Micro Gas Turbines on Mega Yachts - A Feasibility Study

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LIST OF SYMBOLS

S_i: Entropy at stage i

p_i: Pressure at stage i

T_i: Temperature at stage i

P_{ij}: Power between stage i and j

P_C: Power of compressor

P_T: Power of turbine

P_T: Brake power

η_{td}: Efficiency of cycle

w_{cycle}: work of the cycle

q_{in}: Heat input per kg of gas

q_{out}: Heat out of exhaust of gas per kg

q_{HE}: Heat exchanged in heat exchanger

$\dot{Q}$: Heat input

$\dot{Q}_{ij}$: Heat for cycle i-j

$\dot{m}$: mass flow of gas

c_p: Specific heat of gas for constant pressure

c_v: Specific heat of gas for constant volume

κ: Ratio of c_p and c_v

τ: Maximum temperature ratio

π: Pressure ratio

η_C: performance of compressor

η_T: performance of turbine

η_{HE}: Heat exchanger effectiveness

n_c: Constant which relates the temperature ratio and pressure ratio in the compressor

n_t: Constant which relates the temperature ratio and pressure ratio in the turbine

ϕ_0: Cooling power of the chiller

ϕ_A: Released heat

ϕ_H: Supplied heat

ϕ_C: Wasted heat

P_{el}: Electrical power

LIST OF ABREVIATIONS

AC: Air Conditioning

COP: Coefficient of Performance

DPF: Diesel Particulate Filter

FO: Fuel Oil

GA: General Arrangement

GenSet: Generator Set

HSC: Heat Storage Capacity

HVAC: Heating, Ventilation and Air Conditioning

IMO: International Maritime Organization

LO: Lube Oil

MGT: Micro Gas Turbine

SCR: Selective Catalytic Reduction

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ABSTRACT

This thesis has been realized in collaboration with Blohm+Voss Shipyards GmbH, in the Mechanical Engineering Design Department located in Kiel.

The changing of the limits of the exhaust gas in accordance with the IMO Tier III regulations, which enters into force in January 2016 for new ship constructions, makes necessary to adapt the future power units such that they are able to achieve the strictly threshold of oxides of nitrogen (NOx). In order to fulfil such requirements, conventional diesel engines need an additional exhaust gas treatment unit, increasing the investment, operational and maintenance costs, as well as weights and space required inside the ship.

Another solution is to replace the diesel engines by micro gas turbines, which do not require post-treatment in the exhaust system. Besides, the technology of the micro gas turbines is conceived such it only has one rotating component, and all the lubrication needed is carried out with air bearings. Thus, there is no need of LO (lube-oil) system. As a consequence, the maintenance required is broadly reduced, as well as vibrations and noise levels, since the turbines are already installed in a sound enclosure, therefore there is also no need of silencer.

The mega yacht BV80 from Blohm+Voss will be used as the case study to replace its current generator sets by micro gas turbines. The project is currently in an advance stage (the first ship from the BV80 series started to be built on October 2015). For this reason, one of the aim of the study is to replace this system trying to modify the less things as possible in the general arrangement of the ship.

Different solutions are analyzed, starting from a direct comparison of both systems, and followed by different alternatives that could increase the performance of the micro gas turbines. Every solution contains an economical evaluation in order to compare the systems in terms of lifetime costs, technical feasibility, advantages and drawbacks.

Based on the case study of the BV80, the results can be extended to similar projects in the maritime sector, for which micro gas turbines technology offer an outstanding comfort.

1. INTRODUCTION

Mega yachts are pleasure vessels in which comfort is an imperative feature that must be highlighted. In order to provide such class, one of the engineering challenges is to minimize unpleasant sources such as vibrations, noise or rolling. Ideal ambient conditions onboard must be guaranteed for any climate state as well. For this reason, HVAC systems are designed so that their maximum capacity might never be required.

At the same time the mega yacht should be offered with the minimum cost as possible to enter in a market where only few people in the world are able to buy it, and several competitors struggle to sell their products.

1.1. Motivation

Due to the new regulations of IMO Tier III on the exhaust gases, from January 2016, new ship constructions have to fulfil the limits imposed for NOx emissions.

Thus, conventional diesel engines have to be adapted with an additional post-processing unit to reduce the emissions, leading to an increase in weight, space needed onboard, investment and maintenance.

Micro Gas Turbines do not require such units, and thank to their outstanding pleasure characteristics as low noise levels and vibrations, their installation on Mega Yacht will be the matter to study of this Master Thesis.

1.2. Objective

Blohm+Voss Shipyards GmbH is designing mega yacht BV80, with a length of 80 meters. The objective of this work is to analyze the application of micro gas turbines on this yacht for the auxiliary power generation. The first step is to do a direct comparison with the initially conceived auxiliary plant, composed of 3 MTU V2000 M41A installed to provide the power for the auxiliary systems. In this part are compared the differences in auxiliary systems, noise and vibration levels, lifetime costs and power density related to volume and weight.

Based on the direct comparison, additional solutions that could increase the overall efficiency of the power plant are the following matter of study.

One of the solutions that can be adapted inside the ship is the installation of an absorption chiller which can reduce the electrical demand of the ship, and in consequence also, the consumption of fuel-oil and lifetime costs. A MATLAB code has been developed in order to select the most convenient absorption chiller model available in the market.

Due to the advanced stage of the design, one of the goals is to minimize the shipbuilding impact and the variation in the general arrangement. Finally, the results obtained are analyzed taking into account all the factors affecting the characteristics of the vessel and her construction.

Even though the work is focussed on a particular mega yacht, it is expected that the results and the conclusions obtained can be applied to general new ship constructions.

2. MICRO GAS TURBINES

MGTs (micro gas turbines) are very small combustion turbines with outputs varying approximately from 20 kW to 500 kW. There are no size limitations to distinguish micro turbines from small industrial gas turbines. Nevertheless, there are some features that characterize micro gas turbines such as:

- Radial flow compressors
- Low compression ratios
- No blade cooling
- Recuperation
- Low temperature materials leading to low production costs

This kind of turbines offer a number of potential advantages compared to other technologies for small scale power generation, such as compact size and low weight per unit power, leading to reduced engineering costs, small number of moving components, lower noise levels, multi-fuel capabilities and lower emissions. Absence of reciprocating and friction components means that there are just few balancing problems, and the use of lubricating oil is very limited.

2.1. Working principle

Micro gas turbines have their main components mounted on the same shaft (compressor, turbine and generator), reason why they have very low vibration levels. Different parts of a micro gas turbine are shown in Figure 2.1.

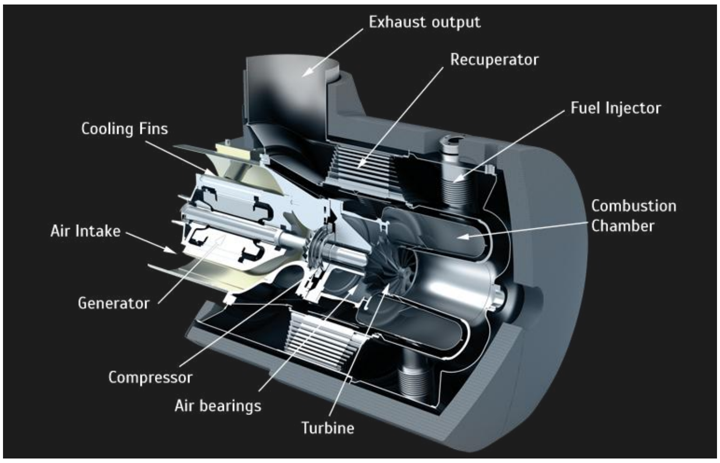


Figure 2.1. Components of a micro gas turbine, [6]

The air taken for the combustion is primarily compressed in the compressor, with average compression ratios varying from 3 to 4. After this stage, the air is driven to the combustion chamber, in which, together with the fuel, it is burned, increasing the entropy and temperature of the mixture gas. Finally, the mixture is directed to the turbine, in which the gas is expanded, and transforming its internal energy into mechanical power.

Micro gas turbines have speeds varying from 30.000 to 120.000 revolutions per minute. The high frequency output of the generator connected to a common shaft is taken, and rectified to DC by using power electronics, then it is inverted back to useable AC power at 50 or 60 Hz.

2.2. Thermodynamic cycle

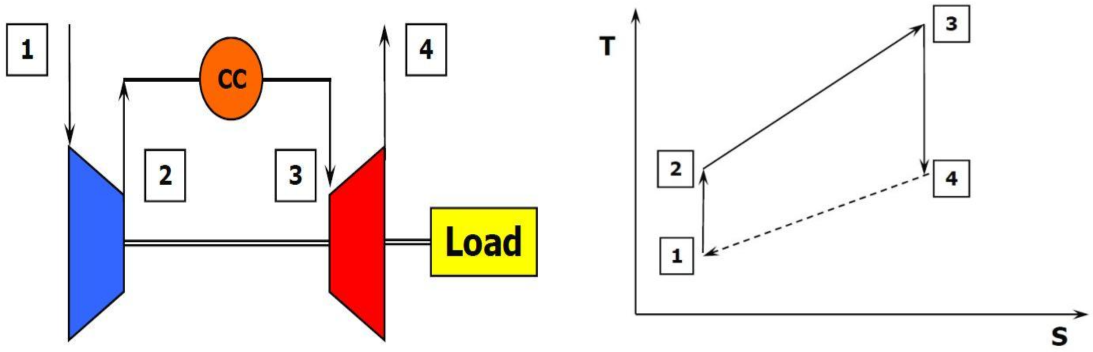
MGTs, as well as conventional turbines, are based on the Brayton cycle. The electrical efficiencies of the micro gas turbines vary from values around 15-20 % for simple cycle, up to 33% for recuperated cycle. The theory developed in this chapter is based on the work done by (Stapersma & Vos, 2014) [8].

2.2.1. Simple cycle

Ideal simple cycle

In the simple cycle, the gas strictly follows step by step the stages explained in the section 2.1 The ideal Brayton cycle is shown in the figure 2.2, in which stages are:

- Stage 1-2: Isentropic compression of the gas (S_1=S_2)
- Stage 2-3: Gas is burned at constant pressure (p_2=p_3)
- Stage 3-4: Isentropic expansion of the gas (S_3=S_4)



(a) (b)

Figure 2.2 Brayton simple cycle, [8]

(a) Scheme; (b) T-S diagram

The power in the compressor and turbine are calculated from the specific enthalpy difference, measured in kJ/kg multiplied by the mass flow (kg/s).

Compressor:

$$P_{12} = \dot{m} \cdot c_p \cdot (T_1 - T_2) \tag{2.1}$$

$$P_C = |\, P_{12}| \tag{2.2}$$

Turbine:

$$P_{34} = \dot{m} \cdot c_p \cdot (T_3 - T_4) \tag{2.3}$$

$$P_T = |\, P_{34}| \tag{2.4}$$

The brake power is the net difference, defined by:

$$P_B = P_T - P_C \tag{2.5}$$

where P is power, T is temperature, $\dot{m}$ is mass flow, c_p is specific heat at constant pressure, sub-indexes *1,2,3,4* refer to the stages in Brayton cycle, sub-indexes C and T refer to compressor and turbine and sub-index B to brake power.

The efficiency of the system is the ratio between the work of the cycle and the heat supplied to the cycle, which is carried out in the combustion chamber, given by equation 2.6 and represented in figure 2.3.

$$\eta_{td} = \frac{w_{cycle}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} \tag{2.6}$$

Where w is the work (W) per mass flow, q is heat (Q) per mass flow, η is efficiency, sub-indexes *in* and *out* refer to the direction of the parameter (received or extracted) and sub-index *td* refer to the whole cycle.

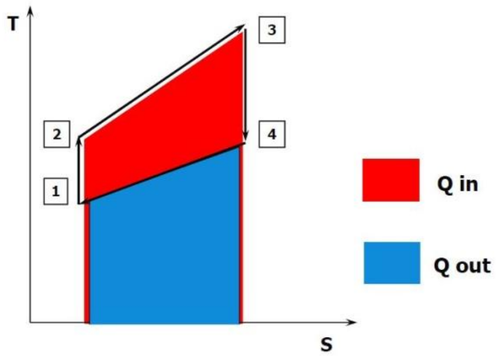


Figure 2.3 Heat into and out of the cycle, [8]

The combustion chamber is an open system in which only heat is supplied, in other words, no work is provided or extracted. As result, the heat input is the variation of enthalpy.

$$\dot{Q} = \dot{m} \cdot (h_e - h_i) \tag{2.7}$$

$$\dot{Q}_{23} = \dot{m} \cdot c_p \cdot (T_3 - T_2) \tag{2.8}$$

$$q_{in} = \frac{\dot{Q}_{23}}{\dot{m}} = c_p \cdot (T_3 - T_2) = c_p \cdot T_1 \cdot \left(\frac{T_3}{T_1} - \frac{T_2}{T_1}\right) \tag{2.9}$$

In order to relate the temperatures and pressures at the different stages, temperature ratio τ and pressure ratio π are defined as follows.

Maximum temperature ratio:

$$\tau = \frac{T_3}{T_1} \tag{2.10}$$

Pressures ratio, in ideal cycle is the same in the compressor and the turbine:

$$\pi = \pi_C = \frac{p_2}{p_1} = \frac{p_3}{p_4} = \pi_T \tag{2.11}$$

Temperature ratio in the compressor:

$$\tau_C = \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}} = \pi^{\frac{\kappa-1}{\kappa}} \tag{2.12}$$

With κ being the ratio of specific heat at constant pressure and specific heat at constant volume of the gas.

$$\kappa = \frac{c_p}{c_v} \tag{2.13}$$

Operating the equation (2.9) and using the relations (2.10) and (2.11) we get the following non-dimensional equation for heat input:

$$\frac{q_{in}}{c_p \cdot T_1} = \tau - \pi^{\frac{\kappa-1}{\kappa}} \tag{2.14}$$

Similarly to the process done to calculate the added heat, extracted heat is calculated with the enthalpy difference of the exhaust gas.

$$q_{out} = \frac{|\dot{Q}_{41}|}{\dot{m}} = c_p \cdot (T_4 - T_1) = c_p \cdot T_1 \cdot \left(\frac{T_4}{T_1} - 1\right) = c_p \cdot T_1 \cdot \left(\frac{T_4}{T_3}\right) \cdot \left(\frac{T_3}{T_1} - \frac{T_3}{T_4}\right) \tag{2.15}$$

In this case it is also defined the temperatures ratio before and after the turbine as:

$$\tau_T = \frac{T_3}{T_4} = \left(\frac{p_3}{p_4}\right)^{\frac{\kappa-1}{\kappa}} = \pi^{\frac{\kappa-1}{\kappa}} \tag{2.16}$$

Operating the equations (2.15), together with (2.16) and (2.10), the non-dimensional heat out is written as:

$$\frac{q_{out}}{c_p \cdot T_1} = \frac{1}{\pi^{\frac{\kappa-1}{\kappa}}} \cdot \left(\tau - \pi^{\frac{\kappa-1}{\kappa}}\right) \tag{2.17}$$

This way, the net work of the cycle is:

$$w_{cycle} = q_{in} - q_{out} = \left(\tau - \pi^{\frac{\kappa-1}{\kappa}}\right) - \frac{1}{\pi^{\frac{\kappa-1}{\kappa}}} \cdot \left(\tau - \pi^{\frac{\kappa-1}{\kappa}}\right) = \left(\tau - \pi^{\frac{\kappa-1}{\kappa}}\right) \cdot \left(1 - \frac{1}{\pi^{\frac{\kappa-1}{\kappa}}}\right) \tag{2.18}$$

So, from equations (2.6), (2.9) and (2.17), the efficiency of the simple ideal cycle is now calculated as:

$$\eta_{td} = \frac{w_{cycle}}{q_{in}} = \frac{q_{in} - q_{out}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1}{\pi^{\frac{\kappa-1}{\kappa}}} \tag{2.19}$$

Real Cycle

In real applications, the components have some losses that lead to a real cycle different from the ideal one. In figure 2.4 can be appreciated that compressor and turbine performances are not exactly isentropic, leading to higher heat out and lower heat supplied as stated in equation (2.20).

$$\begin{gathered} q_{out} = q_{41} > q_{4s,1} \\ q_{in} = q_{23} < q_{2s,3} \end{gathered} \tag{2.20}$$

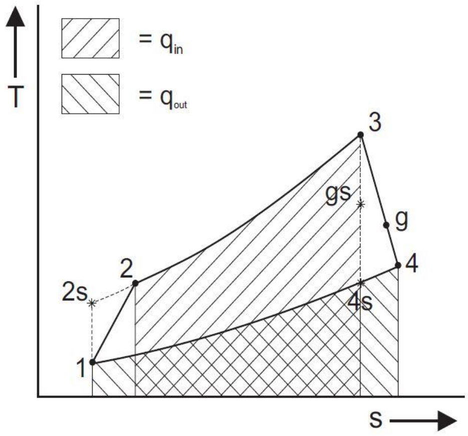


Figure 2.4 T-S diagram of a real Brayton cycle, [8]

These discrepancies from the ideal cycle result in lower efficiency of the real cycle, for which performances of the compressor (η_C) and turbine (η_T) must be taken into account, affecting the temperatures and pressure ratios as follows:

$$\tau_C = \pi^{\frac{n_C-1}{n_C}} \tag{2.21}$$

$$\tau_T = \pi^{\frac{n_T-1}{n_T}} \tag{2.22}$$

With:

$$\frac{n_C-1}{n_C} = \frac{1}{\eta_C} \cdot \frac{\kappa-1}{\kappa} \tag{2.23}$$

$$\frac{n_T-1}{n_T} = \frac{1}{\eta_T} \cdot \frac{\kappa-1}{\kappa} \tag{2.24}$$

The work of compressor and turbine, obtained from the enthalpy difference, is expressed as:

$$w_C = \mathrm{c_p} \cdot (\mathrm{T_1} - \mathrm{T_2}) = \mathrm{c_p} \cdot \mathrm{T_1} \cdot (\tau_C - 1) \tag{2.25}$$

$$w_T = \mathrm{c_p} \cdot (\mathrm{T_3} - \mathrm{T_4}) = \mathrm{c_p} \cdot \mathrm{T_3} \cdot \left(1 - \frac{1}{\tau_T}\right) \tag{2.26}$$

And operating equations (2.25) and (2.26) with (2.21) and (2.22) respectively, the following non-dimensional works are obtained:

$$\frac{w_C}{\mathrm{c_p} \cdot \mathrm{T_1}} = \pi^{\frac{n_C-1}{n_C}} - 1 \tag{2.27}$$

$$\frac{w_T}{\mathrm{c_p} \cdot \mathrm{T_3}} = 1 - \frac{1}{\pi^{\frac{n_T-1}{n_T}}} \tag{2.28}$$

The net work output including losses in compressor and turbine results as:

$$\frac{w_{cycle}}{c_p \cdot T_1} = \tau \cdot \left(1 - \frac{1}{\pi^{\frac{n_T-1}{n_T}}}\right) - \left(\pi^{\frac{n_c-1}{n_c}} - 1\right) \tag{2.29}$$

And the heat input, taking into account the losses in the compressor, is:

$$\frac{q_{in}}{c_p \cdot T_1} = \tau - \pi^{\frac{n_c-1}{n_c}} \tag{2.30}$$

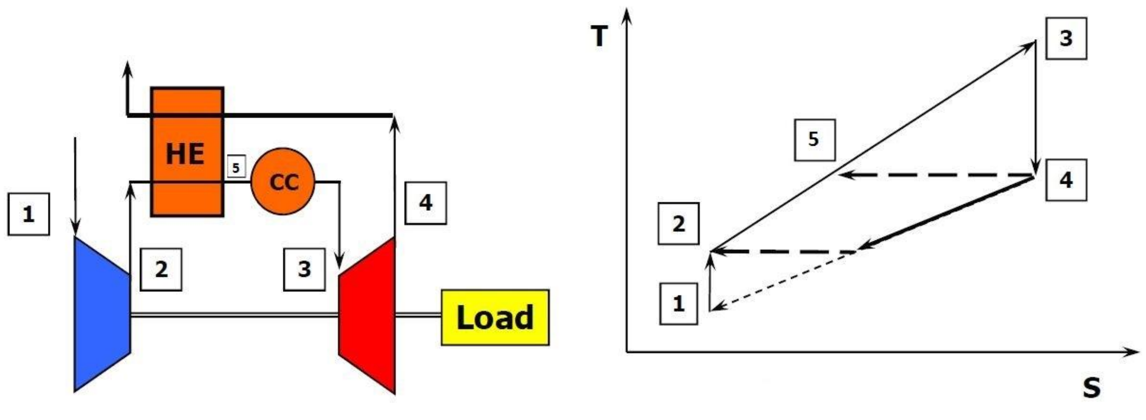
Similarly to the ideal case, the efficiency of the real cycle writes:

$$\eta_{td} = \frac{w_{cycle}}{q_{in}} = \frac{\tau \cdot \left(1 - \frac{1}{\pi^{\frac{n_T-1}{n_T}}}\right) - \left(\pi^{\frac{n_c-1}{n_c}} - 1\right)}{\tau - \pi^{\frac{n_c-1}{n_c}}} \tag{2.31}$$

2.2.2. Regenerative cycle

Regenerative simple cycle

In a regenerative cycle, part of the heat of the exhaust gases is used to increase the temperature of the air before reaching the combustion chamber. It allows to increase the internal energy of the gas, and thus, to extract more power when the gas is expanded in the turbine.



(a) (b)

Figure 2.5 Brayton real cycle , (modified from [8])

(a) Scheme; (b) T-S diagram

In an ideal heat exchanger, which is in other words an infinite length exchanger, the temperature outlet of the air T_5 is equal to the inlet temperature of the exhaust gas T_4.

The total heat to be added in the system is now supplied partially by the heat exchanger and the rest by the combustion. The calculation comes again from the enthalpy difference as:

$$q_{23} = q_{in} + q_{HE} = c_p \cdot (T_3 - T_2) \tag{2.32}$$

$$q_{HE} = c_p \cdot (T_5 - T_2) = c_p \cdot (T_4 - T_2) \tag{2.33}$$

$$q_{in} = c_p \cdot (T_3 - T_5) = c_p \cdot (T_3 - T_4) \tag{2.34}$$

The heat added in the combustion written in non-dimensional form is in this case given with equations (2.34), (2.10) and (2.16).

$$\frac{q_{in}}{c_p \cdot T_1} = \frac{T_3}{T_1} - \frac{T_4}{T_1} = \frac{T_3}{T_1} - \frac{T_4}{T_3} \cdot \frac{T_3}{T_1} = \tau \left(1 - \frac{1}{\pi^{\frac{\kappa-1}{\kappa}}}\right) \tag{2.35}$$

The net work of the cycle is essentially the same as calculated for simple cycle in equation (2.18). The efficiency of the cycle is then:

$$\eta_{td} = \frac{w_{cycle}}{q_{in}} = \frac{\left(\tau - \pi^{\frac{\kappa-1}{\kappa}}\right) \cdot \left(1 - \frac{1}{\pi^{\frac{\kappa-1}{\kappa}}}\right)}{\tau \cdot \left(1 - \frac{1}{\pi^{\frac{\kappa-1}{\kappa}}}\right)} = \frac{\left(\tau - \pi^{\frac{\kappa-1}{\kappa}}\right)}{\tau} = 1 - \frac{\pi^{\frac{\kappa-1}{\kappa}}}{\tau} \tag{2.36}$$

Real cycle

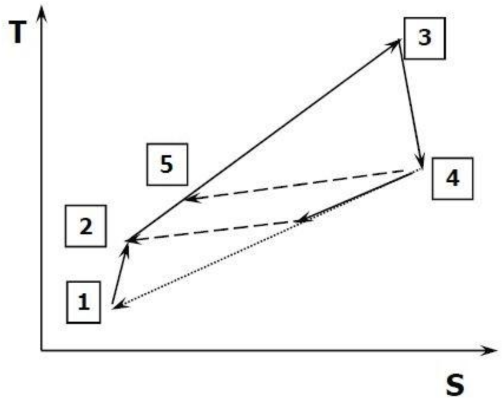


Figure 2.6 T-S diagram of real regenerative Brayton cycle, (modified from [8])

In a real cycle, with a finite heat exchanger, the outlet temperature T_5 of the air is lower than the turbine outlet temperature T_4. In order to calculate the overall efficiency, the heat exchanger effectiveness must be defined as:

$$\eta_{HE} = \frac{(T_5 - T_2)}{(T_4 - T_2)} \tag{2.37}$$

As a consequence, the heat added in the combustion can be calculated subtracting from the total enthalpy difference from stages 2-3 the heat added in the heat exchanger:

$$q_{in} = c_p \cdot [(T_3 - T_2) - \eta_{HE} \cdot (T_4 - T_2)] \tag{2.38}$$

From equations (2.38), (2.10), (2.12), (2.16), (2.21) and (2.22) , the dimensionless heat added can be expressed as:

$$\frac{q_{in}}{c_p \cdot T_1} = \left(\frac{T_3}{T_1} - \frac{T_2}{T_1}\right) - \eta_{HE} \cdot \left(\frac{T_4}{T_1} - \frac{T_2}{T_1}\right) = \left(\frac{T_3}{T_1} - \frac{T_2}{T_1}\right) - \eta_{HE} \cdot \left(\frac{T_4}{T_3} \cdot \frac{T_3}{T_1} - \frac{T_2}{T_1}\right) \tag{2.39}$$

$$\frac{q_{in}}{c_p \cdot T_1} = \left(\tau - \pi^{\frac{n_C-1}{n_C}}\right) - \eta_{HE} \cdot \left(\frac{\tau}{\pi^{\frac{n_T-1}{n_T}}} - \pi^{\frac{n_C-1}{n_C}}\right) = \tau \cdot \left(1 - \frac{\eta_{HE}}{\pi^{\frac{n_T-1}{n_T}}}\right) - (1 - \eta_{HE}) \cdot \pi^{\frac{n_C-1}{n_C}} \tag{2.40}$$

And finally, the efficiency of a regenerative Brayton cycle, taking into account the losses in heat exchanger, compressor and turbine is calculated from equations (2.29) and (2.40).

$$\eta_{td} = \frac{w_{cycle}}{q_{in}} = \frac{\tau \cdot \left(1 - \frac{1}{\pi^{\frac{n_T-1}{n_T}}}\right) - \left(\pi^{\frac{n_C-1}{n_C}} - 1\right)}{\tau \cdot \left(1 - \frac{\eta_{HE}}{\pi^{\frac{n_T-1}{n_T}}}\right) - (1 - \eta_{HE}) \cdot \pi^{\frac{n_C-1}{n_C}}} \tag{2.41}$$

Real regenerative cycle explained in this paragraph is the one used in most of the current micro gas turbines.

2.3. Capstone micro gas turbines

Capstone is the MGT leader in the market, and the only one for the time being with units installed onboard existing ships, although they do not provide directly these turbines for maritime applications. In charge of this labour is MME (Microturbine Marine Energy), which is a German company that provides the Capstone micro gas turbines for such market.

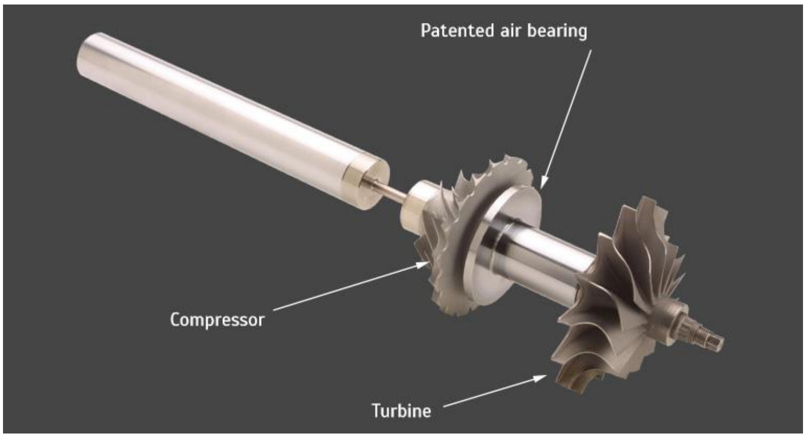


Figure 2.7 Shaft of Capstone micro gas turbine with the air bearing, [3]

Their outstanding feature is the use of a patented air bearing, showed in figure 2.7, that avoids the use of lubricating oil. Air bearings create a thin film of air that separates the shaft from the bearing surfaces when turbines are running over 2.000 rpm, which eliminates the friction between the only one rotating component in the device.

Capstone micro turbines use a lean premix combustion system to achieve low emission levels, but this requires to operate at high air-fuel ratio in the primary combustion zone, reason why their performance relies on the ambient temperature, which has direct influence on the air density.

MME provides the turbines in sound enclosures within a range of models varying from 30 kW to 400 kW. The different models are C30, C65, C130, C200 and C400, for which C130 and C400 sound enclosures contain 2 micro gas turbines C65 and C200 respectively.

The auxiliary GenSets installed onboard BV80 provide a maximum electrical power of 1071 kW, and the maximum electrical demand assumed from the load balance is 782 kW , which corresponds the condition of maneuvering, as can be seen in Appendix B. Taking the electrical requirements of the ship into account, the most appropriate model for replacing this equipments is the micro gas turbine C400, which contains 2xC200 models in its sound enclosure. The selection is based on the maintenance service and electrical efficiencies that model C200 offers (34 % of maximum efficiency) against C65 (30 % of maximum efficiency) and C30 (30% of maximum efficiency) as presented in (Microturbine Marine Energy)[6], as well as spatial reasons, deduced from previous reports of Blohm+Voss..

2.3.1. Heat recovery

Exhaust gas of the micro gas turbines can be harnessed to produce thermal power, which might be used for different applications such as hot water system, heating system or a thermal chiller, as described in the Figure 2.8.

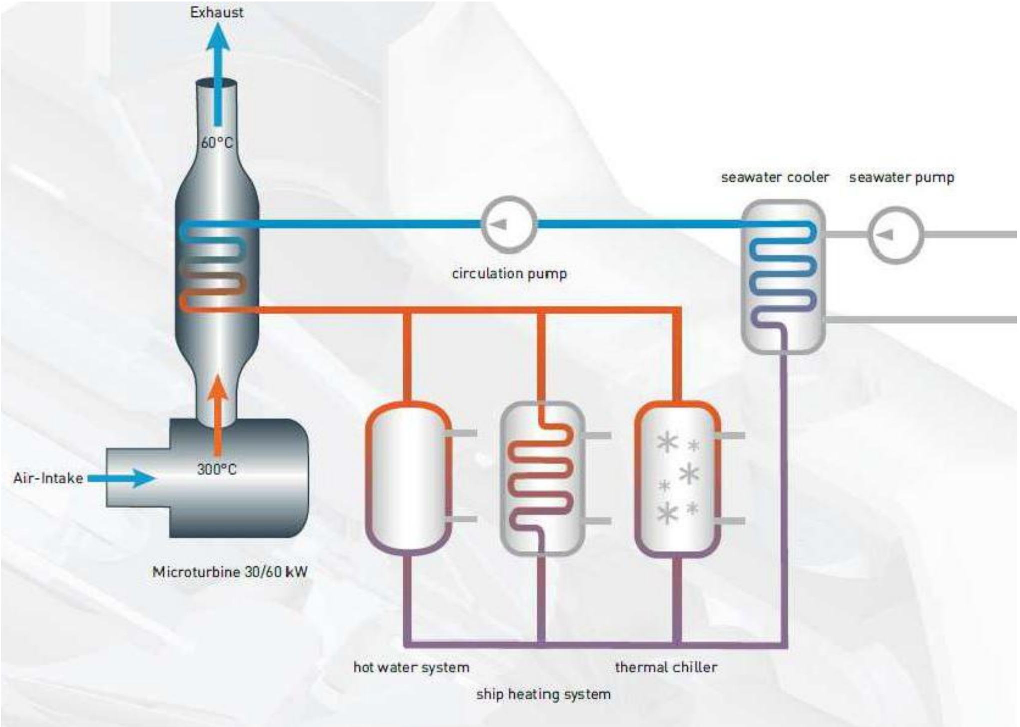


Figure 2.8. Heat recovery options, [7]

When dealing with mega yachts, they generally navigate in summer areas, and for this reason the chilled water plant must be designed so that it will always meet the expectations of the owner. Based on this, the electrical demand of the chilled water plants entails a very important percentage, which is later on traduced into FO (fuel-oil) expenses. For these reasons, and as it is explained more detailed in chapter 5, the possibility to install an absorption chiller together with the micro gas turbines, leading to a cogeneration power plant onboard is analyzed. Together with other solutions as batteries, a number of alternatives are studied combining the different options.

2.4. Selected models

Micro gas turbines C200 and C400 provided by MME are the chosen models for the different alternatives subject to study, reason why their main characteristics are to be highlighted in this chapter.

2.4.1. Model C200

This model is delivered in a sound enclosure with dimensions LxWxH of 2950x1800x2100 mm. It has the inlet combustion air in the front side, and the exhaust in the top, as can be seen in Figure 2.9.

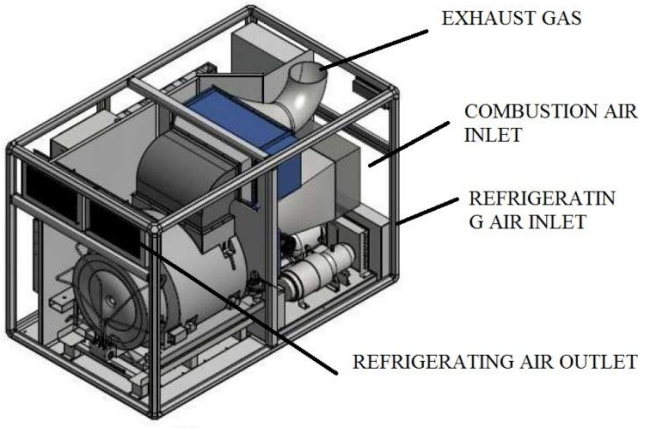


Figure 2.9. Internal view of MGT C200 delivered by MME, (modified from [6])

This unit is the most important device of the study, since it is also the base of the other model used, called C400. This micro gas turbine can achieve up to 34 % of electrical efficiency under optimum conditions. In Table 1 are highlighted the main characteristics of this unit.

Table 1. C200 main characteristics [2], [6], [7]

Characteristic	**Unit**	**Quantity**
Power output*	kW	200
Voltage	V	400
Frequency	Hz	50
Combustion air	m^3/h	4418
Electronics ventilation air	m^3/h	6117
Exhaust gas temperature	ºC	65 with exhaust cooler (280 without)
Exhaust gas mass flow*	kg/s	1,33
Exhaust diameter	mm	305
Maximum back pressure	mbar	20
Maximum ambient temperature	ºC	50
Minimum ambient temperature	ºC	-20
Fuel consumption*	l/h	60

**At full load at ISO conditions (15 ºC and 60% relative humidity at sea level)*

Characteristics showed in table 1 do not fully described the micro gas turbine performance, since they are only achieved at full load and ISO conditions. Nevertheless, thanks to data obtained from Capstone [2, Ch 7], a more exhaust analysis can be performed.

Capstone data allows to visualize the performance of the turbine depending on the ambient temperature.

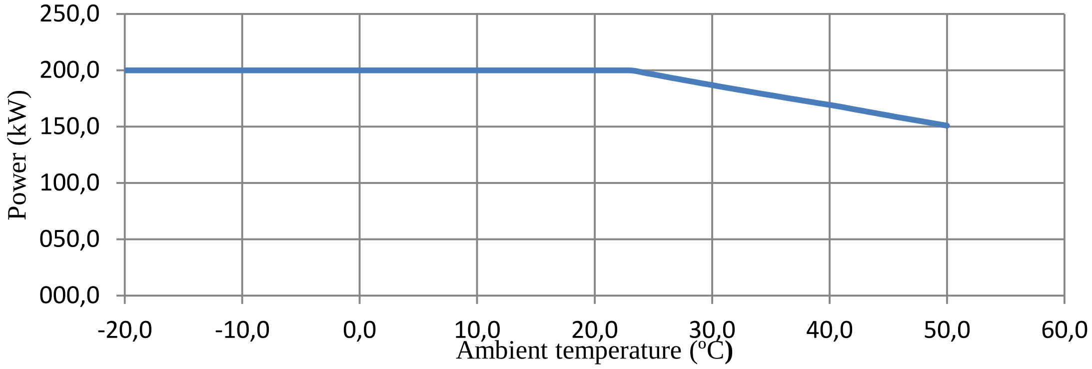
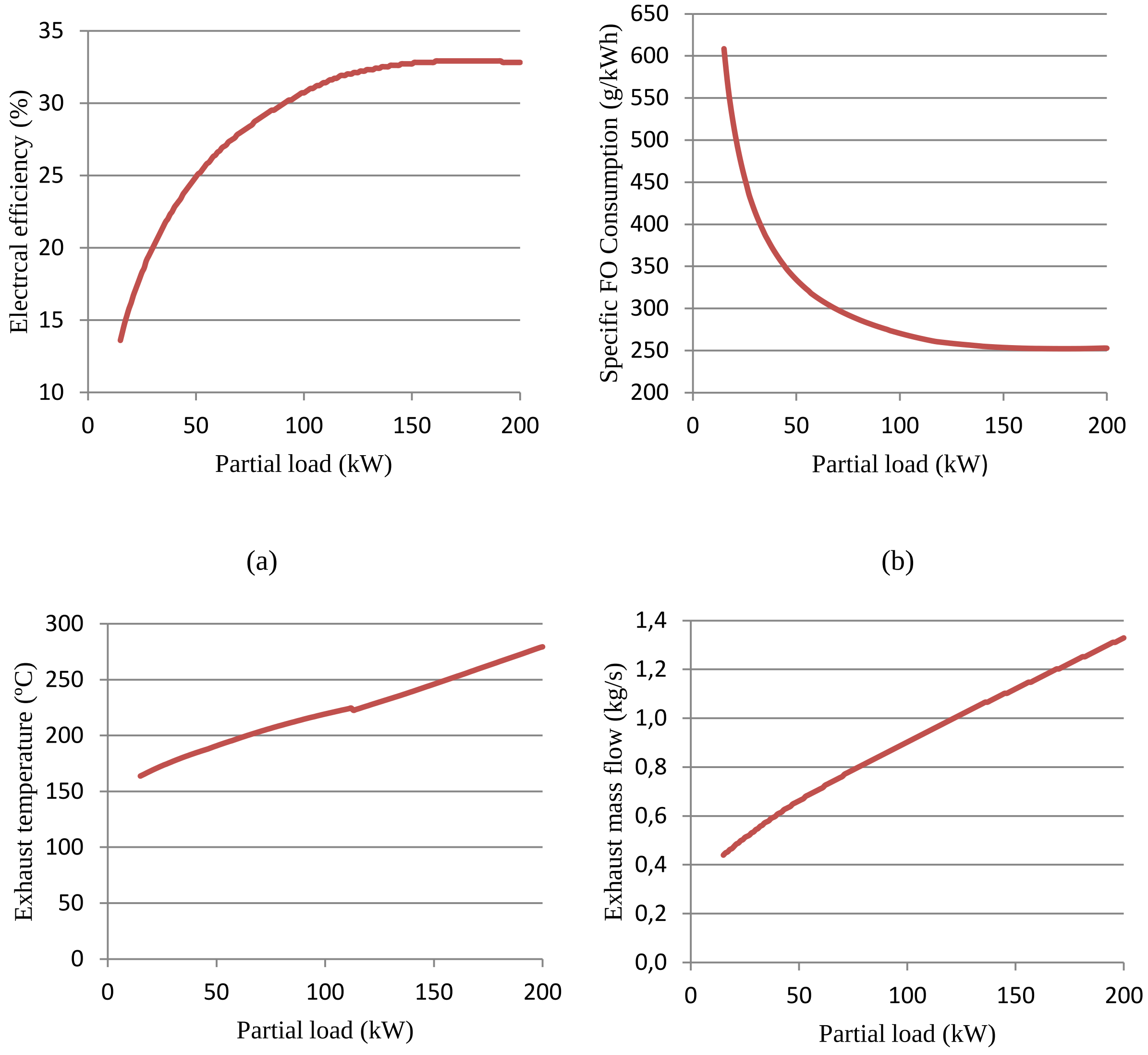


Figure 2.10. C200 Power Output vs Temperature

Figure 2.10 shows that above 23 ºC the net power starts to decrease. The high amount of air needed for the combustion entails that this technology is sensible to its density and thus, one of the goals of this study is to offer solutions so that a good performance of the power plant can be guaranteed for any extreme condition, as it is studied in chapter 5.

Another important feature obtained from Capstone is the performance of MGTs in ISO conditions at partial loads, which enable to visualize important parameters as the electrical efficiency, specific fuel oil consumption, exhaust temperature or exhaust mass flow at different partial loads.

Values at partial load of 200 kW correspond to those at full load in Table 1. Figure 2.11 (a, b, c, and d) contain characteristics for the whole range of partial loads of the micro gas turbine. This allows to know the performance of the power plant of a vessel at every moment if the electrical demand is also known. This concept sets the bases to study the heat recovery mentioned in chapter 2.3.1, and detailed explained between chapters 4 and 5.



(a) (b)

(c) (d)

Figure 2.11. C200 Performance at Partial loads [2]

(a) Electrical efficiency; (b) Specific FO consumption;

(c) Exhaust temperature; (d) Exhaust mass flow

2.4.2. Model C400

As mentioned in chapter 2.3, model C400 is simply a compact sound enclosure which contains two C200 micro gas turbines inside. With dimensions LxWxH of 3000x2100x2250 mm, the module is slightly bigger than the C200 , but it develops logically twice net power of C200, meaning that the specific power in terms of weight and volume will be much higher.

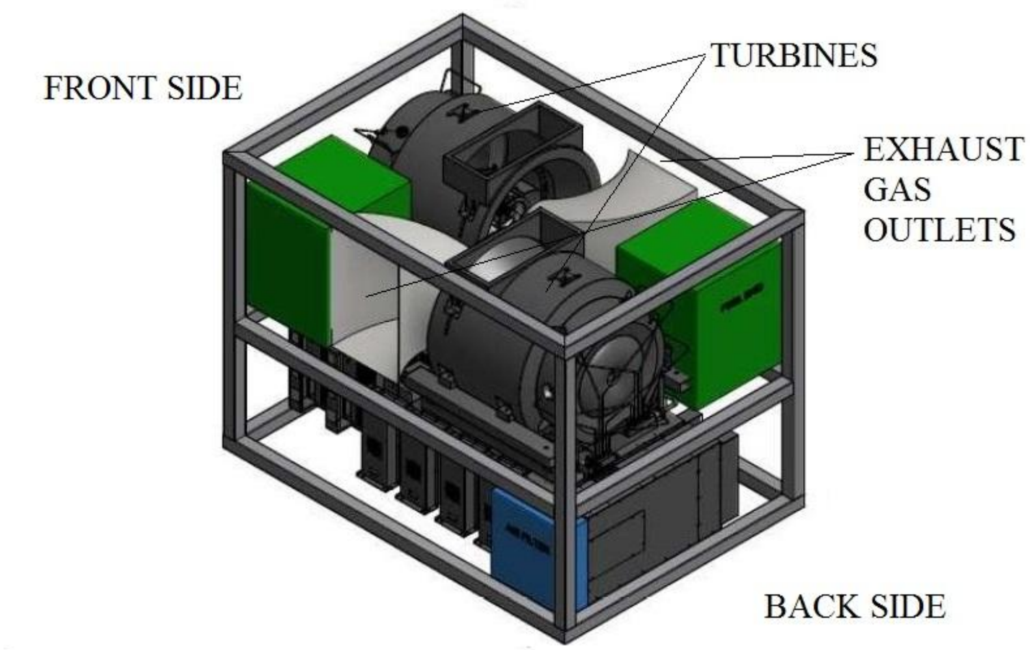


Figure 2.12 Internal view of C400 enclosure containing two C200 micro gas turbines, (modified from [6])

As shown in figure 2.12, model C400 has the inlet air connections at both sides, unlike C200 which has this connection at the front side. For this reason, when they are be installed in the machinery room, the surrounding spaces that are needed to remain empty in order to perform maintenance service, which is explained in chapter 3, differ from one model to another.

Apart from these differences, the performance of the model is the same, and data explained for model C200, can be directly extrapolated for model C400.

3. MICRO GAS TURBINES VS GENERATOR SETS

3.1. Main characteristics

Along this chapter the main differences of both systems (GenSets and MGTs) are analyzed in the machinery room of the Mega Yacht BV80, which was initially conceived with three MTU V2000 M41A generator sets for the generation of power onboard.

Table 2. Main characteristics of GenSet and MGT models for BV80. [2], (Blohm+Voss Database)

		MTU V2000 M41A	**Capstone C400**
Main characteristics			
Rated Power	kW	357	400
Dimensions (LxWxH)	m	3x1,6x1,5	3x2,1x2,1
Dry Weight	kg	6500	5912
Consumption			
Specific fuel consumption (100% CP)	g/kWh	204	252,7
Specific fuel consumption (75% CP)	g/kWh	211	253,5
Specific fuel consumption (50% CP)	g/kWh	219	270,3
Specific fuel consumption (25% CP)	g/kWh	236	334
Lube-oil consumption	% of FO	0,3	-
Lube-Oil System			
Lube-oil tank capacity	m^3	2,2	-
Fuel System			
Service tanks capacity (for 8 hours)	m^3	0,78	0,96
Acoustics			
Noise level exhaust gas	dB(A)	105	Very low
Noise level	dB(A)	102	55
Combustion Air/Exhaust gas			
Combustion air volume flow	m^3/s	0,5	1,454
Exhaust volume flow (at exhaust temperature)	m^3/s	1,02	2,2
Ventilation			
Airflow for evacuation of heat emission	m^3/h	6056,3	12234
Airflow for combustion	m^3/h	1870	8836
Urea system			
Urea Consumption	% of FO	6,5	-
Weight of Equipment	kg/engine	1700	-
Sea water system			
Sea water mass flow	m^3/h	65	28,8

Since the technologies of micro gas turbines and diesel engines are different, they do not require the same characteristics for their operation, as can be observed in the previous table. These differences affect the auxiliary systems in the machinery room, as analyzed in paragraph 3.2.

3.1.1. Power density related to volume and weight

There are different considerations that can be taken into account to estimate the specific power, but a direct comparison taking only the weight and dimensions of the units gives already a good idea of the power density. In this case, with the information given in table 1, following results are obtained.

Table 3. Direct weight and volumetric power densities

Power plant system	**Weight power density (kW/kg)**	**Volumetric power density (kW/m^3)**
Generator sets	0,055	143,95
Micro gas turbines	0,068	60,47

As it can be seen, the weight power density is slightly higher for the micro gas turbines. However, volumetric power density is 2,5 times larger in the case of the generator sets. The reason comes from the differences in the technologies; while the diesel engines have heavy steel blocks which resist the high vibrations produced in their crankshaft, the micro gas turbines require very high amount of air, for which empty space needs to be built.

In addition, for a more realistic comparison, the urea system is included, since in fact it consumes the space in the upper deck of the machinery room. With the information obtained from Marquip, resulting in a equipment of 1.700 kg and 4.96 m^3, the weight and volumetric power densities are as shown below.

Table 4. Indirect weight and volumetric power densities

Power plant system	**Weight power density (kW/kg)**	**Volumetric power density(kW/m^3)**
Generator sets	0,044	88,08
Micro gas turbines	0.068	60,47

Comparing tables 3 and 4 it can be appreciated the effect that the emissions reduction unit has on the power plant. Even though the weight power density is not highly affected, the volumetric power density is reduced 40 %.

3.2. Differences in the auxiliary systems

Every machinery room on a ship must be able to provide appropriate conditions for the correct operation of the power plant. The replacement of the generator sets by micro gas turbines affects the following auxiliary systems.

- Fuel-oil system
- Lube-oil system
- Ventilation of the machinery room
- Sea water cooling
- Emission reduction system (Urea)
- Exhaust silencers

Since one of the goals of this study is to reduce the shipbuilding impact, alterations in auxiliary systems must be analyzed in order to estimate the feasibility of the replacement.

3.2.1. Fuel-oil system

Model C200 is able to work with diesel fuel, as well as biodiesel. The selection of the type of fuel is based on the most simple solution for the machinery room. As the main engines are also installed and they need diesel fuel for their operation, the idea is to work with the same fuel for both (main engines and micro gas turbines), which makes it necessary to choose diesel fuel for micro gas turbines.

3.2.2. Lube-oil system

As explained in the chapter 2.3, one of the advantages of the micro gas turbines is the removal of lubricant thanks to the air bearings. Even though the consumption of LO is very low compared to the fuel oil (0.5% of FO), advantages can be extended also to the avoidance of spills that can be harmful for the environment, leading to a dirty image, as well as unpleasant smells.

From the lube oil tank, oil is driven to the LO transfer module and from there to the main engines and the oil filling hose connection for auxiliary engines. Since the system is shared with the main engines, the equipment required for the generator sets consist only on few meters of pipes, so that the impact of its removal is marginal.

3.2.3. Ventilation of the machinery room

Air demand with conventional generator sets

The initial equipments installed in the machinery room need ventilation for two reasons; due to the heat emission of the equipments, and also because of the air consumption of the engines. The total airflow required can be observed in the table 5.

Table 5. Airflow for machinery room ventilation with Gensets, (Blohm+Voss Database)

Designation	**Quantity**	**Airflow for heat dissipation (m^3/h)**		**Airflow for combustion (m^3/h)**		**Total airflow (m^3/h)**
		Per Unit	Total	Per Unit	Total	
Main Engine MTU 12V4000 M73L	2	7.268	21.803	11.160	22.320	35.195
Genset MTU V2000 M41A	3	6.056	18.168	1.870	5.610	21.534
Transmission	2	883	1.766	-	-	1.766
Exhaust Pipes	1	1.262	1262	-	-	1.262
Electrical Installation	1	10.094	10.094	-	-	10.094
Total Airflow			**53.093**		**27.930**	**69.851**

In table 5, it can be appreciated the air demands from the heat emission and the combustion. A recirculation of 40 % of the airflow for heating emission is assumed to be directed to the air for combustion, and that is how the total airflow for the engines is obtained, having as result 69.851 m^3/h. The distribution of air inside the machinery room can be seen in the Appendix C, which contains the system plan.

Axial fans installed onboard for conventional generator sets

The designed ventilation of the machinery room is carried out with two fans (one at each side of the ship). The model used is the AXC 900 provided by the company Systemair with a unitary capacity of 40.000 m^3/h and electrical consumption of 15 kW. It results in a total airflow capacity of 80.000 m^3/h in order to cover the heating emission and the air consumption of the equipments. The axial fan will create a maximum velocity of air of 18 m/s, as can ben seen in Appendix G1.

Air demand with MGTs

As can be seen in table 2, the airflow needed for the micro gas turbines is much higher than for GenSets. Its installation would result in the following ventilation requirements.

Table 6. Air flow for machinery room ventilation with 4 Micro Gas Turbines C200

Designation	**Quantity**	**Airflow heat dissipation (m^3/h)**		**Airflow for combustion (m^3/h)**		**Total Airflow (m^3/h)**
		Per unit	Total	Per unit	Total	
Main Engine MTU 12V4000 M73L	2	7.268	21.803	11.160	22.320	35.195
MGT Capstone C400	2	12.234	24.468	8.836	17.672	42.140
Transmission	2	3,5	1.766	-	-	1.766
Exhaust Pipes	1	1.262	1262	-	-	1.262
Electrical Installation	1	10.094	10.094	-	-	10.094
Total Airflow			**59.393**		**39.992**	**90.457**

Due to the higher air flow required when MGTs are installed (90.457 m^3/h), initial conceived fans do not have enough capacity to provide such amount (80.000 m^3/h), in consequence, the supply fans of the machinery room have to be replaced with a more powerful model.

Axial fans installed onboard for micro gas turbines

The model chosen to fulfil the higher air demand is the AXC 1000, also from the company Systemair, the main design parameters can be seen in Appendix G2. This model is slightly bigger than the previous one, although fits perfectly in the inlet air duct. The electrical demand is 15 kW as in the case of the model AXC 900, which means that the change will not affect at all the electrical balance of the ship. The maximum velocity is also very similar to the initial model (17.9 m/s for AXC1000 against 18 m/s for AXC900). And the acoustic study obtained from the supplier is also in the same range as the previous model.

3.2.4. Sea water system

Micro gas turbines do not compulsory require cooling water. Nevertheless, since their efficiency relies on the air temperature, it is recommendable to install inlet air coolers to cool down the air in case it is above 25 ºC. The simplest way to cool down the air is using the sea water system which is already projected for the mega yacht to provide sea water to the equipments in the machinery room, including the GenSets.

With the information received from MME, as shown in Appendix A1 or A2, each model C200 contains two intake air coolers; one for the electronics heat dissipation, which is described in Appendix A4, and the other one for the combustion air, described in Appendix A5. The total amount of sea water needed for 2xC400 models is 8 l/s, or 28,8 m^3/h (Table 1).

Compared with MGTs, GenSets sea water demand is more than two times higher (65 m^3/h), which means that the initially conceived system is able to provide sea water for the MGTs.

3.2.5. Emission reduction system (Urea)

The emission reduction system installed onboard the mega yacht BV80 is a combined system consisting on a diesel particulate filter (DPF) which burns the soot, and the selective catalytic reduction unit (SCR), which uses urea to react with the raw gas to absorb the NOx particles in the gas. An scheme of the combined system can be seen in figure 3.1.

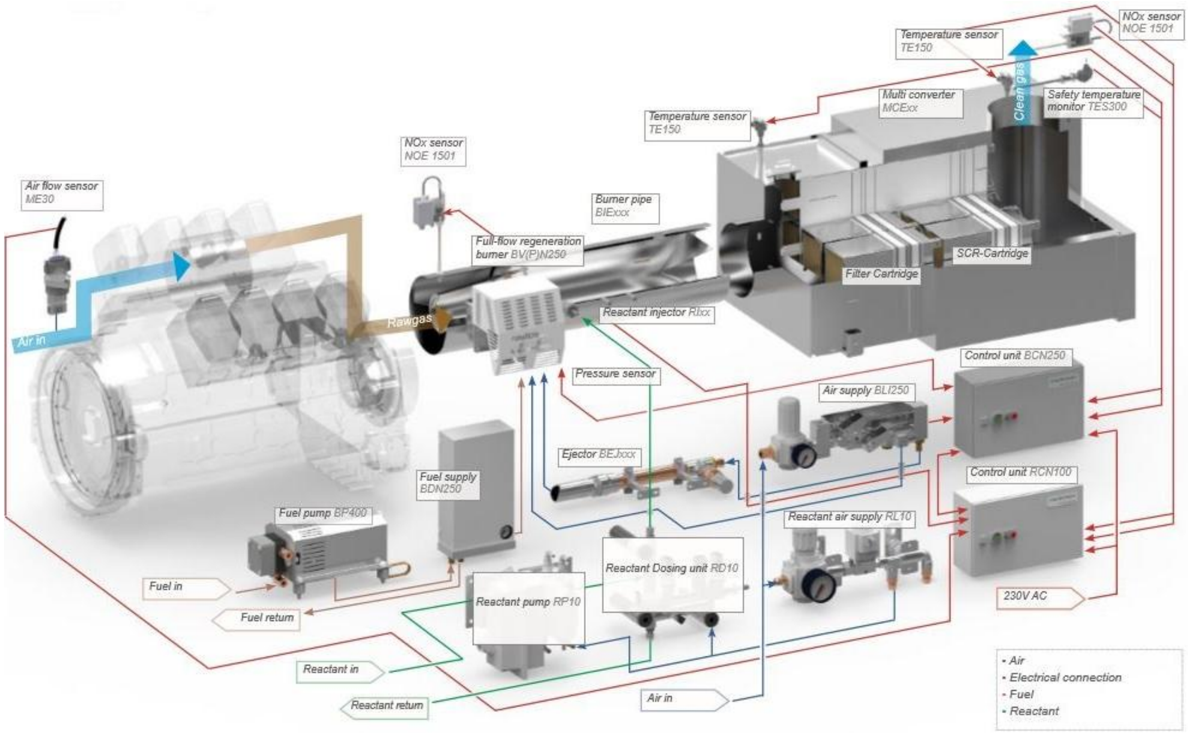


Figure 3.1. Combined DPF and SCR system, [4]

Both main engines and auxiliary GenSets need the SCR system to fulfil IMO Tier III. Besides, DPF system is installed for comfort reasons, and even though it is not compulsory, it is usual to have it onboard pleasure crafts.

In figure 3.2, it can be seen that the location of this system is directly above the generator sets, taking the exhaust gas from their outlet duct, and directing it to the smokestack.

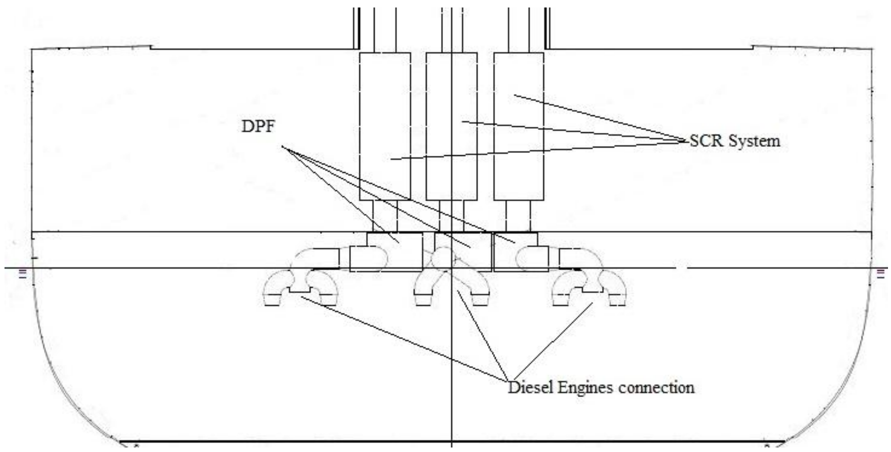


Figure 3.2. Front view of the SCR and DPF system, (Blohm+Voss Database)

The use of micro gas turbines avoids the necessity of such kind of system, which results in free space above the turbines, and that can be harnessed to install other equipments that could increase the efficiency of the power plant, as it is shown more detailed in Chapter 5.

3.2.6. Exhaust system

Generator Sets

The smokestack is a long structure that crosses vertically the ship, from the machinery room to the top, having in some zones direct contact with areas inhabited by owner and passengers. Due to the high noise produced by the diesel engines, it is necessary to install a silencer in the exhaust system in order to ensure the comfort that this kind of ships require.

The silencers installed onboard the exhaust system of the mega yacht BV80 consist of two-stage silencers, with a pre-silencer and a silencer. The combination of this system, together with the SCR and DPF, create a backpressure in certain loading conditions which is very close to the limit established by the GenSet manufacturer.

Micro Gas Turbines

In the case of the micro gas turbines, they do not need such silencers, since the noise levels are in an acceptable range of 55 dB(A). On the other hand, as it can be seen in table 2, its exhaust volumetric flow is twice the one of the generator sets. This means that in order to maintain exhaust velocity, the diameter of the ducts must be increased.

The exhaust velocity must be high enough (around 10 m/s as engineers from Blom+Voss informed) to ensure that the smoke is sent far enough from the accommodation areas, and comfort conditions are not affected. However, the higher the velocity is, the higher the back pressure, resulting in drop of efficiency of the micro gas turbines. For this reason, and taking into account the experience of the shipyard, 15 m/s is found as an appropriate exhaust gas velocity.

With the conditions of the exhaust flow described in table 2, the characteristics of the exhaust system[1] are obtained having as input a length of 20 meters, and 2 bends through the length of

[1] Retrieved from http://www.schweizer-fn.de/

the duct. The backpressure obtained has a value of 1,39 mbar, which entails the 7 % of the maximum allowable backpressure imposed by the manufacturer (20 mbar) [6]. The type of duct found is DIN 2458, with a diameter of 450 mm, which gives a velocity of 15,8 m/s.

In order to not alter the external view of the mega yacht, which can be seen in figure 3.3, the diameter of the duct at the top must have a maximum of 392 mm, which is the external designed diameter at the top of the ducts. This constrain leads to reduce the last 5 meters of duct to a standard duct of 350 mm, which would lead to increase the total backpressure to 3,06 mbar and to have a exhaust flow velocity at the top of 24,7 m/s. The initially conceived exhaust system with GenSets reaches a speed of 27,08 m/s (with a diameter of 219,1mm and exhaust flow of 1,02 m^3/s). This means that a velocity of 24,7 m/s is taken as acceptable.

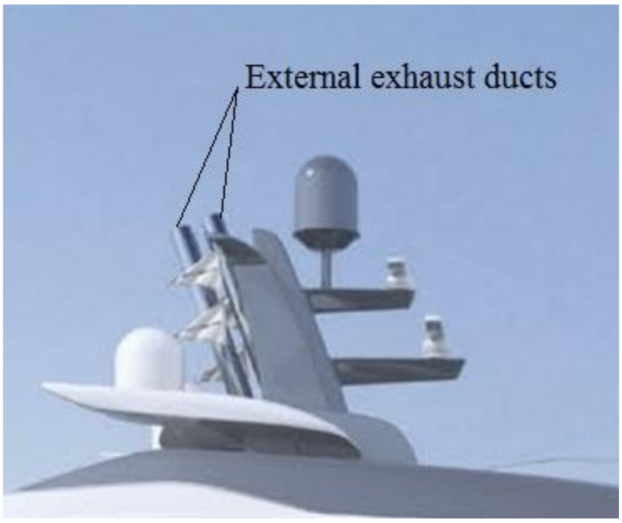


Figure 3.3. External view of exhaust ducts[2]

Furthermore, the system, which affects to the external view of the ship, was conceived with four exhaust ducts; three coming from the generator sets, as can be appreciated in figure 3.2, and 1 from the emergency generator set. As a result, from the exterior of the ship the four ducts are visible. Nevertheless, the arrangement with the micro gas turbines consist of two ducts (one for each C400 model), that in addition to the one of the emergency generator make a total of three ducts. This would involve that one of the external ducts could be removed. However, to not alter the external picture of the ship, this duct must be installed only for appearance reasons.

[2] Retrieved from http://www.superyachtnews.com/business/21984/blohm-voss-bv80-launches-yards-semi-custom-comeback.html

3.3. Maintenance service

3.3.1. Maintenance service plan

The simplicity of the technology of the micro gas turbines, which only have one rotating part and no lubricating oil, makes the maintenance interval to be much longer than the conventional diesel engines. In tables 7 and 8 can be seen the maintenance intervals of both technologies.

Table 7. Maintenance service of the generator set. (Blohm+Voss Database)

MTU V2000 M41A		
Interval	**Item**	**Maintenance task**
Each time oil is changed or 2 years	Engine oil filter	Replace
500 hours or 2 years	Crankcase breathers Fuel Filter Centrifugal oil filter	Clean Replace Clean
1.000 hours or 2 years	Valve gear	Check clearance
3.000 hours or 3 years	Air filters	Replace
3.000 hours or 9 years	Pressure pipe neck (bayonet) Fuel injectors Combustion chambers	Replace Replace Inspect (endoscopy)
6.000 hours or 9 years	Fuel injection pumps Component maintenance*	Replace Overhaul
9.000 hours or 9 years	Cylinder heads	Overhaul
18.000 hours or 18 years	Engine Fuel pressure maintaining valve	Overhaul Replace

Table 8. Maintenance service of the micro gas turbine. [Sent by MME]

C200		
Interval	**Item**	**Maintenance task**
2.000 hours	Air Compressor	Change oil
	Fuel Filter	Replace
8.000 hours	Boost Pump	Replace
	Fuel Pump	Replace
	Engine air filter	Replace
	Electronics air filter	Clean
	Injector assemblies	Replace
	Igniter	Clean
	Air Dryer Stage One	Replace
	Air Dryer Stage Two	Replace
40.000 hours	Enclosure Fan	Replace
	Frame/Engine PM	Replace
	TET Thermocouple	Replace
	Power head	Replace
8.000 hours or 1 year	Battery Pack C6X	Replace
24 Months	UCB Battery	Replace

The simplicity of the technology is also the reason of a higher expected life, with micro gas turbines being able to work up to 80.000 hours, against 36.000 in the case of the GenSets.

In the component Battery Pack of MGT, it can be seen that the replacement is performed each 8.000 hours or 1 year, whatever is first. This fact makes that maintenance costs vary with the operating hours per year of the turbines, as it is seen in chapter 6.2.2.

3.3.2. Maintenance access

Information from MME indicate that the fore and back parts of micro gas turbines should be free to access to the components that must be replaced. Ideally, the four sides of the micro gas turbine would have to be free to develop the maintenance works, but if inlet air ducts are installed onboard, as can be seen in chapter 5.2, it would not be possible to leave these zones free.

3.4. Lifetime costs

Lifetime costs is one of the most important calculations that can be performed, but at the same time, it is a complex issue to calculate. It requires certain estimations and assumptions in order to approach the problem. From the maintenance service it is estimated that the expected life of the micro gas turbines for the mega yacht BV80 is around 20 years. For this reason, this time has been selected to do the comparison of the lifetime costs.

Lifetime costs have been divided in three items; initial investment, which covers the purchase, installation and commissioning of the units; consumption costs, which cover the fuel oil, lube oil and urea expenses during the 20 years; and the maintenance costs. In case of maintenance and investment items, the price has been obtained directly from the manufacturers. Nevertheless, the consumption costs are very dependant on type of use of the mega yacht, which is always a difficult matter to approach. Thus, to identify this item, a Matlab code has been developed.

3.4.1. Initial investment

With the existing information stored in Blohm+Voss database from MTU and Marquip, and by contacting MME, the offers with the initial investment of both plants could be obtained, with the following results.

Table 9. Initial investment costs

Alternative	Items	Currency	Price	Total
1	Purchase and installation of GenSets	€	858.069	**1.263.544**
	Exhaust system	€	405.475	
2	Purchase and installation 2xC400	€	1.120.000	**1.164.400**
	Inlet air ducts	€	14.400	
	Exhaust system	€	30.000	

3.4.2. Consumption costs

Consumption costs include the expenses in FO for both generator sets and micro gas turbines, and additionally LO and urea in the case of generator sets. Their prices have been obtained in August 2015 from Hamburg Bunker Service GmbH in case of FO and LO, and Air1 in case of the urea, for which commercial product is called AdBlue. Following values were obtained:

- 1 € per litre of FO
- 2,6 € per litre of LO
- 0,25 € per litre of AdBlue

Consumption costs is the most significant item of the lifetime costs of the power plants, and at the same time the most difficult to estimate due to the high amount of unknowns that have effect on the consumption. Furthermore, it is the main drawback of micro gas turbines against conventional generator sets. For this reason, the Matlab code has been used to estimate their values with a probabilistic approach, which is explained in Chapter 4.

Thanks to the developed code, the averaged cost per hour of both types of power plants for the different conditions (navigation, manoeuvre, harbour service, anchoring and harbour in rest) can be estimated and thus, an economical comparison can be achieved. The results obtained with the code are shown in tables 10 and 11.

Table 10. Consumption costs of the generator sets

Condition	**Navigation**		**Manoeuvre**	**Harbour service**		**Anchoring**	**Rest**
Season	Summer	Winter	-	Summer	Winter	-	-
Time (%)	9	1	0,5	9	1	14,5	65
Demand (kW)	328	355	592	233	266	361	217
Cost (€/h)	**87,20**	**93,45**	**159,02**	**64,07**	**72,45**	**101,45**	**60,26**

Table 11. Consumption costs of the micro gas turbines

Condition	**Navigation**		**Manoeuvre**	**Harbour service**		**Anchoring**	**Rest**
Season	Summer	Winter	-	Summer	Winter	-	-
Time (%)	9	1	0,5	9	1	14,5	65
Demand (kW)	328	355	592	233	266	361	217
Cost (€/h)	**98,54**	**106,66**	**178,31**	**72,30**	**81,38**	**108,19**	**68,59**

As it is depicted, the higher specific consumption results also in higher consumption costs of fuel oil. Nevertheless, even though the specific consumption of turbines is around 20 % higher, thanks to the lack of lube oil and urea, the consumption costs are more or less 13 % higher, meaning that the avoidance of those components does not fully cover the higher fuel requirements, but it reduces the problem.

3.4.3. Maintenance costs

Maintenance costs are related to the amount of hours that the units are used per year. As the total power installed onboard is 1071 kW in the case of the generator sets and 800 kW in the case of the micro gas turbines, it means that each turbine will have to work more hours per year, since they will have to share the electrical demand with a lower total power installed. From the experience of the shipyard, it is estimated the following working hours:

- 3.000 hours per year each generator set
- 4.000 hours per year each micro gas turbine

With the maintenance costs received from MME, which can be seen in Appendix A3, and the database of Blohm+Voss, the maintenance costs are:

- 5.89 €/h each generator set, with an expected life of 12 years
- 8.87 €/h each micro gas turbine (C200), with an expected life of 20 years

The maintenance costs received from MME assume a frequency of use of 8.000 hours per year during 10 years. From the price/unit listed in the Appendix A3, and considering a frequency of use of 4.000 hours per year it is obtained, with a currency exchange of 1,086[3] $ per €, it is obtained the value of 8,87 €/h.

Even though the maintenance intervals are longer in the case of the turbines, the pieces to replace are more expensive, reason why maintenance costs are around 50% higher. Nevertheless, the expected life of the micro gas turbines is nearly 70% higher, and after 12 years, either new generator sets should be brought into the ship, or they must have a great overhaul that would generate similar or higher expenses, which would increase the total costs.

[3] At 1st December 2015

As information obtained from Blohm+Voss mechanical department, it is estimated to expend 500.000 € to replace the GenSets after 12 years.

3.4.4. Total lifetime costs

Taking into account the different contributions of the lifetime costs, total costs for a continuous operation during 20 years is calculated in this chapter.

In figure 3.4 the evolution of the lifetime costs for both systems can be observed. The initial investment is assumed to be paid at the year 0 in figure 3.3, and the maintenance and consumption costs are assumed during the operation of the ship. At 12 years from the year 0, which is the expected life of the diesel engines, there is a step in the curve of the generator sets, that shows the cost of this replacement.

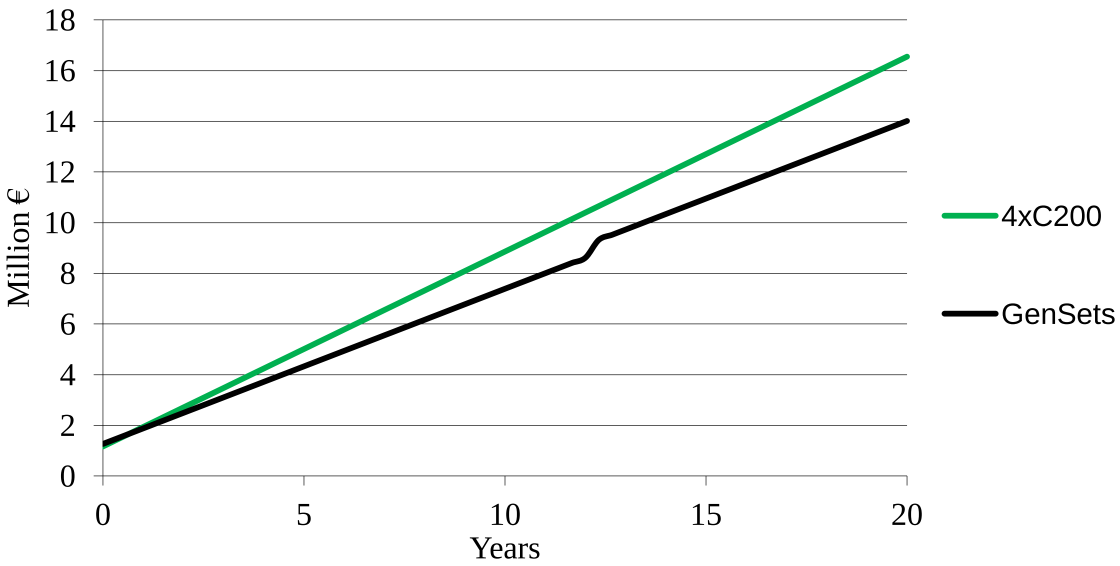


Figure 3.4. Lifetime costs comparison generator sets vs micro gas turbines

Results of lifetime costs over 20 years:

- Auxiliary power plant with generator sets: 14.015.000 €
- Auxiliary power plant with micro as turbines: 16.550.000 €

This means that from the economical point of view, the generator sets are a stronger alternative, having a difference of 2,535 million €. Nevertheless, this difference is small compared with the total costs of this kind of vessels (with prices varying from hundreds of millions, to billion Euros), and thus the owner would have to choose between having better comfort conditions, or saving around 127.000 € per year of operation.

On the other hand, as it was mentioned in the auxiliary systems chapter, micro gas turbines can free the space above them, and this space could be harnessed to install devices able to reduce the FO consumption of the power plant and therefore, to palliate the higher total consumption costs. These solutions are studied in the chapter 5.

4. INTRODUCTION TO THE DEVELOPED CODE

4.1. Probabilistic approach

The operation of an absorption chiller relies on the heating power that can be obtained from the heating source. In the case of the arrangement proposed for the mega yacht BV80, the heating source is the exhaust gas of the micro gas turbines, which, through a heat exchanger, can provide the required hot water. At the same time, the heating power extracted from the exhaust gas depends on the power delivered by the turbines, which is directly related to the electrical demand of the ship. This leads to the fact that the capacity to produce chilled water at every moment in the absorption chiller is linked to the electrical demand of the ship. Furthermore, the requirements of chilled water are not constant during the life of the ship, having variations depending on the hour of the day, season (summer or winter), the ship condition (navigating, anchoring, etc.), and even whether the owner is onboard or not.

Consumption savings generated in the ship by the absorption chiller rely on the correct selection of a model available in the market. This model must be powerful enough to cover a high percentage of the total amount of chilled water that is needed onboard for different load profiles, but not too big so that the exhaust gas of the MGTs can provide the heat power needed in the absorption chiller.

For all these reasons, the method to estimate the most convenient absorption chiller is based on a probabilistic approach, using Gaussian distributions to estimate the electrical profiles on the different conditions.

The electrical balance of the ship, which can be seen in Appendix B, gives an idea of the maximum demand that the ship will experience in the different conditions.

The calculations take into account whether the owner is onboard the ship. Nevertheless, this type of vessels are most of their time at rest, or sometimes used only by the crew, reason why the electrical profile completely changes during a natural year. This is why, the fact of the owner being onboard or not is taken into account, having as a result input presented in table 12 for the BV80.

Table 12. Electrical demands of the different conditions

Condition	Navigation		Manoeuvre	Harbour Service		Anchoring	Harbour in Rest
	Summer	Winter	-	Summer	Winter	-	-
Owner onboard (kW)	526	557	782	401	432	578	0
Owner not onboard (kW)	465	494	722	356	371	512	310

The values obtained when the owner is not onboard were established consulting the electrical department of Blohm+Voss.

As it was mentioned, Gaussian distributions have been used to evaluate the absorption chiller. As there are two different profiles (owner onboard and owner not onboard), two normal distributions for each condition have been built.

A normal distribution is defined by the mean (μ) and the standard deviation (σ). Figure 4.1 is shown to easily understand the concepts.

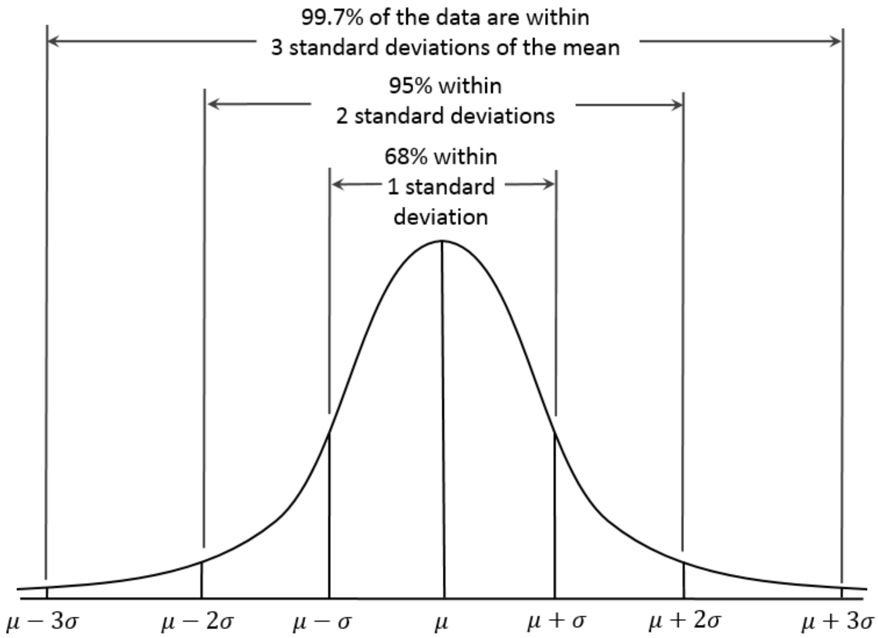


Figure 4.1. Normal distribution[4]

[4] Retrieved from http://study.com/academy/lesson/standard-normal-distribution-definition-example.html

The role of the electrical demands in table 12 are to define the standard deviation of the distributions. Assuming that the minimum loads of the distributions are 75 % of the maxima (those from table 12), the mean (μ) is simply the average value between maximum and minimum. Then, it is assumed that the value of σ for the maxima and minima are +2,5 and -2,5 respectively. As there are two normal distributions for each condition (owner onboard and owner not onboard), the result is a combined distribution, whose shape is dependent on the number of days that the owner is onboard. The following graph shows an example of the results that can be obtained by the code, setting this parameter in 100 days per year.

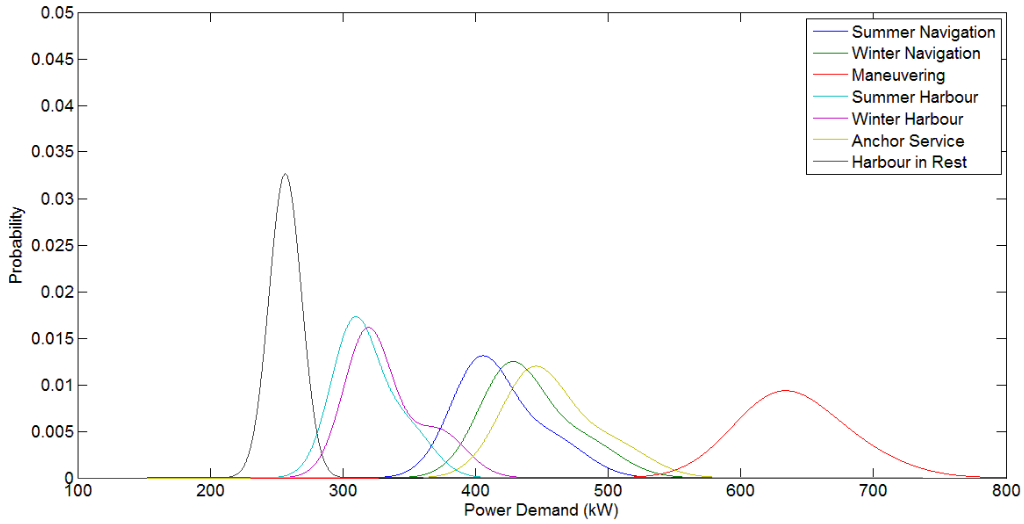


Figure 4.2. Example of distribution with 100 days with the owner onboard the ship

As it can be seen, composing both normal distributions results in a non-symmetrical distribution, except for the case of the condition harbour in rest, since it is assumed that the owner of the ship is never onboard in this condition and thus there is only one distribution in this condition.

For the case study, 14 days per year have been assumed that the owner will be onboard, obtaining the distribution depicted in figure 4.3. Comparing figures 4.2 and 4.3 it can be seen that when the days that owner is onboard is reduced to 14, which corresponds to less than 4% of the time, the distribution obtained is almost a perfect normal distribution since the contribution of one of them is very low.

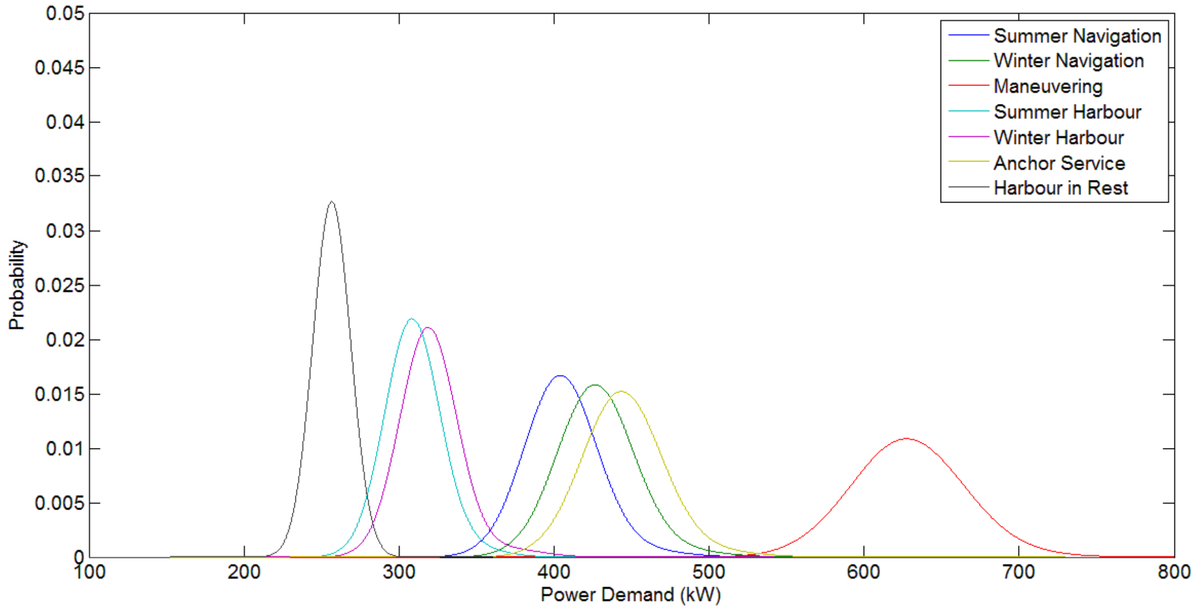


Figure 4.3. Normal distributions of the electrical demand in BV80

Another parameter that is introduced in the code is the variation of the electrical demand along the day. These variations, which are different for summer and winter, are very well known when looking at the installations onshore. In this case, they have been applied in form of a factor with a maximum of 1 located in the peak time of the day, and which varies along the day as shown in figure 4.4

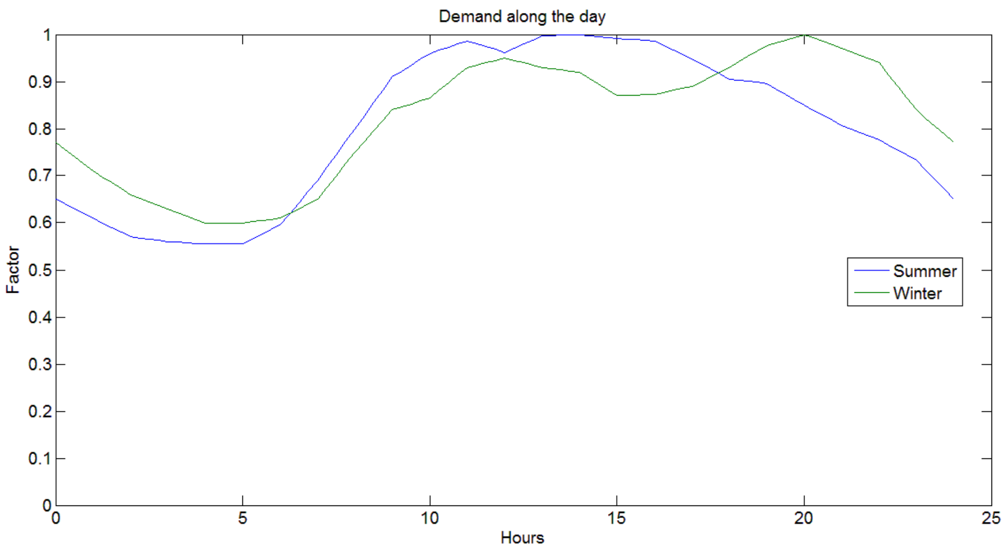


Figure 4.4. Hourly factors of electrical demand[5]

[5] Retrieved from:

http://garvia.blogspot.de/2012/01/estructura-del-mercado-electrico-ii.html

http://reneweconomy.com.au/2014/network-operator-says-rooftop-solar-pv-shifts-peak-by-several-hours-89109

The aim of this factors is to take into account the variations during the day to simulate the behaviour of the system during a day, and identify if there could be some hours in which there is more heat power created than needed or vice versa.

From the electrical distributions, and the demand factors along the day, it is obtained the electrical profiles for each condition, as shown in figure 4.5.

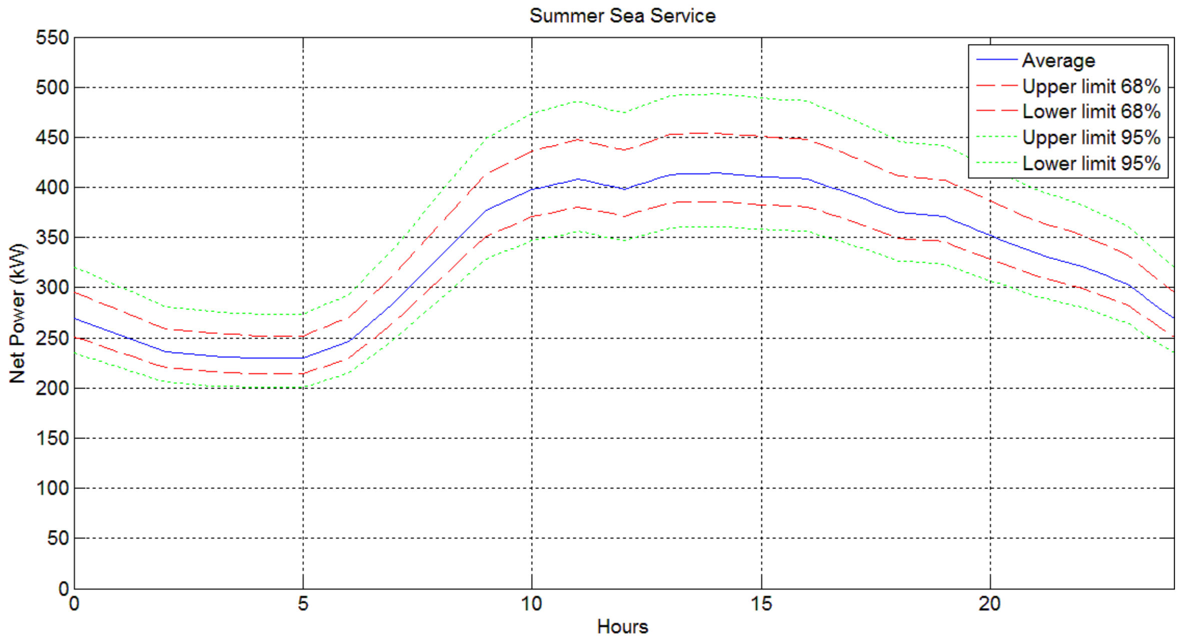


Figure 4.5. Electrical demand profile during a day in summer sea condition

In figure 4.5 average electrical demands during the day (in this case for navigation in summer condition) are shown, as well as the ranges of kW in which normally the ship will have demand, having as conclusion that 95 % of the time the electrical demand will be between the green dotted lines.

4.2. Chilled water plant

Absorption chillers have the advantage that they barely consume electricity (their functioning is explained more detailed in chapter 5). However, they do not instantaneously adapt to the changes in the demand, so that generally several minutes are needed to change the amount of chilled water that they can produce. In contrast, compression chillers are faster machines, which are able to adapt to the variations in the chilled water demand in few seconds. Also, the absorption chiller performance can be affected with heavy motions, meaning that if the ship is in severe sea states, the absoprtion chiller should be turned off. For these reasons, even if an absorption chiller is installed, the compression chiller will still be needed onboard, leading to a hybrid chilled water plant.

The cooling power needed in the different conditions can be obtained from the electrical demand of the compression chiller, given by the electrical balance of BV80 (shown in Table 13) and the technical characteristics of the compression chiller installed onboard (described in Appendix D).

Table 13. Electrcial demand of the compression chiller. (Blohm+Voss Database)

Condition	**Navigation**		**Maneuvering**	**Harbor Service**		**Anchoring**	**Harbor in Rest**
Season	Summer	Winter	-	Summer	Winter	-	-
Demand kW	140,3	41,3	110	115,5	41,3	110	41,3

The Matlab code works with different models of absorption chillers available in the market, summarized in Appendix E1. For each of them, the code calculates the amount of chilled water that the absorption chiller can produce during the day for the different conditions, and thus, the savings in chilled water that the compression chiller does not have to produce, which later on is translated into electrical savings when the COP (coefficient of performance) of the compression chiller is applied.

4.2.1. COP of a compression chiller

COP relates the cooling power (ϕ_0) of the machine with the power consumed by the machine. In compression chillers, consumed power is given by the electrical consumption of the compressor (P_{el}).

$$COP = \frac{\phi_0}{P_{el}}$$

In Appendix D the relations between the three factors can be found.

4.3. Heat power profile

From the electrical profile obtained in the process as the example shown in figure 4.5, and taking into account the electrical savings produced with an absorption chiller, thanks to the information from Capstone [2], the exhaust mass flow and the temperature that MGTs provide are interpolated, and after calculating the net heat exchanged, the available heat power that can be sent to the absorption chiller is obtained and compared with the heat demand that the absorption chiller needs at different hours of the day for different conditions. Figure 4.6 shows an example with the model L40HH, which has a cooling capacity of 141 kW.

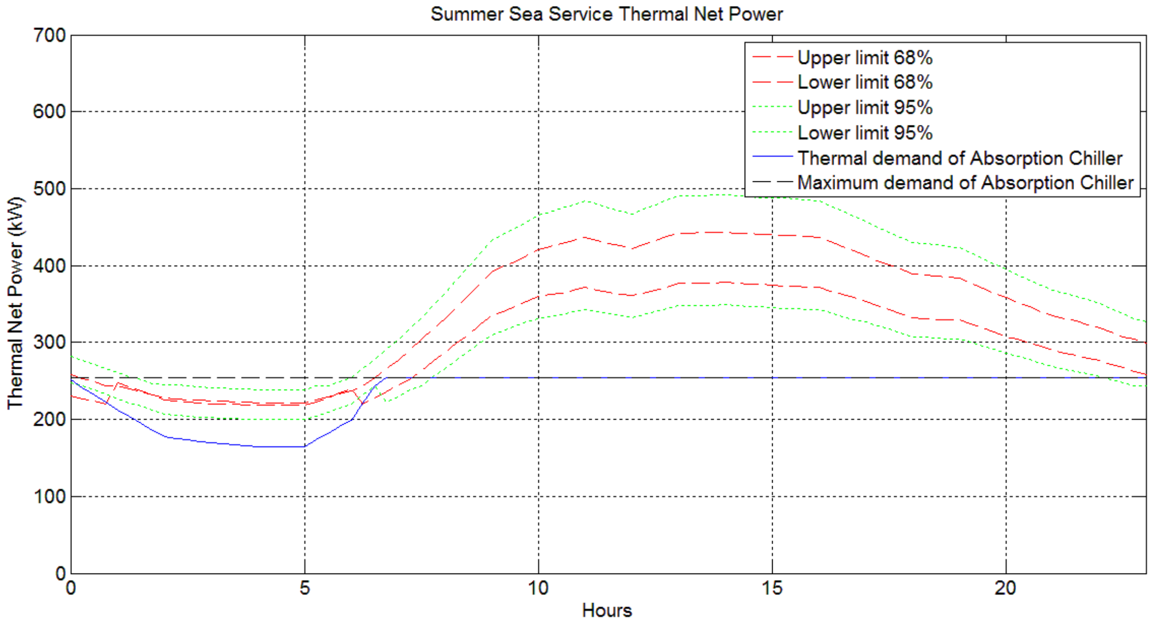


Figure 4.6. Thermal power demand vs thermal power capacity during the day

In figure 4.6 red dashed lines set the limits in which thermal power provided by MGTs will be 68 % of the time. In the same way, green dotted lines set the limits for 95% of probabilities to get a thermal power between them. Blue line describes the thermal power demand of the absorption chiller. As result the graph allows the user to analyze the balance of the system, and select an appropriate model for the ship.

4.4. Selection

One of the input data is the range of percentages of time that is probable for the main conditions to experiment. For the case study, next ranges were established:

Table 14. Range percentages in the different conditions for absorption chiller selection

Conditions		Lower limit	Upper limit
Navigation	%	0	30
Harbour Service	%	0	30
Anchoring	%	0	40
Harbour in Rest	%	50	100

It can be seen that the maneuvering does not take part in this data. The reason is that maneuvering condition is assumed to occur always 0.5 % of the time, except for the case that the ship stands the whole time at rest, meaning 100 % of the time at harbour in rest. In this condition is implicit that if the ship does not move, there is no maneuvering.

Apart from the above mentioned limits, and based on the opinion from Blohm+Voss staff, it was assumed that 90% of the time the ship would operate in Summer areas.

From the high amount of possible combinations that can sum up 100 % with the mentioned limits in Table 14, the code calculates which is the most appropriate absorption chiller for each combination, having as optimization value the electrical savings produced by the hybrid chilled water plant, and highlights which is the most selected absorption chiller from the whole process.

This chapter focuses on explaining the calculation method of the code. Results obtained are shown in chapter 5.3

4.5. Significant information

Apart from selecting a convenient absorption machine, the code provides important data utilized to evaluate the feasibility of the micro gas turbines.

- It is the source where the consumption costs of generator sets and micro gas turbines are calculated and lately compared.
- The electrical distributions help to observe the ranges of demand that the vessel will face.
- Helps to analyze the size of the heat storage tank that must be installed onboard to regulate the hot water flow delivered to the absorption chiller.

5. ADDITONAL SOLUTIONS

Micro gas turbines demonstrate to be a very reliable and feasible option to replace conventional diesel engines in a sector where comfort is one of the key factors. They offer high quality characteristics in terms of noise, vibrations, emissions, lubrication and maintenance, with the only drawbacks of higher fuel oil and air consumptions.

Air is obtained free of costs, but it makes the MGT to be efficiently dependant on its temperature. As per the greater FO consumption, fuel is a material that costs money, and it also requires space to store it onboard. For these reasons, additional solutions that could be installed onboard are studied to improve the quality of the power plant and palliate the drawbacks.

Main solutions that have been studied are:

- Batteries (reduction of air and investment costs)
- Inlet air ducts, inlet air coolers (improve air temperature dependency)
- Absorption chillers, exhaust heat exchangers, heat storage tanks (FO consumption reduction)

5.1. Batteries

5.1.1. Motivation

Appendix B includes the electrical balance of the ship, for which the highest electrical demand is found in manoeuvring condition. From the 782 kW of demand in this condition, 314 kW are used by bow thruster. It must be mentioned that manoeuvring is a very special condition, which barely represents 0,5 % of the lifetime or even less.

From this analysis, an option to be studied is the installation of batteries that could provide the required electrical power to the bow thruster and in this way, one of the micro gas turbines C200 could be removed from the machinery room, since the rest of the electrical balance conditions are fulfilled with only 3 micro gas turbines (600 kW). The information about this option is provided by the French company SAFT.

5.1.2. Technical characteristics

Saft offer consist on a pack of Li-ion battery. Main characteristics are shown in table 15.

Table 15. Technical characteristics of batteries for bow thruster.
[Appendix F], (Conversations with Saft)

Battery system	VL41MFe_Seanergy 48M
Maximum Voltage	479 V
Number of battery // strings	5
Energy installed	162 kWh
Maximum discharge power	369 kW
Maximum charge power	168 kW
System Weight	2.432 kg
Dimensons (LxWxH)	800 x 3.000 x 1.700 mm
Heat emission	2,5 kW
Cycle life	>6.000cycles, >20 years at 20ºC

From the information exchanged with Saft batteries, it is indicated that the maintenance costs needed for the package with a full contract is approximately 8% of the initial cost per year.

5.1.3. Location

As its name indicates, bow thruster is located in the fore part of the hull, close to the fore technical room, which contains the compression chiller among other units. This is the selected area to install the batteries, as can be seen in the figure 5.1.

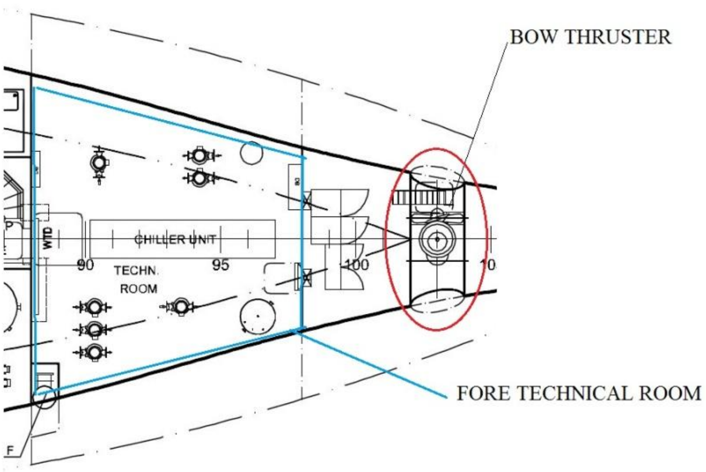


Figure 5.1. Fore technical room, (Modified from Blohm+Voss Database)

5.1.4. Effect on auxiliary systems

Ventilation of technical room

Batteries need heat dissipation in the compartment where are to be installed. As shown in Table 15, the manufacturer specifies that 2,5 kW are necessary for the whole package of batteries. Equation 5.1 relates the cooling power with the air mass flow needed.

$$P = Q \cdot \rho_a \cdot c_e \cdot \Delta T \tag{5.1}$$

with:

- P: Heat dissipation power (kW)
- Q: mass flow of air (m^3/s)
- ρ_a: density of air (kg/m^3)
- c_e: specific heat of air (J/kgK)
- ΔT: temperature difference, assumed to be 12,5 ºc

As result, the mass flow of air required for this case is 600 m^3/h. The technical room located in the forward part of the ship is ventilated through a speed controllable fan from the company Systemair, model RSI 70, which must provide 1.485 m^3/h for different areas in the fore part of the ship. As can be seen in Appendix G3, the optimum operating point of the unit is at 2.505 m^3/h, which means that adding the 600 m^3/h will not only make unnecessary to replace the model, but also the model will operate closer to the maximum efficiency point.

Exhaust system

In the case of having 3 MGTs C200, each turbine has an independent duct, and the problem found in chapter 3.2.6 due to the reduction of the diameter at the top would be avoided, since a diameter of 300 mm (as mentioned in chapter 3.2.6, maximum allowable is 392 mm to not alter the external view) give an exhaust flow speed[6] of 16 m/s.

Ventilation of machinery room

The installation of the batteries will not directly have effect on the ventilation of the machinery room, but indirectly, as one micro gas turbine could be removed, this system will

[6] Calculated from http://www.schweizer-fn.de/

be affected. The removal of one micro gas turbine will result in the ventilation air requirements shown in table 16, similarly to the table 6.

Table 16. Air flow for machinery room ventilation with 3 Micro Gas Turbines C200

Designation	**Quantity**	**Airflow heat dissipation (m^3/h)**		**Airflow for combustion (m^3/h)**		**Total Airflow (m^3/h)**
		Per unit	Total	Per unit	Total	
Main Engine MTU 12V4000 M73L	2	7.268	21.803	11.160	22.320	35.195
MGT Capstone C200	3	6.117	18.351	4.418	13.254	31.605
Transmission	2	3,5	1.766	-	-	1.766
Exhaust Pipes	1	1.262	1.262	-	-	1.262
Electrical Installation	1	10.094	10.094	-	-	10.094
Total Airflow			**53.276**		**35.574**	**79.922**

The total airflow needed is 79.922 m^3/h, which means that the initial axial fans projected for the generator sets could remain onboard the ship, although it would be practically on the limit (80.000 m^3/h).

5.2. Improvement of air dependency

The machinery room is the area of the ship where highest temperatures are generally achieved because of the heat emission from the equipments inside. In the ship specifications [1], a maximum temperature of 45 ºC is assumed with a maximum outside temperature of 35 ºC.

From the technical reference provided by Capstone [2], at a temperature of 45 ºC the net efficiency is lowered from 32.8 % at ISO conditions (15 ºC) to 30.3 %. But the most important fact is that the micro gas turbine C200 can only provide 160 kW at full load, which means a reduction of 20 % from the maximum. This way, the electrical demand could not be fully covered, which would result in critical damage for the micro gas turbines.

In order to avoid these problems, two solutions described in following sections are suggested, in order to ensure the income of air into the turbine in good conditions.

5.2.1. Inlet air ducts

As has been explained, temperature in the machinery room is generally higher than in the exterior. For this reason, if the air driven to the turbine is brought directly from the exterior of the ship, the air in the turbines will operate closer to the desired conditions.

The machinery room receives the cooling and combustion air from two ducts located at each side of the ship, with two axial fans, each one with 40.000 m^3/h of capacity. The air is distributed symmetrically in the machinery room. The general arrangement of the system can be seen in Appendix C.

The size of the ducts is constrained by the airflow needed (10.535 m^3/h each C200 model) and the velocity of the air inside the ducts. The ventilation system of the Mega Yacht BV80 has been designed with a flow velocity of 7,15 m/s. This means that the sectional area of the ducts must be calculated as:

$$A = \frac{Q}{v} = \frac{10.535/3600(m^3/s)}{7{,}15(m/s)} = 0{,}41m^2 \qquad (5.2)$$

The high value of the sectional area of the duct makes difficult to reach the MGTs, since there are some obstacles inside the machinery room that must be eluded. For instance, the fore and back parts must be free to access to the micro gas turbines in order to do the maintenance works. This is depicted in figure 2.12.

Arrangement of the ducts

The ventilation system of the machinery room is aimed to dissipate the heat of different machines inside. The two main sources of heat emission are main engines and micro gas turbines, which work independently from each other, e.g. when the ship is in the condition of harbour service, the main engines are switched off, but the micro gas turbines must provide some power for the energy onboard. As the ventilation ducts are unique for the whole machinery room, all the air departs from the two casings located at each side of the machinery room.

When air is sent through the inlet air ducts to the micro gas turbines, the other ducts designed to distribute it to the remaining equipments will also receive air in a similar proportion (directly related to their sectional area). Nevertheless, as mentioned before, main engines and micro gas turbines will work independently from each other. One of the solutions could be to deliver the air to the micro gas turbines from one of the casings located at one side, and the remaining air from the other casing, in order to have independent ventilation systems. Nevertheless, because of the lack of space to reach the micro gas turbines, it is not a feasible solution. For this reason, it has been decided to build a symmetric system, as shown in the figure 5.2.

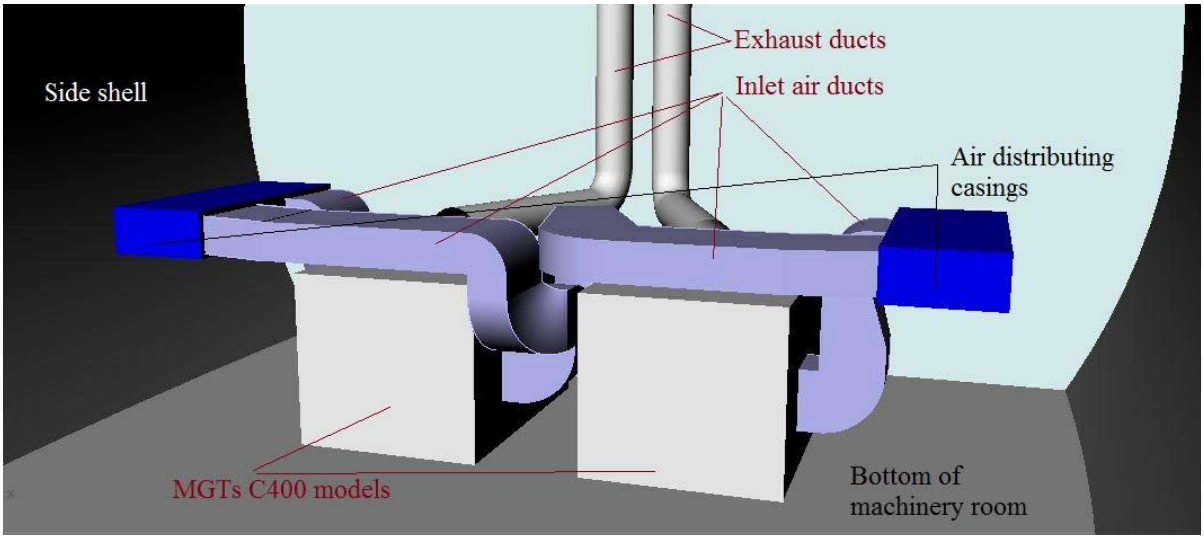


Figure 5.2. 3D model of the inlet air ducts arrangement

In order to solve the problem of air dependency, the system will be provided with frequency controllers, that at any time regulate the airflow to the machinery room. In order to avoid intake of air in a turbine that is not running, each one of the ducts of the micro gas turbines will have a flap with open/closed positions. In this way, if the fans are delivering more air than needed to the main engines, it will automatically go out by natural ventilation through the chimney.

The diagram presented in figure 5.3 shows the proposed air distribution for the lower deck of the machinery room with four Capstone C200 micro gas turbines onboard.

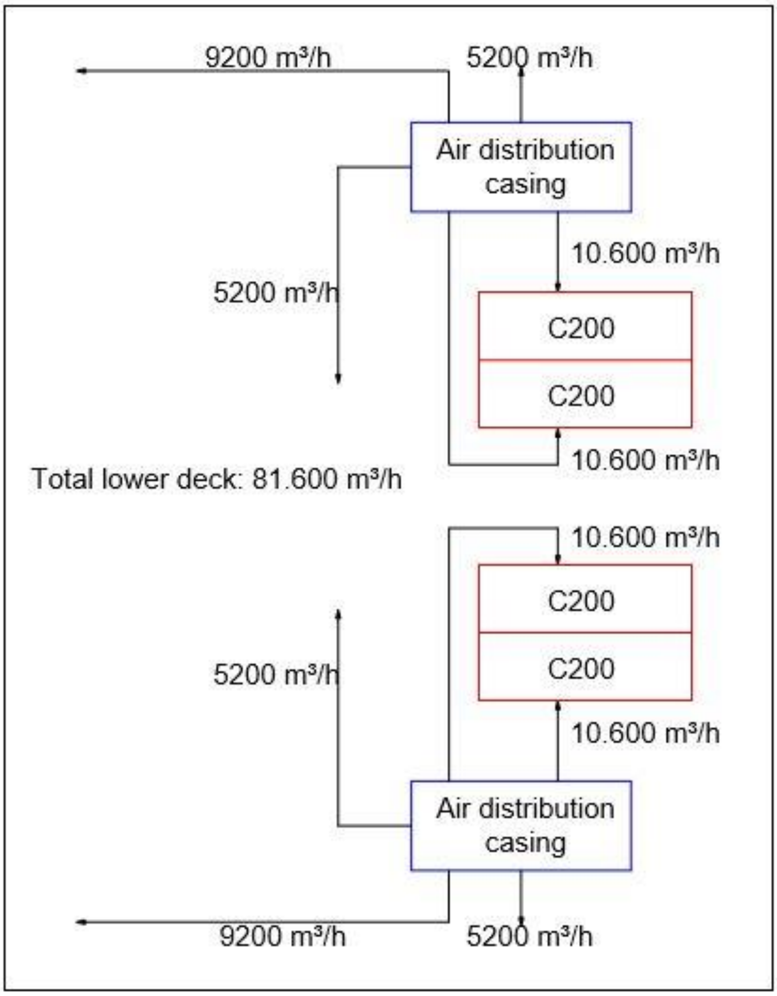


Figure 5.3. Air distribution in lower deck of machinery room with 4xC200 MGTs

5.2.2. Inlet air coolers

Apart from the air ducts, air coolers will be installed in the MGT inlets to cool down the incoming air and thus, being able to work with an optimum air temperature. The technical characteristics of the air coolers received from MME are shown Appendix A4 and A5, from which can be observed that two air coolers for each turbine are needed; one for the air relative to the heat dissipation of the electrical components inside the sound enclosure; and other one for the combustion air. The medium to perform the heat exchange is sea water, obtained from the sea chests located in the machinery room. Sea water used for these coolers was initially conceived for the cooling system of the generator sets. As can be seen in table 2, the sea water requirements for the diesel engines are significantly higher, so that no additional pumps have to be added in the machinery room.

Combining inlet ducts and air coolers, and assuming the extreme summer conditions given by the specifications [1] of:

- Outside air temperature: 35 ºC and 70 % of relative humidity
- Sea water temperature: 32 ºC
- Average engine room temperature: 45 ºC

The net power obtained in this conditions can be raised from 160 kW (net power at 45 ºC [2]) to around 183 kW (net power at 32,5ºC [2]) for the model C200. It must be mentioned that this conditions are barely experienced during the life of the mega yacht.

5.3. Absorption Chillers

5.3.1. Concept and cycle

An absorption chiller is a machine that produces chilled water with a heat source. The operation of an absorption chiller, as shown in the figure 5.4, is similar to a compression chiller, and their differences come from the compressor side. Absorption chillers use thermal compressors, while compression chillers use electrically driven compressors.

Thermal compressors are used in a binary system that consist on a solvent and a refrigerant. The units that are fabricated to produce chilled water for air conditioning units work with a lithium-bromide solution as solvent, and water as refrigerant. The cycle of the absorption chiller is explained below and shown in figure 5.4.

Absorber

Vaporous water, which is the refrigerant, is driven from the evaporator (water cooler in figure 5.4) to the absorber, where also a concentrated solution of lithium bromide is injected. After being introduced in the absorber, the concentrated solution absorbs the water vapor, resulting in a diluted solution. During the absorption, water vapor release heat, denoted as ϕ_A, which is taken by sea water. Resulting solution is in liquid state, and it is pumped by the solvent pump to the higher pressure level.

Desorber

The next stage of the diluted solution is the desorber, where it is heated with the heating medium (in the case of BV80 this is achieved with hot water coming from the exhaust heat exchanger), receiving in this case heat denoted as ϕ_H. When receiving the heat, refrigerant in gas state is released. As result, the diluted solution is expanded to the low pressure level via throttle and enters again in the absorber. On the other hand, the refrigerant evaporated is sent to the condenser

Condenser

The vaporous refrigerant coming from the desorber is cooled down with sea water, and the material is then condensed, giving heat to the sea water denoted as $\phi_{C.}$ Once condensed, the refrigerant in liquid state, by an expansion valve, is sent to the low pressure level, and injected in the evaporator.

Evaporator (water cooler)

When the refrigerant is expanded from the condenser to the evaporator, the refrigerant experiments a pressure drop, which at the same time means a temperature drop. Thanks to the low temperatures reached by the refrigerant, the machine can cool down water, taking heat from the water that is aimed to refrigerate, denoted as ϕ_0.

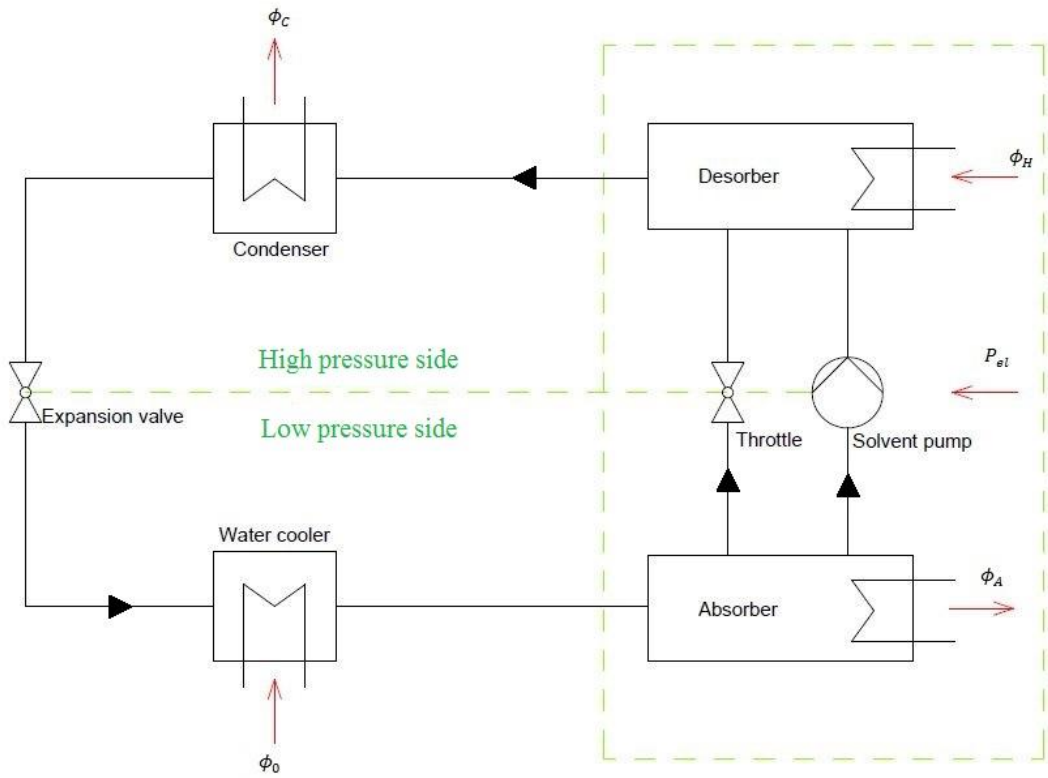


Figure 5.4. Scheme of an absorption chiller

5.3.2. Coefficient of performance

In order to compare the absorption chiller models, the COP (Coefficient of performance) can be used [3]:

$$\xi_{AbCh} = \frac{\phi_0}{\phi_H + P_{el}} \tag{5.3}$$

Since the electrical power P_{el} of an absorption chiller is significantly lower than the heat supplied ϕ_H, the coefficient of performance can be simply the ratio between the cooling capacity ϕ_0 and ϕ_H.

$$\xi_{AbCh} = COP = \frac{\phi_0}{\phi_H} \tag{5.4}$$

The main models in the market of a single-stage absorption chiller have a range of values of COP between 0,6 and 0,83.

5.3.3. Hybrid system

Absorption chillers have as main advantage the reduction in electrical demand of the vessel. On the other hand, as they work with a heating source, they need more time to adapt to the variations in the cooling demand. In addition, their performance is affected by the motions, which means that in severe sea states they should be switched off. The mentioned characteristics make necessary to keep the compression chiller onboard.

The initial design of the mega yacht BV80 is conceived with a compression chiller, model Daikin EWWD650-XS-marine, whose technical data can be seen in Appendix D, and which provides cooling capacity of 552 kW.

Both compression chiller and absorption chiller need sea water for the condenser, and their requirements are 17,3 l/s and 25,5 l/s respectively. As the volumetric flows are relatively similar, there is no need to add an additional pump if the absorption chiller is installed onboard, as was studied by (Feßler, 2015), [3]. Since it is a hybrid system, the same can be said about the chilled water piping, which means that the only pump that should be added onboard if an absorption chiller is installed is the hot water pump driving the water from the exhaust heat exchanger to absorption chiller and heat storage tank. Table 17 shows the main differences from both compression and absorption chiller technologies.

Table 17. Comparison of absorption and compression chillers [3]

	Absorption chiller with LiBr solution	Compression chiller
Compression principle	Thermal	Mechanical
Driving power	Thermal energy	Electrical energy
Refrigerant	Water	Halogenated hydrocarbons
COP/heat ratio	0,6-0,82	3-5

5.3.4. Suitable models for the co-generation plant with micro gas turbines

Absorption chillers can work with different heating sources, as steam, hot water or fired gas. The simplest installation for a vessel with micro gas turbines would be to directly deliver the exhaust gas to the chiller. Nevertheless, experts in the absorption chillers from the company Gasklima, which is the main provider of absorption chillers in Germany, do not recommend to do it through this medium. Instead of it, their advice is to provide hot water to the absorption chiller due to the high oscillations that the exhaust gas may experiment. To have this system, it is needed an exhaust heat exchanger able to transfer the heat from the exhaust gas to the water, and in addition, it is also recommended to install a heat storage tank to regulate the flow and heat delivered to the chiller. Both heat exchange and heat storage tank are analyzed in chapter 5.4.

From the mentioned absorption chillers working with water as heating medium, there are two main world manufacturers that can provide such equipments. Yazaki (from Japan) and World Energy (from South Korea) and their suitable models are summarized in Appendix E1. In order to select the most convenient model, the matlab code explained in chapter 4 can be used.

5.3.5. Class Approval and performance for different motions

Classification Societies have been contacted in relation to the characteristics that this type of machines may have to get a class approval. From both manufacturers, only World Energy was found to have approval certificates for their models, approved by DNV-GL. The classification society owns two types of approval certificates, one for an absorption chiller with steam as heating medium and other one for the models showed in Appendix E2 working with hot water. Both certificates have been obtained during the year 2015, which highlights that this type of devices are beginning to be seriously considered as an application for the maritime sector.

The approval certificate for the steam model is also shown in Appendix E3, where performance of the absorption submitted to different motions is described. This information is been relevant in order to have a realistic approach of the loss of efficiency of these devices when they experiment the typical motions of a ship.

Mega yachts are generally conceived to operate in calm waters, and heavy motions are always tried to be avoided in order to guarantee pleasure conditions. One of their characteristics is the installation of stabilizing fins, which are used to reduce rolling motions. Taking into account the data from Appendix E3 regarding the absorption chiller performance, it is concluded that absorption chillers suit perfectly in a mega yacht as BV80.

5.3.6. Selection and results

From the developed code, the results show that from a total of 242 combinations of time percentages (see table 14 in chapter 4) the model L75HH from World Energy, which corresponds to 264 kW of cooling capacity, was selected 222 times as the most convenient one.

Table 18. Selection results of absorption chiller from the code

Absorption Chiller model	Cooling Capacitiy (kW)	Thermal demand (kW)	Selected times
WFC-SC50	175,8	251	0
WFC-SH30	105,6	151	0
L40HH	141	171	15
L60HH	211	254	5
L75HH	**264**	**319**	**222**
L90HH	316	381	0
L110HH	387	467	0

The results of the heat recovery obtained with the code for this absorption chiller in the different conditions are shown in figures 5.5 to 5.11. For each condition the thermal power demand of the absorption chiller in comparison to the thermal power available from the heat recovery of the micro gas turbines along a day can be seen. The moments during the day that the available heat (strip between dotted green and dashed red curves) is higher than the demand (blue curve) the system gets higher heat than the one needed, which can be harnessed to load the heat storage tank.

In the same way, for the opposite situation in which the demand is over the strip of available thermal power, which only occurs in summer harbour (figure 5.8), the heat storage tank has to be unloaded to provide the extra heat needed. If, in real life, the latter state lasts for several hours, the tank will be fully discharged and the amount of chilled water produced by the absorption chiller will have consequently to be reduced, being needed to provide this amount by the compression chiller.

Figures 5.5 to 5.11 show the profile of use of an absorption chiller with 264 kW of cooling capacity.

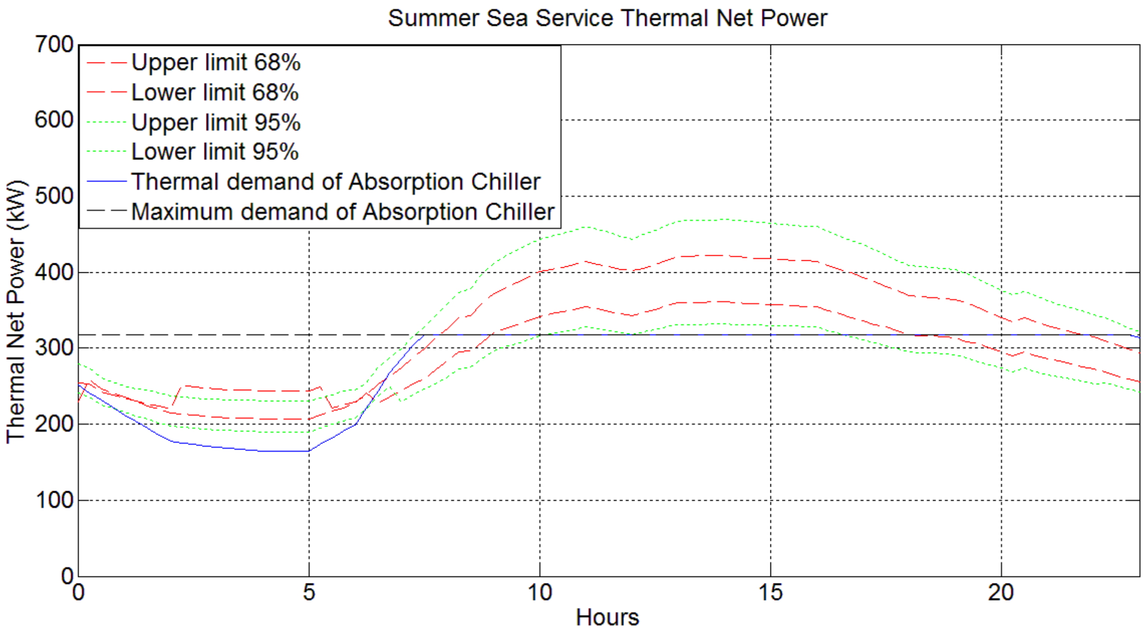


Figure 5.5. Heat recovery in Summer navigation condition

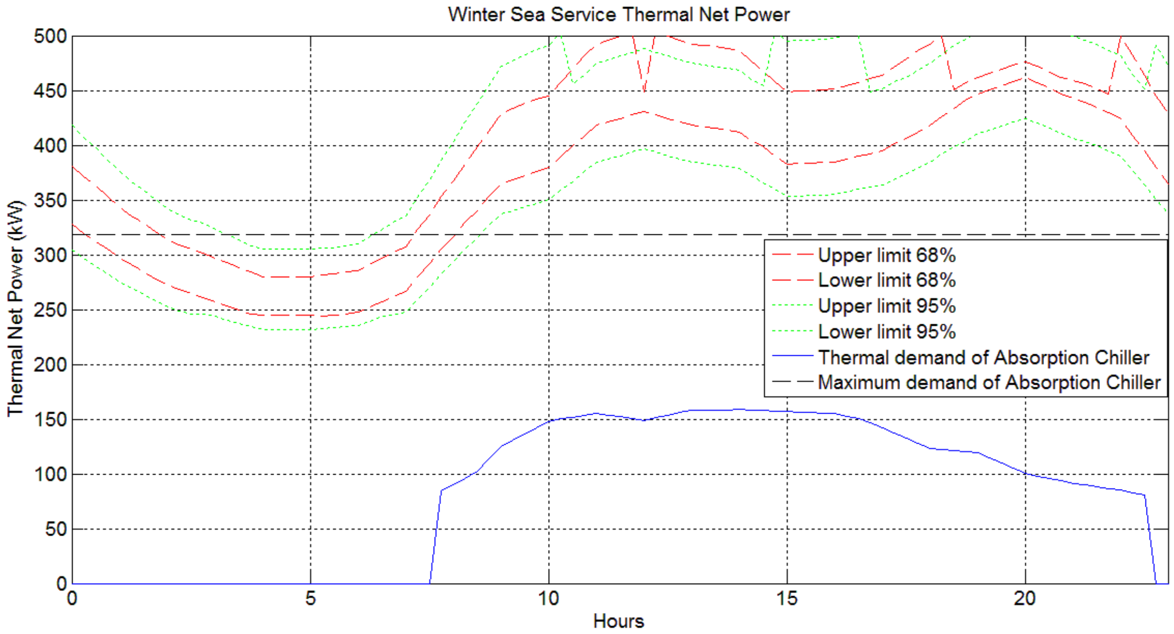


Figure 5.6. Heat recovery in Winter navigation condition

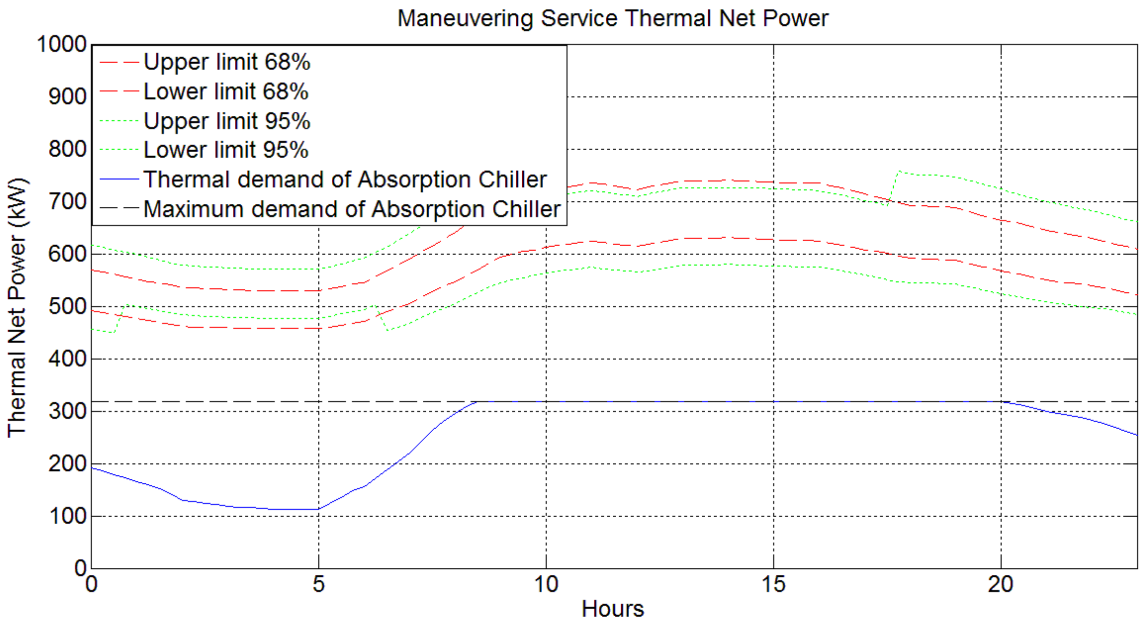


Figure 5.7. Heat recovery in Maneuvering condition

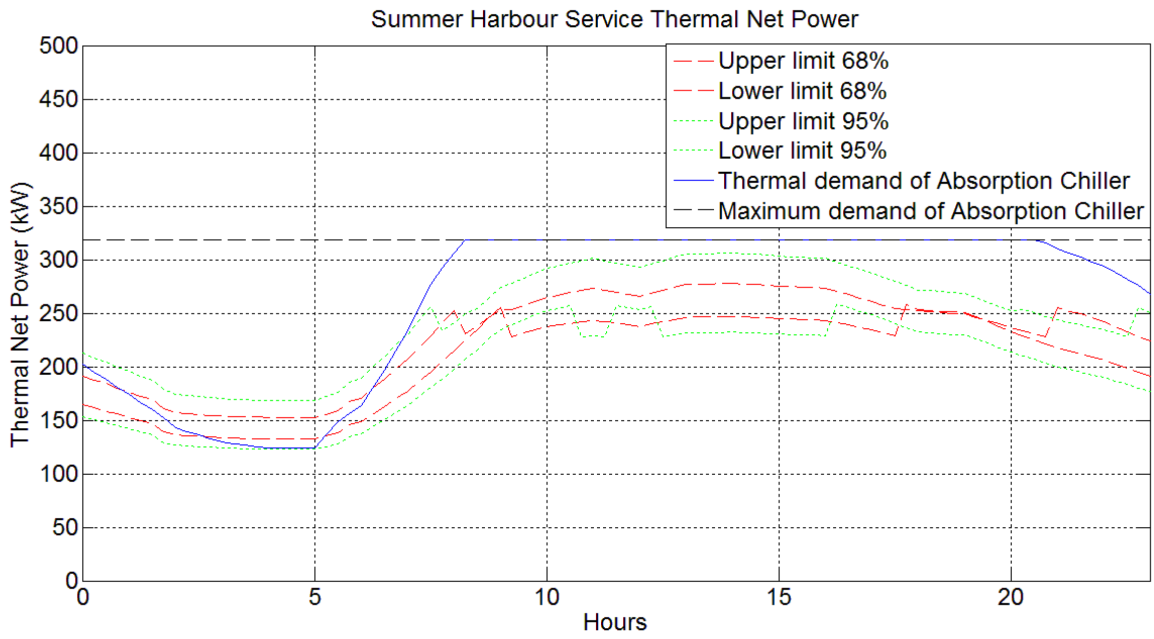


Figure 5.8. Heat recovery in Summer harbour service condition

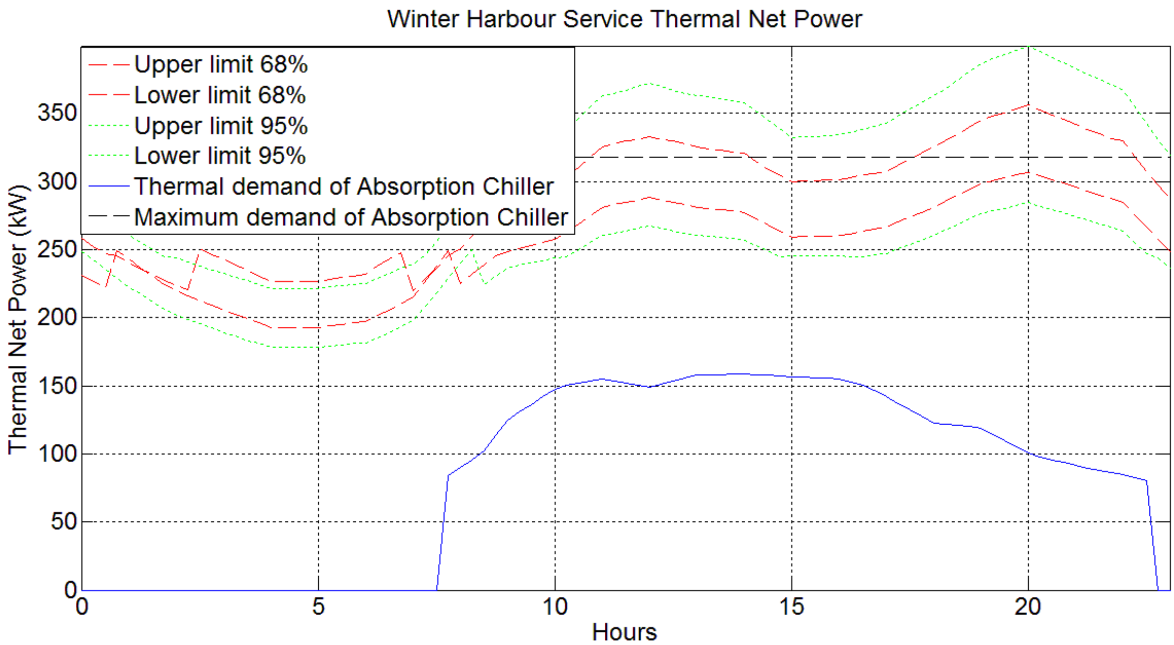


Figure 5.9. Heat recovery in Winter harbour service condition

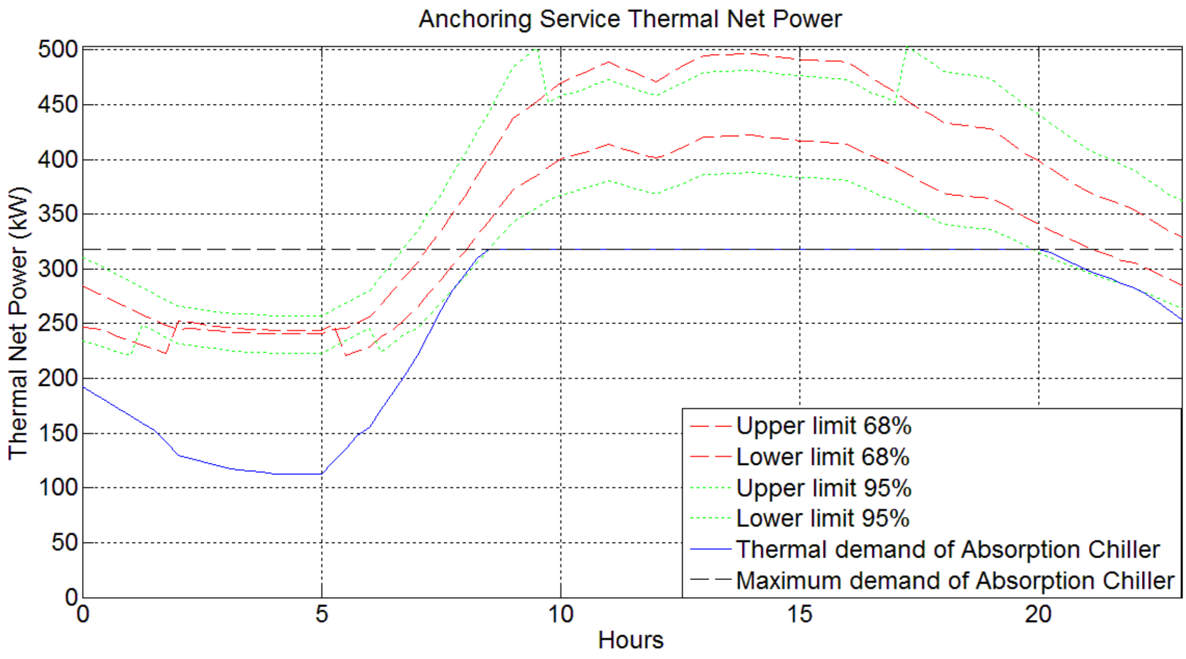


Figure 5.10. Heat recovery in Anchoring condition

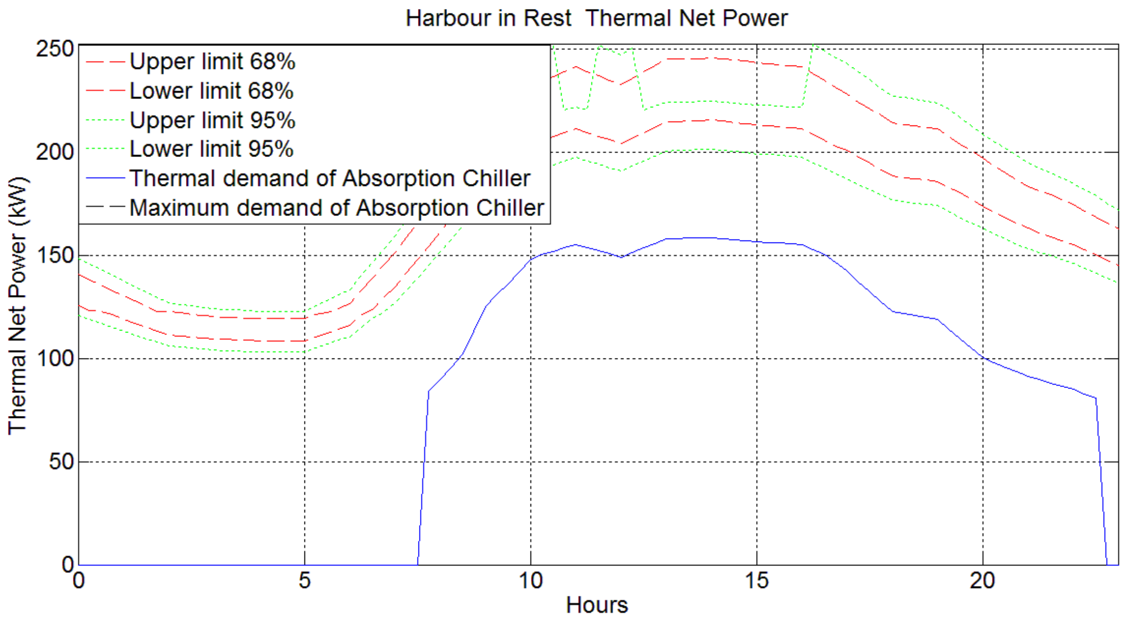


Figure 5.11. Heat recovery in Harbour in rest condition.

The total capacity of the absorption chiller is reached in the conditions of navigation in summer, manoeuvring, harbour service in summer and anchoring, which means that a more powerful absorption chiller could be installed onboard, but on the other hand, if bigger chiller is installed, there would be a high amount of hours in the condition of harbour in rest that the demand would not be higher than 25 % of the partial load, and in this state it is not advisable to run the absorption chiller. This is why a smaller absorption chiller would not result in so many fuel savings, and a bigger one would be oversized. The main characteristics of this model are shown in table 19.

Table 19. Characteristics of selected absorption chiller

Absorption Chiller L75HH			
Cooling Capacity		kW	264
	Inlet Temp./Outlet Temp.	ºC	13/8
Chilled Water	Flow Rate	m^3/h	45,44
	Connection	mm	80
	Inlet Temp./Outlet Temp.	ºC	31/36,5
Cooling Water	Flow Rate	m^3/h	91,6
	Connection	mm	125
	Inlet Temp./Outlet Temp.	ºC	95/80
Hot Water	Flow Rate	m^3/h	19
	Connection	mm	65
	Length	mm	2658
Size	Width	mm	1112
	Height	mm	2473
Weight	Rigging	ton	3,6
	Operation	ton	4,1

5.3.7. Location

As mentioned in chapter 3.2.5, the removal of the emission reduction system (SCR), leaves free space on the upper deck of the machinery room that can be harnessed to install the absorption chiller. The next figures 5.12 and 5.13 show both arrangements.

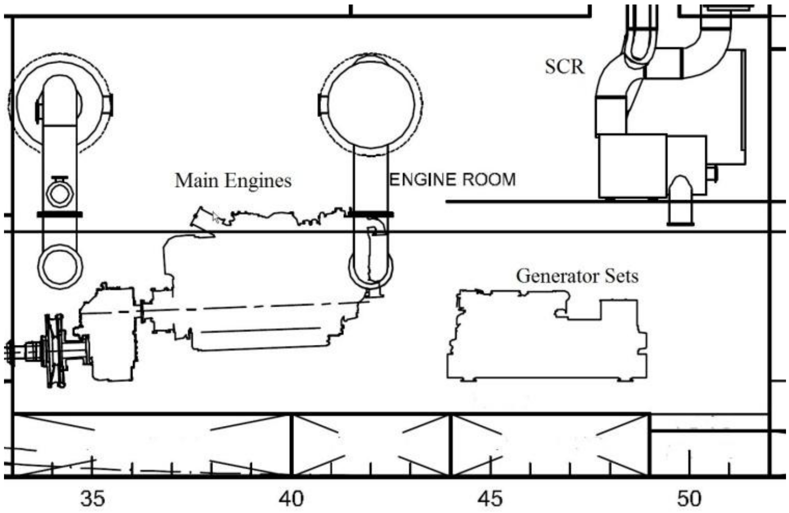


Figure 5.12. GA of Generator Sets and SCR equipment

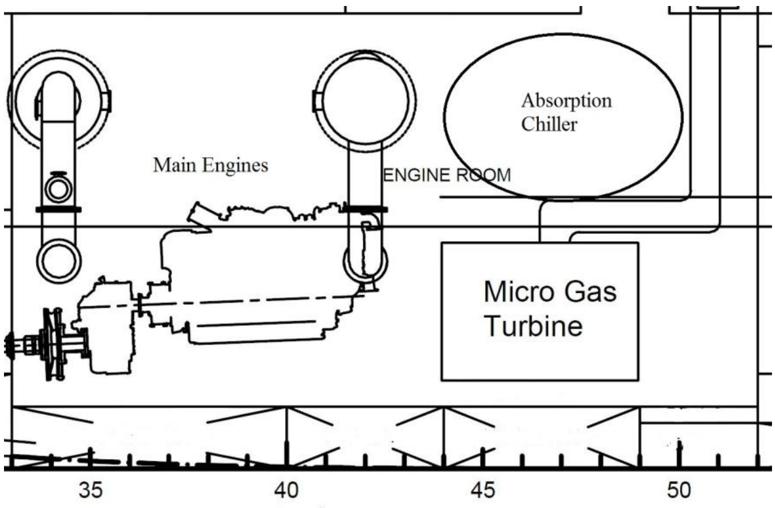


Figure 5.13. GA of Micro Gas Turbines and location of the Absorption Chiller

5.4. Further equipments due to hybrid chilled water plant

As explained previously, the adoption of an absorption chiller with hot water as heating source makes it necessary to install a heat exchanger to transfer the heat power from the exhaust gas to the water, and a heat storage tank to regulate and store heat that can afterwards be delivered to the absorption chiller. This system is further in next sections.

5.4.1. Heat Exchangers

Heat Exchangers can be delivered by MME together with the micro gas turbines and its technical data can be seen in Appendix A6.

The location of the heat exchangers is directly on the outlets of the exhaust gas in each sound enclosure. Where sound enclosures C400 are installed, there is only one heat exchanger, which means that each micro gas turbine C200 inside the enclosure is designed share the same heat exchanger with the other one, and as result, there will only be one exhaust pipe for each C400.

Since two turbines are intended to be connected to the same exhaust system, the latter will be provided by MME with an automatic flap that avoids the backflow to the micro gas turbines. This is an obliged condition imposed by any Classification Society.

Where sound enclosures C200 are installed (as in the case of the adoption of batteries), the heat exchanger will only take the flow from one C200 MGT.

The maximum heat power that can be obtained per turbine C200 is around 287 kW, which means that in case of having 4xC200, the heat exchangers can produce up to 1150 kW of thermal power. This thermal power corresponds to a hypothetical maximum, which would only be produced in maneuvering, and under certain conditions that probably would occur one or two times during the lifetime of the ship. The absorption chiller selected, running at 100 %, only requires a thermal power of 319 kW. Generally the thermal power transferred in the heat exchanger and required in the absorption chiller are not the same, reason why a heat storage tank is installed.

5.4.2. Heat Storage Tank

There are different reasons for the installation of the heat storage tank.

- It regulates the thermal power obtained in the exhaust heat exchanger, by adding or extracting heat to the system in order to provide to the absorption chiller the flow in the desired conditions.

- When micro gas turbines are switched off, the absorption chiller cannot be also turned off instantaneously, it needs to do it gradually. For this reason, when the heat exchanger cannot provide any heat, the heat storage can deliver enough heat to do such process.

Logically, the bigger the size of the tank, the higher capacity to regulate and control the hot water system. On the other hand, the space and weight is a limited and very important feature in the shipbuilding world. For this reason, when consulting with experts of Gasklima, they did not recommend any specific size for the tank, but one that could be suitable for the ship without compromising any other field.

As the design of the BV80 is in an advanced stage, it is difficult to re-arrange the tanks and spaces. For this reason, it has been decided to install the heat storage tank, together with the absorption chiller, in the higher deck of the machinery room, above the micro gas turbines. Studying the available space, a cylindrical tank of 8 m^3 could be installed. This size is slightly smaller than the expected for an absorption chiller of such capacity, taking into account information from (Feßler, 2015), [3]. In order to counter this aspect, it is proposed a system trying to maximize the ΔT so that higher storage capacity can be achieved with the same volume. Design temperatures of the absorption chiller are 95/80 ºC inlet/outlet [9], but it does not mean that they need strictly to be those temperatures. In fact, the inlet temperature can be decreased up to 70 ºC and the massflow regulted within 50-120% from the design value [9]. With this conditions, the ΔT can be 25 ºC.

To increase the storage capacity, the idea is that when the tank receives energy from the system (charge of the tank), it is done from the inlet side, and when it is needed to extract heat from the tank (discharge of the tank), it will be added to the outlet water. This concept can also be seen in the flow chart in figure 5.14, where red flow corresponds to the loading condition and blue to discharge condition. With this configuration, the heat storage capacity (HSC) is calculated as:

$$HSC = \frac{c_{p\,water}}{3600(s/h)} * \Delta T * \rho_{water} * V \tag{5.5}$$

With:

- $c_{p\,water}$ the specific heat capacity of the water: 4.180 J/kgK
- ΔT the temperature range of the system: 25 ºC
- ρ_{water} the water density, assumed to be 1000 kg/m^3
- V the volume of the tank: 8m^3

Thus, Eq. 4.4 results in 232 kWh (29 Wh/kg) of heat storage capacity, which means that fully loaded it has the possibility to provide during 53 minutes full thermal power of the absorption chiller.

There is the possibility of having the heat storage tank fully loaded, and the thermal power produced in the exhaust heat exchanger to be higher than the thermal power required in the absorption chiller. If this condition is met, the system would not be able to remove the extra heat that is being produced in the heat exchanger. In order to solve this problem a sea water heat exchanger is added. This unit would extract the heat from the system and directly send it out of the ship with the sea water open circuit.

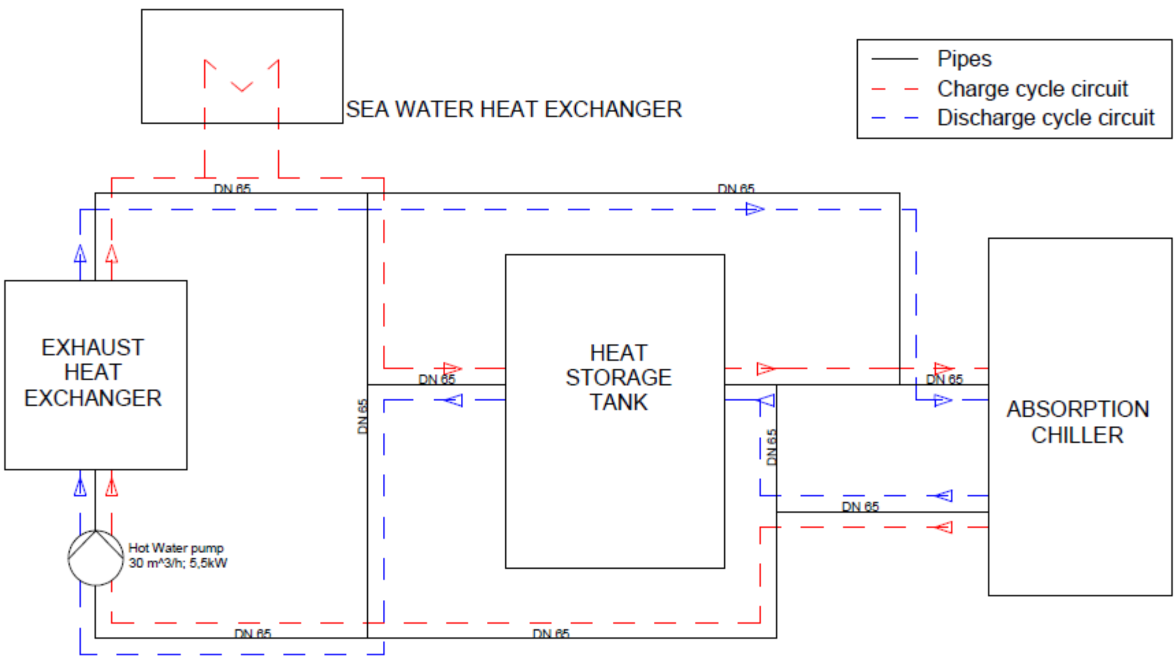


Figure 5.14. Flow diagram of the hot water system

5.4.3. PCM

During the development of this study, and because of the small space available on the ship to install a heat storage tank, new technologies to increase the storage capacity are analyzed. PCM (Phase Change Materials) are elements that take advantage of the change of phase to store or release heat, being able to have capacities. In this way, they are in liquid state when they are warm, and in solid state when cooled down.

Rubitherm is a chemical company that works with these type of materials, offering a wide range of materials with melting points varying from -10 to 90 ºC. The material RT82 that can be seen in Appendix H is offered as a way to store the heat. This material has a melting point in the desired range between the inlet and outlet temperatures of the hot water circuit in the absorption chiller. The heat storage capacity is 49 Wh/kg, as can be seen in Appendix H, which represents almost 70 % higher than the one obtained in previous section 5.4.2 with water.

The material RT82 is not corrosive against metal, which would ease to build a system with conventional pipes. On the other hand, it is an organic material that could have risks of ignition, meaning that the installation may have to be approved by a classification socciety

Another problem found with this technology is the housing. Even though the appropriate material was found, no company has strong solution for the storing problem at the desired temperatures, and most of the systems are still in a development phase.

Because of these problems, PCM are taken as a possible solution of heat storage for the incoming future, but not for the time being, reason why it is offered as a future scope of study.

6. ADDITIONAL SOLUTIONS COUPLING AND COMPARISON OF ALTERNATIVES

Coupling the additional solutions explained in chapter 5 lead to get different alternatives that can be feasible for a mega yacht. The aim of this chapter is to evaluate and compare them in terms of overall efficiency, maintenance service, shipbuilding impact and lifetime costs. Based on these comparisons, the results and recommendations of this master thesis are formulated. In particular, there are 4 alternatives proposed, in addition to the generator sets, which leads to 5 different options.

1. Auxiliary energy provided by three generator sets MTU V2000 M41A
2. Auxiliary energy provided by four micro gas turbines Capstone C200
3. Auxiliary energy provided by three micro gas turbines and a battery pack
4. Auxiliary energy provided by a co-generation power plant composed of four micro gas turbines Capstone C200 and heat recovery module with an absorption chiller of 264 kW of cooling capacity.
5. Auxiliary energy provided by a co-generation power plant composed of three micro gas turbines Capstone C200, a battery pack and heat recovery module with an absorption chiller of 264 kW of cooling capacity.

It must be mentioned that inlet air ducts as well as the intake air coolers are installed in all the alternatives with micro gas turbines, since they are needed to ensure the capability of the system to provide enough power in extreme conditions.

6.1. Overall efficiency

Batteries have marginal influence on the overall efficiency of the systems, since they are only operated in maneuvering condition, and they do not contribute to produce fuel savings but only to reduce the total power installed onboard the ship.

On the other hand, absorption chillers have as main objective reducing fuel consumption and therefore, they are installed in order to increase the efficiency of the power plant. Thus, the alternatives to be compared in terms of efficiency do not take into account adoption of batteries for the bow thruster. This means that for comparison only alternatives 1, 2 and 4 are considered, taking into account that the results of the alternative 2 are similar to 3 and the results of the alternative 4 are also similar to 5.

The alternatives compared do not take advantage of the fuel energy in the same way. While alternatives 1 and 2 only produce electrical power, the alternative 3 produces electrical and thermal power. The thermal power produced, which is delivered to the absorption chiller, causes a reduction in the electrical demand of the compression chiller, which results at last in a reduction in fuel consumption.

As the coefficients of performance of compression and absorption chiller are different, as can be seen in table 17, the power needed to produce one kW of cooling capacity (which is given by the inverse of the COP) is different in both machines, having approximately 1,33 kW of thermal power in the absorption chiller against 0,33 kW of electrical power in the case of the compression chiller. It means that in order to compare the efficiency of the system, the electrical + thermal power provided by the power plant cannot be simply summed up, since there are needed more kW of thermal power to produce the same amount of chilled water. To solve this discrepancy, the thermal power produced is considered as the electrical power that would be needed in the hypothetical case that the chilled water would only be produced by electrical power. This leads to simply consider the electrical demand of the alternative without absorption chiller as the produced power, but taking into account the fuel savings produced thanks to the absorption chiller.

In table 20 the results obtained from the code for the different conditions are summarized. In order to evaluate the average efficiency, each condition has certain weight on the overall result, which is given by the percentages of time shown in the table. These percentages have been assumed after consulting the staff of Blohm+Voss, and from the experience of the shipyard. Thus, the efficiencies are compared in terms of electrical kW produced by one kg of fuel oil.

Table 20. Efficiency comparison of alternatives 1,2 and 4

Condition		**Navigation**		**Manoeuv.**	**Harbour S.**		**Anchor.**	**Rest**
Season		S	W	-	S	W	-	-
Demand (kW)		328	355	592	233	266	361	217
Percentage of time (%)		9	1	0,5	9	1	14,5	65
Alternative 4	FO Consump. (kg/h)	67,81	84,48	131,11	50,38	63,40	78,37	49,25
	Averaged efficiency kW/kg of FO						**3,79**	
Alternative 1	FO Consump. (kg/h)	73,25	78,49	133,57	53,82	60,85	85,22	50,62
	Averaged efficiency kW/kg of FO						**3,62**	
Alternative 2	FO Consump. (kg/h)	82,78	89,59	149,78	60,73	68,36	90,88	57,62
	Averaged efficiency kW/kg of FO						**3,23**	

Differences from alternatives 1 and 2 are in accordance with the comparison made in Chapter 3. But, as it can be seen, the addition of an absorption chiller, which is the solution contemplated in alternative 4, increases drastically the efficiency of the power plant, getting even better results than the initial design with the generator sets (3,79 kW/kg against 3,62 kW/kg of fuel oil).

Comparing alternatives 2 and 4 it is concluded that the absorption chiller increases the 14,7 % the efficiency of the power plant, an ultimate improvement that can lead to take a decision over which alternative suits better to a mega yacht.

6.2. Maintenance service

Maintenance is a very important issue in which micro gas turbines have a strong argument to replace generator sets, as explained in chapters 2 and 3. For this reason, when important equipments as batteries and absorption chillers are added, it must be checked that these units do not harm the high quality that micro gas turbines offer.

6.2.1. Chilled water plant

From the information obtained from Gasklima, absorption chillers have an expected life of around 20-24 years, a very long period when compared with compression chillers (around 15 years). In addition, the maintenance tasks needed are simple. Maintenance costs of both chillers can be found in table 21.

Table 21. Maintenance costs of compression and absorption chillers, [3]

Unit	Maintenance costs per year
Compression chiller	6.000 €
Aborption chiller	2.740 €

When different alternatives are compared, all of them contemplate the possibility of having a compression chiller, which means that only the maintenance costs of the absorption chiller will affect the comparison.

6.2.2. Batteries

The most important effect that batteries have on the maintenance is that, as they make possible to remove one micro gas turbine C200, the amount of hours that the other three turbines will have to work will be increased, since they are less units to share the total demand. As result, the amount of hours will be increased from 4.000 hours per year with an arrangement of 4 micro gas turbines, to 5.300 hours per year with three. This has two consequences.

On one hand, the maintenance cost per hour of operation of each MGT is reduced from 8,87 €/h with an arrangement of 4 MGTs to 7,48 €/h with 3 MGTs, due to the battery packs of the micro gas turbines detailed on Appendix A3, and which replacement is done based on their natural years, and not on the operating hours. On the other hand, micro gas turbines will reduce their expected life from 20 years in the alternatives 2 and 4 to 15 years for the alternatives 3 and 5. The two consequences have then opposite effects. In section 6.4.4 are analyzed their contributions.

The expected life of the batteries, as shown in Table16, can go beyond 20 years.

6.3. Systems

The high amount of units composing the heat recovery system which takes advantage from the exhaust gas of the micro gas turbines, and delivers it to the absorption chiller, create a complex system which is difficult to understand without a proper drawing in which the contributions of each element inside the system can be appreciated. Regarding this aspect, diagrams in figures 6.1 and 6.2 show the configurations of heat recovery system with 4 micro gas turbines C200 (alternative 4) and 3 micro gas turbines C200 (alternative 5).

The figures show 5 different circuits which take part into the whole system.

- Circuit containing air to the turbines, which after the combustion with fuel is the hot exhaust gas used to extract the heat. This circuit is open.
- Sea water circuits. Two sea water circuits are drawn in the diagrams, one for the intake air coolers and other one as the cooling water of both chillers and a heat exchanger to extract heat from the hot water circuit in case the full capacity of the heat storage tank is reached. Both are open circuits.
- Hot water. This circuit, explained in chapter 5.4.2 is a closed circuit which takes the heat from the exhaust gas and bring it to the absorption chiller.
- Chilled water. The circuit combines the chilled water produced in both chillers and provides chilled water to the AC consumers distributed in the ship, in order to come back to the chillers and be cooled down again. It is a closed circuit.

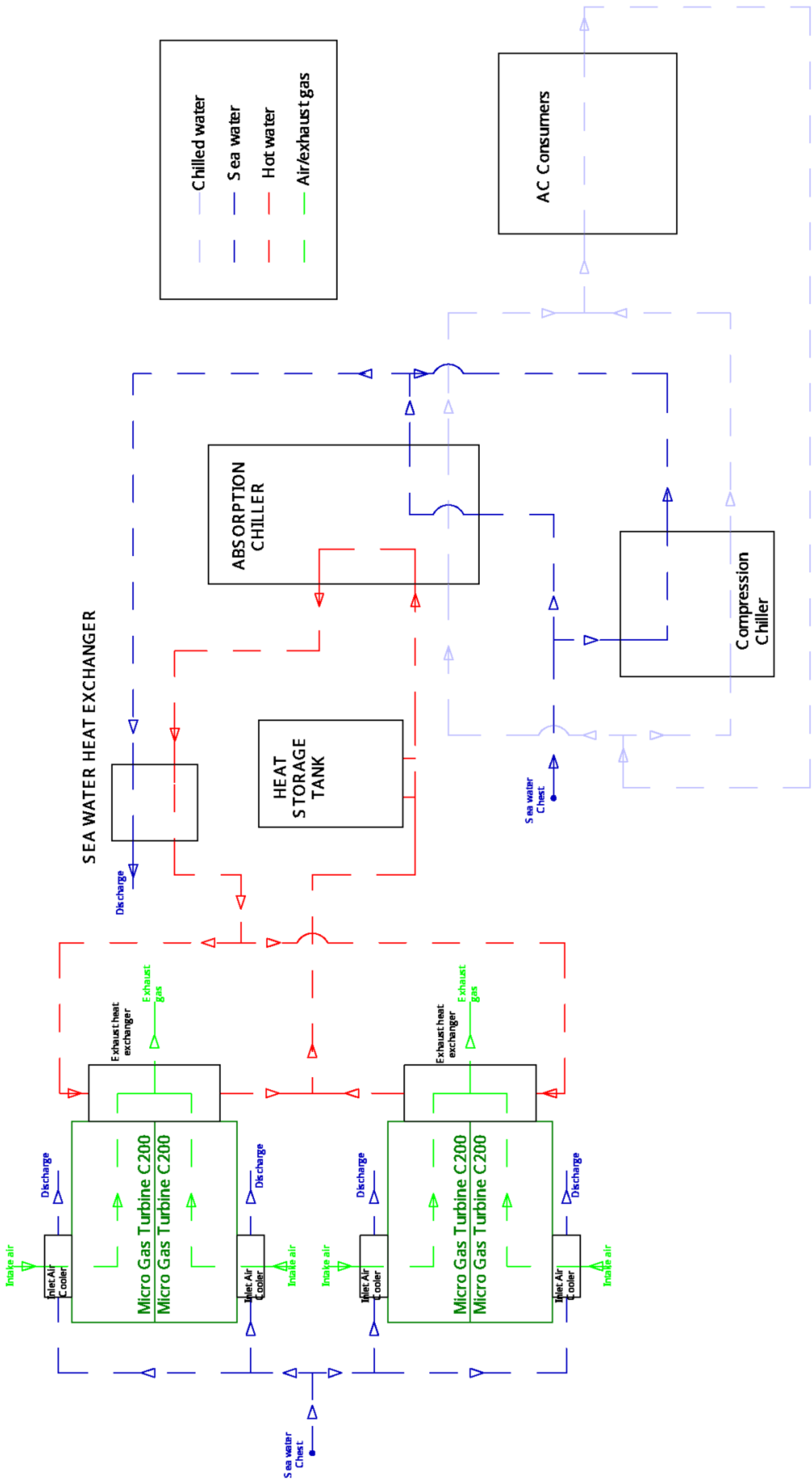


Figure 6.1. Heat recovery and chilled water systems with 4 MGTs (Alternative 4)

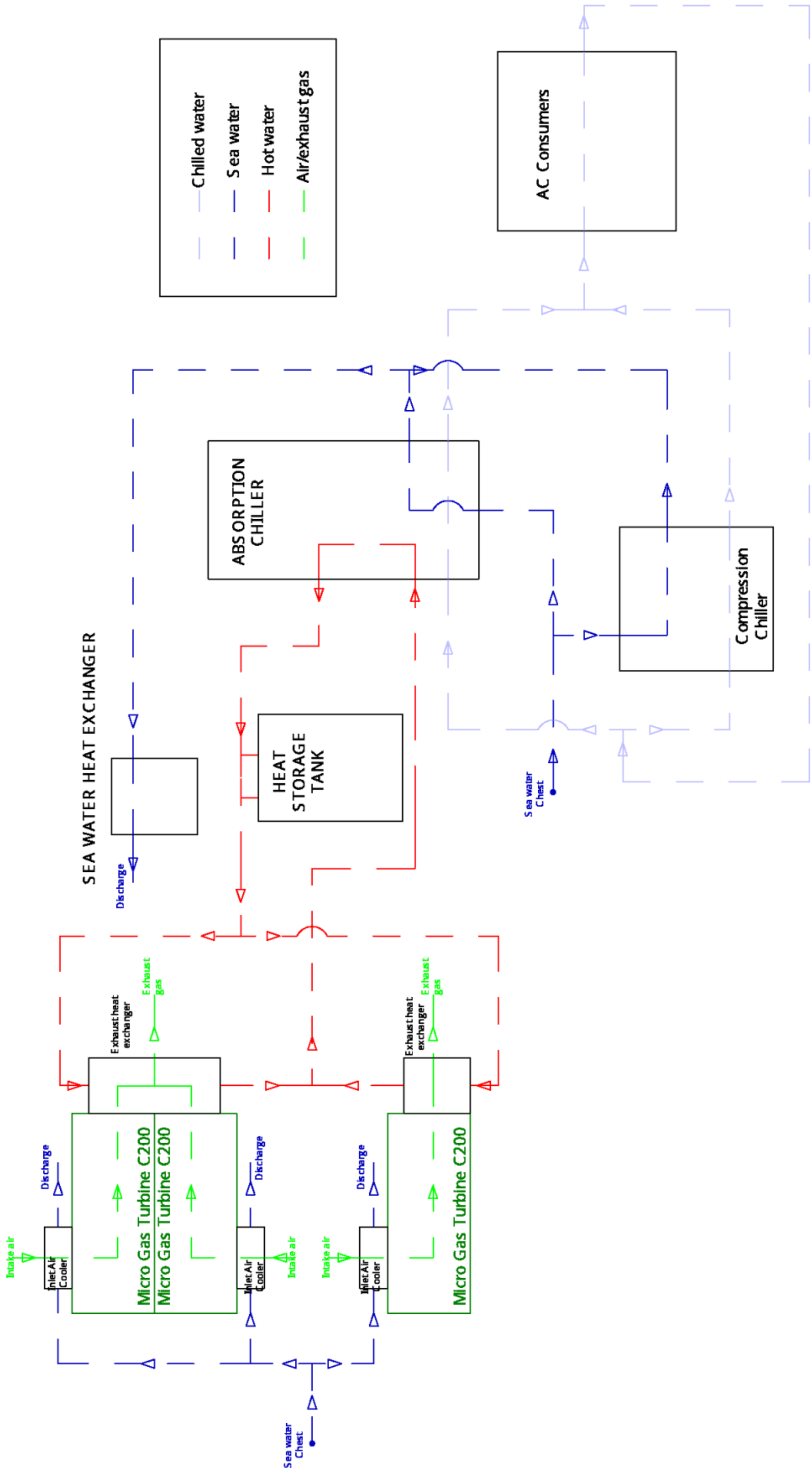


Figure 6.2. Heat recovery and chilled water systems with 3 MGTs (Alternative 5)

Figure 6.1 shows the flow circuits corresponding to the alternative 4, in which 4 MGTs C200 are installed. The hot water flow drawn, which has been also studied in chapter 5.4.2 and represented previously in figure 5.15, has hot water circuit in the condition with the heat storage tank is being loaded, while in the figure 6.2, which contains alternative 5, has been drawn with the heat storage tank being unloaded. This has been done to show both situations in the whole system, but either of the figures could have been drawn with the loading and unloading conditions.

6.4. Lifetime costs

Similarly to the analysis performed in chapter 3.4, the lifetime costs are compared for 20 years of operation, taking into account the expected lifetime of the units, maintenance costs, initial investment costs and consumables. Lifetime costs of alternatives 1 and 2 correspond to the previously calculated in chapter 3.4, reason why here the costs of the additional solutions resulting in alternatives 3, 4 and 5 are described.

Initial investments and maintenance data are obtained from the manufacturers of the different units, and consumption costs, which are the most significant item from the total, are calculated thanks to the developed code.

6.4.1. Initial investment

Offers from the different providers were obtained in order to estimate the initial investment of the different alternatives. Prices for MGTs and batteries can be seen in Appendix A1, A2 and F, while initial investment of GenSets was obtained from the database of Blohm+Voss. The system of the absorption chiller and its piping system was obtained from (Feßler, 2015), [3]. Even though the model is not the same as the selected in this study, it is a very similar one, so its value is a good estimation for the system . Alternatives pricing can be seen in table 22.

The addition of the batteries allow to remove one micro gas turbine, the variation reduces in 125.000 € the initial investment, although it will affect adversely the maintenance costs, as it is presented in next sections.

Table 22. Initial investment costs

Alternative	Items	Currency	Price	Total
3	Purchase and installation 3xC200	€	841.500	**1.039.365**
	Purchase and installation Saft Batteries	€	157.065	
	Inlet air ducts	€	10.800	
	Exhaust system	€	30.000	
4	Purchase and installation 2xC400	€	1.120.000	**1.364.400**
	Absorption Chiller Purchase	€	200.000	
	Inlet air ducts	€	14.400	
	Exhaust system	€	30.000	
5	Purchase and installation 3xC200	€	841.500	**1.239.365**
	Purchase and installation Saft Batteries	€	157.065	
	Absorption Chiller Purchase	€	200.000	
	Inlet air ducts	€	10.800	
	Exhaust system	€	30.000	

6.4.2. Consumption costs

Consumption costs obtained for alternatives 3, 4 and 5 are summarized in tables 23, 24 and 25.

Table 23. Consumption costs of the alternative 3

Condition	Navigation		Manoeuvre	Harbour service		Anchoring	Rest
Season	Summer	Winter	-	Summer	Winter	-	-
Demand (kW)	328	355	292	233	266	361	217
Cost (€/h)	**98,54**	**106,66**	**178,31**	**72,30**	**81,38**	**108,19**	**68,59**

Table 24. Consumption costs of alternative 4

Condition	Navigation		Manoeuvre	Harbour service		Anchoring	Rest
Season	Summer	Winter	-	Summer	Winter	-	-
Demand (kW)	264	335	513	191	246	302	197
Cost (€/h)	**80,72**	**100,57**	**156,09**	**59,98**	**75,47**	**93,30**	**58,63**

Table 25. Consumption costs of alternative 5

Condition	**Navigation**		**Manoeuvre**	**Harbour service**		**Anchoring**	**Rest**
Season	Summer	Winter	-	Summer	Winter	-	-
Demand (kW)	264	335	259	191	246	302	197
Cost (€/h)	**80,72**	**100,57**	**79,57**	**59,98**	**75,47**	**93,30**	**58,63**

The only difference between alternative 2 and 3 is that the batteries added for the bow thruster reduce the electrical demand in manoeuvring condition. This reduction barely affects the total costs, since manoeuvring condition is assumed to occur only 0.5% of the time.

In the same way as the efficiency comparison, it can be seen that the addition of the absorption chiller has greatly benefits on the consumption costs, as can be contrast the alternative 3, which do not contain absorption chiller, with alternatives 4 and 5.

6.4.3. Maintenance costs

As mentioned in chapter 6.2, the removal of one battery will increase the hours per year that the micro gas turbines will have to operate (from 4.000 as stated in chapter 3.4.3 to 5.333), reducing their expected life to 15 years. This will induce to refit new units, for which the price considered is assumed to be the same as the initial purchase, although it is considered to contribute in the maintenance cost part. The amount of operating hours per year for each device is then:

- 3.000 hours per year each generator set (as stated in chapter 3.4.3)
- 4.000 hours per year each micro gas turbine when 4 are installed (alternatives 2 and 4)
- 5.333 hours per year each micro gas turbine when 3 are installed (alternatives 3 and 5)

With the information received by MME, which can be seen in Appendix A3, and the information from the database of Blohm+Voss containing maintenance costs of GenSets, the maintenance costs are:

- 5.89 €/h each generator set, with an expected life of 12 years.
- 8.87 €/h each micro gas turbine (C200) for alternatives 2 and 4.

- 7,48 €/h each micro gas turbine (C200) for alternatives 3 and 5.

The differences in the maintenance costs of alternatives 2 and 4 versus 3 and 5 are explained in section 6.2.2.

Apart from micro gas turbines, it has been estimated the maintenance costs for the absorption chiller and the batteries, as detailed in chapter 5. The costs are:

- 2.750 € per year for absorption chiller
- 12.565 € per year for batteries

6.4.4. Total lifetime costs

Total lifetime costs are calculated from the previously described contributions. In order to compile all the information, they are shown in a timeline graph which covers the comparison for 20 years of life.

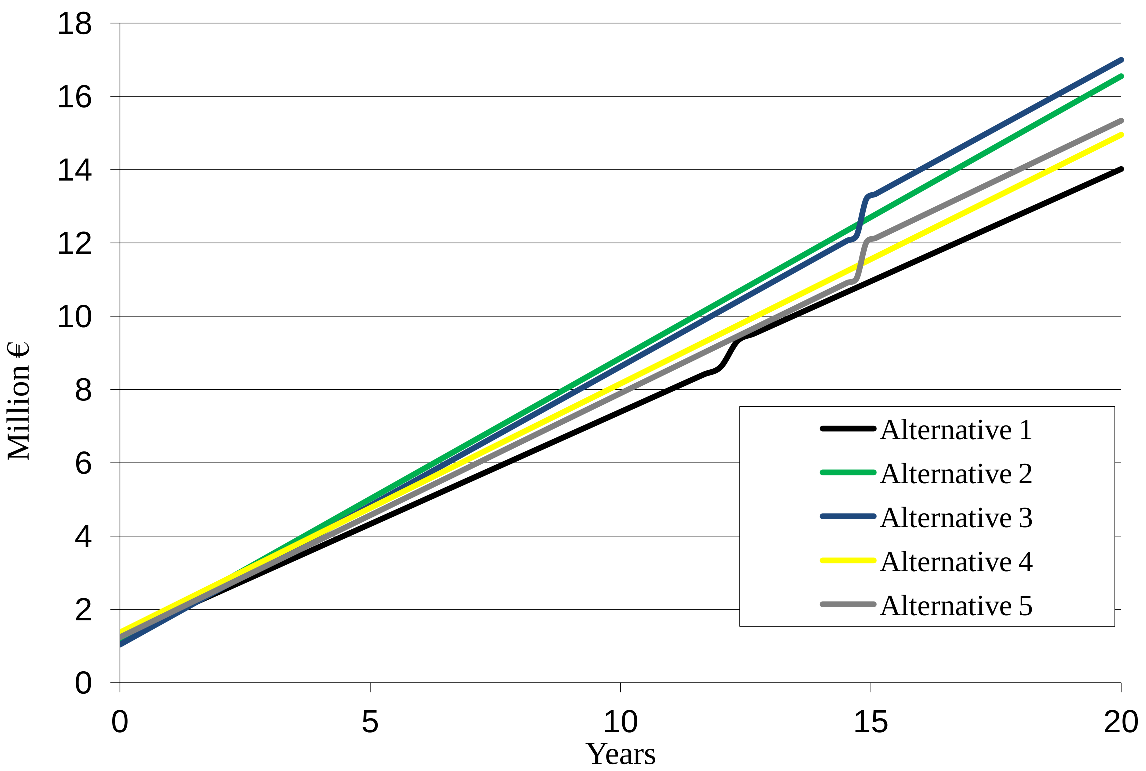


Figure 6.3. Lifetime costs comparison of alternatives

Results of lifetime costs over 20 years:

- Alternative 1: 14.015.000 €
- Alternative 2: 16.550.000 €
- Alternative 3: 16.997.000 €
- Alternative 4: 14.953.000 €
- Alternative 5: 15.338.000 €

The curves in figure 6.3 clearly show the effect that absorption chillers and batteries have on the costs. While absorption chillers contribute to greatly decrease the slope of the curve, which can be seen comparing the alternatives 2 and 4, or 3 and 5, alternatives with batteries (3 and 5) causes that expected life of micro gas turbines reduces, reason why at the 15th year a new bargain to replace them has to be done.

Additionally, batteries might contribute to reduce maintenance costs of the whole system, but due to the effect that they have on the reduction of the expected life of MGTs, the lifetime costs after 20 years is 2,63% higher comparing alternatives 4 and 5.

Even though it has not achieved to fully equalize the lifetime costs of generator sets, the additional solutions proposed have reduced the differences from an 18 % higher to a 6,7 %, which mean approximately 47.000 € per year. On the other hand, better comfort characteristics offered by the MGTs can in this case counter the slightly higher costs, and be a decisive feature to select this type of technology.

7. CONCLUSIONS

7.1. Work review

The results obtained through the whole study allow to make a series of conclusions in order to evaluate the different alternatives.

Each alternative has advantages and disadvantages among others, and the final decision of which is the most suitable one has to be made by the yacht constructor or the owner, depending on their needs and the image that they want to show.

Micro gas turbines are a relatively new source of power in the maritime sector. Even though the technology is not brand new, the forthcoming regulations on the reduction of polluting gases have prompted them to be considered as a possible solution.

They have two main disadvantages; higher consumption and air demand. Air demand results in additional systems to control the air temperature, since turbines lose efficiency when the temperature increases beyond 23 ºC. Higher consumption is translated into that efficiency of micro gas turbines is around 13% lower than diesel engines, which at the end results in nearly an additional cost of 127.000 € per year.

For this type of vessel, in which ship owner expends hundreds of millions in their acquisition and is used as leisure, extra amount that they have to pay out is rewarded in terms of high quality comfort, having a system that needs much lower maintenance, highly reduced level of vibrations, and also very low noise.

Additional advantages are the lack of lube oil and SCR systems, which leads to save space and have a clean image because of the ultra low emissions of CO and NOx particles.

Space savings can be harnessed to install an absorption chiller that will contribute counteract the higher consumption. From the results obtained with the developed Matlab code, an appropriate absorption chiller can contribute to get even higher efficiency of the power plant than the initial configuration with generator sets (3,78 versus 3,62 kW/kg of FO). In summary, the system would not only offer higher comfort characteristics as mentioned before, but also at equal or higher efficiencies.

Absorption chillers were conventionally only used on onshore installations. Nevertheless, models of World Energy with hot water as heating medium have already approval certificate since December 2015, fact that reveals that this type of machines are being considered to be installed onboard ships.

Batteries are a solution that can lead to reduce the total power installed onboard about 25 %, diminish the amount of air that must be provided, decrease the initial investment in 125.000 € and reduce the maintenance costs. On the other hand, they decrease the expected life of MGTs.

One of the objectives set was the aim of not having big impact on the shipbuilding process, since it could hazard the proper feasibility of micro gas turbines on the BV80. From this point of view, it is considered as a great achieve that just few components apart from the GenSets should have to be replaced to ensure good operation of MGTs onboard the ship, as the ventilation fans in the machinery room (which are slightly bigger in case of having 4 MGTs), and the addition of some supports in the upper deck of the machinery room, due to the high weight of absorption chiller and heat storage tank.

7.2. Extrapolation of the results to new constructions

Results have shown that micro gas turbines are a strong alternative even for an existing project which was not initially conceived to house them. This means that if a new project is raised, micro gas turbines can be perfectly selected as source of auxiliary power generation.

From this study, some considerations can be taken into account to have a successful project:

- There will be a higher demand of air to be brought into the machinery room. Special attention must be considered because of the independency of the different equipments on the machinery room, which share a common ventilation system, but if MGTs are conceived since the beginning of the project, they could be arranged with inlet ducts independent from the remaining equipments. Something which is not possible in the BV80 because of the lack of space.
- Alternative fuels apart from diesel can be studied to feed micro gas turbines, with appropriate auxiliary systems conceived from the beginning.

- Absorption chiller must be located close to the centre of gravity and preferably in the centreline of the ship to ensure good performance of the machine with the ship motions.
- Heat storage tank could be located in the bottom of the ship, together with the other tanks. Its capacity is not a fixed value and there are two key factors that must be balanced; from one side the bigger the tank, the higher capacity to regulate and store heat, on the other hand the more weight and space is needed.
- PCM are an interesting technology for the heat storage that can be a future scope of study.

7.3. Recommendations

Batteries are a solution that do not contribute to improve the overall efficiency, and they lead to reduce the expected life of MGTs. But on the other hand, they allow to reduce the air demand on the machinery room, as well as to avoid problems due to the limited dimensions of exhaust pipes at the top of the BV80. In other words, their major advantage is that they can help to ease the installation of micro gas turbines on BV80. For these reasons, they can be an adequate solution in combination with the absorption chiller, but having in mind that absorption chiller is the most contributing solution.

Among solutions studied, it can be concluded that micro gas turbines are a serious alternative to conventional diesel engines. Together with an absorption chiller, a mega yacht has a cogeneration power plant with an expected life of 20 years that compete with the generator sets in terms of efficiency and besides it offer high comfort characteristics. Clean image that owner and ship builder can offer, as well as the innovation of this application in the mega yacht sector are relevant points to prompt both of them in a sector in which reputation is crucial.

On the other hand, the author is aware that absorption chillers are still not very common device in mega yachts and it can lead to adopt a more conservative solution, which can be to simply replace generator sets by micro gas turbines. In this case, the efficiency of the power plant would not reach the level of diesel engines, and it would have to be sacrificed by comfort and clean image. Thus, the last decision would rely in the ship builder/owner opinion.

8. ACKNOWLEDGEMENTS

This thesis covers the work carried out between July and November 2015 in the Mechanical Department of Blohm+Voss Shipyards in Kiel and between November 2015 and January 2016 in Rostock University. Relevant work has been done thanks to the collaboration of MME, who has provided very important information to perform all the studies.

I would like to express my gratitude to my supervisor M. Eng. Benjamin Ullmann for his support, guidance and help during the development of the project. Apart from its support, he gave me a lot of freedom to demonstrate my skills.

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Besides, I also would like to thank the Mechanical Department HKM of Blohm+Voss, as well as the Electrical and Naval Architecture Departments, which were always glad to solve any doubt that I had.

Special thanks to Benjamin Feßler, who always had time to advice and answer any doubt about the chilling plant, to Christian Effe and Daniel Jamaer for his information about the exhaust gas, and for bringing me to see the installations of Blohm+Voss in Hamburg, to Torsten Westphal for his help concerning the diesel engines, to Rainer Bärenwald because he was a second supervisor in case Benjamin was not there and to Julia Grapentin for telling me who was the correct person that could solve my doubts.

I would like to thank also Sara Echeverry, for giving me personal support during the whole time. To Charo, Nico and Guille.

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APPENDIX A. MICRO GAS TURBINES

A1. MME Offer 3xC200

Microturbine Marine Energy

Blohm + Voss Shipyards GmbH
Mechanical Engineering Design HKM
Álvaro F. Benet Pérez
Knooper Weg 71
24116 KIEL

MME MICROTURBINE MARINE GENERATOR

QUOTATION No	DATE	EXPIRE DATE
44001001	November 02, 2015	December 31, 2015

Project no 1458

Inquiry for 600kW AC Microturbines

MME C600kW AC Microturbine Generator System, reliable electrical power in one ultra-low emission, and highly efficient marine package, consisting of:

- ***3 x C200kW AC MT*** LIQ,DM,HH,PKG,CE,MARINE,
  400VAC/50Hz/3-Phase+Neutral
  Integrated power electronics with integrated paralleling functionality. Load control module for automatic starting/stopping/load control
  Fuel type: Diesel (see data sheet)

  Including:
  - Exhaust Cooler
  - Heat Recovery Exchanger
  - Fire Extinguisher system
  - Seawater Heat Exchanger (outside of sound enclosure)
  - Battery unit for start-up , transcient and shut-down (outside of sound enclosure)
  - Advanced Power Server (APS)

System price C200kW per unit EXW	**EUR 330.000, excl. VAT**
3 x C200kW generator systems EXW	**EUR 841.500, excl. VAT**

A2. MME Offer 4xC200

MME

Microturbine Marine Energy

Blohm + Voss Shipyards GmbH
Mechanical Engineering Design HKM
Álvaro F. Benet Pérez
Knooper Weg 71
24116 KIEL

MME MICROTURBINE MARINE GENERATOR

QUOTATION No	DATE	EXPIRE DATE
45001001	November 02, 2015	December 31, 2015

Project no 1458

Inquiry for 800kW AC Microturbines

MME C800kW AC Microturbine Generator System, reliable electrical power in one ultra-low emission, and highly efficient marine package, consisting of:

- ***2 x C400kW AC MT*** LIQ,DM,HH,PKG,CE,MARINE,
  400VAC/50Hz/3-Phase+Neutral
  Integrated power electronics with integrated paralleling functionality. Load control module for automatic starting/stopping/load control
  Fuel type: Diesel (see data sheet)

  Including:
  - Exhaust Cooler
  - Heat Recovery Exchanger
  - Fire Extinguisher system
  - Seawater Heat Exchanger (outside of sound enclosure)
  - Battery unit for start-up , transcient and shut-down (outside of sound enclosure)
  - Advanced Power Server (APS)

System price C400kW per unit EXW	**EUR 560.000, excl. VAT**
2 x C400kW generator systems EXW	**EUR 1.120.00, excl. VAT**

A3. Maintenance Costs of C200

Table received from MME taking into account 8.000 operating hours per year

CAPSTONE C200 Liquid Fuel

Maintenance Interval	Component	Maintenance Action	PartNo.	Price/units * [US$]	Freq. 10 yrs @ 8k hrs	Cost [US$]
2,000 hours	Air Compressor	Change Oil	530742-001	295	39	11.505
	Air Compr. Main Elem.	Inspect				
	Air. Compr. Safety Elem.	Inspect				
	Fuel Filter	Replace	528829-001	60	39	2.340
	Injector Assemblies	Inspect				
4,000 hours	Engine Air Filter	Inspect (note 1)				
	Electronics Air Filter	Inspect				
	Heat Exchanger(s)	Inspect				
	Fuel System	Leak Check				
8,000 hours	Boost Pump	Replace	524022-001	915	9	8.235
	Fuel Pump	Replace	527666-001	7.485	9	67.365
	Engine Air Filter	Replace	523165-001	380	9	3.420
	Electronics Air Filter	Clean / Replace	530017-001	340	9	3.060
	Igniter	Replace (note 2)	610688-100	1.785	9	16.065
	Injector Assemblies	Replace (note 3)	610299-100	8.180	9	73.620
	Air Dryer Stage One	Replace	530740-001	40	9	360
	Air Dryer Stage Two	Replace	530839-001	190	9	1.710
20,000 hours	Engine Combustion Liner	Inspect	531191-100	16.930		-
40,000 hours	Enclosure Fan	Replace	524092-001	1.245	1	1.245
	Frame/Engine PM	Replace	503010-101	130	1	130
	TET Thermocouple	Replace	615243-100	470	1	470
	Powerhead	Replace (w. Reman)	527070-201	153.055	1	153.055
8k / 1yr	Battery Pack C6X	Replace	513182-100	10.965	18	197.370
12 Months	Anti Condence Heaters	Inspect				
24 Months	UCB Battery	Replace	513717-001	105	4	420

* List prices 2014, subject to change

$ 540.370 Grand Total
$ 60.041 Per Year
$ 6,755 Per Hour @ 8,000 h/y

Maintenance costs for 4.000 operating hours per year:

CAPSTONE C200 Liquid Fuel

Maintenance Interval	Component	Maintenance Action	PartNo.	Price/units * [US$]	Freq. 20 yrs @ 4k hrs	Cost [US$]
2,000 hours	Air Compressor	Change Oil	530742-001	295	39	11.505
	Air Compr. Main Elem.	Inspect				
	Air. Compr. Safety Elem.	Inspect				
	Fuel Filter	Replace	528829-001	60	39	2.340
	Injector Assemblies	Inspect				
4,000 hours	Engine Air Filter	Inspect (note 1)				
	Electronics Air Filter	Inspect				
	Heat Exchanger(s)	Inspect				
	Fuel System	Leak Check				
8,000 hours	Boost Pump	Replace	524022-001	915	9	8.235
	Fuel Pump	Replace	527666-001	7.485	9	67.365
	Engine Air Filter	Replace	523165-001	380	9	3.420
	Electronics Air Filter	Clean / Replace	530017-001	340	9	3.060
	Igniter	Replace (note 2)	610688-100	1.785	9	16.065
	Injector Assemblies	Replace (note 3)	610299-100	8.180	9	73.620
	Air Dryer Stage One	Replace	530740-001	40	9	360
	Air Dryer Stage Two	Replace	530839-001	190	9	1.710
20,000 hours	Engine Combustion Liner	Inspect	531191-100	16.930		-
40,000 hours	Enclosure Fan	Replace	524092-001	1.245	1	1.245
	Frame/Engine PM	Replace	503010-101	130	1	130
	TET Thermocouple	Replace	615243-100	470	1	470
	Powerhead	Replace (w. Reman)	527070-201	153.055	1	153.055
8k / 1yr	Battery Pack C6X	Replace	513182-100	10.965	39	427.635
12 Months	Anti Condence Heaters	Inspect				
24 Months	UCB Battery	Replace	513717-001	105	4	420

* List prices 2014, subject to change

$ 770.635 Grand Total
$ 38.532 Per Year
$ 9,633 Per Hour @ 8,000 h/y

Maintenance cost for 5.333 operating hours per year

CAPSTONE C200 Liquid Fuel

Maintenance Interval	Component	Maintenance Action	Comments	PartNo.	Price/units * [US$]	Freq. 15 yrs @ 5,3k hrs	Cost [US$]
2,000 hours	Air Compressor	Change Oil	Note 1	530742-001	295	39	11.505
	Air Compr. Main Elem.	Inspect	Note 1				
	Air. Compr. Safety Elem.	Inspect	Note 1				
	Fuel Filter	Replace	Note 2	528829-001	60	39	2.340
	Injector Assemblies	Inspect					
4,000 hours	Engine Air Filter	Inspect (note 1)	Note 2				
	Electronics Air Filter	Inspect	Note 2				
	Heat Exchanger(s)	Inspect					
	Fuel System	Leak Check					
8,000 hours	Boost Pump	Replace		524022-001	915	9	8.235
	Fuel Pump	Replace		527666-001	7.485	9	67.365
	Engine Air Filter	Replace		523165-001	380	9	3.420
	Electronics Air Filter	Clean / Replace		530017-001	340	9	3.060
	Igniter	Replace (note 2)		610688-100	1.785	9	16.065
	Injector Assemblies	Replace (note 3)		610299-100	8.180	9	73.620
	Air Dryer Stage One	Replace		530740-001	40	9	360
	Air Dryer Stage Two	Replace		530839-001	190	9	1.710
20,000 hours	Engine Combustion Liner	Inspect	Note 4	531191-100	16.930		-
40,000 hours	Enclosure Fan	Replace		524092-001	1.245	1	1.245
	Frame/Engine PM	Replace		503010-101	130	1	130
	TET Thermocouple	Replace		615243-100	470	1	470
	Powerhead	Replace (w. Reman)	Complete Engine	527070-201	153.055	1	153.055
8k / 1yr	Battery Pack C6X	Replace	2pc / C200	513182-100	10.965	28	307.020
12 Months	Anti Condence Heaters	Inspect	Note 3				
24 Months	UCB Battery	Replace		513717-001	105	4	420

* List prices 2014, subject to change

$ 650.020 **Grand Total**

$ 32.501 Per Year

$ 8,125 Per Hour @ 8,000 h/y

A4. Combustion Air Cooler

F A C O srl

mr
Datum: 05/12/13

Datenblatt 1 34 (mr-55N-6)

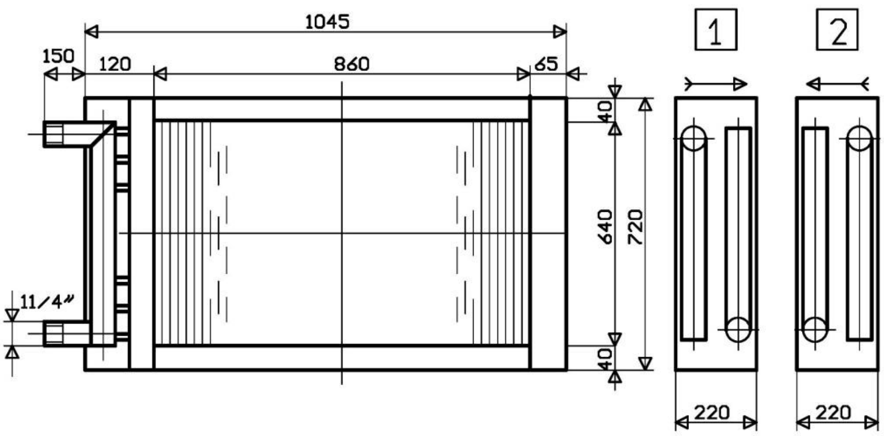
Kunde: MME

Ref: C200 Turb-inlet

ARI 410/C		THERMODYNAMISCHE DATEN		Dro/1/4/195/0101			
LAMELLENSEITE		**gefordert**	**kalkul.**	**Rohrseite**		**gefordert**	**kalkul.**
Medium: Luft				Medium: Wasser			
Durchflussmenge	m3/h		4418	Durchflussmenge	l/s	2	2,00
Trockenluft	kg/s	1,34	1,34	Eintrittstemp.	°C	32	32,0
Spezif. Gewicht	kg/m3	1.092	1,0920	Austrittstemp.	°C		34,6
Eintrittstemp.	°C	50	50,0	Spez. Gewicht	kg/dm3		0,995
Relative Feuchte	%		27	Spez. Waerme	kJ/kg°C		4,178
Feuchte	g/kg	21,0	21,0	Waermefaehigkeit	W/m°C		0,618
Austrittstemp.	°C		34,8	Viskositaet	mPa s		0,760
Feuchtkugeltemp.	°C		27,9	Stroemungsgeschw.	m/s		1,72
Relative Feuchte	%		60	Druckverlust	kPa	50	43,8
Q sens. / Q tot.			1,00				
Anstroemgeschw.	m/sec		2,2				
Druckverlust	Pa		79				
Leistung	kW		21,28				
		KONSTRUKTIONSMERKMALE					
Lamellierte Laenge	mm	860	860	Rohrdurchmesser	mm		16,50
Lamellierte Hoehe	mm	650	640	Rohrwandstaerke	mm		0,40
Anzahl Reihen		4	4,00	Lamellenstaerke	mm		0,20
Ca. Gewicht	kg		89	Oberflaeche	m2		53,8
Medium-Inhalt	dm3		13,9	OUT OF CERTIF. RANGE			

Type: **P40-16 AR 4R-16T-860A-2,5Pa Cu/Cu**

PREIS EURO 1.292,00 Coll.Cu+ Frame=304



Information received from MME

A5. Electronics Air Cooler

mr
Datum: 05/12/13

F A C O srl

Datenblatt 2 35 (mr-55N-6)

Kunde: MME

Ref: C200 Elec-inlet

ARI 410/C | **THERMODYNAMISCHE DATEN** | Dro/1/4/195/0101

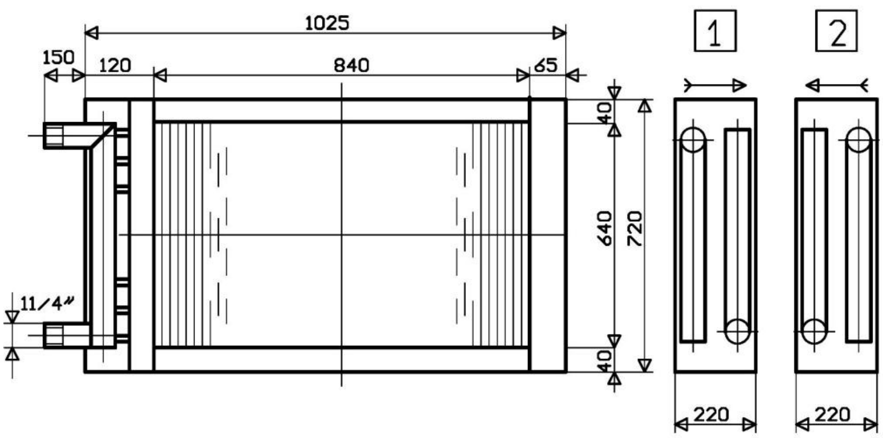
LAMELLENSEITE		**gefordert**	**kalkul.**	**Rohrseite**		**gefordert**	**kalkul.**
Medium: Luft				Medium: Wasser			
Durchflussmenge	m3/h		6117	Durchflussmenge	l/s	2	2,00
Trockenluft	kg/s	1,8555	1,86	Eintrittstemp.	°C	32	32,0
Spezif. Gewicht	kg/m3	1.092	1,0920	Austrittstemp.	°C		35,5
Eintrittstemp.	°C	50	50,0	Spez. Gewicht	kg/dm3		0,995
Relative Feuchte	%		27	Spez. Waerme	kJ/kg°C		4,178
Feuchte	g/kg	21,0	21,0	Waermefaehigkeit	W/m°C		0,618
Austrittstemp.	°C		35,0	Viskositaet	mPa s		0,760
Feuchtkugeltemp.	°C		27,9	Stroemungsgeschw.	m/s		1,72
Relative Feuchte	%		59	Druckverlust	kPa	50	43,3
Q sens. / Q tot.			1,00				
Anstroemgeschw.	m/sec		3,2				
Druckverlust	Pa		152				
Leistung	kW		28,97				

KONSTRUKTIONSMERKMALE

Lamellierte Laenge	mm	840	840	Rohrdurchmesser	mm	16,50
Lamellierte Hoehe	mm	650	640	Rohrwandstaerke	mm	0,40
Anzahl Reihen		4	4,00	Lamellenstaerke	mm	0,20
Ca. Gewicht	kg		101	Oberflaeche	m2	65,0
Medium-Inhalt	dm3		13,7	OUT OF CERTIF. RANGE		

Type: **P40-16 AR 4R-16T-840A-2,0Pa Cu/Cu**

PREIS EURO 1.440,00 Coll.Cu+ Frame=304



Information received from MME

A6. *Exhaust Heat Exchanger*

F A C O srl

mr
Datum: 31/07/13

Datenblatt 3 14 (mr-1,2–225N-9)

Kunde: MME

Ref: 3. C200 ~~Flach~~ Exhaust Cooler

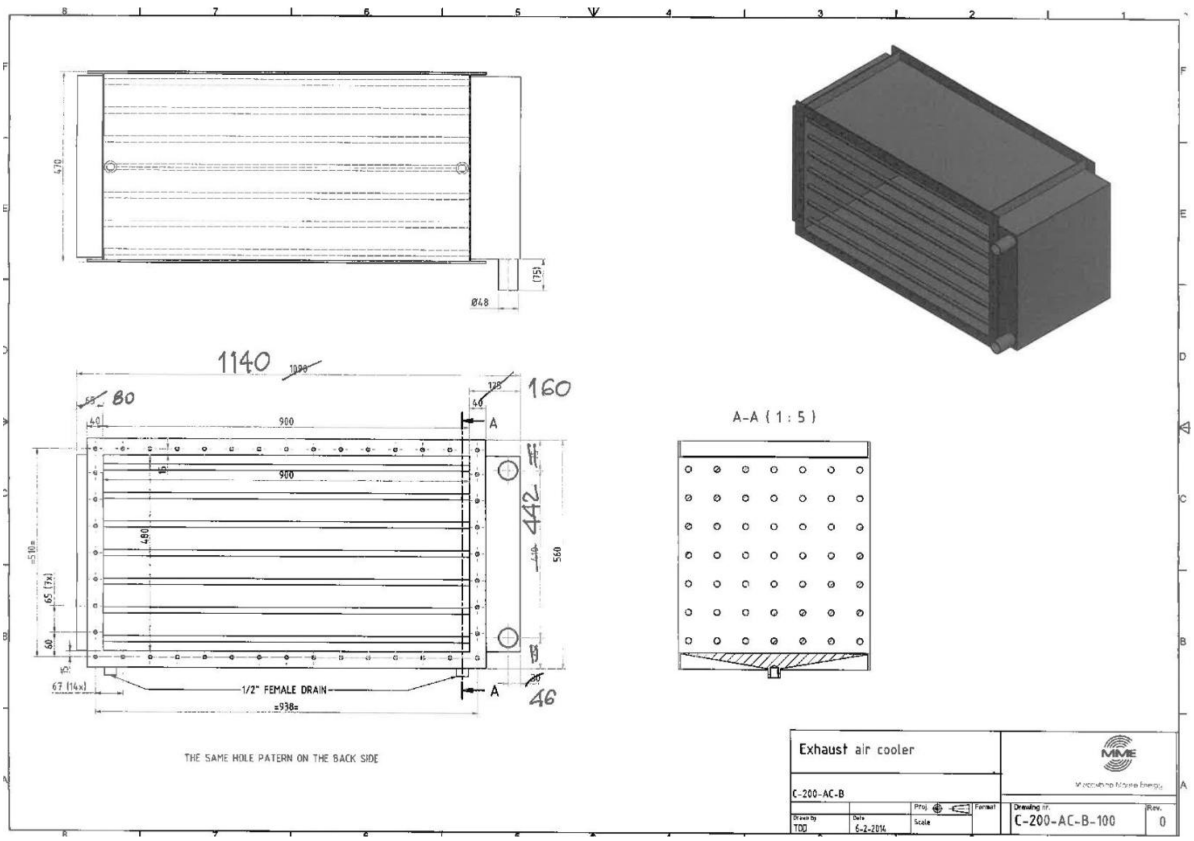
Standard H — THERMODYNAMISCHE DATEN — Dro/1/4/195/0101

LAMELLENSEITE		gefordert	kalkul.	Rohrseite		gefordert	kalkul.
Medium: Luft				Medium: Wasser			
Durchflussmenge	m3/h		7337	Durchflussmenge	l/s		1,45
Trockenluft	kg/s	1,3	1,30	Eintrittstemp.	°C	32	32,0
Spezif. Gewicht	kg/m3	.6379	0,6379	Austrittstemp.	°C	80	80,0
Eintrittstemp.	°C	280	280,0	Spez. Gewicht	kg/dm3		0,985
Austrittstemp.	°C	60	60,0	Spez. Waerme	kJ/kg°C		4,184
Q sens. / Q tot.			1,00	Waermefaehigkeit	W/m°C		0,650
Anstroemgeschw.	m/sec		4,7	Viskositaet	mPa s		0,493
Druckverlust	Pa		275	Stroemungsgeschw.	m/s		1,05
Leistung	kW		287,33	Druckverlust	kPa	25	17,4

KONSTRUKTIONSMERKMALE

Lamellierte Laenge	mm	1200	1200	Rohrdurchmesser	mm	16,50
Lamellierte Hoehe	mm	360	360	Rohrwandstaerke	mm	1,25
Anzahl Reihen		8	7,59	Lamellenstaerke	mm	0,20
Ca. Gewicht	kg		166	Oberflaeche	m2	84,5
Medium-Inhalt	dm3		16,1	OUT OF CERTIF. RANGE		

Type: P40-16 AR 8R-9T-1200A-2,5Pa CuNi-30/Cu
Frame=304



Information received from MME

APPENDIX B. Electrical Balance of BV80

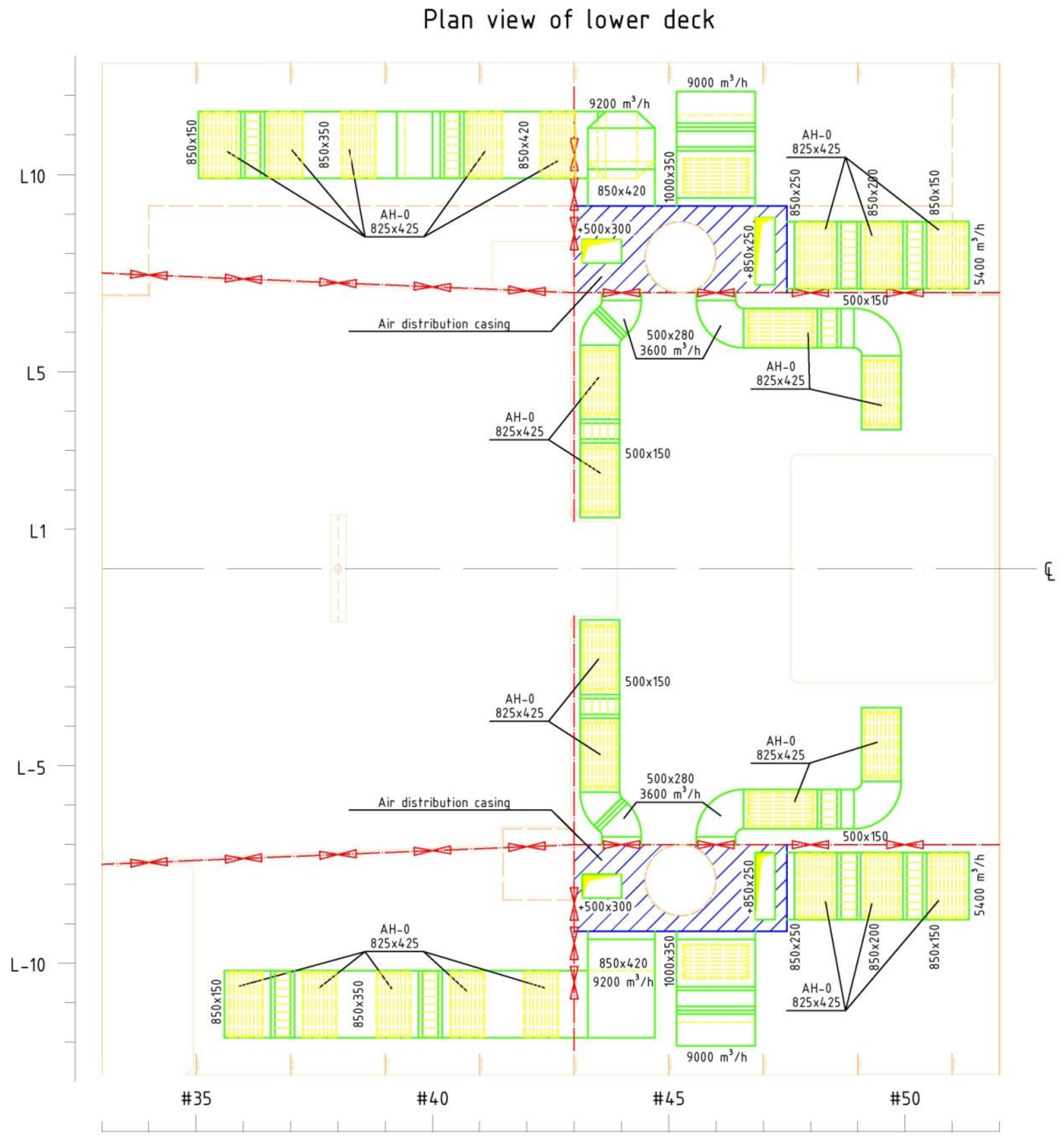
	Group	Sea Service (Summer) [kW]	Sea Service (Winter) [kW]	Manoeuvre Service [kW]	Harbour Service (Summer) [kW]	Harbour Service (Winter) [kW]	Anchor Service [kW]	Harbour in Rest	Emergency Service [kW]
1	Propulsion system	72	72	344	10	10	110	7	14
2	Aux. Machinery	74	74	62	46	46	80	39	86
3	Deck machinery	10	9	16	15	15	25	10	41
4	Alarm and Monitoring, Battery Charger	10	10	10	10	10	10	10	8
5	Heating,Ventilation, Air conditioning	278	305	262	237	265	270	203	0
6	Galley, Laundry	29	29	29	29	29	29	4	0
7	Lighting	33	33	33	35	35	35	26	12
8	Navigation, Communication	10	15	15	8	11	15	4	9
9	Audio Visual, Security System	11	11	11	11	11	4	6	0
	Total	**526**	**557**	**782**	**401**	**432**	**578**	**310**	**169**

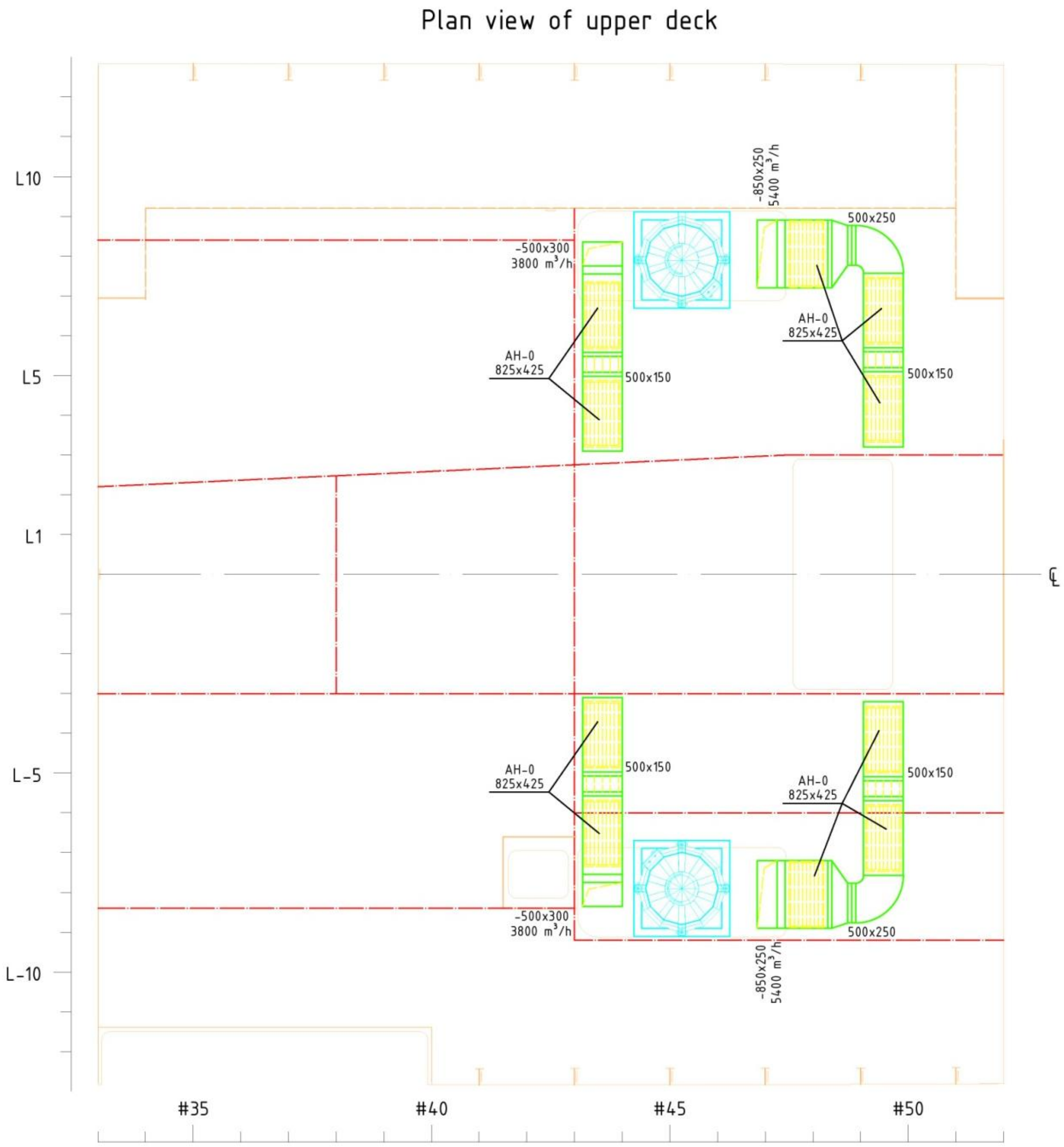
Pcs.			kWe	Generator Load							
1	Alternator	each	357	73,7%	78,0%	73,0%	56,2%	60,5%	81,0%	86,8%	
2	Alternator	each	357	73,7%	78,0%	73,0%	56,2%	60,5%	81,0%		
3	Alternator	each	357			73,0%					
1	Emergency Alternator		194								87%

Pcs.		Supplier	Type	Rated power [kW]	Rated power [kVA]	Σ Power [kW] [kW]	Σ Power [kW] [kVA]
2	Main Engines	MTU	12V 4000 M73L	2.160	-		-
3	Aux. Diesel Gensets	MTU	8V2000M41A / HCM 534 E2	357	446	1.071	1.339
1	Em. Diesel Generator Set	Lindenberg	D 2866 LXE 20 / LSAM 46.2 L 9	194	-	194	243

Retrieved from Blohm+Voss database on 15th August 2015

APPENDIX C. Top view of ventilation system in machinery room





Obtained from Blohm+Voss Database

APPENDIX D. Compression Chiller

DAIKIN

Chiller selection software
CSS - Rev. 9.2
Printing date: 11/12/2014

TECHNICAL SPECIFICATIONS (data referred to EN14511)

MODEL		EWWD650G-XS - marine
Capacity - Cooling	kW	552
Capacity control - Type		Stepless
Unit power input - Cooling	kW	165
EER		3,34
ESEER		5,27
IPLV		6,17
CASING		
Colour *		IW
Material *		GPSS
DIMENSIONS		
Height	mm	1880
Width	mm	860
Length	mm	4305
WEIGHT		
Unit Weight	kg	2990
Operating Weight	kg	3340
WATER HEAT EXCHANGER (Evaporator)		
Type *		S&T
Fluid		Water
Fouling factor	m² °C/W	0,0000176
Water Volume	l	280
Water temperature (in/out)	°C	12,0/6,0
Nominal water flow rate - Cooling	l/s	22,0
Nominal Water pressure drop - Cooling **	kPa	29
Insulation material *		CC
WATER HEAT EXCHANGER (Condenser)		
Type *		S&T
Fluid		Sea Water
Fouling factor	m² °C/W	0,0000880
Water Volume	l	68
Water temperature (in/out)	°C	32,0/37,0
Nominal water flow rate - Cooling	l/s	17,3 17,3
Nominal Water pressure drop - Cooling **	kPa	16 16
COMPRESSOR		
Type		Single Screw
Oil charge	l	32
Quantity	No.	2
SOUND LEVEL		
Sound Power - Cooling	dB(A)	90
Sound Pressure - Cooling	dB(A)	72
REFRIGERANT CIRCUIT		
Refrigerant type		R134a
Refrigerant charge	kg	120
N. of circuits	No.	2
PIPING CONNECTIONS		
Evaporator water inlet/outlet		168.3mm
Condenser water inlet/outlet		5 "

**** IW: Ivory White - GPSS: Galvanized and Painted Steel Sheet - PHE: Plate Heat Exchanger - S&T: Single Pass Shell & Tube***
**** CC: Closed Cell***

Cc is the cooling power, Cpi is the electrical power, and EER is the COP.

ENERGY ANALYSIS

Required Selection: Constant Water 10 Points - Constant condenser inlet water temperature

Number	Part load [%]	Te IN [C°]	Te OUT [°C]	Tc IN [°C]	Tc OUT [°C]	Cc [kW]	Cpi [kW]	EER
1	100	12,00	6,00	32,0	37,0	573	151	3,80
2	90	11,40	6,00	32,0	36,5	516	137	3,76
3	80	10,80	6,00	32,0	36,0	458	123	3,73
4	70	10,20	6,00	32,0	35,5	401	108	3,70
5	60	9,60	6,00	32,0	35,1	343	95,5	3,59
6	50	9,00	6,00	32,0	34,6	286	82,0	3,49
7	40	8,40	6,00	32,0	34,0	228	60,4	3,78
8	30	7,80	6,00	32,0	33,5	171	46,8	3,66
9	20	7,20	6,00	32,0	33,0	114	34,1	3,34
10	15	6,60	6,00	32,0	32,8	82,7	27,6	3,00
							Average value	**3,59**

Cc: Cooling Capacity; Cpi: compressors + water pump power input (according to EN14511)

Retrieved from Blohm+Voss Database.

APPENDIX E. Absorption Chillers

E1. Main characteristics of suitable models

		Absorption Chillers										Comp. Chiller
Manufacturer		Yazaki		World Energy								Daikin
Model		WFC-SC50	WFC-SH30	L30HH	L40HH	L50HH	L60HH	L75HH	L90HH	L110HH	L135HH	EWWD650G -XS-marine
Cooling Capacity	kW	175,8	105,6	105	141	176	211	264	316	387	475	552
Heating Capacity	kW	-	146,2	-	-	-	-	-	-	-	-	-
Chilled Water Temperature	°C	12,5 / 7	12,5 / 7	13,0 / 8	13,0 / 8	13,0 / 8	13,0 / 8	13,0 / 8	13,0 / 8	13,0 / 8	13,0 / 8	12,0 / 6
Chilled Water mass flow	l/s	7,64	4,58	5,02	6,7	8,39	10,08	12,61	15,11	18,47	22,67	22
Cooling Water Temperature	°C	31/35	31/35	31 / 36,5	31 / 36,5	31 / 36,5	31 / 36,5	31 / 36,5	31 / 36,5	31 / 36,5	31 / 36,5	32 / 37
Cooling Water mass flow	l/s	25,5	15,3	10,17	13,58	16,97	20,36	25,44	30,56	37,22	45,83	17,3
Heat Input	kW	251	151	127	171	221	254	319	381	467	573	-
Hot Water Temperature	°C	88 / 83	88 / 83	95 / 80	95 / 80	95 / 80	95 / 80	95 / 80	95 / 80	95 / 80	95 / 80	-
Hot Water mass flow	l/s	12	7,2	2,03	2,72	3,53	4,06	5,08	6,08	7,44	9,14	-
Width	mm	1785	1475	1112	1112	1112	1112	1112	1112	1112	1112	860
Depth	mm	2060	1544	2110	2110	2610	2060	2658	2658	3678	3678	4305
Height	mm	2223	2130	2091	2091	2091	2091	2473	2473	2473	2473	1880
Dry Weight	kg	2100	1450	2100	2200	2600	2700	3600	3700	4600	4800	2990
Operating Weight	kg	2725	1800	2300	2500	2900	3100	4100	4200	5200	5500	3340
COP	-	0,70	0,70	0,83	0,82	0,80	0,83	0,83	0,83	0,83	0,83	3,59
Dimensions	m3	8,17	4,85	4,91	4,91	6,07	4,79	7,31	7,31	10,11	10,11	6,96
Spec. Cooling (Dim.)	kW/m3	21,51	21,77	21,40	28,74	29,00	44,05	36,12	43,23	38,26	46,96	79,31
Spec. Cooling (Weight)	kW/kg	0,0645	0,0587	0,0457	0,06	0,0607	0,0681	0,0644	0,0752	0,0744	0,0864	0,1653

E2. Approval Certificate from DNV-GL for hot water driven absorption chillers

DNV·GL

APPROVAL CERTIFICATE

This is to certify, that the undernoted products have been approved in accordance with the relevant requirements of the DNV GL Approval System.

Certificate No.	**42 195 - 15 HH**
Company	**World Energy Co., Ltd.** **10,24 Beon-gil, Daeya 1-ro,** **Gunpo-si, Gyeonggi-do, KOREA, REPUBLIC OF**
Product	**Hot Water Driven Absorption Chiller for Marine Applications**
Type	**HWAR - L & LH & LHH Series / L30HH - 1300HH (105 kW - 4,571 kW)**
Technical Data / Application	**Main Components:** **Evaporator, Absorber, Low Temp. Solution Heat Exchanger, High Temp. Solution Heat Exchanger, Low Temp. Generator, Condenser, Purge Unit, Refrigerant Pump, Absorbent Pump, Operating Devices and Gauges, Chilled Water Freeze Prevention Unit, Absorbent Crystallization Prevention Unit.** **Media:** **Chilled water: 4 to 25 °C** **Cooling water: 20 to 40 °C** **Hot water: 80 to 109 °C** **Absorbent solution: 55% of LiBr (Lithium Bromide), 44.97% water, 0.03% corrosion inhibitor, lithium molybdate (LiMoO4).** **Refrigerant: Water** **Design pressure: 10 bar chilled /cooling water (H2O); 16 bar hot water**
Approval Standard	**Rules for Classification and Construction: I-1-2 Machinery Installations; I-1-3 Electrical Installations; Ed. 2014**
Documents	**HWAR-L,-LH,-LHH Series; Techn. Data.**
Remarks	**Absorption Chiller incl. Pressure Vessels are subject to individual Survey and Testing in the Presence of a DNV-GL Surveyor.**

Valid until **2020-12-15**
Page **1** of **1**
File No. **XI.B.09**
Hamburg, 2015-12-16

DNV GL

www.dnvgl.com

Olaf Drews

Christian Kaemmer

Internet Publication: GL-Approvals

Found in DNV-GL Website

E3. Approval Certificate from DNV-GL for steam driven absorption chillers

DNV·GL

APPROVAL CERTIFICATE

This is to certify, that the undernoted products have been approved in accordance with the relevant requirements of the DNV GL Approval System.

Certificate No.	**11 518 - 14 HH**
Company	**World Energy Co., Ltd.** **10,24 Beon-gil, Daeya 1-ro,** **Gunpo-si, Gyeonggi-do, KOREA, REPUBLIC OF**
Product	**Double Effect Steam Driven Absorption Chiller**
Type	**SW100 - 1500 (352 - 5.274 kW)**
Technical Data / Application	**Main Components:** **Evaporator, Absorber, Low Temp. Solution Heat Exchanger, High Temp. Solution Heat Exchanger, High Temp. Generator, Low Temp. Generator, Condenser, Purge Unit, Refrigerant Pump, Absorbent Pump, Operating Devices and Gauges, Chilled Water Freeze Prevention Unit, Absorbent Crystallization Prevention Unit.** **Media:** **Inhibitor / Absorbent: LiBr (Lithium Bromide)** **Refrigerant: Distilled Water** **Additive: Octyl Alcohol**
Approval Standard	**Rules for Classification and Construction: I-1-2 Machinery Installations; I-1-3 Electrical Installations; Ed. 2014**
Documents	**P & I-Diagram Dwg-No: SWO12300, Techn. Data Sheet, Piping Specification for Absorption Chiller, User Manual; Electrical System, GL-Ref No: 14-056623, Design Evaluation of Pressure Vessels, GL-Ref No: 14-049729** **Test Plan 2015.2.20 rev.01 Test report dated 06 July 2015**
Remarks	**Absorption Chiller incl. Ist Pressure Vessels are subject to individual Survey and Testing in the Presence of a DNV-GL Surveyor.**

Valid until **2020-07-22**
Page **1** of **2**
File No. **XI.B.09**
Hamburg, 2015-07-23

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Olaf Drews

Christian Kaemmer

Internet Publication: GL-Approvals

DNV·GL

APPROVAL CERTIFICATE

Certificate No. **11 518 - 14 HH**

PERFORMANCE TEST OF APBSORPTION CHILLER:

Model: SW120
Cooling Capacity 352 kW
Heat Source 6barg saturated steam / Chilled Water Inlet 12°C
Electric Power 440V; 60 Hz, 3phase

	Stationary	Heel	Rolling	Rolling	Rolling	Rolling	Trim	Pitching
Angle [°]	**0°**	**1.5°**	**7°**	**11°**	**15°**	**22.5°**	**1.5°**	**7.5°**
Cylces [1/min]	**Hold**	**Hold**	**5**	**5**	**3**	**3**	**Hold**	**6**
Capacity Ratio [%]	**100**	**94**	**95**	**87**	**81**	**72**	**92**	**95**

Cooling Capacity: Cooling Capacity@test conditions / Cooling Capacity@Stationary Conditions (0°)
Test effected dated 30 June ~ 1 July 2015

Documents:
Test Plan 2015.2.20 rev.01
Test report dated 06 July 2015

Valid until **2020-07-22**
Page **2** of **2**
File No. **XI.B.09**
Hamburg, 2015-07-23

DNV GL

www.dnvgl.com

Olaf Drews

Christian Kaemmer

Internet Publication: GL-Approvals

Found in DNV-GL Website

APPENDIX F. Batteries offer from Saft

Space & Defence Division

Álvaro Francisco Benet Pérez

Propulsion Plants & Power Generation
Mechanical Engineering Design Department HKM

Blohm + Voss Shipyards GmbH
Knooper Weg 71
24116 Kiel
Telefon: +49 431 88777-4867
Telefax: +49 431 88777-664896
francisco.perez@blohmvoss.com
http://www.blohmvoss.com

Copy: David Reulier, Didier Jouffroy, Ecaterina Hauser (Saft)

Paris, 22nd Sep, 2015

Saft Ref.: A0768-15

Your Ref.: NA

Subject: ROM Offer for Li-ion Battery System for Mega Yacht

Dear Sir,

In response to your request, we are pleased to provide you the following offer:

1 - Offer description:

This offer is based on

- PSR document filled by you on 17th Sep 2015

Any requirement for changes will lead to an updated technical offer and a new commercial and financial offer. This might be the case if power profiles or ship propulsion architecture would change. Any additional requirement which is not covered by Saft technical offer will lead to an additional technical offer and an additional commercial and financial offer.

The system will be delivered with the following documentation:

- User manual

Additional information which can be provided by Saft (for battery) on request:

- Quality certificates
- Status report on certifications (BV/LR)
- Commissioning protocols
- Health, Safety, Environment (HSE) documentation

2 - Physical integration and data links in the application:

The batteries will be integrated by Saft. Before integration, Saft will verify and approve the system.

The safety recommendations will be imperatively followed up and a check list will be done by Saft and the customer after the integration and before the operational use starts.

The BMMs MBMMs parameters will be studied at the beginning of the project. After this, they will be frozen before the commissioning in order to be designed in the usage configuration. The possible further software modifications (outside the initial parameters) or hardware modifications are not included in this offer.

3 – Baseline price:

Synthesis of sizing for project	Customer
Scenarion type	Project
Battery system configuration	VL41MFe_Seanergy 48M
Nbr independantes batteries	1
Modules type	Seanergy 48 M
module configuration	2P-14S air cooled
Nbr modules serie per ESSU	9
Max Voltage	479 V
Nbr battery // strings	5
Energy installed (kWh)	162 kWh

Energy used per cycle	160 kWh
Max discharge power	369 kW
Max Charge power	168 kW
DoD vs Energy installed BOL	99%

System components	
Cells	1260
modules	45
BMM	5
MBMM* (+ additional I/O card)	1
Height of battery compartment	1700
Cabinets 33 U height / ESSU	1
Cabinets 33 U height	5
System weight (kg)	2 432

One battery system of 162 kWh is composed of the following building blocks:
1 sub-system.
Each sub-system is made of 5 ESSU (strings) and controlled by 1 Master Battery Management Module (MBMM) installed inside 5 cabinets 33U (1668mm).
Each ESSU is made of 9 air cooled Marine Modules and a Battery Management Module (BMM)
Each Marine Module is 2P14S format with VL41MFe cells (Energy)

Each cabinet is 800mmx600mm of footprint

Total Offer Price (without cabinets) for Battery: 143,118€

Total Offer Price (with cabinets and I&C) for 1 Battery: 157,065€

Received from SAFT batteries

APPENDIX G. Ventilation fans

G1. Axial fan of machinery room with capacity 40.000 m^3/h.

systemair

AXC 900-10/18°-4 (15.00 kW) S V1

Item no. CAX90014IE3

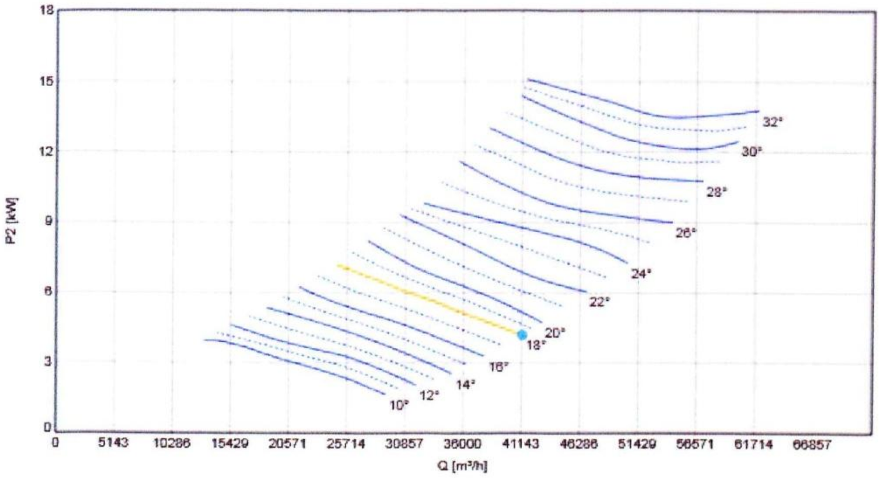
Document type: **Product card**
Document date: **2015-10-13**
Generated by: **Systemair Online Catalogue**

Description

Axial fan Series AXC, suitable for operating temperatures of up to 55°C

- Air direction Form A (from motor to impeller), direct driven
- Aerofoil impeller with adjustable pitch angle for maximum efficiency
- aluminium hub and blades, Impeller balanced statically and dynamically in accordance with DIN ISO 1940-1, quality grade G6,3
- Long casing, hot dip galvanized steel, to DIN EN ISO 1461
- Spun flanges according Eurovent 1/2
- VDE certified terminal box in IP65 mounted at the outside of the fan casing for easy wiring
- three-phase motors IE2 efficiency or IE3 efficiency , IP55, insulation class F, in accordance with EN 60034-5/IEC 85

The Systemair AXC range of long cased medium pressure axial fans is available in sizes from 315 up to 2.000 mm nominal diameter. The adjustable pitch angle setting offers a wide performance and maximum flexibility to match precisely individual airflow requirements. The AXC axial fans have been performance tested in accordance with DIN ISO 5801, DIN 24163 and AMCA 210-99 on the Systemair fan test rig. The motors are equipped with PTC thermistors for optimum motor protection. The motor is speed controllable by frequency converter.



Technical data

	Required point			Working point (T=20°C, ρ=1.204 kg/m³)								
	Q [m³/h]	Ps [Pa]	ρ [kg/m³]	Q [m³/h]	Ps [Pa]	Pdyn [Pa]	Ptot [Pa]	V [m/s]	η [%]	P2 [kW]	P2 max [kW]	Angle [°]
User	40000	5	1,204	41184	5.83	195	200	18	55.1	4.16	7.21	18

	Technical data											
	Blades	Voltage [V/Hz]	P2 nominal [kW]	Pol	n [r.p.m.]	IN [A]	IA/IN	Frame	Motor	IP	Protection class	Fan weight [kg]
User	10	400/50	15	4	1465	28.7	7.5	160L	IE3	IP55	F	259

Fan weight may vary depending on used motor type

Acoustic data

Sound level Speed 1		63	125	250	500	1k	2k	4k	8k	Tot
Sound power Lw6	dB(A)	63	73	82	86	86	83	79	72	91
Sound power Lw4	dB(A)	74	84	92	97	97	94	90	83	102
Sound pressure Lp	dB(A)	45	56	64	68	69	66	62	55	74

Lw6: free-outlet conditions, Lw4: in-duct conditions, Lp: free field conditions | Sound pressure level (Lp) distance: 3 m

Calculated in System air website

G2. Axial fan of machinery room with capacity 50.000 m³/h.

systemair

AXC 1000-10/16°-4 (15.00 kW) S V1

Item no. CAX100011IE3

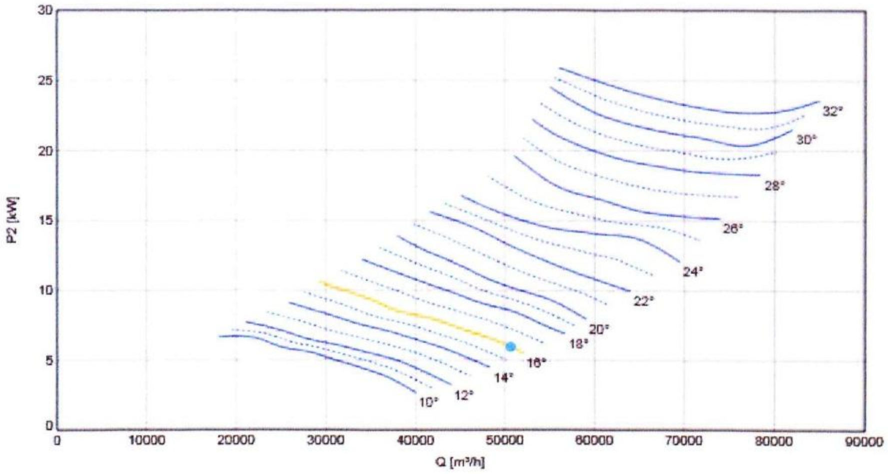
Document type: **Product card**
Document date: **2015-10-13**
Generated by: **Systemair Online Catalogue**

Description

Axial fan Series AXC, suitable for operating temperatures of up to 55°C

- Air direction Form A (from motor to impeller), direct driven
- Aerofoil impeller with adjustable pitch angle for maximum efficiency
- aluminium hub and blades, Impeller balanced statically and dynamically in accordance with DIN ISO 1940-1, quality grade G6,3
- Long casing, hot dip galvanized steel, to DIN EN ISO 1461
- Spun flanges according Eurovent 1/2
- VDE certified terminal box in IP65 mounted at the outside of the fan casing for easy wiring
- three-phase motors IE2 efficiency or IE3 efficiency , IP55, insulation class F, in accordance with EN 60034-5/IEC 85

The Systemair AXC range of long cased medium pressure axial fans is available in sizes from 315 up to 2.000 mm nominal diameter. The adjustable pitch angle setting offers a wide performance and maximum flexibility to match precisely individual airflow requirements. The AXC axial fans have been performance tested in accordance with DIN ISO 5801, DIN 24163 and AMCA 210-99 on the Systemair fan test rig. The motors are equipped with PTC thermistors for optimum motor protection. The motor is speed controllable by frequency converter.



Technical data

	Required point			Working point (T=20°C, ρ=1.204 kg/m³)								
	Q [m³/h]	Ps [Pa]	ρ [kg/m³]	Q [m³/h]	Ps [Pa]	Pdyn [Pa]	Ptot [Pa]	V [m/s]	η [%]	P2 [kW]	P2 max [kW]	Angle [°]
User	50000	50	1,204	50626	51.5	193	245	17.9	57.7	5.94	10.6	16

Technical data

	Blades	Voltage [V/Hz]	P2 nominal [kW]	Pol	n [r.p.m.]	IN [A]	IA/IN	Frame	Motor	IP	Protection class	Fan weight [kg]
User	10	400/50	15	4	1465	28.7	7.5	160L	IE3	IP55	F	266

Fan weight may vary depending on used motor type

Acoustic data

Sound level Speed 1		63	125	250	500	1k	2k	4k	8k	Tot
Sound power Lw6	dB(A)	67	77	85	90	90	87	83	76	95
Sound power Lw4	dB(A)	77	87	95	100	100	97	93	86	105
Sound pressure Lp	dB(A)	49	59	68	72	72	69	65	58	77

Lw6: free-outlet conditions, Lw4: in-duct conditions, Lp: free field conditions | Sound pressure level (Lp) distance: 3 m

Calculated in System air website

G3. Fan of fore technical room with.

systemair

RSI 70-40 L3 A-W INS.REC.FAN +

Item no. 1791

Version: 50 Hz

Document type: **Product card**
Document date: **2015-10-15**
Generated by: **Systemair Online Catalogue**

Description

- Speed-controllable
- Integral thermal contacts
- Can be installed in any position
- Maintenance-free and reliable

The RSI models have impellers with backward-curved blades and external rotor motors. The motor and impeller are mounted on the access cover to facilitate easy maintenance. The RSI models are thermally and acoustically insulated with 50 mm of mineral wool, with perforated sheet steel on the inner surface. To protect the motor from overheating the RSI fans have integral thermal contacts with external leads for connection to a motor protection device. The fans can be installed in any position and are easy to connect using the DS flexible connections. The casing is manufactured from galvanised sheet steel.

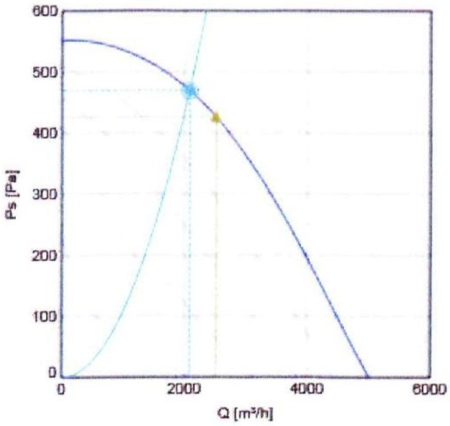
Technical parameters

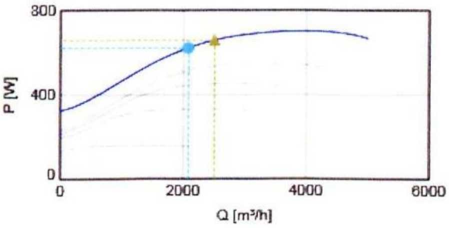
Voltage	400	V
Frequency	50	Hz
Phase	3	~
Input power (P1)	704	W
Current	1,7	A
Max. airflow	5008	m³/h
Fan impeller speed	1410	r.p.m.
Max. temperature of transported air	70	°C
Max. temperature of transported air when voltage-controlled	70	°C
Sound pressure level at 3 m (20m² Sabine)	50,5	dB(A)
Weight	78	kg
Insulation class	F	
Enclosure class, motor	54	IP

Performance

Diagrams

Operational point with batteries





Hydraulic data

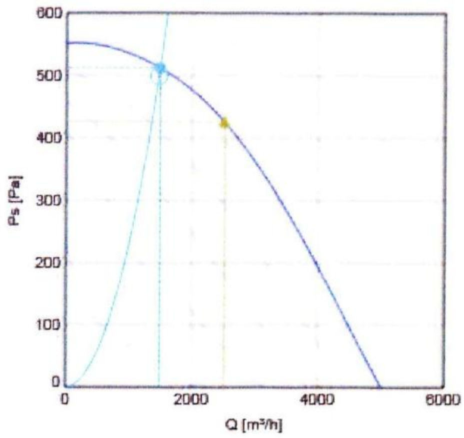
	Required point		Working point						
	Q [m³/h]	Ps [Pa]	Q [m³/h]	Ps [Pa]	P [W]	n [r.p.m.]	I [A]	SFP [kW/m³/s]	U [V]
Max efficiency			▲ 2505	▲ 427	▲ 660	1416	1.65	0.949	400
User	○ 2075	○ 470	● 2077	● 471	● 624	1423	1.62	1.08	400

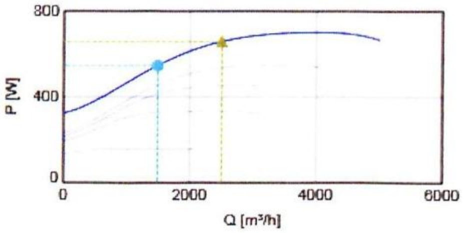
Acoustic data

Sound power level		63	125	250	500	1k	2k	4k	8k	Tot
Inlet	dB(A)	57	62	62	62	57	58	55	49	68
Outlet	dB(A)	63	66	77	75	75	72	65	57	81
Surrounding	dB(A)	39	46	51	53	50	48	44	39	58

Sound power level		63	125	250	500	1k	2k	4k	8k	Tot
Inlet	dB(A)	57	62	62	62	57	58	55	49	68
Outlet	dB(A)	63	67	77	75	75	72	65	57	81
Surrounding	dB(A)	39	46	52	53	50	48	44	39	58

Operational point without batteries





Hydraulic data

	Required point		Working point						
	Q [m³/h]	Ps [Pa]	Q [m³/h]	Ps [Pa]	P [W]	n [r.p.m.]	I [A]	SFP [kW/m³/s]	U [V]
Max efficiency			▲ 2505	▲ 427	▲ 660	1416	1.65	0.949	400
User	○ 1465	○ 500	● 1485	● 513	● 548	1434	1.56	1.33	400

Acoustic data

Sound power level		63	125	250	500	1k	2k	4k	8k	Tot
Inlet	dB(A)	57	62	62	62	57	58	55	49	68
Outlet	dB(A)	63	66	77	75	75	72	65	57	81
Surrounding	dB(A)	39	46	51	53	50	48	44	39	58

Sound power level		63	125	250	500	1k	2k	4k	8k	Tot
Inlet	dB(A)	57	62	62	62	57	58	55	49	68
Outlet	dB(A)	63	67	77	75	75	72	65	57	81
Surrounding	dB(A)	39	47	52	53	51	48	44	39	58

Calculated in System air website

APPENDIX H. PCM

Data sheet

RT82

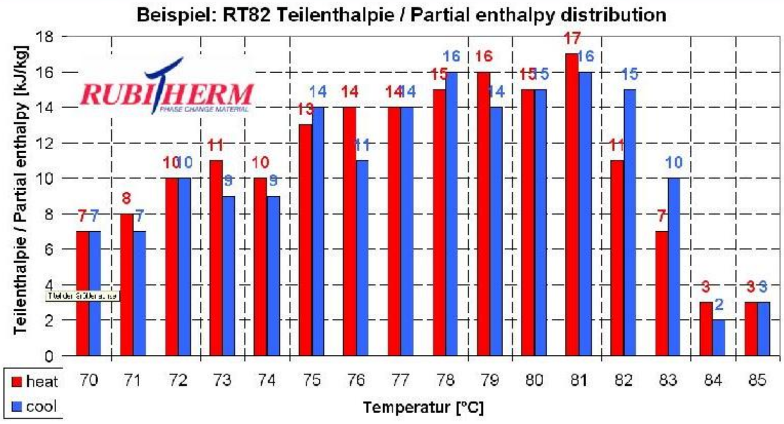
RUBITHERM® RT is a pure PCM, this heat storage material utilising the processes of phase change between solid and liquid (melting and congealing) to store and release large quantities of thermal energy at nearly constant temperature.
The RUBITHERM® phase change materials (PCM's) provide a very effective means for storing heat and cold, even when limited volumes and low differences in operating temperature are applicable.

We look forward to discussing your particular questions, needs and interests with you.

Properties:
- high thermal energy storage capacity
- heat storage and release take place at relatively constant temperatures
- no supercooling effect, chemically inert
- long life product, with stable performance through the phase change cycles
- melting temperature range between -4 °C and 100 °C

The most important data:

	Typical Values	
Melting area	**77-85** main peak: 82	**[°C]**
Congealing area	**85-77** main peak: 83	**[°C]**
Heat storage capacity ± 7,5%	**175**	**[kJ/kg]***
Combination of latent and sensible heat in a temperatur range of 70°C to 85°C.	**49**	**[Wh/kg]***
Specific heat capacity	**2**	**[kJ/kg·K]**
Density solid at 15 °C	**0,88**	**[kg/l]**
Density liquid at 90 °C	**0,77**	**[kg/l]**
Heat conductivity (both phases)	**0,2**	**[W/(m·K)]**
Volume expansion	**12,5**	**[%]**
Flash point (PCM)	**>200**	**[°C]**
Max. operation temperature	**100**	**[°C]**



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The product information given is a non-binding planning aid, subject to technical changes without notice. Version: 13.02.2015

**Measured with 3-layer-calorimeter.*

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