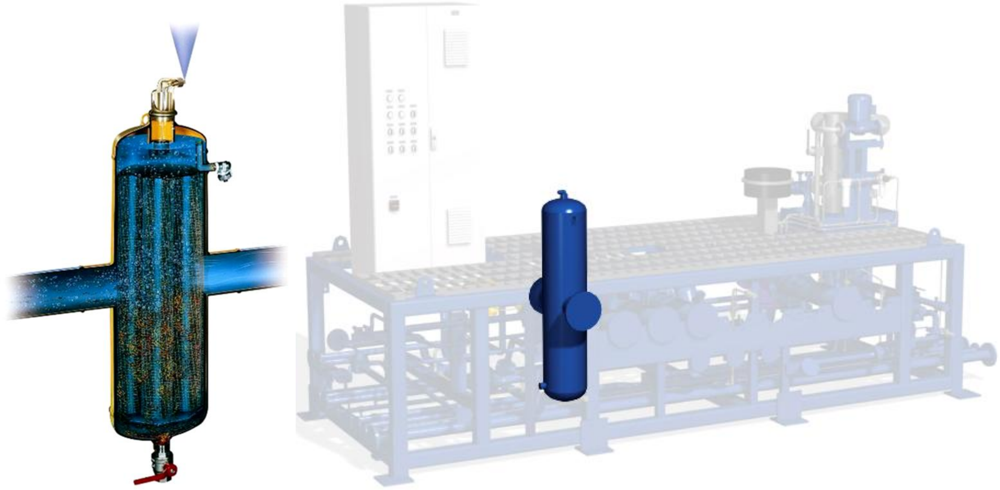


Figure 43. Air separator used in marine installations /8/

A spirovent air and dirt separator is another option available for removing air and particles from the coolant. It is a combined filtering and de-aeration component and included in the power plant installations on the engine auxiliary module as shown in Figure 44. The air bubbles rise at the top of the spirovent and air is released from an automatic air vent. Dirt particles sink to the bottom of the tubed structure and can be removed via the drain valve. /2/



4.2.7 **Figure 44. Spirovent air and dirt separator and its location on engine auxiliary module /2/**

4.2.8 Pumps in External System

Pumps used off the engine are typically electrical motor driven centrifugal pumps as shown in Figure 45. Pumping in the external system is needed for the following purposes:

- Maintenance water / drain tank pump (PP, SP)
- Pre-heater pump (SP, PP)
- Cooling tower system pumps (PP)
- Stand-by pump for LT and HT circulating pumps and sea water pump (SP)
- Pumps for external auxiliary cooling equipment (SP)
- Sea water pump in sea water cooling systems (SP) /16/ /27/ /8/

In marine installations stand-by pumps for LT and HT circulating pumps are required by classification societies especially in the single main engine applications. The pumps will turn on if the pressure falls below the set point. /27/ /25/ /20, 14-15/

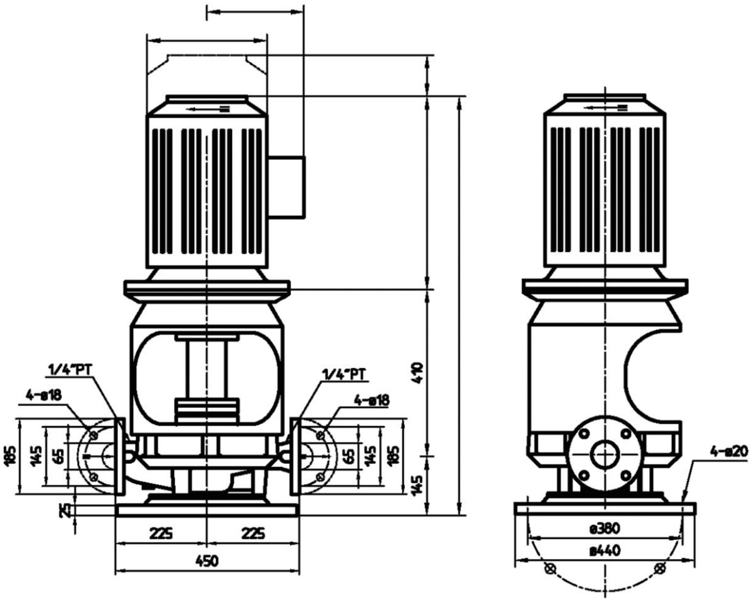


Figure 45. Dimensional drawing of a stand-by circulating pump /22/

4.2.9 Wärtsilä Water Conditioning Unit

The Wärtsilä Water Conditioning Unit (WWCU, Figure 46.) is a cooling water treatment product for both marine and power plant applications to limit bacterial growth, corrosion, sludge and scaling in heating and cooling systems. The WWCU is a non-chemical water treatment unit based on filtering the water through a granulated bed. The unit is installed to a side stream of the closed loop system and is meant for fresh water or for a mixture of glycol / antifreeze and fresh water. When using the WWCU there is no need to use chemical additives in the cooling water to prevent corrosion, fouling and deposit formation. /52/

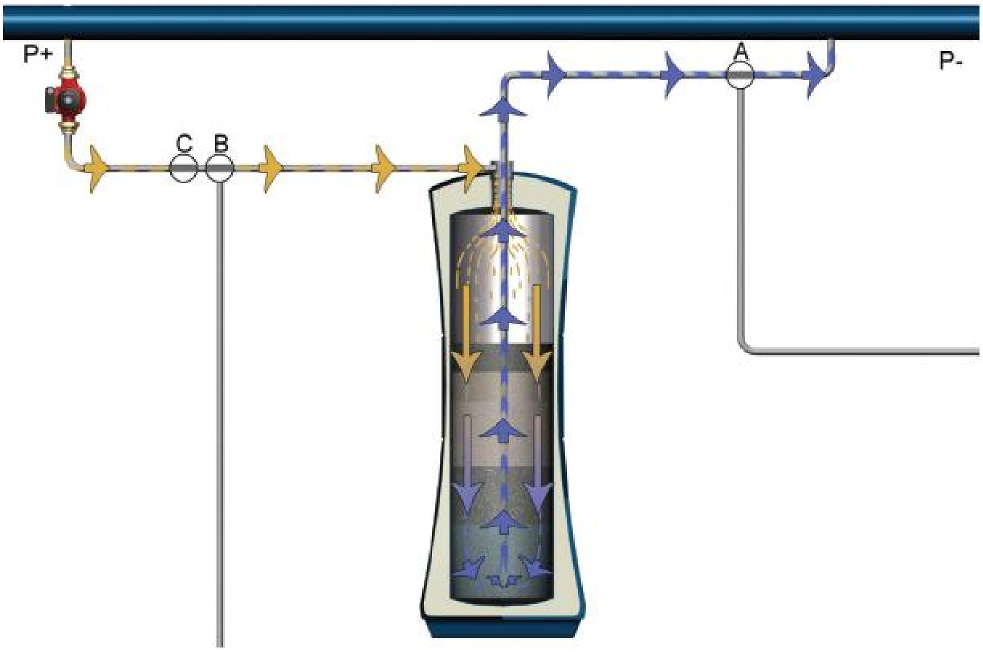
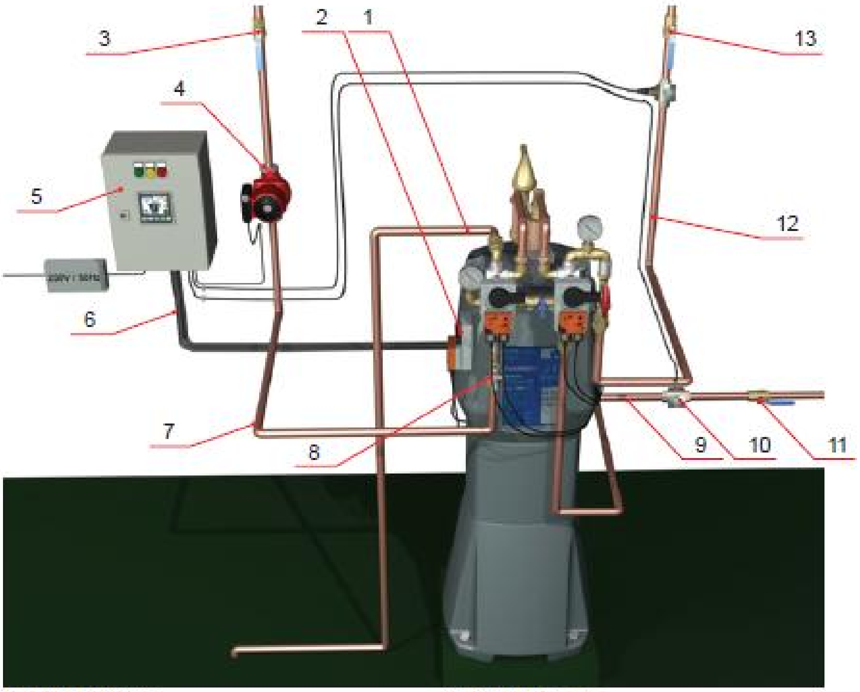


Figure 46. Wärtsilä Water Conditioning Unit /52/

The WWCU consists of a tank with five filtering layers and needed piping, valves and control system to ensure proper water quality (Figure 47.) The unit controls and adjusts the levels of pH, alkalinity and hardness and removes solids as well as particles from the water. The unit filtering bed has to be backwashed regularly to remove the solids and to regenerate the filter media. A PLC (programmable logic controller) is used as a control system to control the unit valves and to run a required backwash cycle automatically. The unit can be either run independently or it can be connected to a vessel's Integrated Alarm, Monitoring and Control System (IAMCS). /52/



1 Piping: Drain
2 WWCU with pipework and motor valves
3 Shut-off valve, inlet
4 Circulation pump
5 Control unit including 230V power cable
6 Cables
7 Piping: Inlet (untreated water)
8 Sample valve
9 Piping: Mains Cold Water Service (MCWS)
10 Flow meter (FT2, 1-50 l/min) (MCWS)
11 Shut-off valve, Mains Cold Water Service (MCWS)
12 Piping: outlet (treated water)
13 Shut-off valve, outlet

Figure 47. System components for WWCU /52, p. 2-7/

4.3 Heat Disposal Systems

Heat disposal systems used in Wärtsilä 4-stroke installations include radiators, cooling towers and raw water cooling with central coolers. These systems are described in further detail in this chapter. Box coolers have become more common in marine installations in the recent years but are still fairly uncommon. They are shortly presented in Chapter 2.4. Typical marine cooling system description.

4.3.1 Radiator Systems

Radiators are air/water cooling systems without a need for a water flow in the secondary circuit. Radiators are the most commonly used heat disposal methods in power plant installations. Heat disposal takes place in radiators where coolant flows in finned tube coils and is cooled down by a forced air flow from radiator fans. In power plant installations one engine has 1-6 radiator cells in one bank for reaching the required cooling level but each radiator bank is serving only one engine. /17, 2/; /24/

The key benefit in radiator systems is that they do not require water for cooling effect which enables to locate power plants away from water sources. In addition, radiators have low service needs and operating costs and the environmental impact is limited to noise. The disadvantages of radiators are a higher footprint needed and slightly higher investment costs as well as power consumption needed for operating the radiator fans. The radiator field is installed either on the roof of the power plant building (Figure 32.) or next to the building. /17, 2, 14-15/

Figure 32. Wärtsilä Oil Cube with radiators installed on the roof of the building /47/

Radiator sizing is done based on required temperature difference between the ambient air and cooling water outlet from the radiator (temperature approach). The temperature approach is higher in liquid fuel engines compared to gas and dual fuel engines, meaning that the cooling water in gas and dual fuel engines needs to be cooled down to a lower temperature than in liquid fuel engines. This is to prevent the knocking phenomena in gas and DF engines where the pre-mixing of fuel to inlet air makes the engine more sensitive to knocking and requires lower temperatures from the charge air when it enters the engines. As a consequence the radiators for gas and DF engines need to be dimensioned for a higher capacity than the radiators for diesel engines. /24/;/17, 3/; /28/

In 1-circuit mixed cooling systems the LT and HT water are mixed prior to radiators and there is only one flow through the radiators. In 2-circuit systems the LT and HT circuits can be separated throughout the system, meaning that there are two separate flows through radiators: LT water at a lower level and HT water at a higher level. The principal differences between mixed and separate circuit systems are shown in Figure 33. The dimensioning of the radiators is checked at the ambient temperature where the heat load is the highest: engine output has to be derated in ambient temperatures above certain limit. Derating leads to a lower heat load from the engine and therefore the highest ambient temperature does not necessarily coincide with the highest heat load of the engine. In separate 2-circuit systems there can be differing needs for the different circuits and therefore the 2-circuit systems need to be dimensioned also for the maximum ambient temperature. /17/; /24/

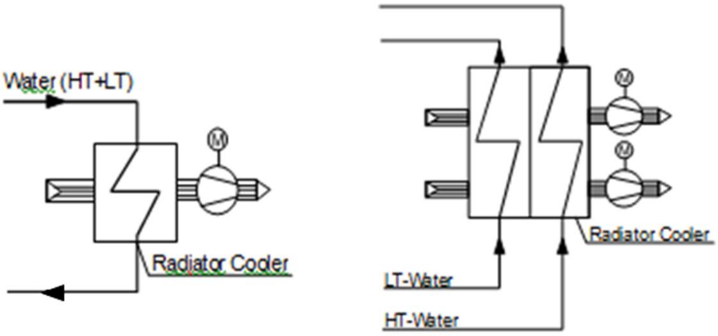


Figure 33. Mixed and separate cooling system radiators /17/

Radiators are controlled with frequency converters. The on/off approach has been used previously but frequency converters are the standard today. In the on/off approach radiator fans are turned on and off based on the cooling need. As there are multiple radiators for each engine, some of them can be turned on while others are off. When the control includes frequency converters, the rotating speed of the fans can be adjusted according to the cooling needs. Frequency converters allow a more detailed control and help to save energy needed in cooling but there is a higher investment cost related to them. /17, 12/ /24/ /25/

When using variable frequency drives (VFD) in controlling the radiators, the whole set of radiators belonging to one engine is controlled with one VFD. The control parameter is the LT water temperature after the radiator. Open loop control strategy is used i.e. there is no feedback loop. The fan speed range used is 30 – 100 %. The minimum level is set to ensure fan motor cooling and corresponds with the LT water outlet from the minimum temperature of the radiators. The maximum level of 100 % is aligned with the LT water maximum temperature out of the radiators allowing TCV to use the entire operating range. /19, 29/

4.3.2 Cooling Tower Systems

The cooling tower is a water / water heat disposal method used in power plant installations. Cooling towers are more efficient compared to radiator systems and therefore recommended if water is available. The primary circuit is a closed circuit operating on treated fresh water. The secondary circuit is a partially closed circuit also using treated fresh water. The cooling tower cools down the water in the secondary circuit of the system after it has been heated in the central cooler. The hot water is led to the upper part of the cooling tower where it is injected as a fine spray to the air in the tower. The spray is cooled due to an air flow induced by a fan and falls at the basin on the bottom of the tower from where it is pumped back to the central cooler. The cooling tower operating principle is presented in Figure 34. /15/; /25/

Cooling tower systems consists of cooling towers, fans installed at the top of the towers, water basin, electrically driven centrifugal pumps to enable the water flow in the system, central cooler and related piping. The fan speed for the cooling towers is recommended to be controlled with variable frequency drives. /15/; /19, 31-32/

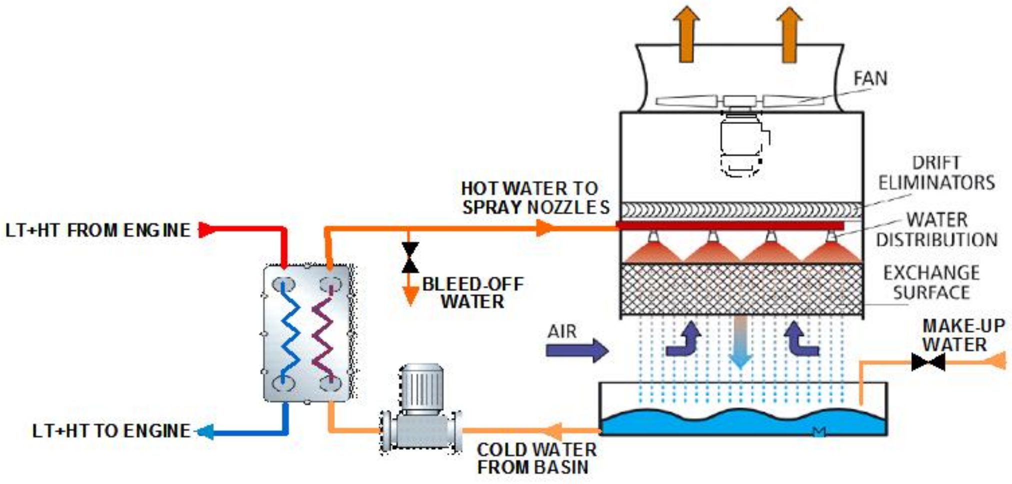


Figure 34. Cooling tower operating principle /15/

Cooling towers are not recommended to be used in cold conditions due to the risk of freezing: the temperature of the water coming from the cooling tower should not sink below +5°C. Since the cooling tower is an open construction, it is also sensitive to possible contamination in the air (e.g. cement and textile plants). Additional filtering of the circulating water is then required. /25/; /15; 2; 9/

Cooling towers are installed on the ground outside the power plant building on a plane concrete surface or on a plane steel framework (Figure 35). Recommendations are available on how far apart from each other the towers need to be set on the cooling tower field. The basins for the cooling towers are either individual for each tower or common for multiple towers. Individual basins enable disconnecting individual towers from the circulation e.g. for cleaning purposes. A common basin on the other hand enables to connect any tower with any engine and to compensate the underperformance of one tower due to mixing of the cold water in the common basin. /15, 9-10/

The materials used in cooling tower systems are of concrete or fiber glass for the basin, FRP (fiber reinforced plastic) or stainless steel for the framework and FRP for the casing panels. Nozzles and fill pack are made out of PP (polypropylene) but also PVC (polyvinyl chloride) is a suitable material for fill pack. The sulfur in the fuel can cause corrosion in the cooling tower materials if steel is used, thus tendency is to use FRP also in casing panels. /15/; /25/

Figure 35. Cooling towers installed on a common concrete basin /15/

The capability of cooling towers to reduce the temperature of the secondary circuit water is based on the ambient temperature and relative humidity of the air. The surrounding temperature can be referred to as dry bulb temperature, i.e. temperature indicated by a thermometer that is not directly affected by the solar radiation. Since the most of the cooling effect in cooling towers is based on evaporation of water and evaporating requires energy, it is possible to cool the water below the dry bulb temperature in cooling towers. The temperature that can be reached is called wet bulb temperature. The lower the relative humidity of the air is, the further below the air temperature the water can be cooled as the wet bulb temperature has linkage to the saturation of the air. If the air is saturated with humidity, there is no further cooling potential based on evaporation of the water. The impact of the relative air humidity on the wet bulb temperature of the air is shown in Figure 36. /15, 3/ ;/31; /48/

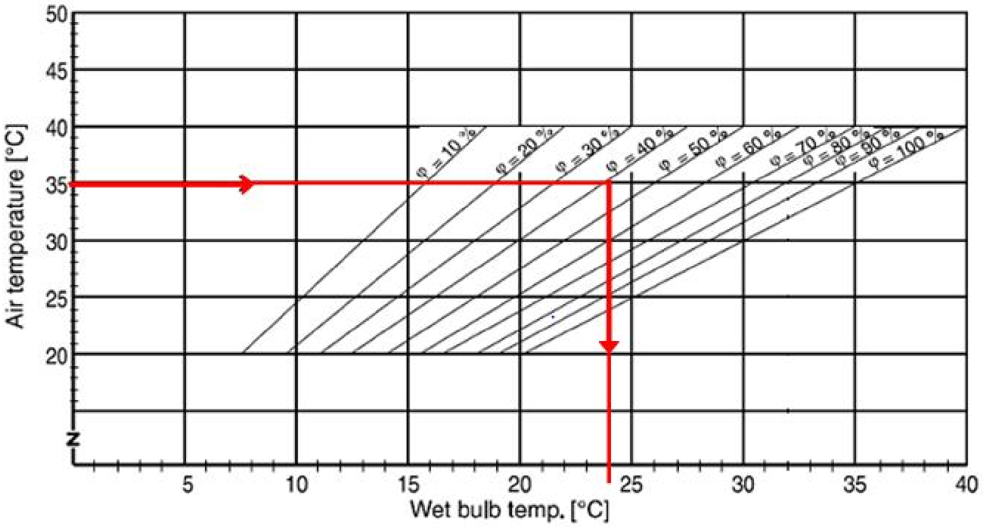


Figure 36. The impact of the relative humidity on wet bulb temperature /15/

There are actually two heat exchanges taking place in the secondary circuit of the cooling tower systems: one in the central cooler where the heat from the primary cycle is transferred to the secondary cycle and another in the cooling towers where the water circulating in the cooling tower system is cooled down by the ambient air and evaporation process to maintain its capacity to absorb heat from the central cooler. The wet bulb temperature together with the central cooler and cooling tower approach temperatures is used in calculating the engine inlet temperature for the primary circuit coolant:

$$T_{EI} = T_{WB} + T_{aCC} + T_{aCT} \qquad (3)$$

Where T_{EI} = Temperature at engine inlet (or central cooler outlet)

T_{WB} = Wet bulb temperature of the prevailing ambient temperature and humidity

T_{aCC} = Central cooler approach temperature

T_{aCT} = Cooling tower approach temperature /15, 3/

The differences in the temperature approach for diesel engines and SG/DF engines are similar to in radiator systems: diesel engines allow a higher temperature approach i.e. do not require as low charge air temperature. In cooling tower systems this difference is taken into account in the central cooler temperature approach so that temperature approach for diesel engines is higher than for the SG/DF engines.

The biggest limitation in using cooling towers is that they consume water due to evaporation, bleed off and splashing. For example, a large W50SG engine requires 15 m^3 of water per hour for sufficient cooling. Evaporation is an inevitable part of the process as the cooling effect is based on evaporation of the fluid. Evaporation causes the mineral content of the water to rise quickly unless part of the water is continuously bled off and replaced with suitable raw water. Without the bleed off the increased mineral content would lead to faster deposit formation, decreased heat transfer abilities and shorter lifetime of the system. The impact of the splashing is minimal compared to the water losses caused by evaporation and bleed off, thus it can be either left out of water consumption calculations or included with a small additional percentage. /15, 6/; /24/

4.3.3 Raw Water Cooling

Raw water cooling is a water/water heat disposal system and used in most of the marine installations. In marine installations the cooling water flows through a heat exchanger where it is cooled by sea water. The sea water system is an open system and separated from the closed cooling system that operates on treated fresh water. The principle of the sea water cooling is shown Figure 37. The sea water system consists of sea water pump, suction strainer, central cooler, temperature control valve (optional) and related piping. In marine installations the system typically has redundant components to ensure operations even during a component failure. /8/; /22/

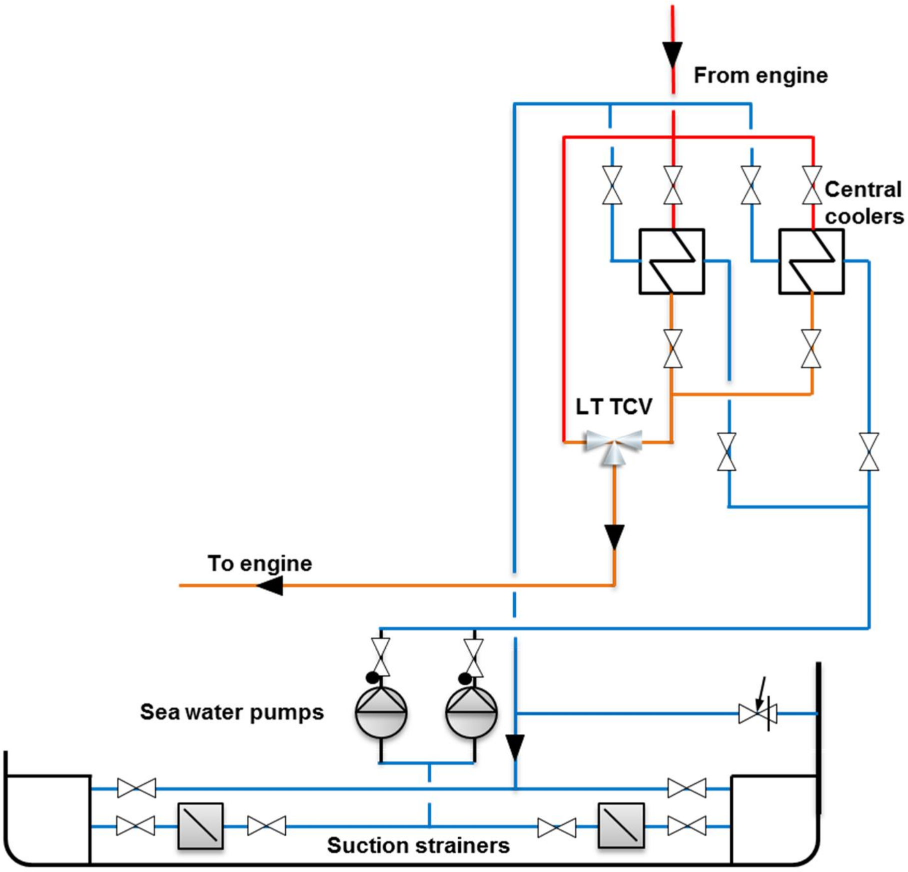


Figure 37. Sea water cooling system with central coolers /8/; /27/

A suction strainer is a filter used to prevent large particles and pieces of material (e.g. debris or ice) from getting into sea water pump and breaking it. Sea water pump is usually an electrical motor driven centrifugal pump that enables suitable flow in the sea water system. Systems with engine driven pumps are configured as well. The pump can be equipped with a frequency controller to adjust the energy consumption according to the flow requirements but this has not become common in marine installations so far. A stand-by pump for pumping sea water is required to ensure cooling capability in case of a malfunction of the pump. The temperature control valve is an optional component in the sea water system to regulate the flow from the central cooler either back to the suction strainer, pump and central cooler or to the sea chest. The TCV prevents the suction strainer from being blocked with ice and can therefore be a necessity in arctic conditions. /22/; /25/

As sea water has a high corrosive impact, the materials in the sea water need to be selected to withstand corrosion. Sea water pump casings are made of bronze. Titanium is used as plate material in sea water / fresh water central coolers. /22/

In power plant installations raw water cooling is seldom recommended. It can be used if a raw water source with the right quality is close enough and if the raw water system investment cost is lower than the cost of cooling tower or radiator system. In power plant installations the heat from the primary cycle is released to the same location all the time. As the increase in temperature can have high impact on aquatic ecosystems, the tightening environmental regulations may prevent releasing return water with elevated temperature back to the environment. /18, 2/

The raw water cooling system in power plant installations follows the same principles as in marine installations. The filtering system is usually more complex in power plant systems and done in multiple steps. The water intake area may require antifouling treatment to be applied to prevent growth of living organisms on the equipment, especially if warm sea water is used for cooling. /18, 2; 5/

4.4 Components Used Both on and off the Engine

Components that are installed both on and off engine include thermostatic valves, lubricating oil cooler and different flow control components, such as orifices, throttle valves and non-return valves.

4.4.1 Thermostatic Valves

Thermostatic valves are 3-way valves used to adjust the temperatures in the cooling water flows. Wax element thermostatic valves, electrically operated thermostatic valves and pneumatically operated thermostatic valves are used in Wärtsilä 4-stroke engines.

Electrically controlled thermostatic valves that are located on the engine auxiliary module are typically used in power plant installations. The LT thermostatic valve controls the temperature of the charge air and the HT thermostatic valve controls the jacket cooling outlet temperature. If there is a heat recovery system in the installation, a second TCV is used in HT-circuit to ensure optimal heat recovery. /19, 9-10; 19; 26/ ;/14, 8/

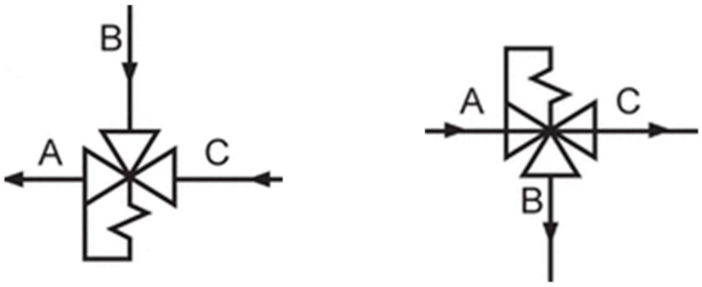
In Ship Power installations there are more variations available for the TCV locations:

- The LT TCV in diesel engines can be located off the engine after the central cooler and before the LT engine inlet (common for multiple engines if there is a common cooling system), on the engine after the LO cooler or even between the LT CAC and LO cooler on the engine (W46F). In some installations both an on engine TCV after LT CAC and off engine TCV after the central cooler are used.
- In diesel engines there is usually a wax element thermostatic valve in the engine in the HT circuit after the HT CAC.
- In DF engines there is usually an externally actuated thermostatic valve in the LT circuit after the LT CAC and LO cooler at the engine outlet.

- Variations with externally actuated LT TCV located off the engine between the LT CAC and LO cooler have been tried in DF engines but this lead to issues with low combustion air on low engine loads and the above set-up was taken into use instead.
- In DF engines the HT TCV is either a wax element thermostatic valve located in the same place as on diesel engines i.e. on engine after the HT CAC or an externally actuated thermostatic valve located off the engine but still in principle in the same place after the HT CAC and returning the flow back to the HT engine inlet when needed. /8/

If there is a heat recovery system in a marine installation, a TCV is used after the heat recovery system to adjust whether the flow continues to the central cooler or back to the engine HT inlet. The TCV located after the central cooler to regulate how much of the flow by-passes the central cooler can at times be used as the only LT TCV but is often needed as a second TCV in the LT circuit if the external cooling systems require LT water at e.g. 38 ºC and the charge air temperature control is taken care of with an additional TCV in LT circuit. /22/; /8/

Thermostatic valves can be installed either in mixing mode or diverting mode. In mixing mode there are two input flows to the TCV and the valve mixes a suitable temperature to one output flow. In diverting mode a single input flow is directed in suitable proportions to two outputs. The principles of mixing mode and diverting flow are shown in Figure 48. For both self-actuated and externally actuated thermostatic valves the maximum pressure drop recommended is 0,3 bar. /22/; /8/



Mixing mode:
A: output
B and C: inputs

Diverting mode:
A: intput
B and C: outputs

Figure 48. Thermostatic valve modes /22/

Wax element thermostatic valves (Figure 49) are self-actuated and operate based on a pre-defined set point. The control power is based on wax / copper mixture which is highly sensitive to temperature changes and expands and contracts in temperatures close to the set point. The temperature range of the wax elements is 8-12 ºC around the control point: for example with a set point of 35 ºC the valve starts to open at 29 ºC and is fully open at 41 ºC. Wax element thermostatic valves do not require additional control other than selecting the correct set point and thus there is no need for control power either. The downside is that due to lack of control the valve is not as accurate as externally actuated valves are and changing the set point requires a change of the entire wax element assemblies to ones with the correct set point. This type of thermostatic valves is typically used in diesel engines that do not require as accurate temperature control as engines running on gas (DF and SG). /8/; /14, 12/

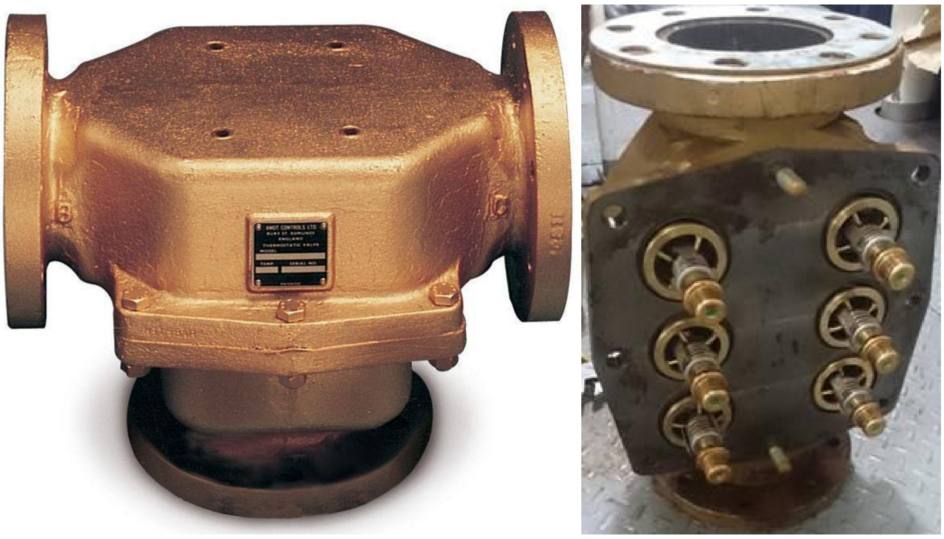


Figure 49. Wax element thermostatic valve /8/

Externally actuated thermostatic valves in Wärtsilä applications are controlled either electrically or pneumatically. Electrical control is common in marine installations whereas power plant installations often use pneumatic control. Externally actuated TCV:s are used in SG and DF installations where more accurate temperature control is needed. The control can be built either with TCV:s own control unit and sensor or with the UNIC system. The valve types used are rotary plug valves or globe type valves. The globe type valve is often selected in power plant installations for hot ambient conditions due to its low leakage level that helps prevent derating due to excessive by-pass line leakage. /14, 10/

Rotary plug valves (e.g. AMOT G-valve) are used in both marine and power plant applications. The control principle of a rotary plug valve shows in Figure 50: a rotor moves inside the valve based on control signals and affects the flow. Valves are available with 90º or 180º rotors, of which the 90º rotor can use either port 1 or 3 as a common port and the 180 º rotor uses port 2 as a common port. The valve can be operated both electrically and pneumatically. /14, 10/ ;/8/; /1, 7/

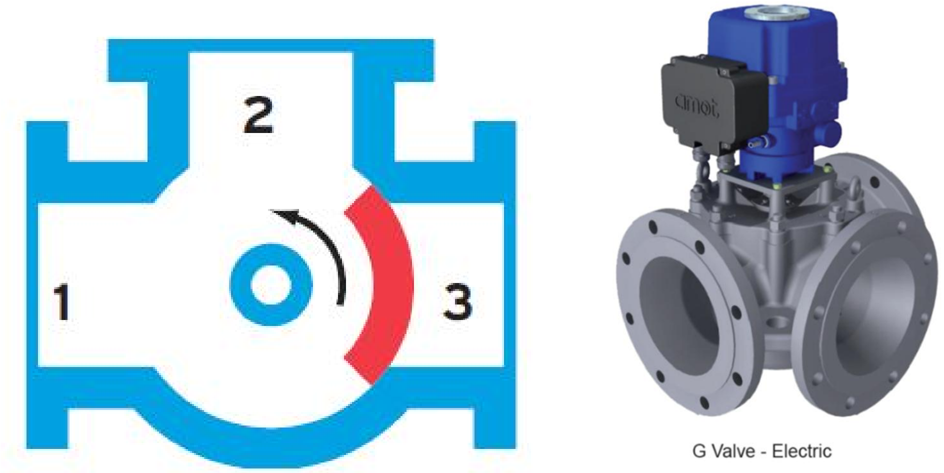
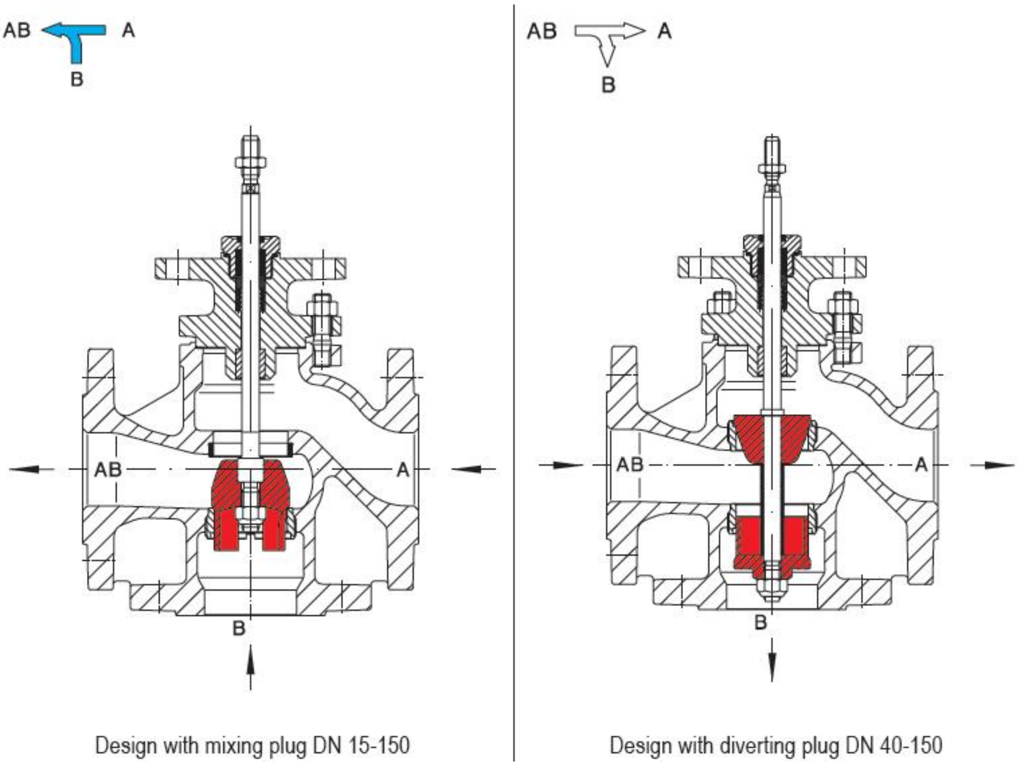


Figure 50. Rotary plug valve with 90 degree rotor and electrically actuated rotary plug valve /1, 7/

The globe type valve is used in power plant installations as the standard LT circuit temperature control valve on the EAM module. Globe type valves can be electrically or pneumatically actuated. The flow is controlled by a linearly moving plug that allows the flow either to mix or to divert when it moves up and down on the vertical axis of the valve. Due to the structure of the valve the common port is fixed and when selecting the valve, it has to be defined if the diverting mode or mixing mode is needed. The operating modes of the valve are shown in Figure 51 and the valve is presented in Figure 52. /14, 11/; /4/



Design with mixing plug DN 15-150

Design with diverting plug DN 40-150

Figure 51. The operating modes of a globe type thermostatic valve /4, 3/

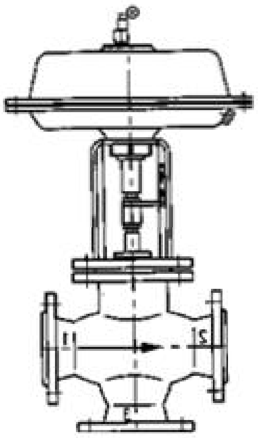
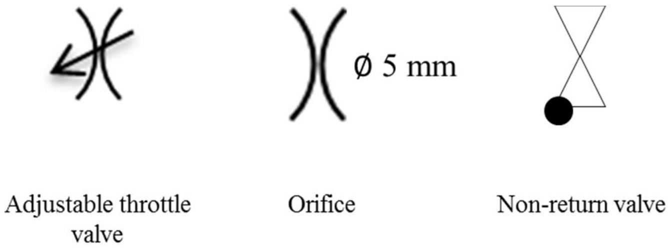


Figure 52. Globe type thermostatic valve /14, 11/

4.4.2 Flow and Pressure Regulating Components

The cooling system is adjusted with a number of components, such as throttle valves, orifices and non-return valves to regulate the pressure and flow across the system.

Adjustable throttle valves are needed in all by-pass lines to ensure balanced operating conditions for the temperature control valves. Orifices with a standard 5 mm diameter are used for regulating the flow e.g. in the air venting pipes. Non-return valves are installed e.g. after pumps and after the engine outlet to prevent the flow from changing direction. The graphic symbols for these components are shown in Figure 53. /3/; /8/



Adjustable throttle valve

Orifice

Non-return valve

Figure 53. Graphic symbols for selected flow and pressure regulating components /8/

4.4.3 Lubricating Oil Cooler

Lubricating oil cooler is a heat exchanger ensuring that the lube oil temperature stays within the set limits during engine operations and thus retains the properties required. The LO cooler can be a plate heat exchanger, tube heat exchanger or brazed plate heat exchanger of its type. The LO cooler is installed either on engine or off engine and it is included in the LT-circuit of the cooling system, after the LT CAC. As the LO cooler is considered as a part of the LO system further details of the component can be found in Engine Auxiliary System Guideline – Lubricating oil system. /16/; /22/; /25/

5 COOLING WATER QUALITY

Water is used as the cooling agent n Wärtsilä 4-stroke engines. Water is an ideal coolant due to its high specific heat capacity and high thermal conductivity. Additives are needed in the cooling water to protect the system from corrosion, fouling and deposit formation. /9/; /30,333/

Corrosion is an electrochemical process in which the oxidation of metals or alloys leads to a gradual destruction of materials. Corrosion causes damage to the strength of the materials it affects. The term fouling is used when referring to substances (e.g. insoluble salts, corrosion products, oils, fats and debris from the air) being caught physically to the surfaces of the cooling systems. Fouling may also involve biomass, for example bacterial growth. Fouling has a negative impact on the flow of cooling water as we all as on the heat transfer properties of the system. Deposit formation means the formation of hard crystalline scales built up from insoluble salts or metal oxides on the heat-transfer surfaces of the cooling system. Deposit formation reduces the heat-transfer capabilities of the cooling system. Furthermore, the corrosion process may speed up significantly under the deposit formations. /21, 86-87, 105/

The requirements set for Wärtsilä 4-stroke engines considering the raw water treated to become cooling water, the cooling water chemical specification and the additives used are defined in Chapters 4.1. – 4.3.

5.1 Raw Water Quality and Additives

To make sure the cooling water meets the specifications there are limitations for the raw water used in the cooling systems. The raw water has to meet the specification defined in Table 5.

Table 5. Raw water specification for Wärtsilä cooling water /9/

Property	Unit	Limit
pH	-	6,5 – 8,5
Hardness	°dH	Max. 10
Chlorides	mg/l	Max. 80
Sulphates	mg/l	Max. 150

As defined in Chapter 3.4 the pH level of the water has a high impact on the corrosive properties of the cooling water. If the water is too hard, the deposit formation is intense and the heat transfer capabilities of the system suffer. If the water is too soft, it has a high ability to dissolve oxygen and carbon dioxide from the air thus leading to higher acidity and increased corrosion. /9/

The levels of chlorides and sulphates in the raw water have to be known as both are aggressive corrosives against iron. The corrosive effect can be controlled with additives, such as nitrite but the dosing of the additive needs to be increased in case of a high level of this corrosive chemical is present in the raw water or cooling water. /9/

Sodium nitrite based additives are used commonly as passivators in closed cooling systems Nitrite based additives are also the most common ones used in Wärtsilä 4-stroke engines and they can be used in both powder and liquid format. In addition to nitrite based products there are also more environmentally friendly alternatives available, such as carboxylic acid based products. /9/ /7/; /21,150/

Nitrites act as anodic inhibitors thus preventing corrosion. The passivating qualities of the nitrites are fairly good but a relatively high dose is needed to ensure no pitting corrosion takes place in the cooling system. High levels of chlorides or sulphates require a higher dosage to be used. In order to use nitrite based corrosion inhibitors economically and sustainably the cooling system has to be pre-cleaned to expose the anode, the system has to have de-aeration in place to prevent nitrite from oxidizing to nitrate and the volume of the cooling system needs to be known in order to add the correct amount of additive. /21, 150/

Glycol is the selected anti-freezing additive for Wärtsilä 4-stroke engines. All Wärtsilä approved corrosion inhibitors can be used together with glycol. Since glycol has a negative impact on the cooling water heat transfer capabilities the amount of glycol used has to be minimized. The use of glycol may also lead to the need of derating the engine output. Two types of glycol, monopropylene glycol (MPG) and monyethylene glycol (MEG) can both be used on Wärtsilä engines. Out of these, MPG is considered as a more environmentally friendly option. /9/

The dosage recommendations for different additives depend on the selected product and are based on the manufacturer specifications and raw water quality. Wärtsilä provides the dosage recommendations for approved additives based on normal raw water quality with minimum and maximum limits. A slight overdosing is usually better than under-dosing but significant overdosing of nitrite based additives (2-3 times the recommendation) may cause corrosion on soft alloys, such as copper and brass and may impact also deposit formation in addition to being expensive. With nitrite based additives under-dosing can lead to higher rate of corrosion since the corrosion rate is increased with low nitrite levels and only decreased after sufficient concentration is reached (see Figure 54). If there is glycol in the cooling system, the additives have to be dosed for the volume including both the water volume and glycol volume as glycol does not include corrosion inhibitors. /9/; /26/

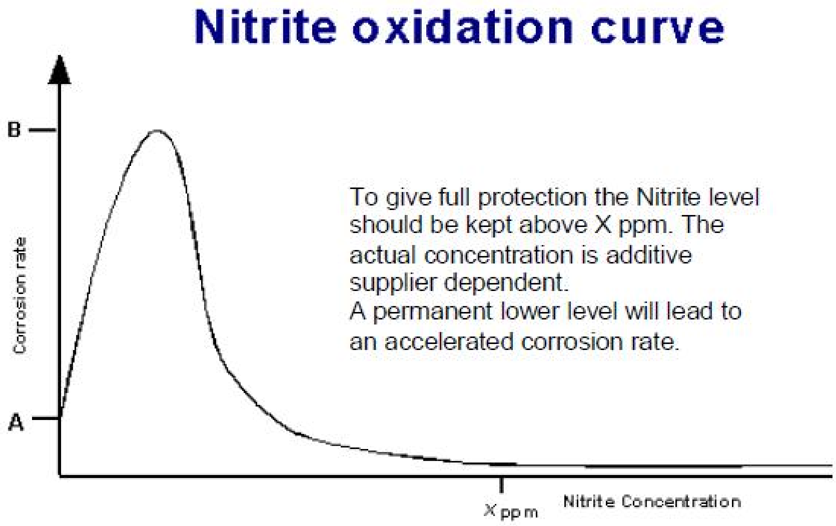


Figure 54. Nitrite oxidation curve /9/

Cooling water additives are not fully compatible with each other. The mixing of additives may cause difficulties in dosage and for example foaming issues and therefore it is not allowed to mix the additives. When changing from one additive to another the system needs to be drained and, in case dirty, also washed prior to filling in and adding a different additive. Additives that come in powder form should be dissolved into water in the maintenance tank prior to adding to the system. /9/; /26/

5.2 Cooling Water Quality

Cooling water has to meet specifications related to acidity (pH) and levels of nitrite (NO_2), chlorides (Cl) and sulphates (SO_4). It is recommended that these parameters are followed up on a regular basis i.e. on 1-4 week intervals depending on the stability of the system. Additionally the amounts of iron (Fe), nitrate (NO_3), calcium (Ca), magnesium (Mg) and copper (Cu) are recommended to be followed up from cooling water 2-4 times per year. The recommended values are shown in Table 6. /9/

Table 6. Cooling water properties requiring follow-up /9/

Property	**Typical level**	**Follow-up interval**
pH	8 – 11	1-4 weeks depending on the stability of the system
Nitrite (NO_2)	500 – 2500 ppm depending on the additive	
Chlorides (Cl)	< 40 mg/l	
Sulphates (SO_4)	< 100 mg/l	
Iron (Fe)	< 1 mg/l	2-4 times per year
Nitrate (NO_3)	< ~200 mg/l	
Calcium (Ca)	Total hardness ($Ca + Mg$) < 10°dH	
Magnesium (Mg)		
Copper (Cu)	< 1 mg/l	

The level of iron in the cooling systems is often higher in new or recently overhauled systems due to loose iron debris but should come down to recommended level gradually over time. Increase in the nitrate levels especially combined with decrease in the nitrite level may indicate bacterial activity and contamination of the cooling water. /9/

Entrained air (bubbles) in the cooling water can affect the heat transfer properties of the system as air has significantly lower thermal conductivity than water. Air bubbles can build up on the hot surfaces of the cooling system and they tend to accumulate in locations with low flow, thus creating a possibility for hot spots to develop. Therefore, the de-aeration of the system has to be taken care of. /26/

Dissolved oxygen in the cooling water on the other hand may cause the nitrite to oxidize into nitrate. Nitrite has the capability to react with the iron surfaces of the cooling system and to form a layer that prevents corrosion. If the nitrite in the system reacts with dissolved oxygen prior to reacting with the layers to be protected corrosion can take place. /26/

6 TROUBLESHOOTING

The typical issues in cooling systems covered by Services bulletins are presented in this chapter. The cooling system is a system requiring specific maintenance and the importance of the maintenance is highlighted in this chapter by describing the outcomes if neglecting “good housekeeping” on cooling systems.

6.1 Services Bulletins on Cooling System

Services bulletins referring to the cooling systems of 4-stroke engines are listed in Table 7 with the document number. Each bulleting is presented shortly in this chapter.

Table 7. Cooling system related Services bulletins

	W20	W20DF	W26	W32	W32GD	W34DF	W34SG	W38	W46	W46F	W50DF	W50SG
Cooling system												
Cooling water quality	4619Q002; WS19Q265											
Control system											5001S223	
LT and HT circulating pumps				WS19T007			WS19T007					
Charge air cooler												
Temperature control valves												
Engine jacket												
Pre-heater												
Piping												
Maintenance tank												
Expansion tank												
Pumps installed off the engine												
Radiators												
Cooling towers												
Raw water cooling												
Heat recovery equipment												

6.1.1 4619Q002 - Cooling Water Treatment and Analysis

Services bulletin 4619Q002 presents the requirements for raw water used in cooling systems as well as the requirements for cooling water when it has been treated with additives. The bulletin describes the importance of following up the quality of the cooling water and provides guidelines on how often to do it. See

Chapter 4 for further details as this bulletin has been used as the source of information over there. /45/

6.1.2 WS19Q265 - General Flushing Instructions for the Engine Internal Cooling Water System

Services bulletin WS19Q265 defines the procedure for flushing the engine cooling system if there is a need to remove deposit formations, scaling or rust from the surfaces of the system. A visual inspection of the surfaces of both the LT and HT cooling water circuits should be done when overhauling the engine. It is more common that the HT circuit requires flushing but the LT circuit should be inspected, nevertheless. Flushing is to be done if there are visible signs of corrosion or deposit formation on the surfaces of the system as the excess material on the heat removal surfaces of the system will eventually impact the heat transfer capabilities of the cooling system. /45/

The cleaning agent for flushing is selected based on the need:

- Contamination of purely oily nature is removed with Degreaser
- Contamination that includes both oily and hard deposits is removed with CombiDegreaser
- Hard deposits such as scale and corrosion are removed with Descaler

Prior to flushing preparations need to be taken to separate the on-engine cooling system from off-engine parts of the system and to close out e.g. thermostatic valves from the flushing. The instructions for these steps are engine specific. A tank, heater, pump, filter and hoses to connect the equipment are needed in order to set up the flushing. The tank needs to accommodate the volume of both the LT and HT systems. The pump should be selected so that it provides a sufficient flow for effective flushing but does not exceed the pump capacity of the cooling system or the pressure limits set for the engine. The heater is used to warm up the flushing water to required temperature (typically > 60 ºC). The filter should be installed between the engine and the tank to capture the particles and prevent them from entering the tank. Hoses of the suitable diameter are used to connect the flushing equipment to the engine. Recommendations on the equipment sizing are given in the bulletin. /45/

Once flushing is done, fresh water meeting the raw water requirements set for the cooling systems is used to balance the pH level in the system and rinse out the detergents. When a pH level similar to the water is reached, the system is drained and cooling water treated with additives as described in bulletin 4619Q002 is added to the system. Cooling water heated up to approximately 60ºC should be circulated in the engine with for two hours to ensure that a coating is formed on the surfaces of the system and all residues of the detergent are removed. /45/

6.1.3 5001S223 - HT Cooling Water Temperature Reference Modification

Services bulletin 5001S223 defines a new HT cooling water temperature reference after cylinders for certain engines equipped with a specific automation system. Cold corrosion has been noted on these engines due to HT temperature being too low on low loads, thus the temperature reference is increased and instead of using even value for all loads the reference temperature is set to be higher at low loads and decreases as the load increases. /45/

6.1.4 WS19T007 - Repair Sleeve for Cooling Water Pump Shaft

Services bulletin WS19T007 provides instruction on how to use a repair sleeve on the cooling water pump shaft instead of replacing the shaft on certain engine configurations. An oil leakage has been noted on these engines from the telltale hole of the cooling water pumps caused by a wear on the pump shaft at the shaft seal. The bulletin describes how to mount the repair sleeve on different pump types and when and how to remove it before bearing removal. /45/

6.2 Impacts of Lack of Maintenance on Cooling Systems

As described in Chapter 2.2 the cooling system is essential for the engine to operate flawlessly and sustainably. Since there is water based coolant flowing in the system built mainly out of steel components, the maintenance of the system has to be taken care of. Otherwise, there will be impacts on the system flow, pressure and heat transfer capabilities.

Maintaining the cooling water quality within specification ensures that the cooling system heat transfer capabilities stay on the right level and that corrosion does not damage the system. The cooling system goes through a visual inspection if the engine is “opened” in such a way during an overhaul that it is possible to take a look into heat transfer surfaces or piping surfaces. The system is expected to stay in operating condition for years by following the cooling system maintenance guidelines. Therefore, the follow-up of the cooling water quality is essential as in worst case the damages in the cooling system may lead to damages in engine components, such as the cylinder liner and to expensive maintenance work on the cooling system, such as mechanical cleaning of the piping with excessive deposit formation and scaling. /9/ /26/

The pH level of the cooling water, the nitrite levels and the chloride level are the most important cooling water components to follow-up. An increased pH level indicates that the corrosive capabilities of the cooling water are becoming stronger. Nitrite is the additive that protects the cooling system from corrosion by forming a protective layer on the surfaces of the system. If the nitrite levels in cooling water are too low, the corrosion protection capabilities are compromised. Chloride is a strong detergent that has the capability to break other molecules, for example the bonds that nitrites form in the protective layer of the steel surfaces in the cooling system. Therefore, the nitrite dosing has to be increased if the levels of chlorides are high in the coolant. Corrosion will eventually impact the strength of the components, such as the exhaust gas seat or even the cylinder liner and lead to expensive overhauls. /26/

In addition to preventing corrosion the cooling water additives protect the system from fouling and scaling. Both fouling and scaling will eventually show on the cooling water system as temperature increases: if there are additional layers of material on the heat transfer surfaces, the heat transfer capabilities are decreased and the system is not able to cool the engine as it should. There can be changes also in the flow or pressure of the system: if the pipe diameters start to decrease due to deposit formation, the pressure resisting the flow in the system is increased and the flow is reduced. That will also impact the heat transfer capabilities of the system. Formations can be removed by flushing or mechanical cleaning but these are costly procedures requiring an engine stoppage and should therefore be reduced, by instead maintaining cooling water additives on the correct level and ensuring the correct raw water quality. /26/

The heat exchangers in the system (charge air cooler, central cooler, radiators) require cleaning up from time to time. Usually the cleaning is not needed on the cooling water side of the heat exchanger but on the opposite side: the tubes through which the coolant flows in radiators need to be cleaned from the outside, the central cooler raw water side needs to be cleaned up as fairly untreated water is flowing there and the charge air cooler air side may become clogged if it is not cleaned. It is important to take care of cleaning up the charge air coolers and central coolers during maintenance breaks to avoid an unplanned service break from taking place due to the cooling system components losing their heat transfer capability. Radiators are typically not washed unless they show signs of reduced heat transfer capabilities. /24/; /25/; /26/; /27/

Good maintenance of the cooling system requires regular follow-up of the cooling water quality. The checking of the coolant should be done more often when the engine has just been taken into use as there is plenty of surface area available then for the nitrites to react with and the nitrite level in the coolant can decrease rapidly. When the system is in steady state the coolant analysis can be done on 2-4 weeks intervals. /26/

6.3 Cooling System Balance

Due to the dynamics of the cooling systems (pressure affects the flow and vice versa; each component on the system affects the pressure; flow and pressure affect the cooling capability of the system) the balance of the system has to be ensured when commissioning the system or doing any changes in the system. Typical issues on the cooling system impacting the balance of the system are for example the following:

- The system is not built up fully according to the specification, e.g.
    - Instructions are not followed when it comes to TCV location and/or temperature sensor linked to TCV
    - Piping diameter has been changed
    - Throttle valves or orifices are missing
- The flow through the expansion tank is not restricted with orifices leading to too high flow through the expansion tank which can further lead to too high LT water inlet temp to engine
- Flow is too high or too low causing too low heat transfer at heat exchangers
- Pressure losses in the external cooling equipment (marine installations) are higher than expected
- Wrongly dimensioned pump for the external cooling equipment leading to variations on the on-engine cooling system. /24/;/25/; /26/; /27/

6.3.1 TCV Location and Temperature Sensor Location

In marine installations the TCV linked to the heat recovery system is installed in the mixing mode and controls the temperature of the water going back to the HT circuit on the engine. The by-pass line of the TCV carrying hot HT water is connected to the LT line after the TCV intake from LT line (see Figure 55). If the hot connection is too close to the TCV cold connection, the hot flow might get back to the TCV and cause the coolant in the HT circuit flowing back to the engine to be too warm. Externally actuated temperature control valves utilize temperature sensors for the control. The sensors are also sensitive for location and need to be installed according to the instructions to make sure a correct reading is used to control the system. The sensor should be e.g. installed at a straight part of the pipe for a minimum distance from curves. /26/

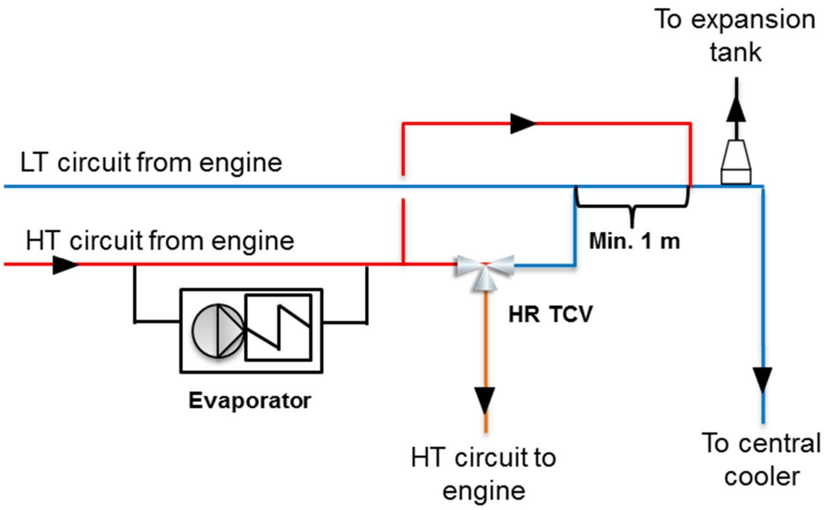


Figure 55. Distance required between LT intake for HR TCV and HT connection to mix to LT circuit /8/

6.3.2 Missing Throttle Valves or Orifices

Throttle valves and orifices are used in the system to balance the flow and the pressure. If these components are not used where planned or not adjusted during commissioning to balance the system, issues with flow, pressure or event heat transfer capabilities may occur. A typical case is that the orifices from vent pipes leading to the expansion tank are missing which leads to a too high flow back to the LT circuit from the expansion tank. As the flow through expansion tank is not going through the heat disposal system the temperature in the HT circuit may become too high. /25/; /26/

6.3.3 Too High Flow through Heat Disposal System

The heat transfer capability at heat exchangers is dependent on the temperature difference between the coolant in the primary cycle and the cooling media in the secondary cycle (e.g. coolant and ambient air in case of radiators) but also about the time that the cooling media affects the coolant. If the flow in the primary cycle is too high, the speed of the coolant is so fast that the cooling media in heat exchangers does not have sufficient time to absorb enough heat. The heat transfer capability can be adjusted by bringing the flow to nominal levels by e.g. adjusting throttle valves. /24/

6.3.4 External Systems Affecting the balance of the Engine Cooling System

In marine installations there is often additional equipment connected to the same sea water heat disposal system that engines are using. Known issues with external systems are e.g. large pumps that cause the pressure on the on-engine systems to become too high. Too high pressure caused by external pumps is identified as cause for wax element thermostatic valve pins to become hammered and therefore seize. In addition to large pumps increasing the pressures too much there are also occasions with external systems causing too high pressure losses. /25/

6.4 Relevant Services Report Summaries

Approximately 25 cooling system related site survey / inspection reports were read and analysed. Seven of them were selected for report summaries. Selection was done in such a way that many different engine types and the typical issues highlighted in the expert discussions were represented. The report summaries were plotted on a matrix showing the correlation of the report to the engine type and cooling system components (Table 8). All relevant components / elements of the system were listed for each report i.e. the same report summary was referred to on multiple rows. The template used for report summaries is shown in Appendix A. The report summaries and the actual matrix are not public information and therefore not presented in this thesis.

Table 8. Matrix used in plotting the Services reports with exemplary data

	Engine 1	Engine 2	Engine 3	Engine 4	Engine 5	Engine 6	Engine 7	Engine 8	Engine 9	Engine 10	Engine 11	Engine 12
System balance	F			G				C				
Cooling water quality	F						D			A		
Control system								C	E			E
LT and HT circulating pumps	F								E			E
Charge air cooler												
Temperature control valves				G				C				
Engine jacket												
Pre-heater												
Throttle valves / orifices	F			G				C				
Piping	F		B	G								
Maintenance tank		G								A		
Expansion tank			B									
Stand-by pumps		G										
Radiators												
Cooling towers												
Raw water cooling												
Heat recovery equipment												
External cooling equipment				G				C				

7 CONCLUSIONS

7.1 Summary of Cooling System as Engine Auxiliary System

The cooling system is one of the engine auxiliary systems in addition to e.g. fuel oil system and lubricating oil system. The cooling system carries away the heat load from the hot parts of the engine and thus protects the engine from thermal damages but also cools down the charge air to enable efficient combustion process and cools down the lubricating oil to maintain the lubricating capability of it. The cooling system on the engine is a closed system using treated fresh water as cooling agent. Different temperatures from the LT and HT circuits are used in controlling the operations of the engine and the cooling system. Pressures from the LT and HT circuits are used as indicator of the system capability to perform the work and volume flows in the circuits are one means of gathering information in troubleshooting situations.

Cooling systems on Wärtsilä 4-stroke engines have a wide variety of different configurations and set-ups available. The heat disposal methods used are radiators, cooling towers or raw water cooling. Raw water cooling can be arranged with central coolers, box cooler or keel cooler. The cooling equipment is arranged in LT and HT circuits so that the LT circuit typically includes the LT CAC and LO cooler and the HT circuit includes the engine jacket and the HT CAC but in some cases the HT CAC is part of the LT circuit. The LT and HT circuits often mix at some point prior to heat exposal equipment (central cooler or radiators) but set-ups with fully separate LT and HT circuits are also available. The selection and dimensioning of the cooling equipment is done according to the engine heat load, ambient conditions, availability of water, investment and operating costs and the preferences of the customer.

The cooling systems in power plant installations are usually engine specific and built according to standard configurations. Components installed off the engine are assembled on engine auxiliary modules. Systems are balanced during commissioning and after that balancing issues are fairly rare. Radiators are the most common heat disposal method but cooling towers are also used from time to time.

Taking into account the ambient conditions, especially temperature and humidity are key points in dimensioning the cooling systems.

The cooling systems in marine installations are typically common for all the engines in the same engine room. There are often external cooling equipment, such as a generator and gear box cooling connected to the same sea water cooling system than the engine cooling. Raw water cooling is the predominant heat disposal method: central coolers are the most common ones but box coolers have become more common in recent times. As the cooling systems are more complex than the engine specific configurations used in power plants, there are more issues with system balancing on marine installations.

Cooling water used in both marine and power plant installations is treated fresh water. Additives are needed to prevent corrosion and bacterial growth in the systems. Sodium nitrite based additives are the most common ones used. Glycol is added to the cooling water in case protection from freezing is needed. The quality of the cooling water has to be followed up regularly to make sure corrosion, fouling or deposit formation is not taking place in the system. Corrosion impacts the tensile strength of the components and can lead to leakages. Deposit formation and fouling impact the heat transfer capabilities of the cooling system and may also lead to higher pressure losses in the system if the water channels start to narrow down and lose diameter due to excess coating on them.

7.2 Conclusions on the Thesis Process

The structure of the thesis was agreed in meetings with the initiator of the work and the thesis supervisor. At the same time the initial list of the experts to be interviewed was defined. The guideline for cooling systems was done by first reviewing the existing documentation within the case company and by studying the available literature on cooling systems and 4-stroke engines. The majority of the guideline text was written first based on the document sources.

The experts were interviewed when the basic structure of the guideline was put on paper. The relevant parts of the work were walked through with the experts in one to one meetings and the content of the guideline was that way validated. At the same occasion questions that had risen during the writing process were discussed and further details and clarifications were acquired.

The combination of using both written sources and discussions with experts worked well in gathering the information. The timing of the discussions could have been better considered: if the experts would have been notified in an earlier phase of the work, they would have been able to provide the latest documents and training materials to be used as source. On the other hand, prior to studying the existing materials and writing the main parts of the guideline there was not enough knowledge to ask the right questions and fully benefit from expert discussions.

Even though there is plenty of material available in the company on the cooling systems there are only few documents that cover both power plant and marine installations. As Technical Services is serving both businesses, there was a need for a guideline combining knowledge from both areas. The matrices built in the troubleshooting part of the guideline are planned to be further complemented when new Services bulletins are published and when new reports from the Technical Services cases are available. If matrices are systematically used from here on, they provide structured information on different cooling system cases and may help in identifying trouble areas that require preventive actions.

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APPENDIX 1

Template for report summaries:

Report name:	Site survey report *Engine type* *Site name* Cooling water system
DocID:	*DBAAxxxxxxx*

Background
Short description about the background of the case, the issue and the starting point.
Conclusions
Short description of the actions taken on the site to find out the root cause of the issue. *Short description of the corrections and balancing activities taken on the site.*
Recommendations
Further recommendations given to the customer to ensure sustainable operations. Can be e.g. corrections that need to be done during an overhaul or continuous maintenance instructions.