Software tool for the design and operation of the loading / unloading facilities

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Foreword

The present document describes the software tool developed in the context of the GASVESSEL project to support the design and the operation of the CNG loading and unloading system and its application to the assessment of the loading and unloading time for the reference GASVESSEL scenarios.

The basic requirements, the preliminary design of the GASVESSEL and the GASVESSEL operational scenarios have been used to identify the basic configuration of the loading and unloading system and to define the basic operational conditions (Chapter 2).

The fundamental equations necessary to describe the dynamics of CNG in the basic plant components have been defined and implemented using MATLAB and SIMULINK. Models of the basic components (Chapter 3) have been verified and integrated and the overall model for the loading and unloading system has been validated (Chapter 4).

The GASVESSEL scenarios for the three geographical areas of interest have been simulated and analysed as summarized in Chapter 6, 7 and 8. Using as input the basic configuration data for the three geographical areas the results summarized in Table 9.1 and Table 9.2 have been produced for both the minimum time and the maximum capacity options.

The model is now ready to support further optimization of the design that would eventually be considered necessary in the context of the GASVESSEL project and will be fine-tuned and further verified to support the operational phase in a real life application.

The software tool implementing the model is available at CENERGY premises and shall be used further to support sensitivity analyses, to optimize loading and unloading operations, and to minimize potential operation risks as they will emerge during the HAZOP assessment.

1. Introduction: Software Requirements and GASVESSEL Scenarios

We hereby summarize the GASVESSEL operational scenarios valid for the three geographical areas of interest and the requirements for the simulation model and the software that responds to the need to support both the design phase and the operational phase.

The main design data of the pressure cylinders and of the ship considered in the project are collected in Table 1.1 . In terms of gas composition, to simplify the assessment we refer to a pure methane case, however we recall that natural gas composition ranges from 87-90% methane (with 4-6% Ethane, no H2S, no CO2, no mercury) for the Black Sea scenario to 97-99% methane (0.5-1.5% Ethane, no H2S, no CO2, no mercury) for the Mediterranean Sea Scenario, with the Barents Sea Scenario somehow in between with 90% methane (7% ethane, 3% propane, no H2S, no CO2, no mercury).

Table 1.1 – Gasvessel project: CNG vessel and ship design main specifications.

Pressure Vessel main specifications:	
gas cylinder outer diameter	3.4 m
gas cylinder length	22.5 m
volume (water)	175 m^3
vessel mass capacity @300 bar, 20°C (*)	38 ton
design pressure	300 bar
CNG ship design:	
length, overall	205 m
max breadth	36 m
height to main deck	22.0 m
design draft	7.5 m
n° cylinders in the CNG ship	272
total cylinders volume (water)	44800 m^3
total gas mass @ 300 bar 20°C (*)	9771 ton
total gas volume	13.762 MNm^3
cargo gas /container weight ratio	1.5

(*) referred to pure methane

The pressure cylinders arrangement in the CNG carrier ship is vertical. To reduce fire hazard, the holds are saturated with nitrogen. The pressure cylinders are made of austenitic stainless steel liner (5 mm) externally reinforced with a composite made of carbon fiber, impregnated with epoxy resin (approximately 35 mm as a preliminary value).

These aspects will affect heat exchange between the pressure cylinders, the holds, the ships structure and the external environment and are of great importance for the overall dynamics of the loading and unloading process and for the thermal processes during the ship transfer from the loading point to the unloading point.

2. Fundamental Plant Arrangement and Model Architecture

2.1 Plant Arrangement for the Loading and Unloading System

A number of configurations of the loading and unloading plants have been investigated[1] and are summarised in figures from Figure 2.1 to Figure 2.4. Following the plant configuration choices, the simulation model and the software hereby implemented and described are designed to handle the following operational phases:

- free loading from a delivery terminal to the GASVESSEL Pressure Cylinders
- forced loading from a delivery terminal to the GASVESSEL Pressure Cylinders
- transport phase
- free unloading from the GASVESSEL Pressure Cylinders to a receiving terminal
- forced unloading from the GASVESSEL Pressure Cylinders to a receiving terminal.

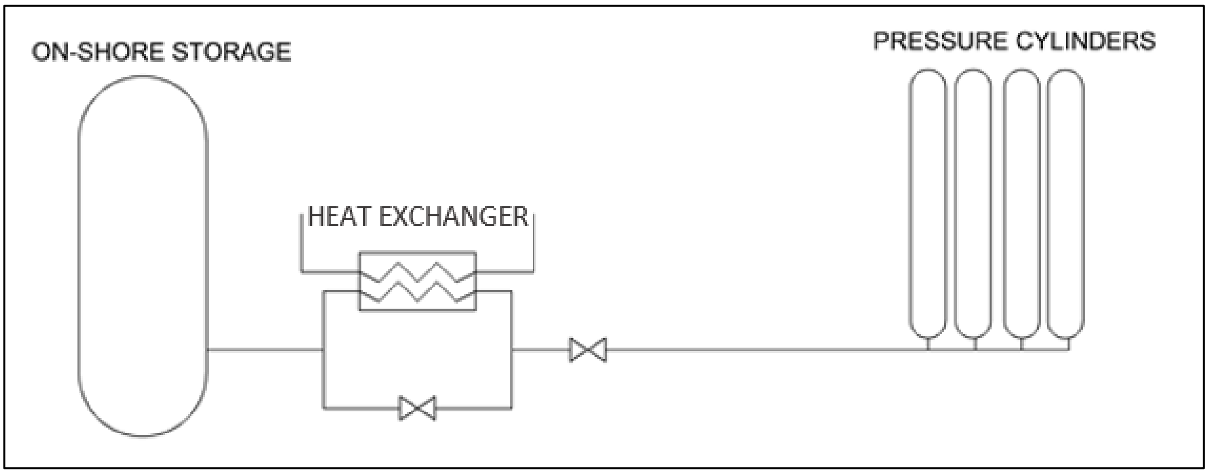

Figure 2.1 – Schematics of the free CNG loading plant
(Heat exchanger is primarily used to cool down the gas).

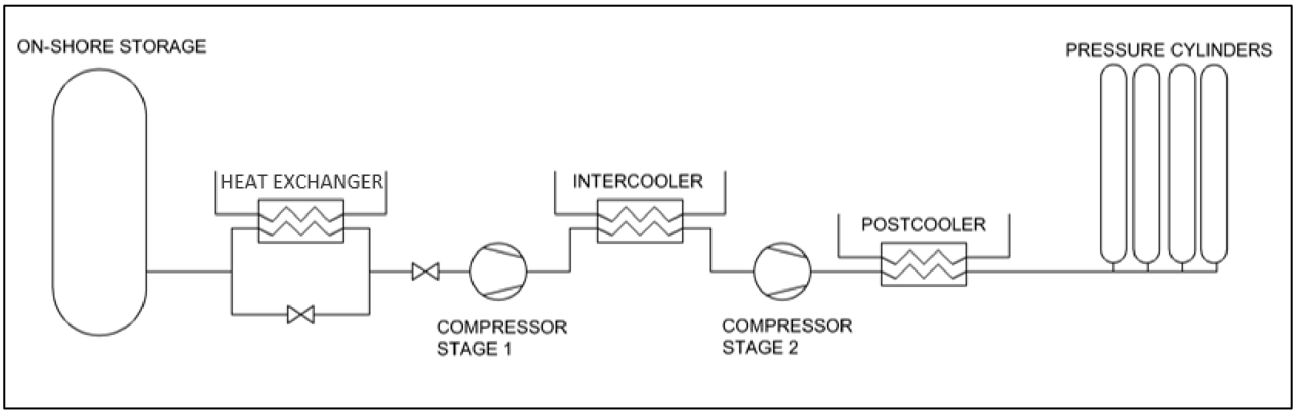

Figure 2.2 – Schematics of the forced CNG loading plant
(Heat exchanger is primarily used to cool down the gas).

[1] "Deliverable 6.1 - Technical proposals for the construction and equipment of Loading / unloading modules"

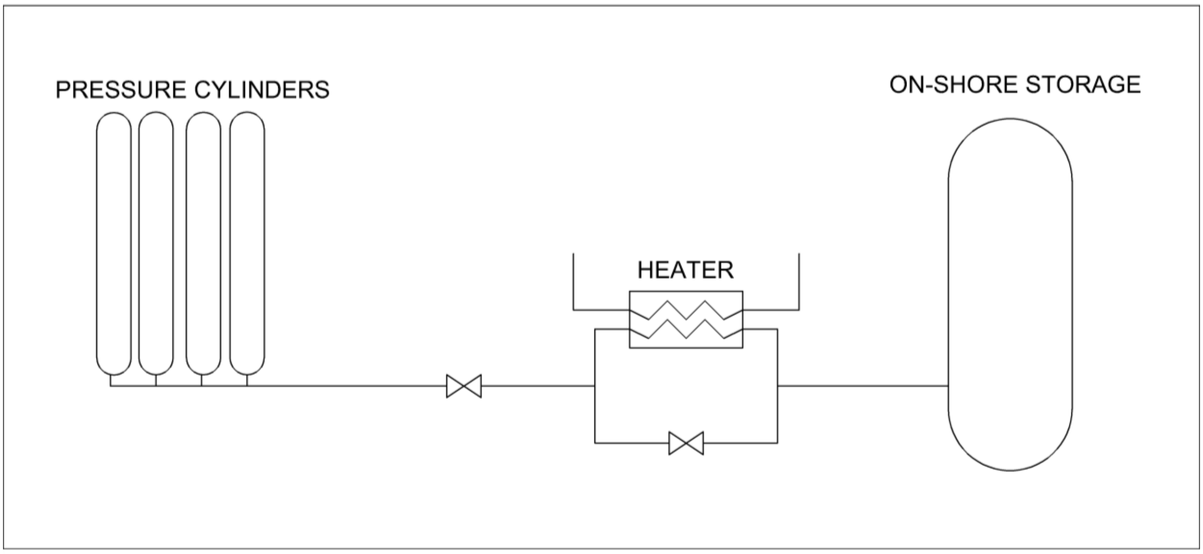

Figure 2.3 – Schematics of the free CNG unloading plant.

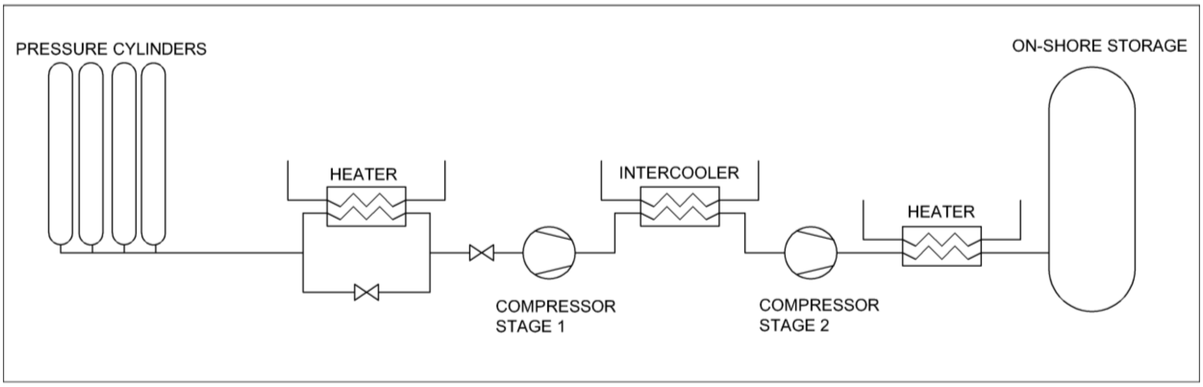

Figure 2.4 – Schematics of the forced CNG unloading plant.

The loading/unloading processes are divided into two subsequent free and forced phases. During the free phases, the gas flow is due to the pressure difference between the pressure cylinders and the storage terminal or the pipeline, respectively. During the forced phases, the centrifugal compressor provides the pressure cylinders complete filling in the loading process and the most complete as possible emptying in the unloading one. A cooler is always presents after the compressor to increase the compressed gas density. The heater is used only in the unloading phase, because the temperature of the pressure cylinders can reach values as low as -60°C, due to the expansion of the gas contained in it.

The two valves mounted before and after the compressor introduce a variable pressure drop, allowing the compressors to operate in non–flooding conditions. Furthermore, by acting on the valve placed on the intake, the compressors can be operated even when the pressure of the upstream tanks is higher than that of the downstream pipeline. This is necessary when the flow in the "free" discharge phase falls, for example, below 20 kg/s and, therefore, it is more convenient to operate the compressors to speed up the process.

2.2 Model architecture

The focus of the present model is on the processes on board the GASVESSEL. The simulation model takes into consideration the main components necessary for the loading and unloading process. In the following diagrams (from Figure 2.7 to Figure 2.10) the structure of the program is shown for the four main operating phases. In the following a "cargo tank" is a bundle of 4 pressure cylinders.

Table 2.1 – Plant (and Model) Components

Component	Description
DUCT DN 250_1	It represents the duct that goes from the manifold to the compressor room. The entire gas flow rate, having the density of the storage, passes through this pipe at the inlet or outlet.
HEATER (*)	The Heater in the Free / Forced Loading phase can be used to cool the gas coming from the storage. In the Free / Forced Unloading phase it can be used to heat the gas.
By Pass (*)	The By Pass represents the possibility in the various operating phases to exclude from the calculation the presence of the Heater.
VALVE DN 250 (*)	The Valve DN 250 in the Free Loading / Unloading phases represents the regulating valve to control the speed of the gas in the ducts. In the Forced Loading / Unloading phases it represents the regulating valve that allows to control the compressor suction pressure.
DUCT DN 250_2	The Duct DN 250_2 represents the pipe section leaving the compressor room, through which the entire gas flow passes, until the first branch with the two DN 150 pipes directed to the first two holds.
DUCT DN 250_3	The Duct DN 250_3 tube represents the section of the tube after the first branch.
DUCT DN 250_4	The Duct DN 250_3 pipe represents the section of the pipe that carries half the total gas flow towards the two stern holds.
DUCT DN 150	The Duct DN 150 pipe represents the section of the pipe that carries the gas from the DN 250 manifold to the single holds. In this pipe is assumed a flow rate equal to 1/8 of the total.
DUCT DN 100	The Duct DN 100 pipe represents the stretch of the pipe that carries the gas from the Duct DN 150 to the single "cargo tank". A "cargo tank" is bundle of 4 pressure cylinders.
DUCT DN 50	The DUCT DN 50 pipe represents the section of the pipe that carries the gas from the Duct DN 100 to the single cylinder.

Component	Description
COMPRESSOR STAGE 1 (*)	The COMPRESSOR STAGE 1 is the first stage of compressor.
COMPRESSOR STAGE 2 (*)	The COMPRESSOR STAGE 1 is the second stage of compressor.
INTERCOOLER (*)	The INTERCOOLER is the heat exchanger that cools down the gas between the two stages of the compressor.
POSTCOOLER (*)	The POSTCOOLER is the heat exchanger that cools down the gas at the outlet from the second stage of the compressor.
STORAGE	The STORAGE is the onshore terminal that supplies the gas to the ship or receive it.
PRESSURE VESSEL	The PRESSURE VESSEL represent all the storage capacity of the Gas Vessel.
(*) For all the components contained in the COMPRESSORS ROOM it must be considered that the processed or circulating flow rate is 1/2 of the total. The gas entering the COMPRESSOR ROOM is distributed over two lines and for each of them the components schematized in figures from Figure 2.7 to Figure 2.10 are present.	

At the start the program asks, through a graphic interface, for the input data to initialize the simulation. The graphic interface is characterised by two sheets, one for the loading phase (Figure 2.5) and one for the unloading phase (Figure 2.6).

In the loading module the following data are asked: air and sea water temperature, pressure and temperature of the gas coming from the on–shore storage, pressure of the gas already present in the cylinders and the hold temperature. The temperature of the gas in the cylinders is considered at equilibrium with the one of the hold.

The presence of the heater used to cool down the gas coming from the on–shore storage represents a choice for both the free and forced loading phases. The remaining parameters allows the user to choose the preferred loading strategy between the “minimum time” and the “12 MNm^3”. For what concerns the “12 MNm^3” strategy the temperature that the gas has to reach before the start of the compressors is asked; from the results of the simulations it is possible to point out that if the gas reaches a temperature of about 40°C before the beginning of the forced loading phase, the amount of charged gas is about 12 MNm^3.

The possibility to give an upper constraint to the flow rate in the free loading phase is given. If this constraint is not given the program works to keep the maximum speed that is regulated by equation (17) at chapter 3.2.

For what concerns the forced loading phase the program asks for the final pressure of the cylinders and the outlet gas temperature of the various heat exchangers, intercoolers and postcoolers.

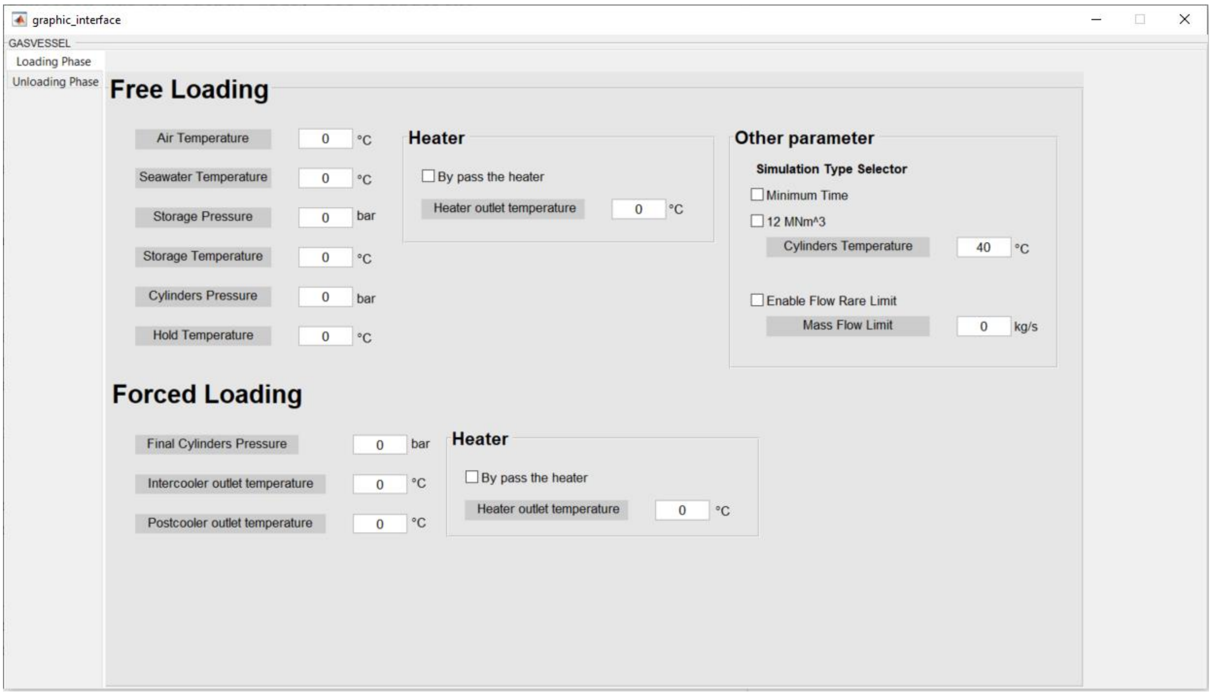

Figure 2.5 – Graphical user interface for the input data of the loading phase

In the module describing the unloading phase, at the Navigation section, the input of the navigation days or, alternatively, the fuel consumption during the route can be entered. In the first case the program evaluates the fuel used during the navigation by referring to a reference value of 142.6 g/kWh.

In case both the parameters are leaved blank the program takes not into consideration the fuel consumption of the ship during the trip.

In the free unloading section, the following data are asked: the ambient conditions (air and sea temperature), on–shore storage pressure, temperature of the gas in the cylinders at the discharge time and the hold temperature. The cylinders pressure is assessed by the program as a function of the mass of gas in the cylinders and the entered cylinders temperature.

The presence of the heater used to heat the discharged gas represents a choice for both the free and forced unloading phases.

As happens for the free loading phase in the free unloading phase the choice to give an upper constraint to the flow rate is possible as well.

In the forced unloading section, the input of the final value of the cylinder pressure and the outlet gas temperature of the heat exchangers, intercoolers, postcoolers and heaters are required.

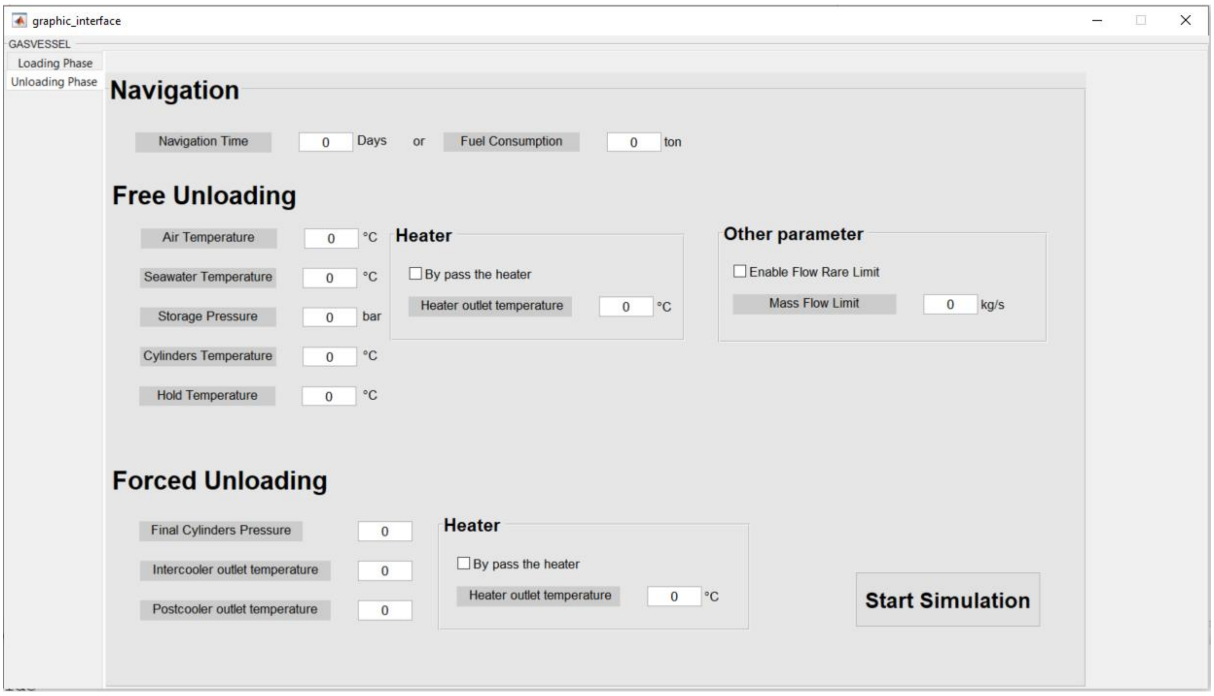

Figure 2.6 – Graphical user interface for the input data of the unloading phase

After all the required data have been entered, to start the simulation, press the "start the simulation" button and so the program simulates all the phases in a row.

2.3 Schematics of the Operational Phases to be Simulated

The results discussed in the following have been obtained considering pure methane, treated as a real gas. Its properties are obtained from the NIST database by using the software tool Coolprop[2].

The onshore storage terminal is considered with unlimited capacity and constant pressure equal to 240 bar. The initial pressure in the ship's gas bottles is 20 bar and the loading process ends when the design value of 335 bar is reached.

The loading process begins with the free loading phase. The program workflow is shown schematically by the diagram in figures from Figure 2.7 to Figure 2.10. At the beginning of this phase, the gas inside the cylinders is considered at a pressure of 20 bar and at a temperature of 15°C. The free loading phase continues until the pressure in the cylinders is close to the storage pressure, however, for the choice of the time when to stop the free loading there are two options:

1. The first option is to reduce loading times to a minimum. In this case, the free loading process ends when the pressure difference between the Storage and the pressure cylinders is about 3 bar. In this way, the final temperature of the gas contained in the cylinders is high and

[2] CoolProp is an open-source database of fluid properties collecting the most accurate and update formulations available from the open literature, validated against the most accurate data available from the relevant references (http://www.coolprop.org/).

therefore the quantity of gas loaded, at the pressure of 335 bar, is lower since it is more rarefied.

2. The second option involves loading the gas as in the previous case, but in this case, the free loading phase is continued even if the gas flow rate, due to the reduced pressure difference, is low. In this way load times increase, but the gas contained in the cylinders has time to cool down. In this way, thanks to the lower final temperature of the gas, at the pressure of 335 bar, it is possible to increase the quantity of gas loaded.

During the free loading process, the valve "VALVE DN 250" is used to regulate the inlet flow rate to limit the speed in the pipes. In this phase, the "heater" heat exchanger can be used to cool the gas coming from the storage.

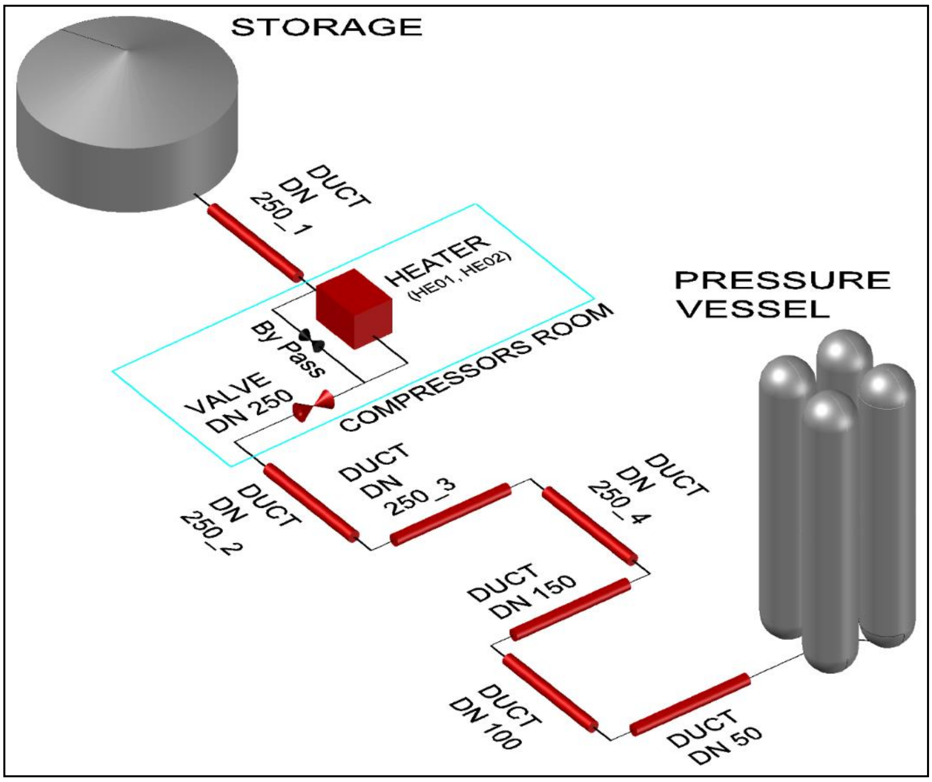

Figure 2.7 – Schematic of free loading phase

The forced loading phase starts at the end of the free load. The on–board compression station is composed of two dual–stage centrifugal compressors that can operate in parallel. The polytropic efficiency varies from 0.5 near the stonewall limit up to the maximum value, supposed to be 0.73.

At the beginning of this phase the pressure inside the pressure cylinder is lower than the Storage pressure and therefore it is necessary to adjust the compressor suction pressure. The regulation is carried out by means of a throttling valve "VALVE DN 250" and by varying the speed of the compressors. This prevents the compressor from functioning like a turbine with consequent damage to the system and also allows to optimize the mass flow, keeping the absorbed power below the maximum design value of 10 MW.

When the pressure in the cylinders increases, the valve “VALVE DN 250” is gradually opened. The loading process is interrupted when the 335 bar pressure is reached inside the pressure cylinders.

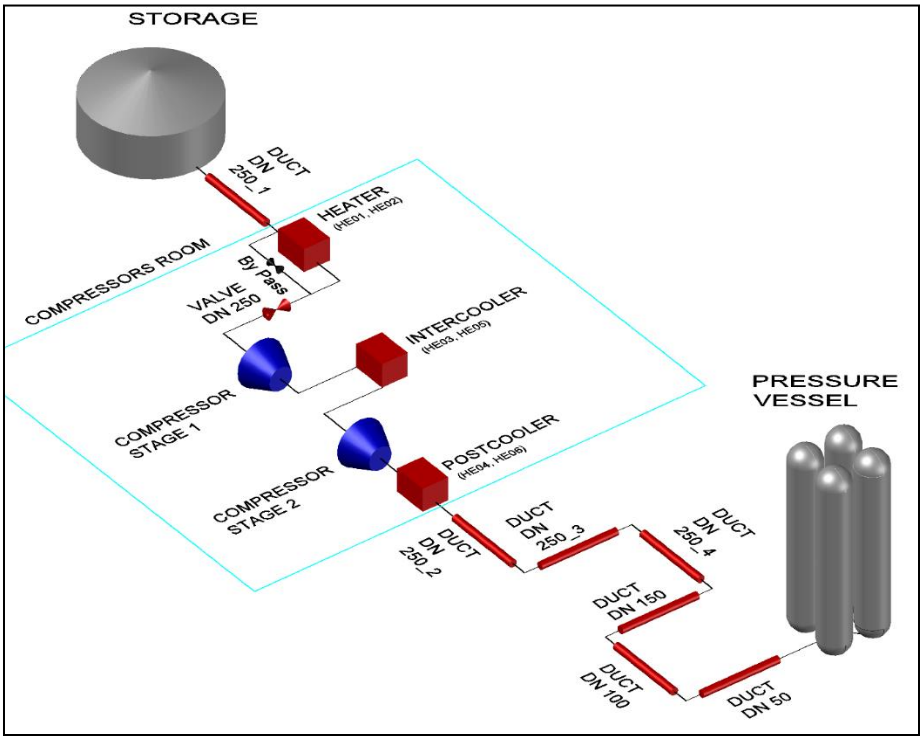

Figure 2.8 – Schematic of forced loading phase

The methane, in the unloading process, is discharged in a constant pressure pipeline at 80 bar.

The pressure of the cylinders at the beginning of the discharge phase depends on the temperature of the gas. To reduce the discharge time it is suggested that the temperature of the cylinders is high and therefore, during navigation, the hold is kept at a temperature of 40 °C using the heat exchangers. At this temperature the pressure is about 300 bar.

The unloading phase begins with the free unloading phase. During this phase the gas flows freely from the pressure cylinders to the storage onshore. The VALVE DN 250 valve is used to regulate the flow to limit the speed of the gas in the pipes.

The free unloading process stops when a pressure difference of about 3 bar is reached between the pressure cylinders and the storage pressure. This value has been set to prevent the flow rate from falling too low.

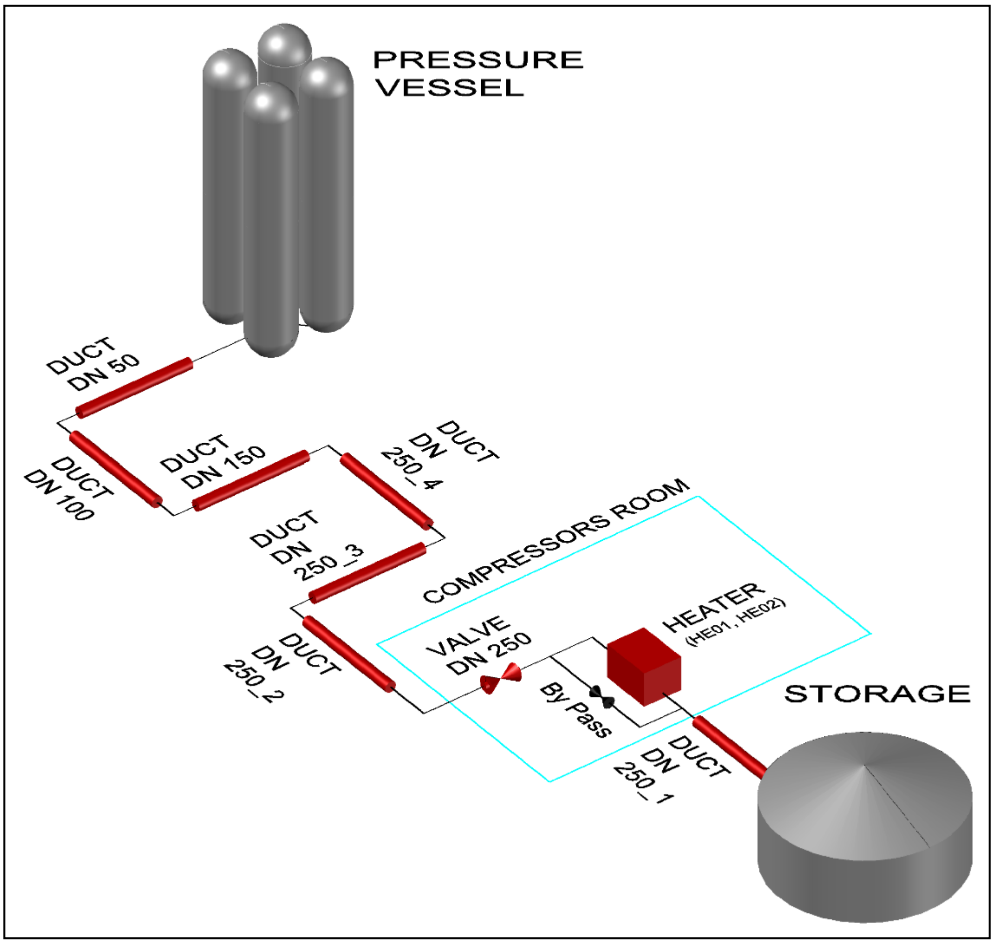

Figure 2.9 – Schematic of free unloading phase

The forced unloading phase starts at the end of free unloading. At the start of the compressor the pressure inside the pressure cylinder is greater than the storage pressure and therefore initially it is necessary to act on the VALVE DN 250 valve to regulate the suction pressure of the compressor. This prevents it from working like a turbine and damaging the system. In this phase the heater is used to heat the gas entering the compressor. The unloading process ends when the pressure in the pressure cylinder reaches 20 bar. Such final value has been imposed considered that the remaining gas must be sufficient to guarantee the fuel for the return journey. If the ship's return journey requires more fuel, it is possible to complete the unloading process by maintaining a higher pressure in the cylinders.

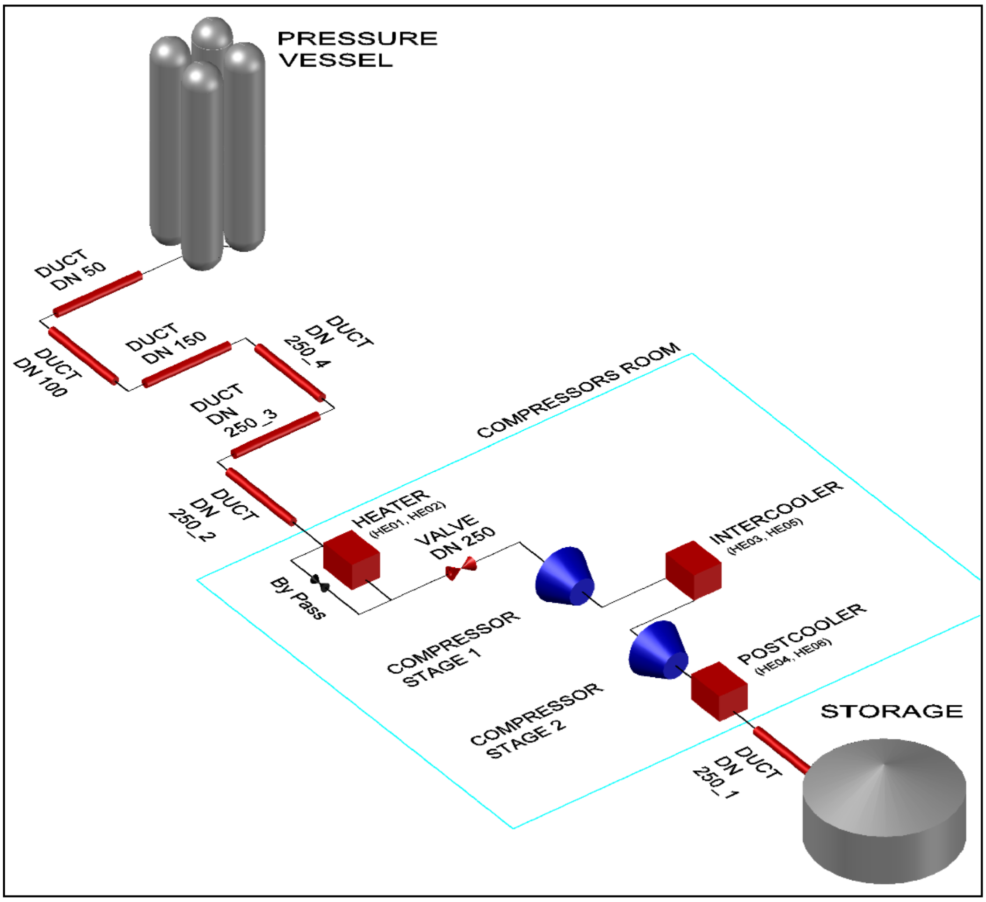

Figure 2.10 – Schematic of forced unloading phase

3. Model governing equations

3.1 Introduction

The model is implemented using MATLAB and SIMULINK simulation environment. The components considered in the model are:

- vertical cylindrical tanks (pressure cylinders);
- regulation valves;
- heat exchangers (cooler / heater);
- centrifugal compressors;
- ducts.

3.2 The tank model

The time–dependent variables of the tank model are:

- gas pressure;
- gas temperature;
- mass of gas;
- cylinder wall temperature.

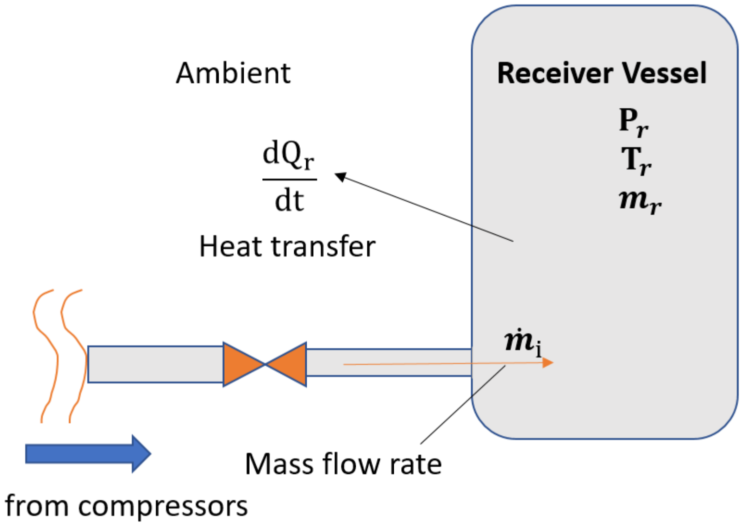

Figure 3.1 – Schematic representing the variables of the receiving tank

Some hypotheses have been made to simplify the equations characterizing this element:

- the potential energy linked to any difference in altitude between the supply unit and the tanks is neglected;
- the kinetic energy of the gas inside the tanks is neglected;
- the pressure and temperature of the gas inside the cylinders does not depend on the spatial coordinates (perfect mixing occurs in the tank);
- the mass flow rate is calculated, in the case of free loading / unloading, as an isenthalpic expansion through an orifice while, if compressors are used, it is taken from the machine characteristic curve, once the compression ratio is known;

- the heat exchange, from the control volume of the tank to the wall, is described by a convective heat flow towards the wall, considered a concentrated mass: this implies that the cylinder wall temperature does not depend on the spatial coordinates but assumes a uniform average value.

The four equations needed to calculate the values of the tank model variables are [1], [2]:

– conservation of mass:

$$\frac{dm_r}{dt} = \dot{m}_i \tag{1}$$

– energy balance:

$$\frac{d(m_r \cdot u_r)}{dt} = \dot{m}_i \left(h + \frac{v^2}{2}\right)_i + \frac{dQ_r}{dt} \tag{2}$$

– mass flow rate:
  a) free loading cases:

$$\dot{m}_i = C_d \cdot A_1 \cdot \sqrt{2P_s \cdot \rho_s \frac{k}{(k-1)}\left[\left(\frac{P_r}{P_s}\right)^{\frac{2}{k}} - \left(\frac{P_r}{P_s}\right)^{\frac{(k+1)}{k}}\right]} \quad \text{if} \quad \frac{P_r}{P_s} > \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{3}$$

$$\dot{m}_i = C_d \cdot A_1 \sqrt{k \cdot P_s \cdot \rho_s \left[\left(\frac{2}{k+1}\right)^{\frac{(k+1)}{(k-1)}}\right]} \quad \text{if} \quad \frac{P_r}{P_s} \leq \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{4}$$

  b) forced loading cases: centrifugal compressor curves (see paragraph §3.5)

– cylinder wall temperature:

$$\frac{dT_w}{dt} = \frac{1}{M_w \, Cp_w}\left(-\frac{dQ_r}{dt} - \frac{dQ_{amb}}{dt}\right) \tag{5}$$

where, assuming that natural convection is dominant, the internal heat flux of the cylinder is:

$$\frac{dQ_r}{dt} = -\alpha_i \, A_i \, (T_r - T_w) \tag{6}$$

and the external heat flux between the vessel surface and the atmosphere is:

$$\frac{dQ_{amb}}{dt} = \alpha_e \, A_e \, (T_w - T_{amb}) \tag{7}$$

3.3 The model for regulation valves

The type of formulation used to tie the pressure loss through the valve with the mass flow rate, is the so–called universal gas sizing method:

$$\dot{m}_1 = 1.06 \, C_g \cdot \sqrt{P_1 \cdot \rho_1} \cdot \sin\left(\frac{59.64}{C_1} \cdot \sqrt{\left(1 - \frac{P_2}{P_1}\right)}\right) \tag{8}$$

The valve manufacturers supply the gas flow–sizing coefficient, Cg, in conditions of maximum opening. The coefficient $C_1 = C_g/C_v$ can be assumed equal to 25 if the value of the fluid flow size coefficient C_v is unknown. The correlation between coefficient and percentage of opening depends on the type of characteristic of the valve, which can be linear, equal–percentage or quick opening.

3.4 The cooler/heater model

The heat powers transferred in the heat exchangers are given by Eq. 9–10:

$$\dot{m}_1\,(h_{in} - h_{out})\ - Q_{cool} = 0 \tag{9}$$

$$\dot{m}_1\,(h_{in} - h_{out})\ + Q_{heat} = 0 \tag{10}$$

The pressure drop is assumed to be one percentage point of the pressure at the heat exchanger inlet.

3.5 The centrifugal compressor model

The centrifugal compressor is a two–stage type with inter–refrigeration. For the simulations, the characteristic curves provided by the manufacturer are used, recalculated as a function of dimensionless parameters to make them independent of the suction conditions. They represent the compression ratio according to the corrected mass flow rate, for different values of the corrected angular speed, as shown in Figure 3.2.

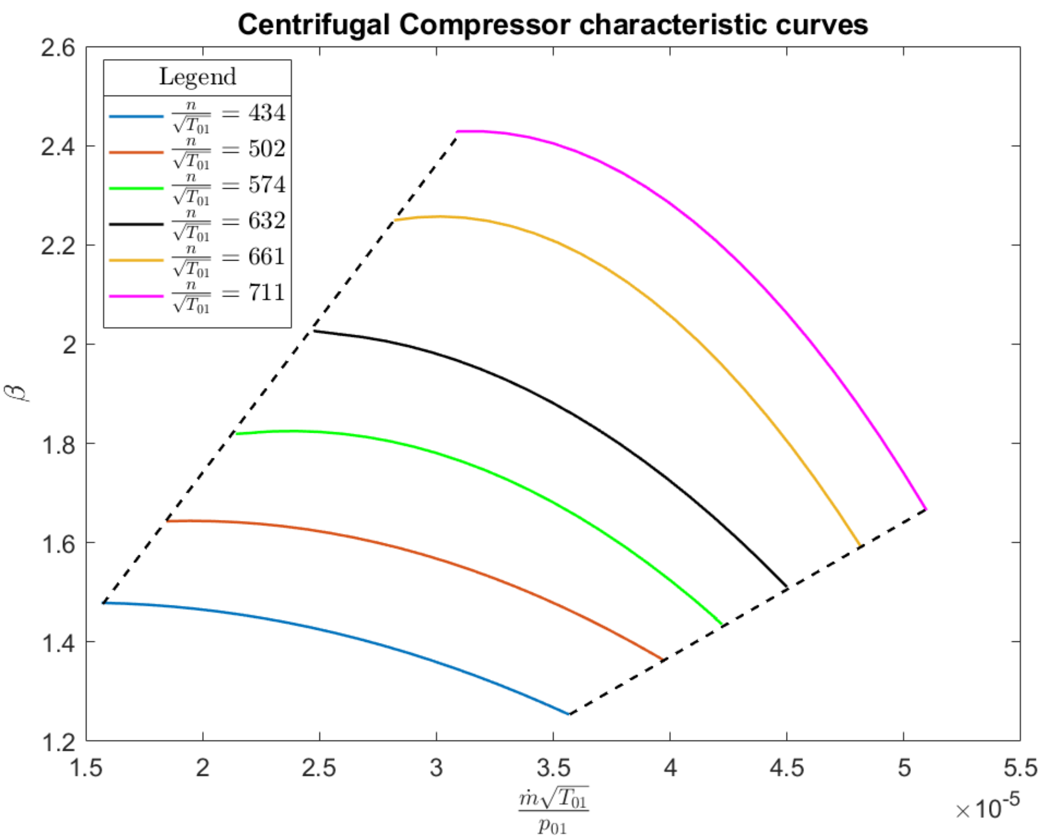

Figure 3.2 – Compressor characteristic curves

In the simulation, the input parameters of the compressor model are the suction temperature and the compression ratio. The last one is determined by the tank pressures, the pressure drop in the ducts and the pressure losses introduced by the valves. Once the compression ratio is known, the mass flow rate can be obtained from the characteristic curves.

The other outputs to be calculated are the absorbed power and the temperature of the gas leaving the compressor. The power is given by Eq.11:

$$P = \dot{m}\Delta\mathrm{h} = \dot{m}\left(\frac{\Delta h_p}{\eta_p}\right) = \dot{m}\cdot\frac{\mathrm{n}}{\mathrm{n}-1}Z_1\mathrm{RT}_1\left[\left(\left(\frac{\mathrm{p}_2}{\mathrm{p}_1}\right)^{\frac{\mathrm{n}-1}{\mathrm{n}}}-1\right)\right]\cdot\left(\frac{1}{\eta_p}\right) \tag{11}$$

The Coolprop libraries are used to calculate the end compression temperature, given the corresponding enthalpy and pressure values. Alternatively, this temperature can be obtained by means of Eq. 12, which provides an approximate result but in good agreement with the Coolprop outputs.

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k\eta_p}} \tag{12}$$

3.6 The ducts model

For the calculation of the pipes present in the diagrams of figures from Figure 2.7 to Figure 2.10 the following hypotheses have been introduced:

- one–dimensional flow;
- perfect gases, with specific heat at constant pressure function of temperature only;
- uniform gas properties in the duct;
- isenthalpic transformation;
- the friction forces per unit of length are calculated with the following formula:

$$\mathrm{f}_{frict} = \frac{\lambda\cdot\rho v^2}{2D} \tag{13}$$

With these hypotheses, the mass and momentum conservation equations for the duct are:

$$\frac{\mathrm{dp_e}}{\mathrm{dt}} = \frac{\mathrm{kRT_l}}{AL}\left(\dot{\mathrm{m}}_e - \dot{\mathrm{m}}_l\right) \tag{14}$$

$$\frac{\mathrm{d}\dot{\mathrm{m}}_l}{\mathrm{dt}} = \frac{A}{\mathrm{L}}\left(\mathrm{p}_e + \mathrm{p}_l\right) - \frac{\lambda\mathrm{RT_l}\,\dot{\mathrm{m}}_l{}^2}{DA(\mathrm{p}_e+\mathrm{p}_l)} \tag{15}$$

where the Darcy factor is derived from Colebrook equation:

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{\varepsilon}{3.71*D} + \frac{2.51}{Re*\sqrt{\lambda}}\right) \tag{16}$$

the speed of the gas in the pipes has been set so as to guarantee the maximum flow rate. The maximum speed was considered to be the minimum between 60 m/s and the value obtained using the formula [3].

$$Vmax = MIN\begin{cases}175 * \left(\frac{1}{\rho}\right)^{0.43} \\ 60 \quad m/s\end{cases} \tag{17}$$

4. Model Validation and Preliminary Verifications

4.1 Validation of the Tank Model

The validation of the model was carried out by comparison with experimental literature data [4]. The cylinder considered in the study is shown in Figure 4.1: it has an aluminium liner with a reinforcement in composite material (epoxy resin with carbon fiber). The cylinder has a diameter of 396 mm, a length of 830 mm and a volume of 70 liters.

The service pressure of the cylinder is equal to 207 bar and is fed by a supply unit of 450 liters and a pressure of 400 bar.

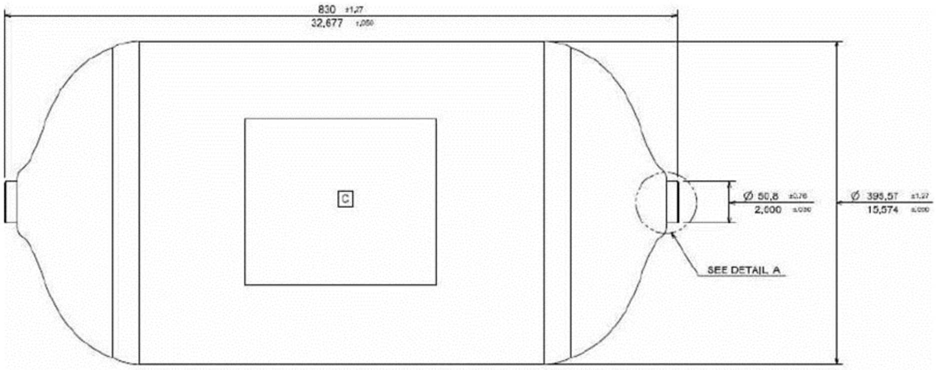

Figure 4.1 – Geometry of the CNG cylinder considered for the simulation model validation [4]

The average temperature reported in [4] has been compared with simulation results. The ambient temperature is not given in the paper and, therefore, it was assumed 25°C, since the measurements were performed in a summer period. The initial cylinder temperature is -8°C and its initial pressure is 10 bar. The results obtained are shown in Figure 4.2.

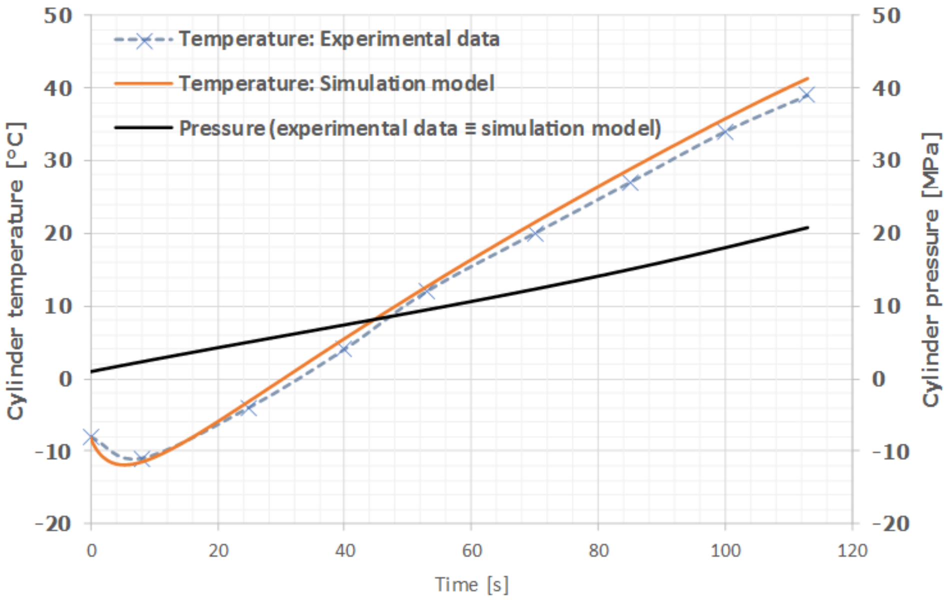

Figure 4.2 – Comparison between experimental [4] and numerical results.

The final temperature reached by the numerical model is 41°C while the experimental temperature is 39°C. The error is over 5% but we must consider that not all the error is attributable to the model, as the temperature of the external environment is not exactly known.

4.2 Simulations in Adiabatic Conditions

To highlight the strong dependence on environmental conditions, an analysis was performed in adiabatic conditions and one in non–adiabatic conditions. In the non–adiabatic case the heat exchange of the cylinders with the environment was considered assuming a constant hold temperature. This analysis was developed considering a general condition not linked to a specific scenario.

The results discussed below has been obtained considering the following hypothesis.

The loading process is carried out from a onshore storage terminal. The storage pressure is assumed equal to 240 bar. The initial pressure in the ship gas cylinders is 30 bar and the loading process ends when it is reached the design value of 300 bar. The forced loading phase starts when the mass flow rate due to the free loading falls below 20 kg/s.

The methane is released in a pipeline at a constant pressure of 120 bar.

The initial pressure in the ship gas cylinders is supposed to be the same reached at the end of the loading process, 300 bar, neglecting the possible variations due to the ship engines consumption and to the heat exchange with the surroundings.

The forced unloading phase starts when the mass flow rate due to the free unloading falls below 20 kg/s. The unloading process ends when it is reached the final value of 30 bar.

Figure from Figure 4.3 to Figure 4.8 show the results obtained with reference to the loading process.

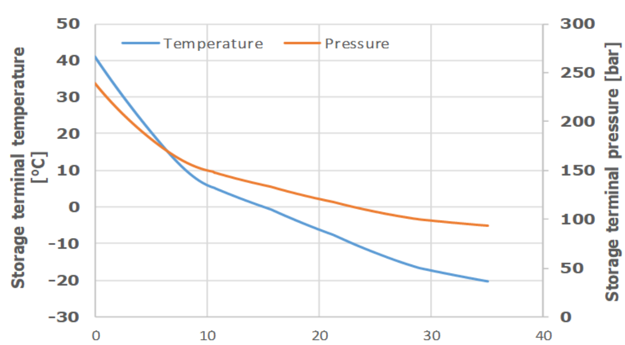

Figure 4.3 – Storage conditions (adiabatic loading)

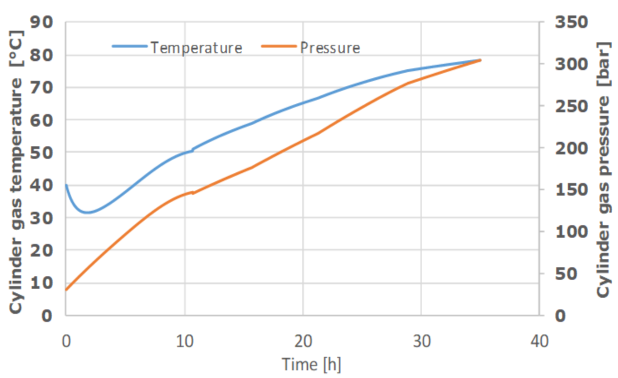

Figure 4.4 – Cylinder conditions (adiabatic loading)

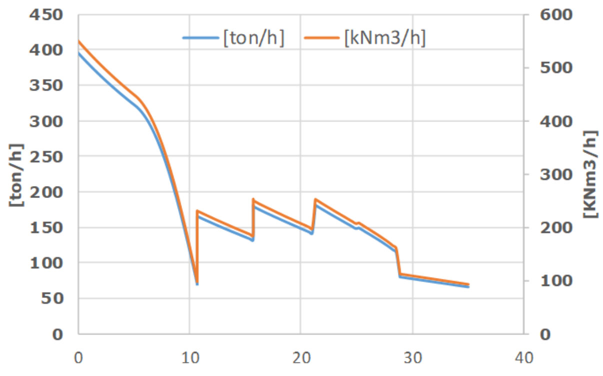

Figure 4.5 – Flow rate (adiabatic loading)

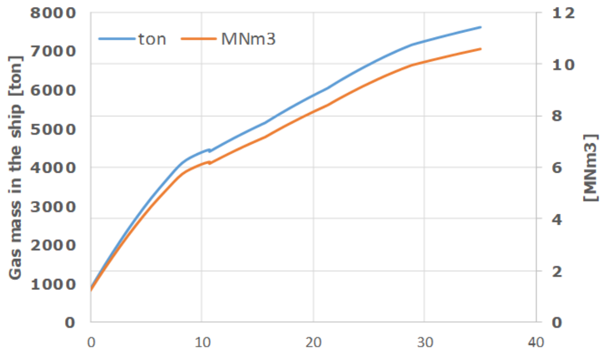

Figure 4.6 – CNG in the ship (adiabatic loading)

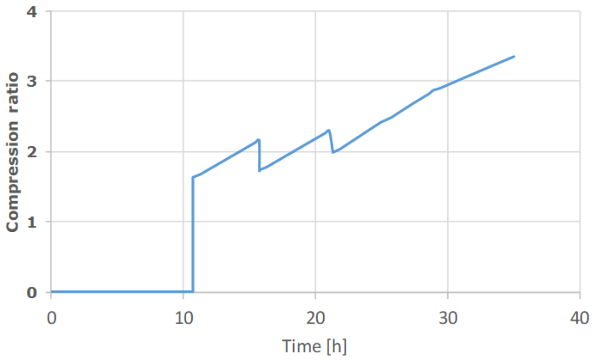

Figure 4.7 – Compression ratio (adiabatic loading)

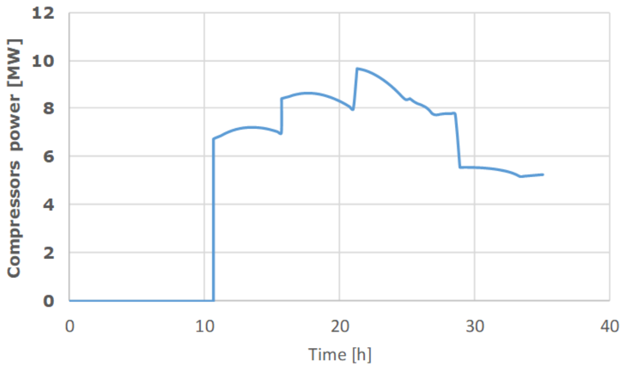

Figure 4.8 – Absorbed power (adiabatic loading)

The loading phase needs about 35 h, while the forced loading phase requires 24 h. The mass loaded is about 6750 ton ($9.4*10^6$ Nm^3). The overall mean flow rate is about 192 ton/h ($268.57*10^3$ Nm^3/h) but the mean value is 133 ton/h ($185.3*10^3$ Nm^3/h) when compressors are running. The maximum compression ratio is 3.3, obviously at the end of the forced loading phase. The fuel consumption is 36 ton (≃ 0.5% of the total cargo) and the specific energy consumption is 96 kJ/kg.

Figures from Figure 4.9 to Figure 4.13 show the results obtained with reference to the unloading process.

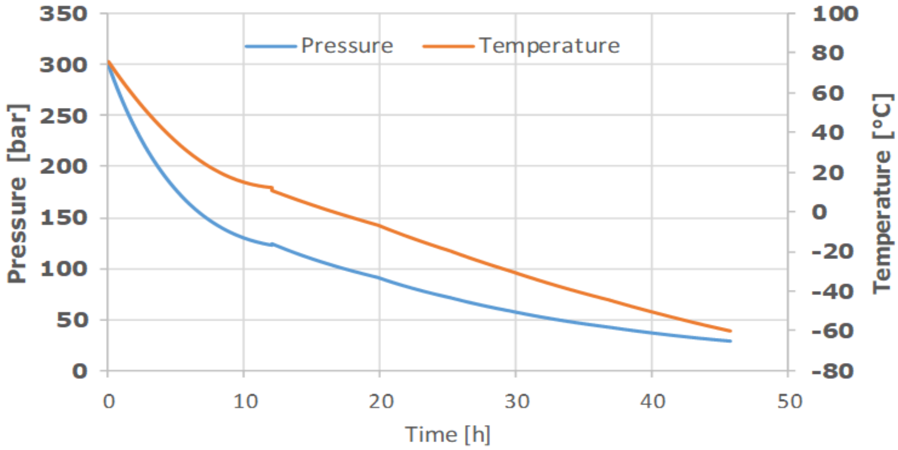

Figure 4.9 – Cylinder conditions (adiabatic unloading)

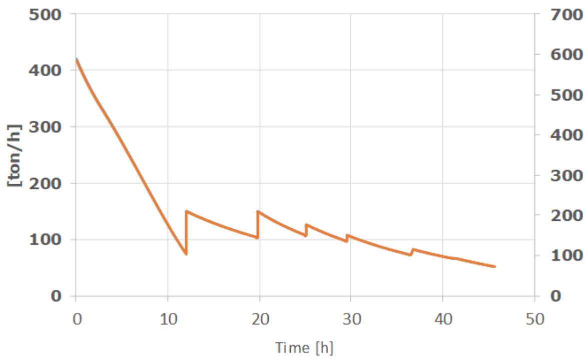

Figure 4.10 – Flow rate (adiabatic unloading)

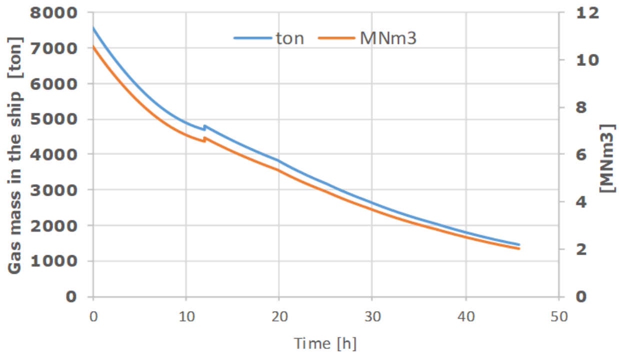

Figure 4.11 – CNG in the ship (adiabatic unloading)

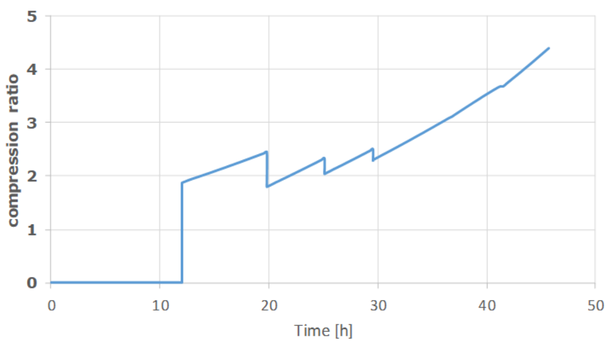

Figure 4.12 – Compress. ratio (adiabatic unloading)

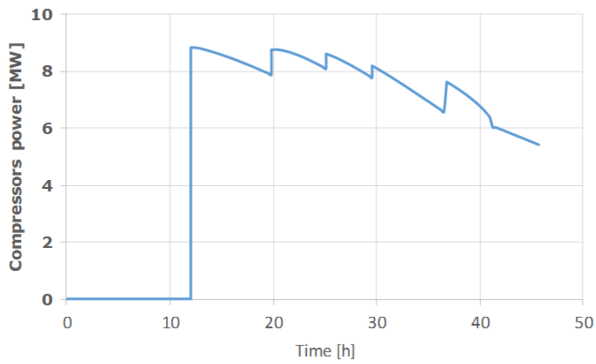

Figure 4.13 – Absorbed power (adiabatic unloading)

The unloading phase needs about 46h while the forced unloading phase requires 34 h (10h more than the loading phase because of the higher compression ratio). The unloaded mass is about 6150 ton (8.6*10^6 Nm^3). The mass left in the cylinders is higher than the loading phase because of the low temperatures: the residual mass is 600 ton. The mean flow rate is about 135 ton/h (188*10^3 Nm^3/h).

Fuel consumption is equal to 51 ton (≃ 0.7 % of the total cargo) and the specific energy consumption 151 kJ/kg.

Taking into account the entire process, the adiabatic overall fuel consumption is ≃ 1.14% of the total cargo, corresponding to about three pressure cylinders.

4.3 Non adiabatic processes

The heat exchange between the pressure cylinders and the nitrogen of the holds has been calculated based on the specifications of Table 4.1 and assuming an external heat coefficient of 4.5 $W/m^2/K$ [5].

Table 4.1 – Gasvessel project: CNG vessel wall properties.

	thickness [m]	density [kg/m^3]	specific heat [j/kg/K]	thermal conductivity [W/m/K]
liner	0.005	7800	500	60
carbon fibre epoxy	0.035	938	1494	1

Summer conditions are obviously the worst condition for loading, as the heat exchange is not favoured by the high temperatures of the external environment. The hold in summer is supposed to have a temperature of 40°C, while the gas temperature initially present in the tanks is 40°C and the pressure is 30 bar. The results obtained are summarized in Figure 4.14 and in Figure 4.15.

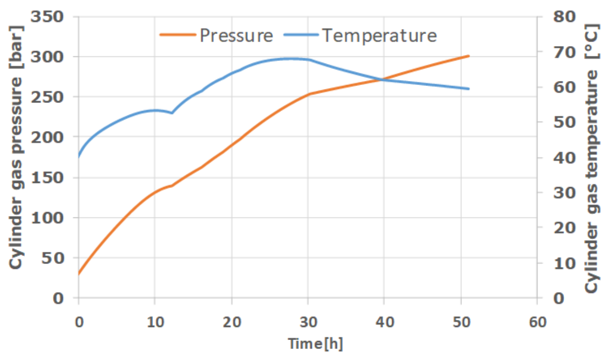

Figure 4.14 – Cylinder conditions (summer loading)

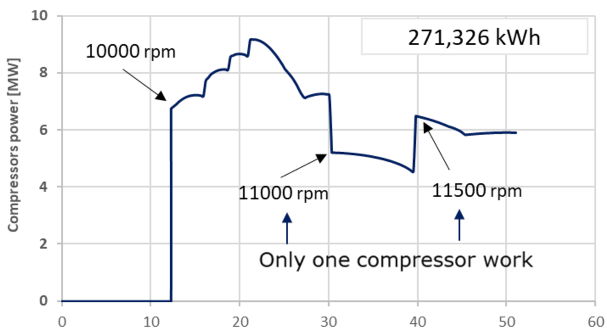

Figure 4.15 – Absorbed power (summer loading)

The loading phase needs about 51h, 16h more than the adiabatic case because of the higher compression ratio and the greater mass loaded. The forced loading phase requires 39h. The mass loaded is about 7290 ton ($10.2*10^6$ Nm^3), the mean flow rate is about 143 ton/h ($199.14*10^3$ Nm^3/h) and the maximum compression ratio is 4.3. The fuel consumption is 51 ton (≃ 0.6 % of the total cargo) and the specific energy consumption is 134 kJ/kg.

The peak power dispersed by the single cylinder is equal to 32 kW and the energy dispersed in the hold is 658 kWh. Considering that there are 256 cylinders in the hold, which are filled at the same time, there is a total maximum dispersed power of 8.2 MW and a total dispersed energy of 168.448 kWh.

The winter condition is the most favourable for loading as it allows containing the temperature increase of the gas, but is the worst condition for unloading. In the simulation, the temperature of the hold is assumed equal to 5°C. Also the initial gas temperature in the tanks is 5°C, with a pressure of 30 bar. The results obtained unloading in not adiabatic winter condition are reported in Figure 4.16 and Figure 4.17.

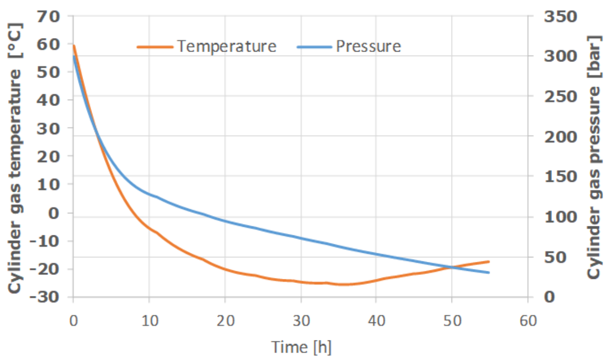

Figure 4.16 – Cylinder conditions (winter unloading)

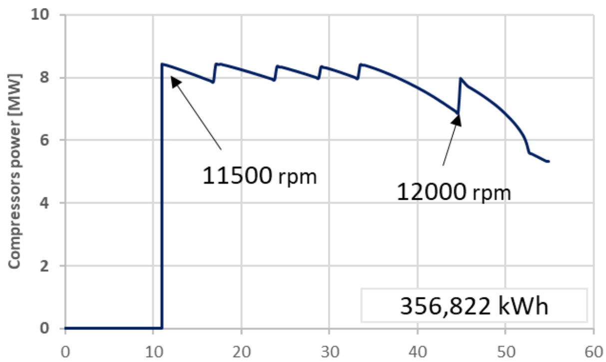

Figure 4.17 – Absorbed power (winter unloading)

The unloading phase needs about 55h. The minimum temperature is –25°C (in the adiabatic case it is –60°C). The forced unloading phase requires 44h. The mass unloaded is about 7025 ton (9.8*10^6 Nm^3). The mean flow rate is about 119 ton/h (165.88*10^3 Nm^3/h). The residual mass is 265 ton, due to the higher minimum temperature with respect to the adiabatic case. The fuel consumption is 67 ton (≃ 1 % of the total cargo) and the specific energy consumption is 183 kJ/kg. Considering the not adiabatic process overall balances, the total fuel consumption is ≃ 1.45 % of the total cargo, corresponding to about 3.5 pressure cylinders.

5. Simulation of the GASVESSEL Scenarios

5.1 Introduction to GASVESSEL Scenarios

Simulation of the loading and unloading processes for the GASVESSEL scenarios are hereby introduced and discussed.

Table 5.1 – Macro areas GASVESSEL scenarios

Macro area	Loading point	Unloading Point
Mediterranean Sea	Vasilokos (Cyprus)[3]	Lebanon
Mediterranean Sea	Vasilokos (Cyprus)[3]	Egypt
Mediterranean Sea	Vasilokos (Cyprus)[3]	Linoperamata(Crete)
Black Sea	Poti (Georgia)	Yuzne (Ukraine)
Barents Sea	Johan Castberg Platforms	Aasta Hansteen
Barents Sea	Johan Castberg Platforms	Nyhamna Gas Plant

In order to limit the number of the necessary simulations, it was chosen to group the GASVESSEL scenarios into three macro areas (Mediterranean Sea, Black Sea and Barents Sea)(Table 5.1). For the simulations relating to each macro area, the average annual temperatures for air and sea water have been considered.

Figure 5.1 – Map of the Mediterranean Sea scenarios

[3] The Mediterranean Sea scenarios actually include Cyprus EEZ as a possible gas source.

For the Mediterranean Sea area one loading point and three unloading point are considered as shown in Figure 5.1.

For the Mediterranean Sea scenarios the average annual condition was considered with an air temperature of 20°C and a sea temperature of 20°C. With this boundary conditions, two simulations were performed: one that minimizes the load time and one that facilitates the quantity of gas loaded.

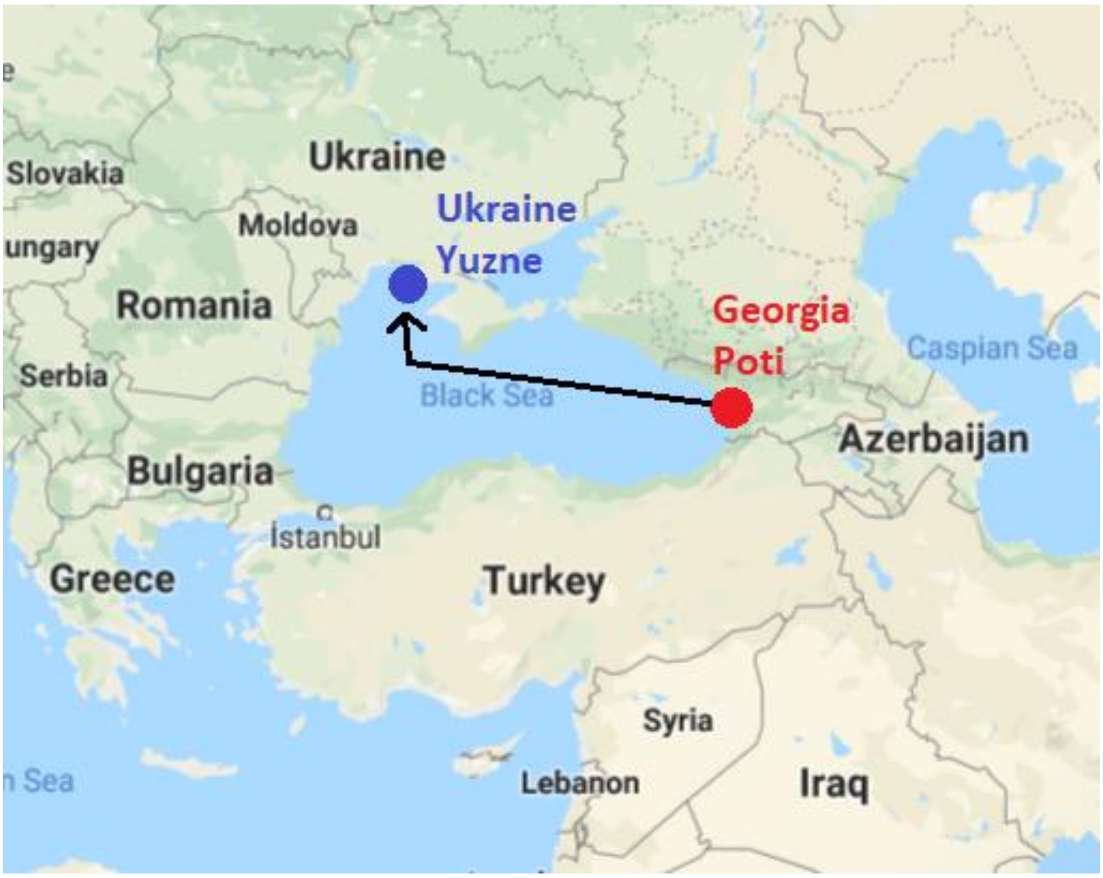

Figure 5.2 – Map of the Black Sea Scenarios

For the Black Sea area one loading point and one unloading point are considered as shown in Figure 5.2.

For the Black Sea scenarios the average annual condition was considered with an air temperature of 12.2°C and a sea temperature of 14.9°C. With this boundary conditions, two simulations were performed: one that minimizes the load time and one that facilitates the quantity of gas loaded.

Figure 5.3 – Map of the Barents Sea scenarios

For the Barents Sea area one loading point and one unloading point are considered as shown in Figure 5.3.

For the Barents Sea scenarios the average annual condition was considered with an air temperature of 4°C and a sea temperature of 7.8°C. With this boundary conditions, two simulations were performed: one that minimizes the load time and one that facilitates the quantity of gas loaded.

In addition to these three scenarios, the SUMMER and WINTER conditions were considered, these situations represent the extreme summer and winter conditions.

SUMMER conditions represent the extreme summer conditions. For SUMMER CONDITION simulations, an air temperature of 35°C and a sea water temperature of 32°C were considered.

WINTER conditions represent the extreme winter conditions. For WINTER CONDITION simulations, an air temperature of -20°C and a sea water temperature of -1°C were considered.

The simulations were performed in non–adiabatic conditions considering the heat exchange between the cylinders and the nitrogen atmosphere in the hold. The temperature of the hold was considered variable taking into account the heat exchange between the hold atmosphere and the cylinders, the external environment and the fan coils used to control the temperature.

For all the considered cases, two simulations were performed: one simulation with the aim to minimize the loading time and one with the aim to guarantee the discharge of about 12 MNm^3 of gas.

5.2 SUMMER CONDITION

5.2.1 Minimum loading time simulation – Loading Phase

The SUMMER conditions represent the worst conditions for the loading phase because the high temperature hampers the loading process. Due to the high ambient temperature it is more difficult to cool down the gas and the hold. Under these conditions, at the same loading time it is possible to charge a smaller quantity of gas.

For the loading phase it was considered an initial hold temperature of 15°C. This temperature is obtained by cooling down the hold with fan coils during navigation with the empty vessel. The cold power is provided by four chillers of 1.4 MW each. The remaining initial parameters for the simulation are shown in the Table 5.2.

Table 5.2 – Simulation data – Loading phase – Min. Time – SUMMER CONDITION

Loading Phase		
Initial On–Shore Storage Pressure	bar	240
Initial On–Shore Storage Temperature	°C	25
Initial Cylinders Pressure	bar	20
Initial Cylinders Temperature	°C	15
Initial Cylinder Density	kg/m^3	14
Final On–Shore Storage Pressure	bar	240
Final On–Shore Storage Temperature	°C	25
Final Cylinders Pressure	bar	335
Final Cylinders Temperature	°C	74
Final Cylinder Density	kg/m^3	185
Loading Time	h	28
Loading Compressors Consumption	ton	6
Average Flow Rate	kg/s	82
	Nm^3/h	408,777
Maximum Flow Rate	kg/s	128
	Nm^3/h	641,228
Mass Inside Cylinders	ton	8,822
	Nm^3	12,296,430
Loaded Mass	**ton**	**8,159**
	Nm^3	**11,371,529**

The loading phase lasts 28 hours, 22 hours of free loading and 6 hours of forced loading. As shown in Table 5.2, the cylinder temperature at the end of the process is 74°C. In these conditions the total mass of gas, at a pressure of 335 bar, which can be stored in the cylinders is 12.296,420 Nm^3 and the mass loaded during the process is 11.371.529 Nm^3.

The figures from Figure 5.4 to Figure 5.10 show the graphs of the main parameters of the loading phase.

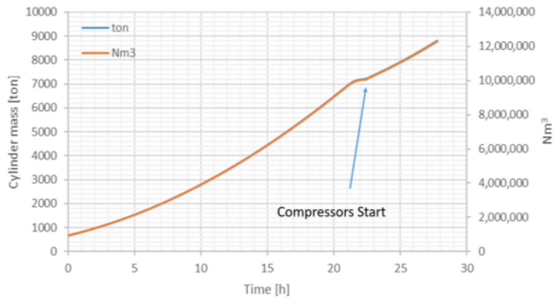

Figure 5.4 – Cylinder mass – Loading phase – Min. Time – SUMMER CONDITION

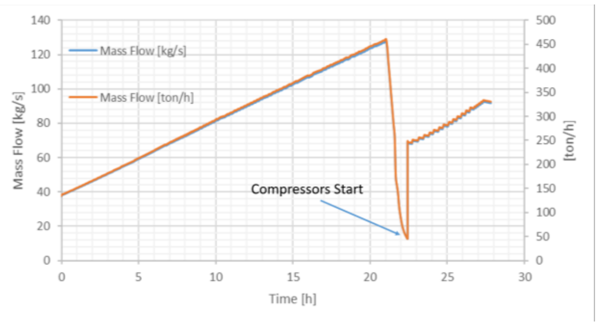

Figure 5.5 – Flow rate – Loading phase – Min. Time – SUMMER CONDITION

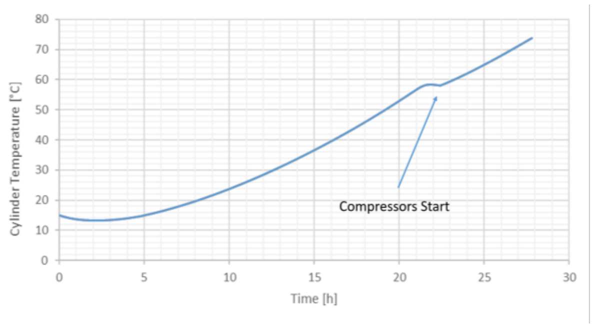

Figure 5.6 – Cylinder temperature – Loading phase – Min. Time – SUMMER CONDITION

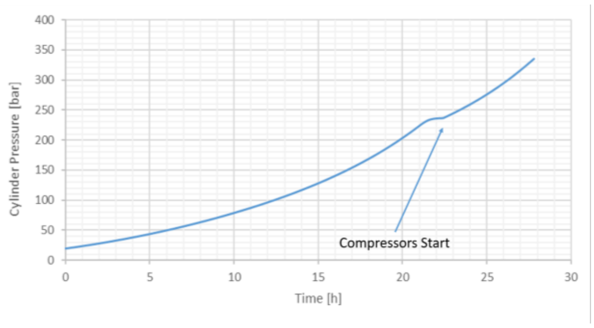

Figure 5.7 – Cylinder pressure – Loading phase – Min. Time – SUMMER CONDITION

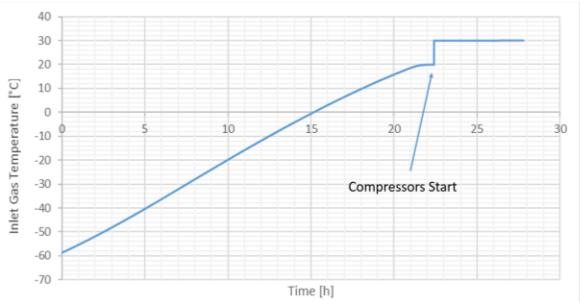

Figure 5.8 – Inlet gas temperature – Loading phase – Min. Time – SUMMER CONDITION

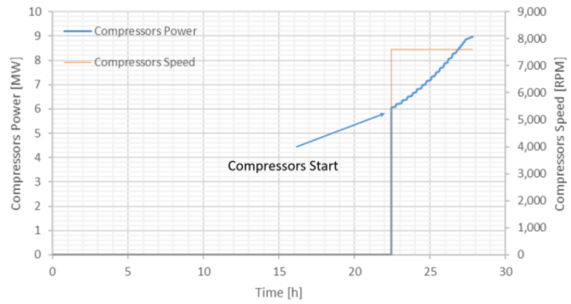

Figure 5.9 – Compressors power – Loading phase – Min. Time – SUMMER CONDITION

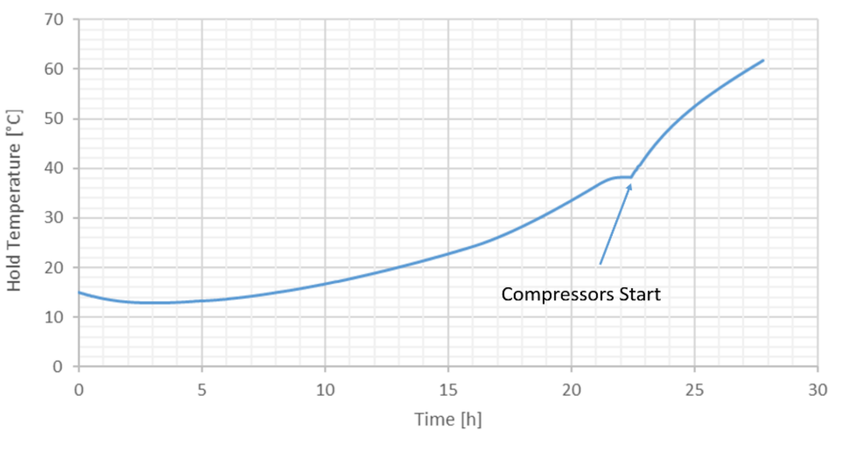

Figure 5.10 – Hold temperature – Loading phase – Min. Time – SUMMER CONDITION

Figure 5.4 shows the increasing of the gas quantity contained in the pressure cylinders. In the free loading phase the flow rate (Figure 5.5) is controlled by the regulating valve in order to limit the gas speed in the pipes. At the beginning the flow rate increases thanks to the increase of the gas density downstream of the valve and in the cylinders. When the pressure difference between the storage and the cylinders is small, the flow rate drops and the compressors are started. The oscillatory course of the flow curve and the curve of the power absorbed by the compressors (Figure 5.9) are related to the opening of the throttle valves of the compressors.

Figure 5.6 and Figure 5.7 show the increasing trend of temperature and pressure inside the cylinders. The temperature of the gas at the cylinders inlet is shown in Figure 5.8 with a minimum temperature of –59°C at the beginning of the process. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler. Figure 5.9 shows the power absorbed by the compressors with a maximum of 9 MW at 7600 rpm. The temperature of the hold is shown in Figure 5.10 with a maximum value of 62°C.

5.2.2 Minimum loading time simulation – Unloading Phase

At the end of the loading phase the cylinders reach a temperature of 74°C and, therefore, the temperature of the hold tends to reach the same value. The high temperature in the hold facilitates the unloading process but a temperature too high in the hold is not acceptable due to safety reasons.

During navigation, in a first phase, it is necessary to cool down the hold to maintain a temperature of about 40°C so that the hold can be accessible by operators equipped with the appropriate protections in case of emergency operations. Once this temperature is reached, it is kept constant until the beginning of the unloading phase by supplying heat, if necessary, using two boilers of 3 MW each. For the unloading phase, an initial hold temperature of 40°C was considered. If at the time of discharge the gas temperature is still higher than 40°C it is better for the process.

The SUMMER conditions represent the best conditions for the unloading phase as high temperatures facilitates the process.

Table 5.3 – Simulation data – Unloading phase – Min. Time – SUMMER CONDITION

Unloading Phase		
Initial On–Shore Storage Pressure	bar	80
Initial Cylinders Pressure	bar	272
Initial Cylinders Temperature	°C	40
Initial Cylinder Density	kg/m^3	185
Final On–Shore Storage Pressure	bar	80
Final Cylinders Pressure	bar	20
Final Cylinders Temperature	°C	32
Final Cylinder Density	kg/m^3	13
Unloading Time	h	65
Unloading Compressors Consumption	ton	17
Average Flow Rate	kg/s	35
	Nm^3/h	176,083
Maximum Flow Rate	kg/s	83
	Nm^3/h	415,844
Remaining Mass Inside Cylinders	ton	622
	Nm^3	866,306
Unloaded Mass	**ton**	**8,183**
	Nm^3	**11,406,192**

The unloading phase lasts 65 hours, 18 hours of free unloading and 47 hours of forced unloading. During the process 11.406,192 Nm^3 of gas are unloaded. To assess the quantity of gas unloaded, the gas consumed by the compressors was taken into account.

The figures from Figure 5.11 to Figure 5.17 show the graphs of the main parameters of the unloading phase.

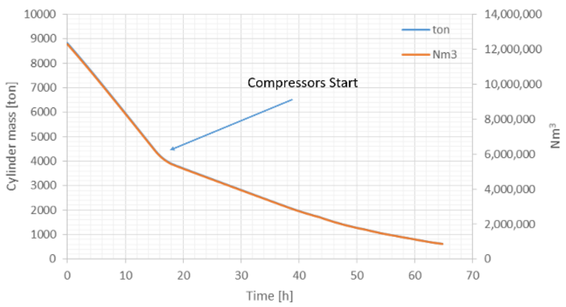

Figure 5.11 – Cylinder mass – Unloading phase – Min. Time – SUMMER CONDITION

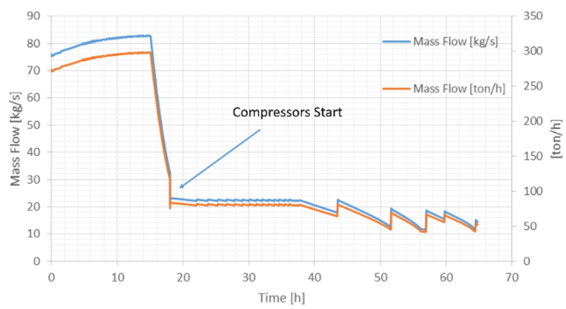

Figure 5.12 – Flow rate – Unloading phase – Min. Time – SUMMER CONDITION

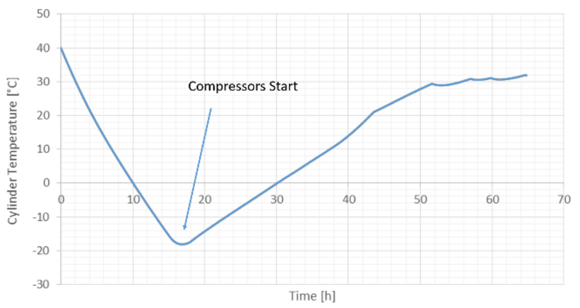

Figure 5.13 – Cylinder temperature – Unloading phase – Min. Time – SUMMER CONDITION

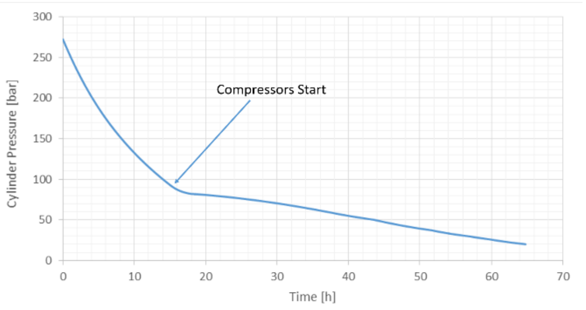

Figure 5.14 – Cylinder pressure – Unloading phase – Min. Time – SUMMER CONDITION

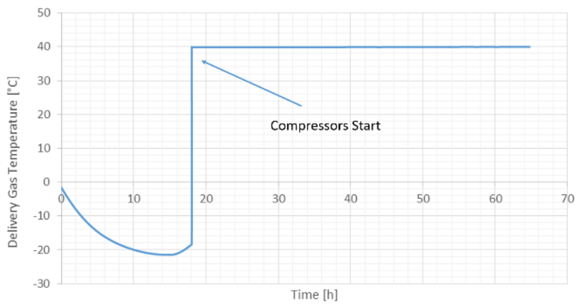

Figure 5.15 – Delivery gas temperature – Unloading phase – Min. Time – SUMMER CONDITION

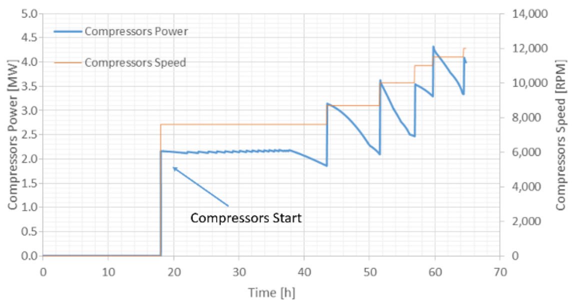

Figure 5.16 – Compressors power – Unloading phase – Min. Time – SUMMER CONDITION

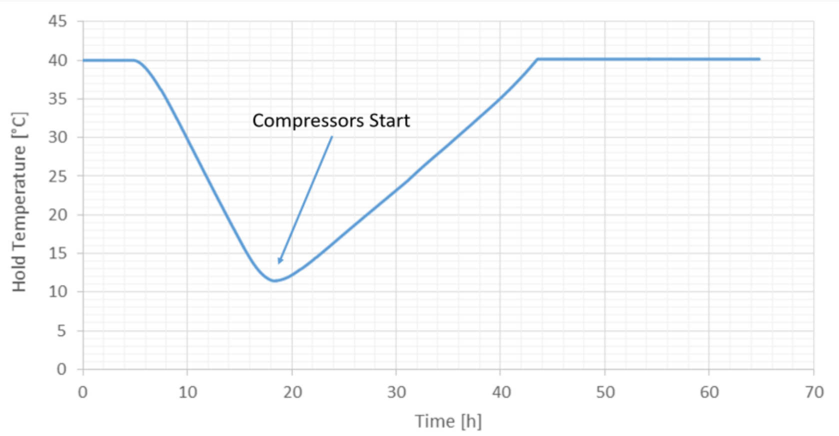

Figure 5.17 – Hold temperature – Unloading phase – Min. Time – SUMMER CONDITION

Figure 5.11 shows the decrease of the gas quantity contained in the pressure cylinders. In the free unloading phase the flow rate (Figure 5.12) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow increases thanks to the decrease of the gas density upstream of the valve and in the cylinders.

When the pressure difference between the cylinders and the storage is small, the flow rate drops and the compressors are started. In the first part of the flow rate curve, from the start of the compressors there are oscillations related to the opening of the throttle valves of the compressors. In the second part of the curve, some peaks corresponding to the change of the speed of the compressors can be observed.

Figure 5.13 and Figure 5.14 show the temperature and pressure trends inside the cylinders.

The delivery gas temperature is shown in Figure 5.15 with a minimum temperature, during the free unloading phase, of –21°C. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler.

Figure 5.16 shows the power absorbed by the compressors with a maximum of 4.3 MW at 11,500 rpm. The maximum compression ratio is 4. The temperature of the hold is shown in Figure 5.17 with a maximum value of 40°C and a minimum of 11°C.

5.2.3 12 MNm^3 simulation – Loading Phase

For the loading phase it was considered an initial hold temperature of 15°C because the low temperature facilitates the loading process. This temperature is obtained by cooling down the hold with fan coils during navigation with the empty vessel. The cold power is provided by four chillers of 1.4 MW each. The remaining initial parameters for the simulation are shown in the Table 5.4.

Table 5.4 – Simulation data – Loading phase – 12 MNm^3 – SUMMER CONDITION

Loading Phase		
Initial On–Shore Storage Pressure	bar	240
Initial On–Shore Storage Temperature	°C	25
Initial Cylinders Pressure	bar	20
Initial Cylinders Temperature	°C	15
Initial Cylinder Density	kg/m^3	14
Final On–Shore Storage Pressure	bar	240
Final On–Shore Storage Temperature	°C	25
Final Cylinders Pressure	bar	336
Final Cylinders Temperature	°C	59
Final Cylinder Density	kg/m^3	197
Loading Time	h	51
Loading Compressors Consumption	ton	5
Average Flow Rate	kg/s	47
	Nm^3/h	236,468
Maximum Flow Rate	kg/s	128
	Nm^3/h	641,228
Mass Inside Cylinders	ton	9,374
	Nm^3	13,065,961
Loaded Mass	**ton**	**8,711**
	Nm^3	**12,141,060**

The loading phase lasts 51 hours, 23 hours more than the minimum time strategy simulation. The cylinder temperature at the end of the process in this case is 59°C and therefore lower than the previous case by 15°C. The total mass of gas in the cylinders, at the pressure of 335 bar, is 13.065,961

Nm³ and the loaded mass is 12.141.060 Nm³, therefore higher than the previous case of 769.531 Nm³.

The figures from Figure 5.18 to Figure 5.24 show the graphs of the main parameters of the loading phase.

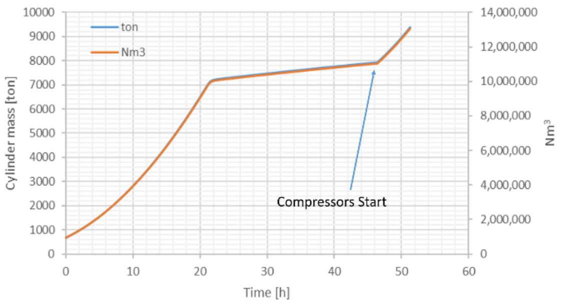

Figure 5.18 – Cylinder mass – Loading phase – 12 MNm³ – SUMMER CONDITION

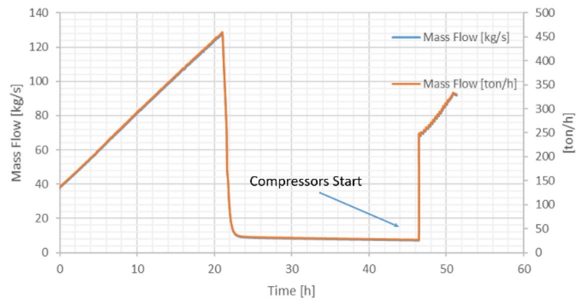

Figure 5.19 – Flow rate – Loading phase – 12 MNm³ – SUMMER CONDITION

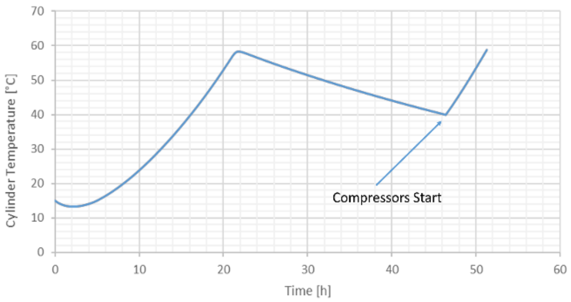

Figure 5.20 – Cylinder temperature – Loading phase – 12 MNm³ – SUMMER CONDITION

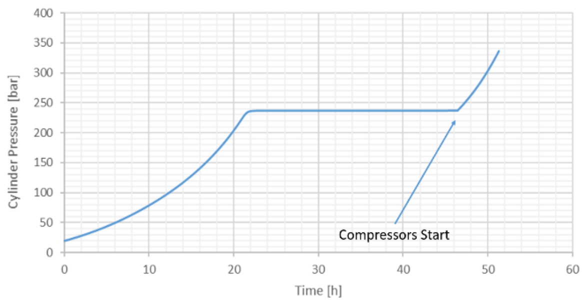

Figure 5.21 – Cylinder pressure – Loading phase – 12 MNm³ – SUMMER CONDITION

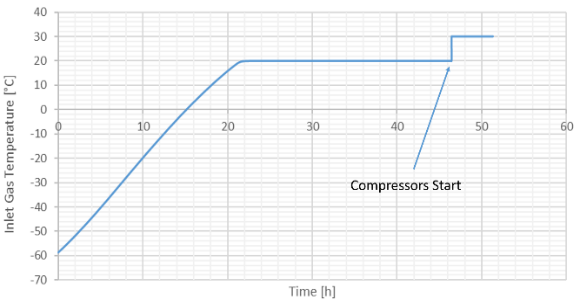

Figure 5.22 – Inlet gas temperature – Loading phase – 12 MNm³ – SUMMER CONDITION

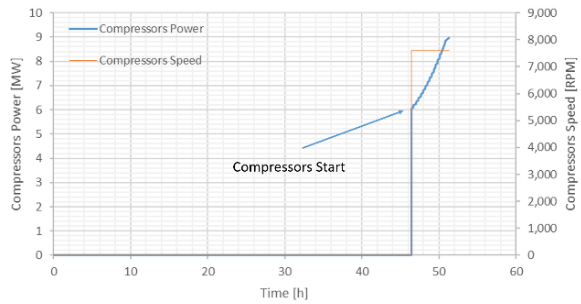

Figure 5.23 – Compressors power – Loading phase – 12 MNm³ – SUMMER CONDITION

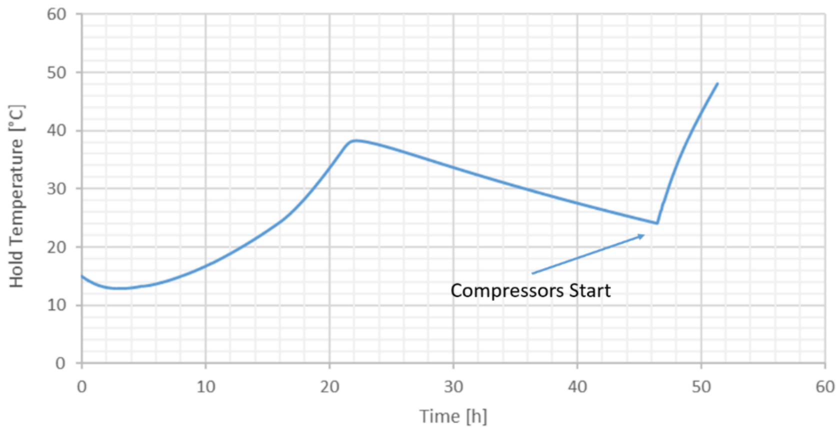

Figure 5.24 – Hold temperature – Loading phase – 12 MNm^3 – SUMMER CONDITION

Figure 5.18 shows the increasing of the gas quantity contained in the pressure cylinders. In the free loading phase the flow rate (Figure 5.19) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow rate increases thanks to the increase the density of the gas downstream of the valve and in the cylinders. When the pressure difference between the storage and the cylinders is small, the flow rate drops, but in this case, the compressors start when the cylinder temperature to drop to 40°C, carrying out the free loading phase with a minimum flow rate. If the temperature of the gas in the cylinders is brought to this temperature before starting the compressors, a commercial mass of gas of about 12 MNm^3 is guaranteed. When the compressors are started, the flow rate curve shows oscillations related to the opening of the throttle valves of the compressors.

Figure 5.20 and Figure 5.21 show the trend of temperature and pressure inside the cylinders. The temperature of the gas at the cylinders inlet is shown in Figure 5.22 with a minimum temperature of –59°C at the beginning of the process. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressors and must be cooled down in the post cooler. Figure 5.23 shows the power absorbed by the compressors with a maximum of 9 MW at 7600 rpm. The temperature of the hold is shown in Figure 5.24 with a maximum value of 47°C.

5.2.4 12 MNm^3 simulation – Unloading Phase

At the end of the loading phase the cylinders reach a temperature of 59°C and, therefore, the temperature of the hold tends to get to the same value. The high temperature in the hold facilitates the unloading process but a temperature too high in the hold is not acceptable due to safety reasons.

During navigation, in a first phase, it is necessary to cool down the hold to maintain a temperature of about 40°C so that the hold can be accessible by operators equipped with the appropriate protections in case of emergency operations. Once this temperature is reached, it is kept constant until the beginning of the unloading phase by supplying heat, if necessary, using two boilers of 3

MW each. For the unloading phase, an initial hold temperature of 40°C was considered. If at the time of discharge the gas temperature is higher than 40°C it is better for the process.

Table 5.5 – Simulation data – Unloading phase – 12 MNm^3 – SUMMER CONDITION

Unloading Phase		
Initial On–Shore Storage Pressure	bar	80
Initial Cylinders Pressure	bar	297
Initial Cylinders Temperature	°C	40
Initial Cylinder Density	kg/m^3	197
Final On–Shore Storage Pressure	bar	80
Final Cylinders Pressure	bar	20
Final Cylinders Temperature	°C	32
Final Cylinder Density	kg/m^3	13
Unloading Time	h	67
Unloading Compressors Consumption	ton	18
Average Flow Rate	kg/s	36
	Nm^3/h	180,553
Maximum Flow Rate	kg/s	85
	Nm^3/h	424,164
Remaining Mass Inside Cylinders	ton	620
	Nm^3	863,723
Unloaded Mass	**ton**	**8,737**
	Nm^3	**12,177,693**

The unloading phase lasts 67 hours, 19 hours of free unloading and 48 hours of forced unloading. During the process 12,177,693 Nm^3 of gas are unloaded. To assess the quantity of gas unloaded, the gas consumed by the compressors was taken into account.

In this case it is possible to unload 771,501 Nm^3 more than the minimum time strategy.

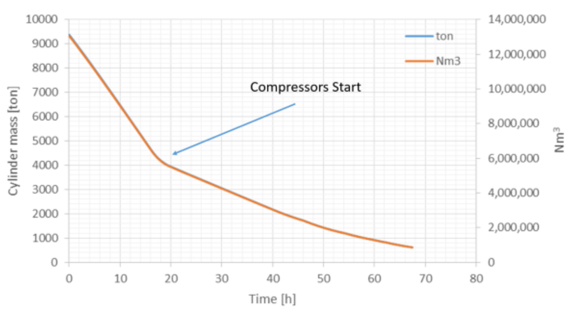

Figure 5.25 – Cylinder mass – Unloading phase – 12 MNm^3 – SUMMER CONDITION

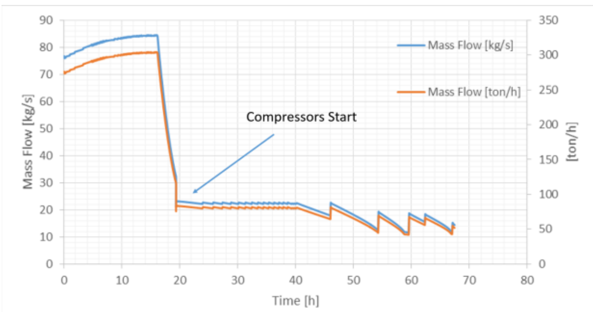

Figure 5.26 – Flow rate – Unloading phase 12 MNm^3 – SUMMER CONDITION

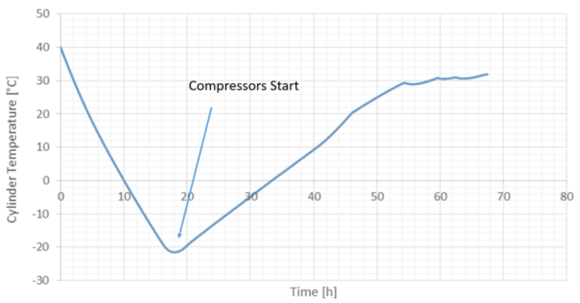

Figure 5.27 – Cylinder temperature – Unloading phase – 12 MNm³– SUMMER CONDITION

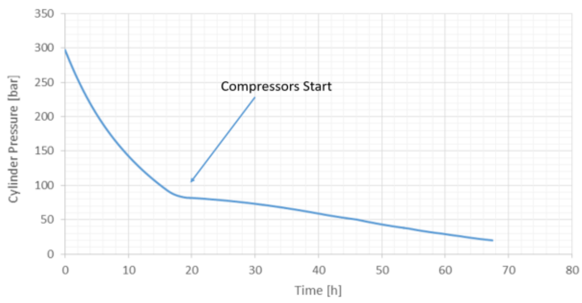

Figure 5.28 – Cylinder pressure – Unloading phase – 12 MNm³– SUMMER CONDITION

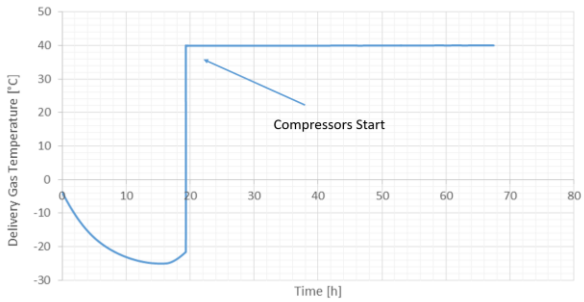

Figure 5.29 – Delivery gas temperature – Unloading phase – 12 MNm³ – SUMMER CONDITION

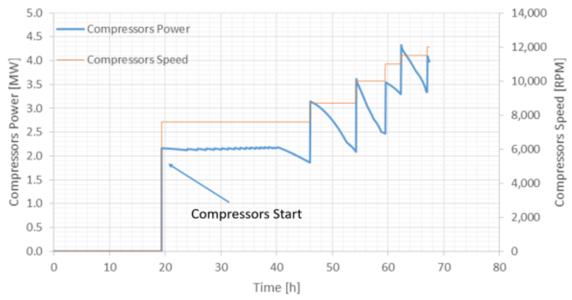

Figure 5.30 – Compressors power – Unloading phase – 12 MNm³– SUMMER CONDITION

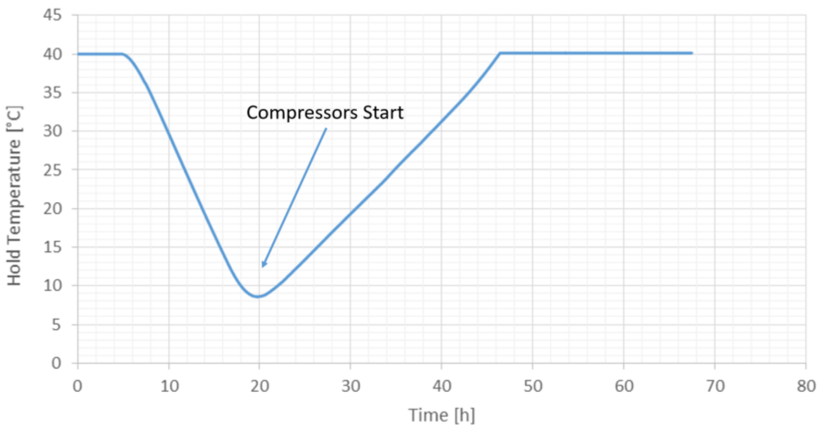

Figure 5.31 – Hold temperature – Unloading phase – 12 MNm³ – SUMMER CONDITION

The figures from Figure 5.25 to Figure 5.31 show the graphs of the main parameters of the unloading phase.

Figure 5.25 shows the decrease of the gas quantity contained in the pressure cylinders. In the free unloading phase the flow rate (Figure 5.26) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow rate increases thanks to the decrease of the gas density upstream of the valve and in the cylinders.

When the pressure difference between the cylinders and the storage is small, the flow rate drops and the compressors are started. In the first part of the flow rate curve, since from the start of the compressors there are oscillations related to the opening of the throttle valves of the compressors. In the second part of the curve, some peaks corresponding to the change of the speed of the compressors can be observed.

Figure 5.27 and Figure 5.28 show the temperature and pressure trends inside the cylinders.

The delivery gas temperature is shown in Figure 5.29 with a minimum temperature, during the free unloading phase, of –25°C. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler.

Figure 5.30 shows the power absorbed by the compressors with a maximum of 4.3 MW at 11,500 rpm. The maximum compression ratio is 4. The temperature of the hold is shown in Figure 5.31 with a maximum value of 40°C and a minimum of 9°C.

5.3 WINTER CONDITION

5.3.1 Minimum loading time simulation – Loading Phase

The WINTER conditions represent the best conditions for the loading phase because the low temperature facilitates the loading process. Thanks to low temperatures it is possible to cool down the gas efficiently using sea water and it is also easier to keep the hold cool. Under these conditions, at the same load time it is possible to charge a greater amount of gas.

For the loading phase it was considered an initial hold temperature of 15°C. This temperature is obtained by cooling down the hold with fan coils during navigation with the empty vessel. The cold power is provided by four chillers of 1.4 MW each. The remaining initial parameters for the simulation are shown in the Table 5.6.

Table 5.6 – Simulation data – Loading phase – Min. Time – WINTER CONDITION

Loading Phase		
Initial On–Shore Storage Pressure	bar	240
Initial On–Shore Storage Temperature	°C	20
Initial Cylinders Pressure	bar	20
Initial Cylinders Temperature	°C	15
Initial Cylinder Density	kg/m^3	14
Final On–Shore Storage Pressure	bar	240
Final On–Shore Storage Temperature	°C	20
Final Cylinders Pressure	bar	335
Final Cylinders Temperature	°C	67
Final Cylinder Density	kg/m^3	191
Loading Time	h	28
Loading Compressors Consumption	ton	6
Average Flow Rate	kg/s	84

Loading Phase		
	Nm^3/h	418,861
Maximum Flow Rate	kg/s	129
	Nm^3/h	644,647
Mass Inside Cylinders	ton	9,072
	Nm^3	12,644,071
Loaded Mass	**ton**	**8,408**
	Nm^3	**11,719,170**

The loading phase lasts 28 hours, 22 hours of free loading and 6 hours of forced loading. As shown in Table 5.6, the cylinder temperature at the end of the process is 67°C. In these conditions the total mass of gas, at a pressure of 335 bar, which can be stored in the cylinders is 12,644,071 Nm^3 and the mass loaded during the process is 11,719,170 Nm^3.

The figures from Figure 5.32 to Figure 5.38 show the graphs of the main parameters of the loading phase.

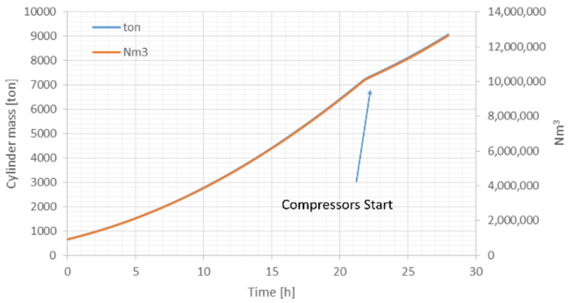

Figure 5.32 – Loaded mass – Loading phase – Min. Time – WINTER CONDITION

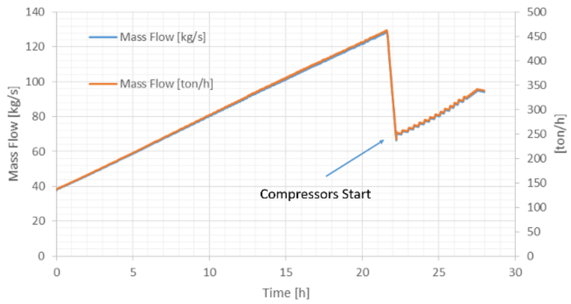

Figure 5.33 – Flow rate – Loading phase – Min. Time – WINTER CONDITION

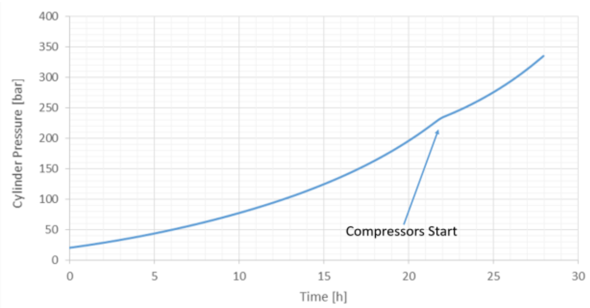

Figure 5.34 – Cylinder temperature – Loading phase – Min. Time – WINTER CONDITION

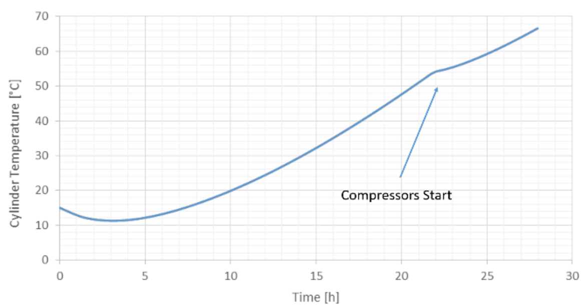

Figure 5.35 – Cylinder pressure – Loading phase – Min. Time – WINTER CONDITION

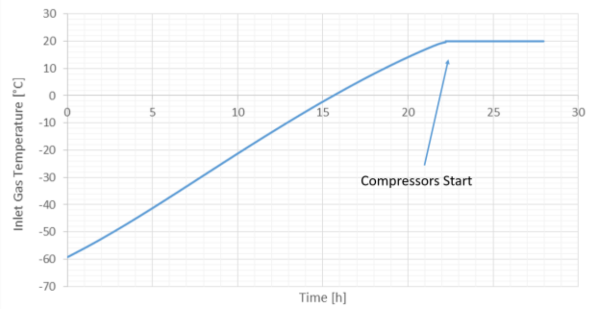

Figure 5.36 – Gas temperature at cylinder inlet – Loading phase – Min. Time – WINTER CONDITION

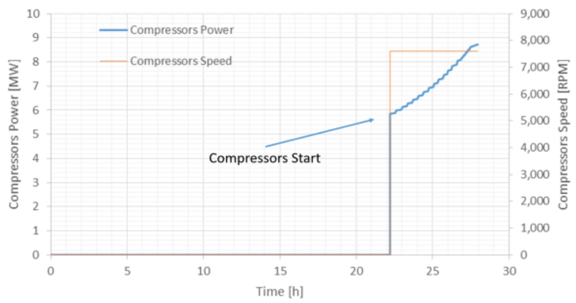

Figure 5.37 – Compressors power – Loading phase – Min. Time – WINTER CONDITION

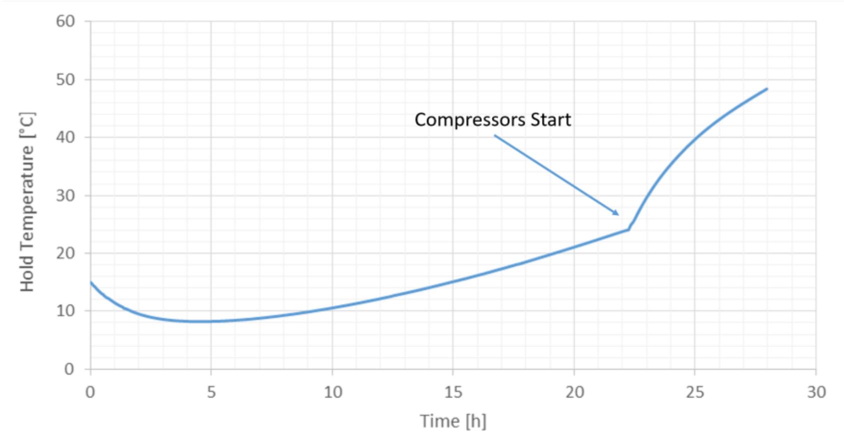

Figure 5.38 – Hold temperature – Loading phase – Min. Time – WINTER CONDITION

Figure 5.32 shows the increasing of the gas quantity contained in the pressure cylinders. In the free loading phase the flow rate (Figure 5.33) is controlled by the regulating valve in order to limit the gas speed in the pipes. At the beginning the flow rate increases thanks to the increase of the gas density downstream of the valve and in the cylinders. When the pressure difference between the storage and the cylinders is small, the flow rate drops and the compressors are started. The oscillatory course of the flow curve and the curve of the power absorbed by the compressors (Figure 5.37) are related to the opening of the throttle valves of the compressors.

Figure 5.34 and Figure 5.35 show the increasing trend of temperature and pressure inside the cylinders. The temperature of the gas at the cylinders inlet is shown in Figure 5.36 with a minimum temperature of –59°C at the beginning of the process. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler. Figure 5.37 shows the power absorbed by the compressors with a maximum of 8.7 MW at 7600 rpm. The temperature of the hold is shown in Figure 5.38 with a maximum value of 48°C.

5.3.2 Minimum loading time simulation – Unloading Phase

At the end of the loading phase the cylinders reach a temperature of 67°C and, therefore, the temperature of the hold tends to reach the same value. The high temperature in the hold facilitates the unloading process but a temperature too high in the hold is not acceptable due to safety reasons.

During navigation, in a first phase, it is necessary to cool down the hold to maintain a temperature of about 40°C so that the hold can be accessible by operators equipped with the appropriate protections in case of emergency operations. Once this temperature is reached, it is kept constant until the beginning of the unloading phase by supplying heat, if necessary, using two boilers of 3 MW each. For the unloading phase, an initial hold temperature of 40°C was considered. If at the time of discharge the gas temperature is still higher than 40°C it is better for the process.

The WINTER conditions represent the worst conditions for the unloading phase as low temperatures disadvantage the process.

Table 5.7 – Simulation data – Unloading phase – Min. Time – WINTER CONDITION

Unloading Phase		
Initial On–Shore Storage Pressure	bar	80
Initial Cylinders Pressure	bar	283
Initial Cylinders Temperature	°C	40
Initial Cylinder Density	kg/m^3	13
Final On–Shore Storage Pressure	bar	80
Final Cylinders Pressure	bar	20
Final Cylinders Temperature	°C	32
Final Cylinder Density	kg/m^3	13
Unloading Time	h	69
Unloading compressors consumption	ton	18
Average Flow Rate	kg/s	34
	Nm^3/h	171,463
Maximum Flow Rate	kg/s	85
	Nm^3/h	427,741
Remaining Mass Inside Cylinders	ton	622
	Nm^3	867,525
Unloaded Mass	**ton**	**8,431**
	Nm^3	**11,750,984**

The unloading phase lasts 69 hours, 18 hours of free unloading and 51 hours of forced unloading. During the process 11,750,984 Nm^3 of gas are unloaded. To assess the quantity of gas unloaded, the gas consumed by the compressors was taken into account.

The figures from Figure 5.39 to Figure 5.45 show the graphs of the main parameters of the unloading phase.

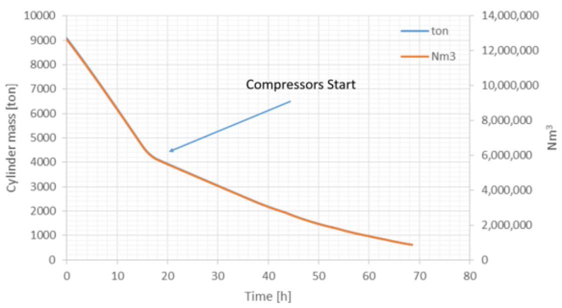

Figure 5.39 – Unloaded mass – Unloading phase – Min. Time – WINTER CONDITION

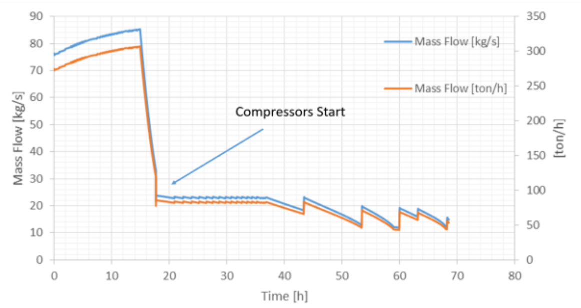

Figure 5.40 – Flow rate – Unloading phase – Min. Time – WINTER CONDITION

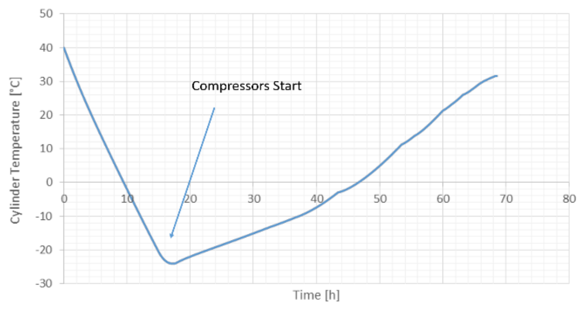

Figure 5.41 – Cylinder temperature – Unloading phase – Min. Time – WINTER CONDITION

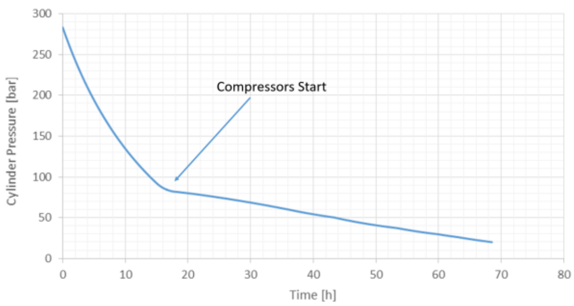

Figure 5.42 – Cylinder pressure – Unloading phase – Min. Time – WINTER CONDITION

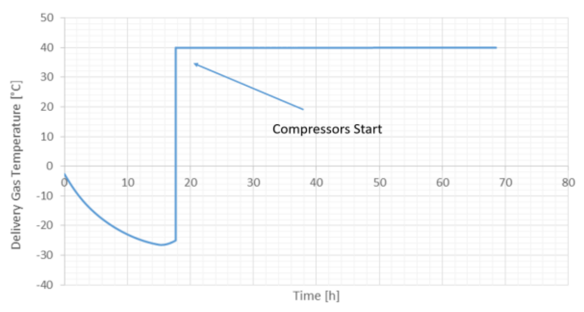

Figure 5.43 – Delivery gas temperature – Unloading phase – Min. Time – WINTER CONDITION

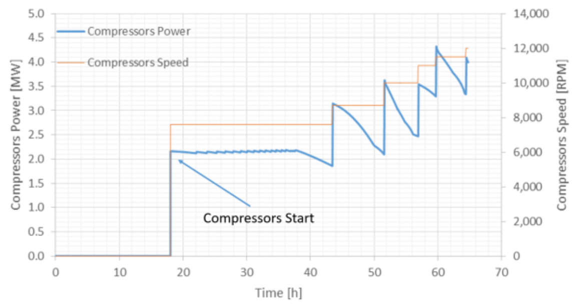

Figure 5.44 – Compressors power – Unloading phase – Min. Time – WINTER CONDITION

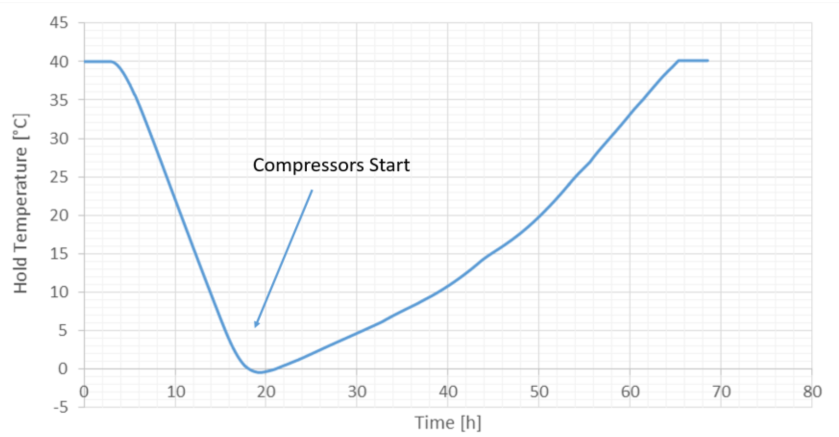

Figure 5.45 – Hold temperature – Unloading phase – Min. Time – WINTER CONDITION

Figure 5.39 shows the decrease of the gas quantity contained in the pressure cylinders. In the free unloading phase the flow rate (Figure 5.40) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow increases thanks to the decrease of the gas density upstream of the valve and in the cylinders.

When the pressure difference between the cylinders and the storage is small, the flow rate drops and the compressors are started. In the first part of the flow rate curve, from the start of the compressors there are oscillations related to the opening of the throttle valves of the compressors. In the second part of the curve, some peaks corresponding to the change of the speed of the compressors can be observed.

Figure 5.41 and Figure 5.42 show the temperature and pressure trends inside the cylinders.

The delivery gas temperature is shown in Figure 5.43 with a minimum temperature, during the free unloading phase, of –26°C. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler.

Figure 5.44 shows the power absorbed by the compressors with a maximum of 4.2 MW at 11,500 rpm. The maximum compression ratio is 4. The temperature of the hold is shown in Figure 5.45 with a maximum value of 40°C and a minimum of 0°C.

5.3.3 12 MNm^3 simulation – Loading Phase

For the loading phase it was considered an initial hold temperature of 15°C because the low temperature facilitates the loading process. This temperature is obtained by cooling down the hold with fan coils during navigation with the empty vessel. The cold power is provided by four chillers of 1.4 MW each. The remaining initial parameters for the simulation are shown in the Table 5.8.

Table 5.8 – Simulation data – Loading phase – 12 MNm^3 – WINTER CONDITION

Loading Phase		
Initial On–Shore Storage Pressure	bar	240
Initial On–Shore Storage Temperature	°C	20
Initial Cylinders Pressure	bar	20
Initial Cylinders Temperature	°C	15
Initial Cylinder Density	kg/m^3	14
Final On–Shore Storage Pressure	bar	240
Final On–Shore Storage Temperature	°C	20
Final Cylinders Pressure	bar	336
Final Cylinders Temperature	°C	55
Final Cylinder Density	kg/m^3	200
Loading time	h	42
Loading compressors consumption	ton	5
Average Flow Rate	kg/s	59
	Nm^3/h	295,000
Maximum Flow Rate	kg/s	129
	Nm^3/h	644,647
Mass Inside Cylinders	ton	9,515
	Nm^3	13,261,386
Loaded Mass	**ton**	**8,851**
	Nm^3	**12,336,485**

The loading phase lasts 42 hours, 14 hours more than the minimum time strategy simulation. The cylinder temperature at the end of the process in this case is 55°C and therefore lower than the previous case by 12°C. The total mass of gas in the cylinders, at the pressure of 335 bar, is 13,261,386 Nm^3 and the loaded mass is 12,336,485 Nm^3, therefore higher than the previous case of 617,315 Nm^3.

The figures from Figure 5.46 to Figure 5.52 show the graphs of the main parameters of the loading phase.

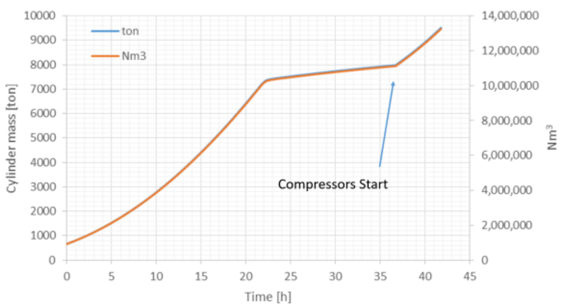

Figure 5.46 – Loaded mass – Loading phase – 12 MNm^3 – WINTER CONDITION

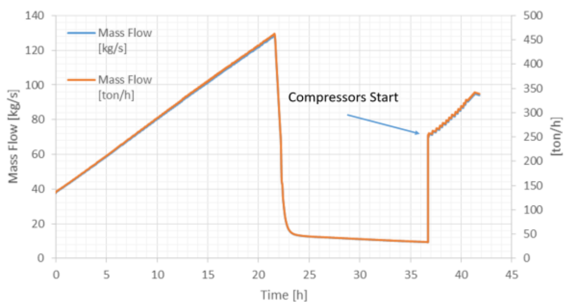

Figure 5.47 – Flow rate – Loading phase – 12 MNm^3 – WINTER CONDITION

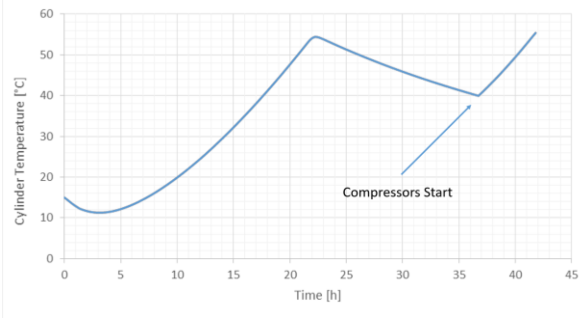

Figure 5.48 – Cylinder temperature – Loading phase – 12 MNm^3 – WINTER CONDITION

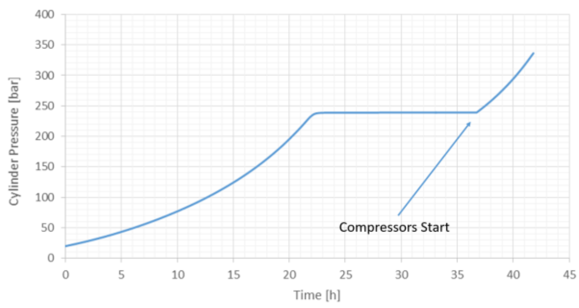

Figure 5.49 – Cylinder pressure – Loading phase – 12 MNm^3 – WINTER CONDITION

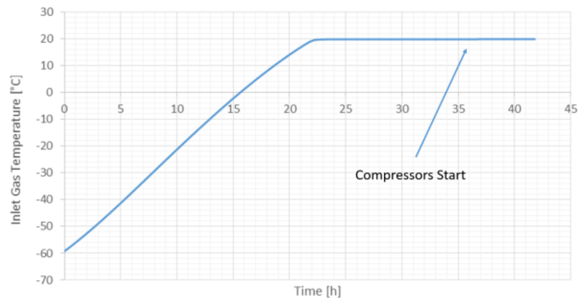

Figure 5.50 – Gas temperature at cylinder inlet – Loading phase – 12 MNm^3 – WINTER CONDITION

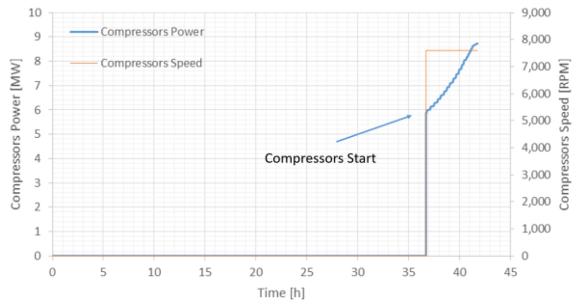

Figure 5.51 – Compressors power – Loading phase – 12 MNm^3 – WINTER CONDITION

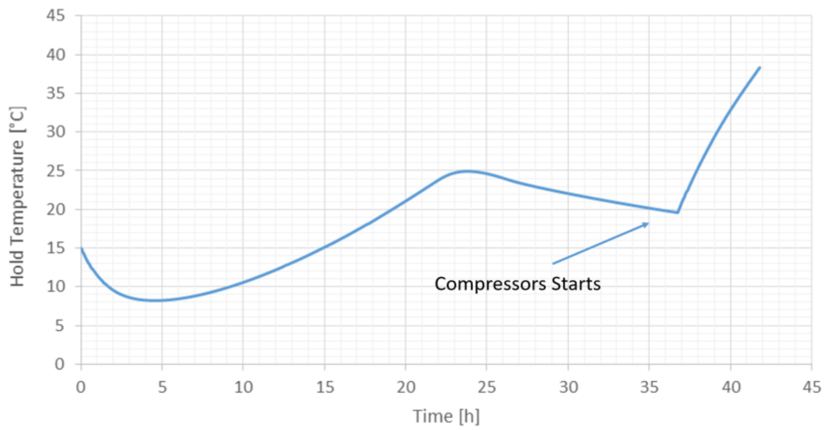

Figure 5.52 – Hold temperature – Loading phase – 12 MNm^3 – WINTER CONDITION

Figure 5.46 shows the increasing of the gas quantity contained in the pressure cylinders. In the free loading phase the flow rate (Figure 5.47) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow rate increases thanks to the increase the density of the gas downstream of the valve and in the cylinders. When the pressure difference between the storage and the cylinders is small, the flow rate drops, but in this case, the compressors start when the cylinder temperature to drop to 40°C, carrying out the free loading phase with a minimum flow rate. If the temperature of the gas in the cylinders is brought to this temperature before starting the compressors, a commercial mass of gas of about 12 MNm^3 is guaranteed. When the compressors

are started, the flow rate curve shows oscillations related to the opening of the throttle valves of the compressors.

Figure 5.48 and Figure 5.49 show the trend of temperature and pressure inside the cylinders. The temperature of the gas at the cylinders inlet is shown in Figure 5.50 with a minimum temperature of -59°C at the beginning of the process. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressors and must be cooled down in the post cooler. Figure 5.51 shows the power absorbed by the compressors with a maximum of 8.7 MW at 7600 rpm. The temperature of the hold is shown in Figure 5.52 with a maximum value of 38°C.

5.3.4 12 MNm^3 simulation – Unloading Phase

At the end of the loading phase the cylinders reach a temperature of 55°C and, therefore, the temperature of the hold tends to get to the same value. The high temperature in the hold facilitates the unloading process but a temperature too high in the hold is not acceptable due to safety reasons.

During navigation, in a first phase, it is necessary to cool down the hold to maintain a temperature of about 40°C so that the hold can be accessible by operators equipped with the appropriate protections in case of emergency operations. Once this temperature is reached, it is kept constant until the beginning of the unloading phase by supplying heat, if necessary, using two boilers of 3 MW each. For the unloading phase, an initial hold temperature of 40°C was considered. If at the time of discharge the gas temperature is higher than 40°C it is better for the process.

Table 5.9 – Simulation data – Unloading phase – 12 MNm^3 – WINTER CONDITION

Unloading Phase		
Initial On–Shore Storage Pressure	bar	80
Initial Cylinders Pressure	bar	304
Initial Cylinders Temperature	°C	40
Initial Cylinder Density	kg/m^3	13
Final On–Shore Storage Pressure	bar	80
Final Cylinders Pressure	bar	20
Final Cylinders Temperature	°C	32
Final Cylinder Density	kg/m^3	13
Unloading Time	h	71
Unloading compressors consumption	ton	19
Average Mass Flow Rate	kg/s	35
	Nm^3/h	174,550
Maximum Mass Flow Rate	kg/s	87
	Nm^3/h	435,055
Remaining Inside Cylinders	ton	622
	Nm^3	867,324
Unloaded Mass	**ton**	**8,873**
	Nm^3	**12,367,916**

The unloading phase lasts 71 hours, 19 hours of free unloading and 52 hours of forced unloading. During the process 12,367,916 Nm^3 of gas are unloaded. In assessing the quantity of gas unloaded, the gas consumed by the compressors was taken into account. In this case it is possible to unload 616,932 Nm^3 more than the minimum time strategy. The figures from Figure 5.53 to Figure 5.59 show the graphs of the main parameters of the unloading phase.

Figure 5.53 shows the decrease of the gas quantity contained in the pressure cylinders. In the free unloading phase the flow rate (Figure 5.54) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow rate increases thanks to the decrease of the gas density upstream of the valve and in the cylinders.

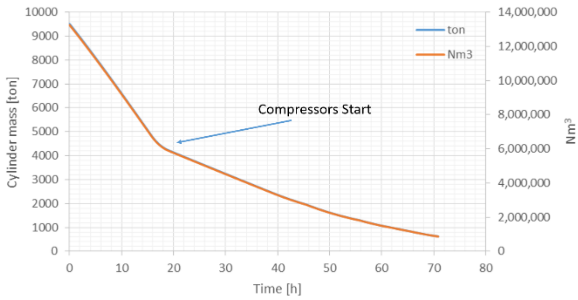

Figure 5.53 – Unloaded mass – Unloading phase – 12 MNm^3 – WINTER CONDITION

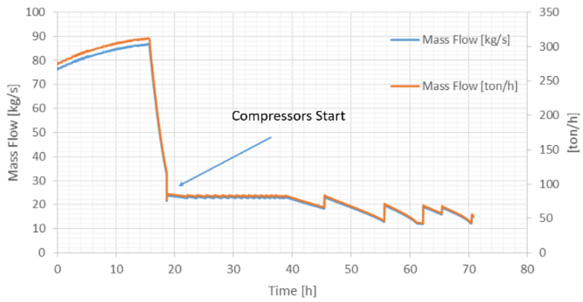

Figure 5.54 – Flow rate – Unloading phase – 12 MNm^3 – WINTER CONDITION

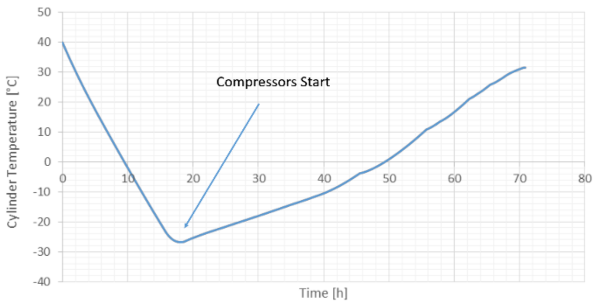

Figure 5.55 – Cylinder temperature – Unloading phase – 12 MNm^3 – WINTER CONDITION

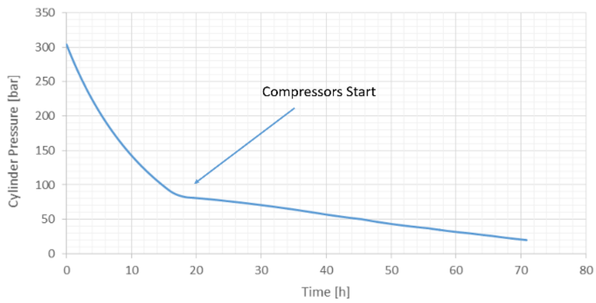

Figure 5.56 – Cylinder pressure – Unloading phase – 12 MNm^3 – WINTER CONDITION

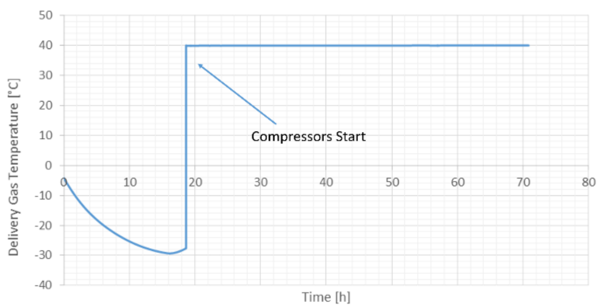

Figure 5.57 – Delivery gas temperature – Unloading phase – 12 MNm^3 – WINTER CONDITION

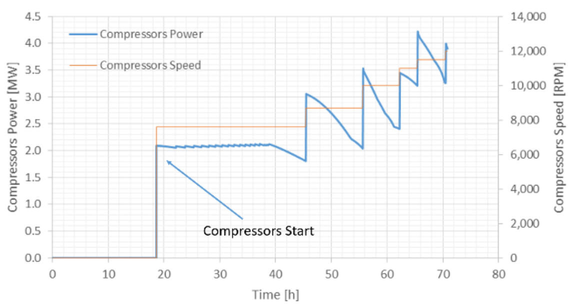

Figure 5.58 – Compressors power – Unloading phase – 12 MNm^3 – WINTER CONDITION

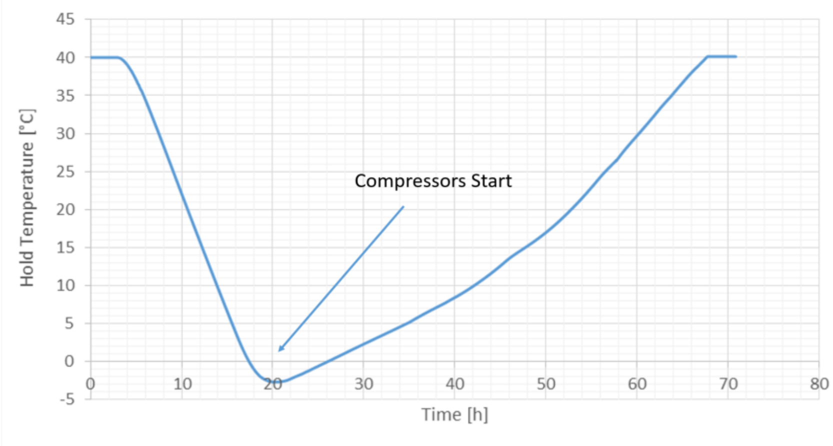

Figure 5.59 – Hold temperature – Unloading phase – 12 MNm^3 – WINTER CONDITION

When the pressure difference between the cylinders and the storage is small, the flow rate drops and the compressors are started. In the first part of the flow rate curve, since from the start of the compressors there are oscillations related to the opening of the throttle valves of the compressors. In the second part of the curve, some peaks corresponding to the change of the speed of the compressors can be observed.

Figure 5.55 and Figure 5.56 show the temperature and pressure trends inside the cylinders.

The delivery gas temperature is shown in Figure 5.57 with a minimum temperature, during the free unloading phase, of –29°C. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler.

Figure 5.58 shows the power absorbed by the compressors with a maximum of 4.2 MW at 11,500 rpm. The maximum compression ratio is 4. The temperature of the hold is shown in Figure 5.59 with a maximum value of 40°C and a minimum of -3°C.

6. Mediterranean Sea Conditions

6.1 Minimum loading time simulation – Loading Phase

For the loading phase it was considered an initial hold temperature of 15°C because the low temperature facilitates the loading process. This temperature is obtained by cooling down the hold with fan coils during navigation with the empty vessel. The cold power is provided by four chillers of 1.4 MW each. The remaining initial parameters for the simulation are shown in the Table 6.1.

Table 6.1 – Simulation data – Loading phase – Min. Time – Mediterranean Sea

Loading Phase		
Initial On–Shore Storage Pressure	bar	240
Initial On–Shore Storage Temperature	°C	25
Initial Cylinders Pressure	bar	20
Initial Cylinders Temperature	°C	15
Initial Cylinder Density	kg/m^3	14
Final On–Shore Storage Pressure	bar	240
Final On–Shore Storage Temperature	°C	25
Final Cylinders Pressure	bar	336
Final Cylinders Temperature	°C	70
Final Cylinder Density	kg/m^3	188
Loading time	h	28
Loading compressors consumption	ton	6
Average Flow Rate	kg/s	82
	Nm^3/h	408,984
Maximum Flow Rate	kg/s	128
	Nm^3/h	641,560
Mass Inside Cylinders	ton	8,962
	Nm^3	12,491,833
Loaded Mass	**ton**	**8,299**
	Nm^3	**11,566,932**

The loading phase lasts 28 hours, 22 hours of free loading and 6 hours of forced loading. As shown in Table 6.1, the cylinder temperature at the end of the process is 70°C. In these conditions the total mass of gas, at a pressure of 335 bar, which can be stored in the cylinders is 12,491,833 Nm^3 and the mass loaded during the process is 11,566,932 Nm^3.

The figures from Figure 6.1 to Figure 6.7 show the graphs of the main parameters of the loading phase.

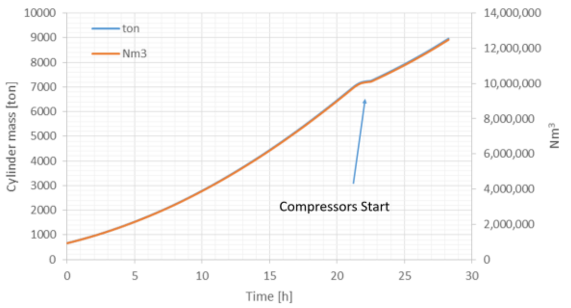

Figure 6.1 – Loaded mass – Loading phase – Min. Time – Mediterranean Sea

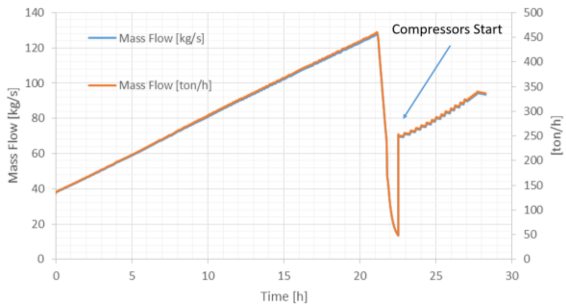

Figure 6.2 – Flow rate – Loading phase – Min. Time – Mediterranean Sea

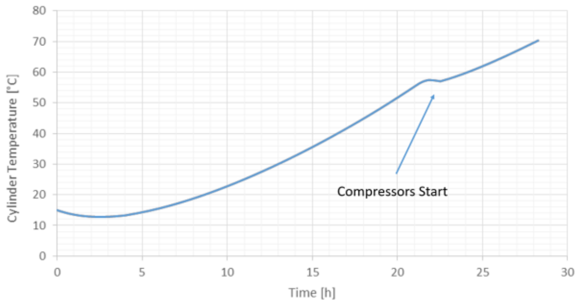

Figure 6.3 – Cylinder temperature – Loading phase – Min. Time – Mediterranean Sea

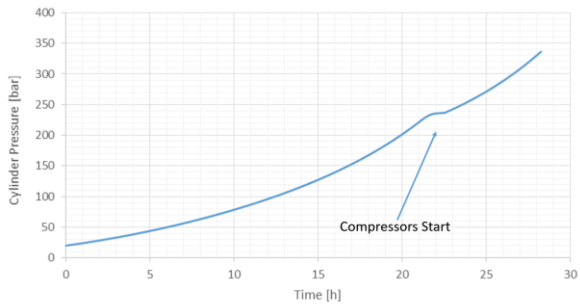

Figure 6.4 – Cylinder pressure – Loading phase – Min. Time – Mediterranean Sea

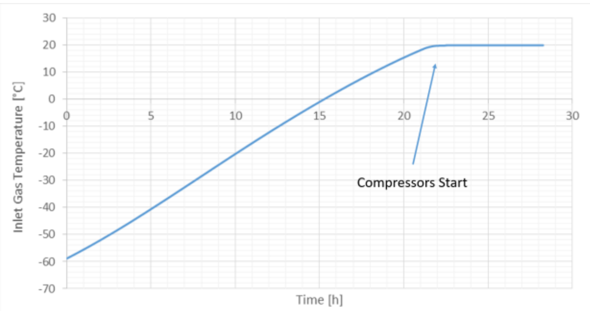

Figure 6.5 – Gas temperature at cylinder inlet – Loading phase – Min. Time – Mediterranean Sea

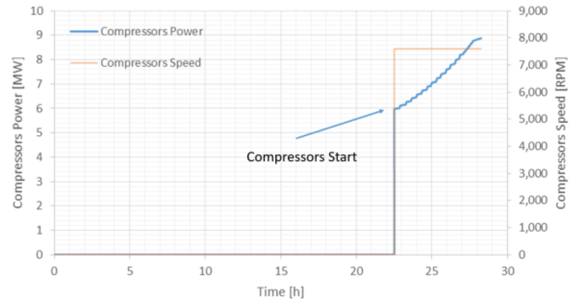

Figure 6.6 – Compressors power – Loading phase – Min. Time – Mediterranean Sea

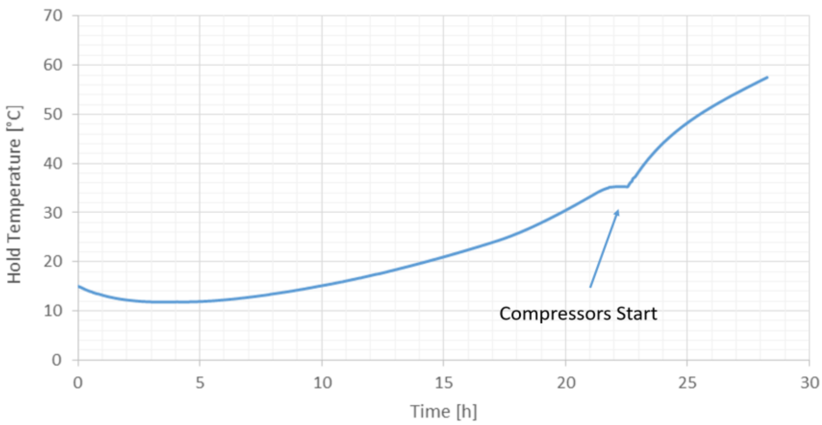

Figure 6.7 – Hold temperature – Loading phase – Min. Time – Mediterranean Sea

Figure 6.1 shows the increasing of the gas quantity contained in the pressure cylinders. In the free loading phase the flow rate (Figure 6.2) is controlled by the regulating valve in order to limit the gas speed in the pipes. At the beginning the flow rate increases thanks to the increase of the gas density downstream of the valve and in the cylinders. When the pressure difference between the storage and the cylinders is small, the flow rate drops and the compressors are started. The oscillatory course of the flow curve and the curve of the power absorbed by the compressors (Figure 6.6) are related to the opening of the throttle valves of the compressors.

Figure 6.3 and Figure 6.4 show the increasing trend of temperature and pressure inside the cylinders. The temperature of the gas at the cylinders inlet is shown in Figure 6.5 with a minimum temperature of –59°C at the beginning of the process. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler. Figure 6.6 shows the power absorbed by the compressors with a maximum of 8.9 MW at 7600 rpm. The temperature of the hold is shown in Figure 6.7 with a maximum value of 57°C.

6.2 Minimum loading time simulation – Unloading Phase

At the end of the loading phase the cylinders reach a temperature of 70°C and, therefore, the temperature of the hold tends to reach this value. The high temperature in the hold facilitates the unloading process but a temperature too high in the hold is not acceptable due to safety reasons.

During navigation, in a first phase, it is necessary to cool down the hold to maintain a temperature of about 40°C so that the hold can be accessible by operators equipped with the appropriate protections in case of emergency operations. Once this temperature is reached, it is kept constant until the beginning of the unloading phase by supplying heat, if necessary, using two boilers of 3 MW each. For the unloading phase, an initial hold temperature of 40°C was considered. If at the time of discharge the gas temperature is still higher than 40°C it is better for the process.

Table 6.2 – Simulation data – Unloading phase – Min. Time – Mediterranean Sea

Unloading Phase		
Initial On–Shore Storage Pressure	bar	80
Initial Cylinders Pressure	bar	279
Initial Cylinders Temperature	°C	40
Initial Cylinder Density	kg/m^3	188
Final On–Shore Storage Pressure	bar	80
Final Cylinders Pressure	bar	20
Final Cylinders Temperature	°C	32
Final Cylinder Density	kg/m^3	13
Unloading Time	h	66
Unloading compressors consumption	ton	17
Average Flow Rate	kg/s	35
	Nm^3/h	175,312
Maximum Flow Rate	kg/s	84

Unloading Phase		
	Nm^3/h	419,957
Remaining Mass Inside Cylinders	ton	620
	Nm^3	864,171
Unloaded Mass	**ton**	**8,325**
	Nm^3	**11,603,357**

The unloading phase lasts 66 hours, 18 hours of free unloading and 48 hours of forced unloading. During the process 11,603,357 Nm^3 of gas are unloaded. To assess the quantity of gas unloaded, the gas consumed by the compressors was taken into account.

The figures from Figure 6.8 to Figure 6.14 show the graphs of the main parameters of the unloading phase.

Figure 6.8 shows the decrease of the gas quantity contained in the pressure cylinders. In the free unloading phase the flow rate (Figure 6.9) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow increases thanks to the decrease of the gas density upstream of the valve and in the cylinders.

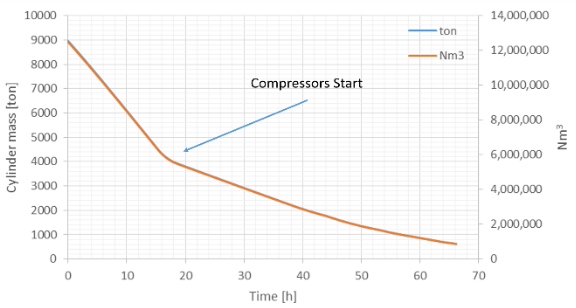

Figure 6.8 – Loaded mass – Unloading phase – Min. Time – Mediterranean Sea

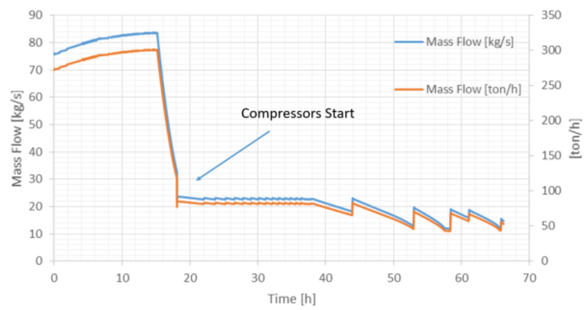

Figure 6.9 – Flow rate – Unloading phase – Min. Time – Mediterranean Sea

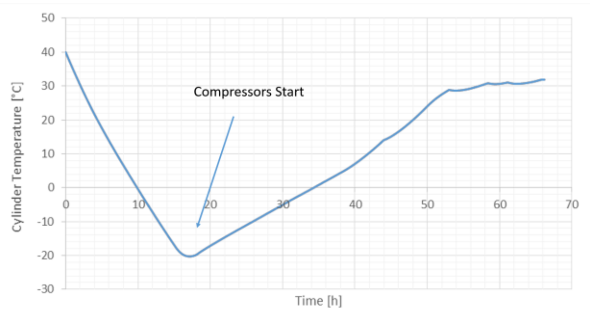

Figure 6.10 – Cylinder temperature – Unloading phase – Min. Time – Mediterranean Sea

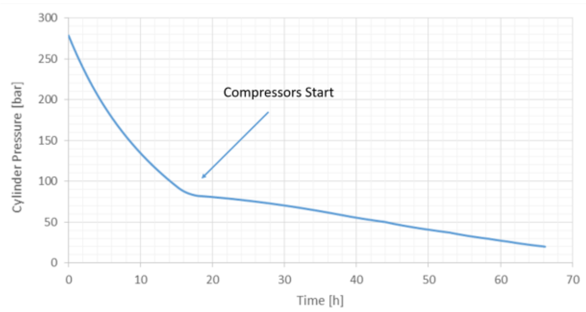

Figure 6.11 – Cylinder pressure – Unloading phase – Min. Time – Mediterranean Sea

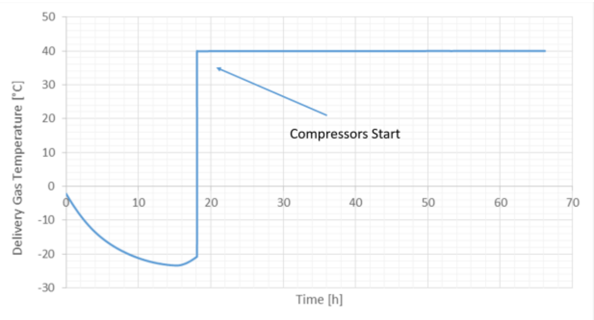

Figure 6.12 – Gas temperature at cylinder inlet – unloading phase – Min. Time – Mediterranean Sea

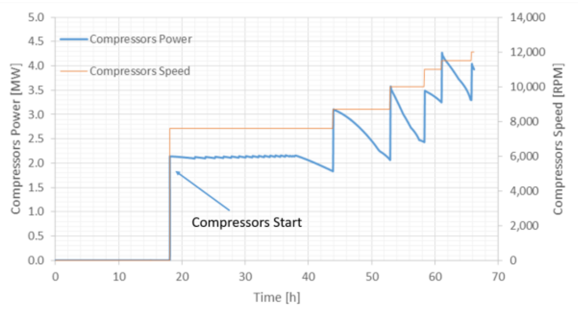

Figure 6.13 – Compressors power – Unloading phase – Min. Time – Mediterranean Sea

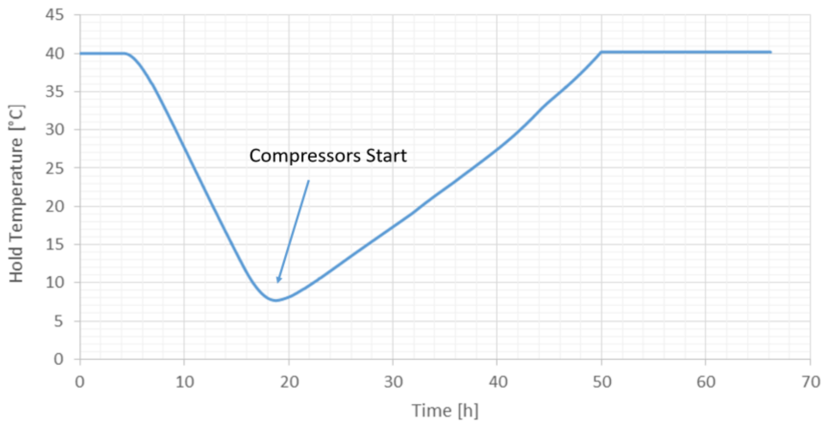

Figure 6.14 – Hold temperature – Unloading phase – Min. Time – Mediterranean Sea

When the pressure difference between the cylinders and the storage is small, the flow rate drops and the compressors are started. In the first part of the flow rate curve, from the start of the compressors there are oscillations related to the opening of the throttle valves of the compressors. In the second part of the curve, some peaks corresponding to the change of the speed of the compressors can be observed.

Figure 6.10 and Figure 6.11 show the temperature and pressure trends inside the cylinders.

The delivery gas temperature is shown in Figure 6.12 with a minimum temperature, during the free unloading phase, of -23°C. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler.

Figure 6.13 shows the power absorbed by the compressors with a maximum of 4.3 MW at 11,500 rpm. The maximum compression ratio is 4. The temperature of the hold is shown in Figure 6.14 with a maximum value of 40°C and a minimum of 8°C.

6.3 12 MNm^3 simulation – Loading Phase

For the loading phase it was considered an initial hold temperature of 15°C because the low temperature facilitates the loading process. This temperature is obtained by cooling down the hold with fan coils during navigation with the empty vessel. The cold power is provided by four chillers of 1.4 MW each. The remaining initial parameters for the simulation are shown in the Table 6.3.

Table 6.3 – Simulation data – Loading phase – 12 MNm^3 – Mediterranean Sea

Loading Phase		
Initial On–Shore Storage Pressure	bar	240
Initial On–Shore Storage Temperature	°C	25
Initial Cylinders Pressure	bar	20
Initial Cylinders Temperature	°C	15
Initial Cylinder Density	kg/m^3	14
Final On–Shore Storage Pressure	bar	240
Final On–Shore Storage Temperature	°C	25
Final Cylinders Pressure	bar	336
Final Cylinders Temperature	°C	57
Final Cylinder Density	kg/m^3	199
Loading Time	h	48
Loading Compressors Consumption	ton	5
Average Flow Rate	kg/s	51
	Nm^3/h	254,743
Maximum Flow Rate	kg/s	128
	Nm^3/h	641,560
Mass Inside Cylinders	ton	9,457
	Nm^3	13,180,834
Loaded Mass	**ton**	**8,793**
	Nm^3	**12,255,933**

The loading phase lasts 48 hours, 20 hours more than the minimum time strategy simulation. The cylinder temperature at the end of the process in this case is 57°C and therefore lower than the previous case by 13°C. The total mass of gas in the cylinders, at the pressure of 335 bar, is 13,180,834 Nm^3 and the loaded mass is 12,255,933 Nm^3, therefore higher than the previous case of 689,001 Nm^3.

The figures from Figure 6.15 to Figure 6.21 show the graphs of the main parameters of the loading phase.

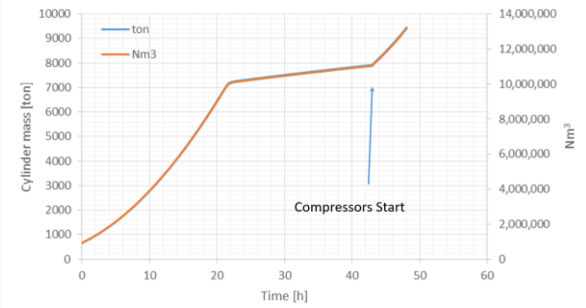

Figure 6.15 – Loaded mass – Loading phase – 12 MNm³ – Mediterranean Sea

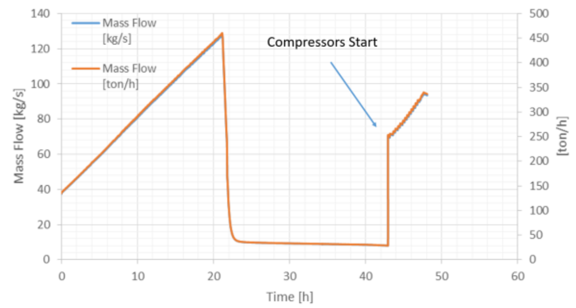

Figure 6.16 – Flow rate – Loading phase – 12 MNm³ – Mediterranean Sea

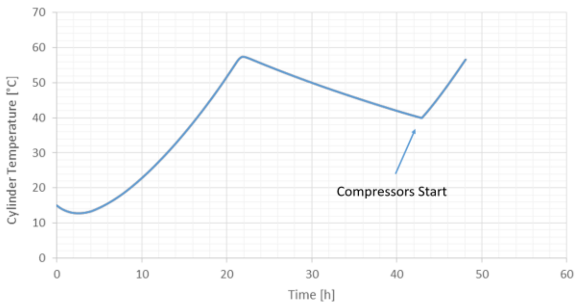

Figure 6.17 – Cylinder temperature – Loading phase – 12 MNm³ – Mediterranean Sea

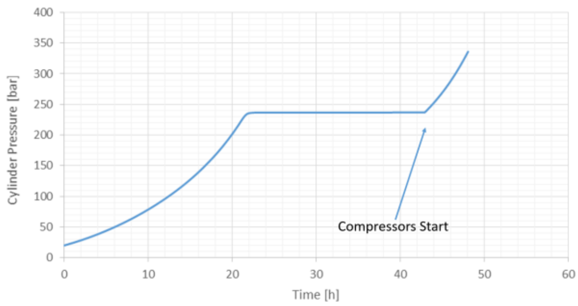

Figure 6.18 – Cylinder pressure – Loading phase – 12 MNm³ – Mediterranean Sea

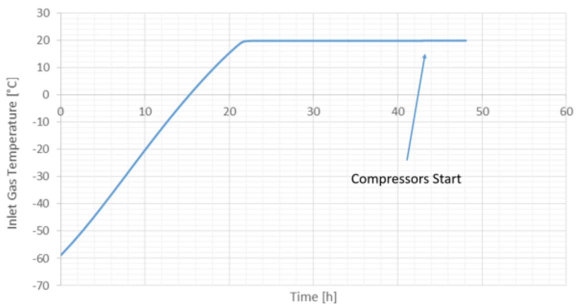

Figure 6.19 – Gas temperature at cylinder inlet – Loading phase – 12 MNm³ – Mediterranean Sea

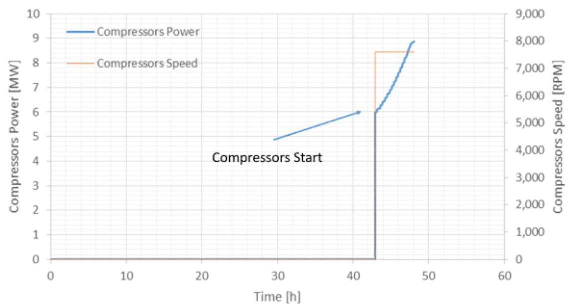

Figure 6.20 – Compressors power – Loading phase – 12 MNm³ – Mediterranean Sea

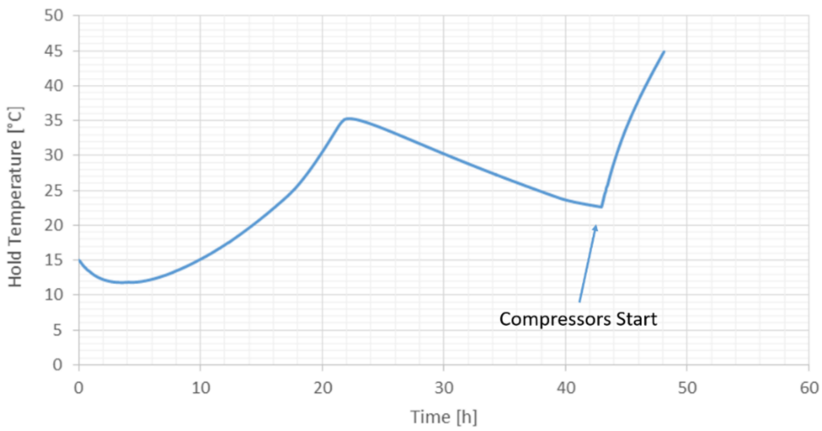

Figure 6.21 – Hold temperature – Loading phase – 12 MNm³ – Mediterranean Sea

Figure 6.15 shows the increasing of the gas quantity contained in the pressure cylinders. In the free loading phase the flow rate (Figure 6.16) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow rate increases thanks to the increase the density of the gas downstream of the valve and in the cylinders. When the pressure difference between the storage and the cylinders is small, the flow rate drops, but in this case, the compressors start when the cylinder temperature to drop to 40°C, carrying out the free loading phase with a minimum flow rate. If the temperature of the gas in the cylinders is brought to this temperature before starting the compressors, a commercial mass of gas of about 12 MNm^3 is guaranteed. When the compressors are started, the flow rate curve shows oscillations related to the opening of the throttle valves of the compressors.

Figure 6.17 and Figure 6.18 show the trend of temperature and pressure inside the cylinders. The temperature of the gas at the cylinders inlet is shown in Figure 6.19 with a minimum temperature of –59°C at the beginning of the process. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressors and must be cooled down in the post cooler. Figure 6.20 shows the power absorbed by the compressors with a maximum of 8.9 MW at 7600 rpm. The temperature of the hold is shown in Figure 6.21 with a maximum value of 45°C.

6.4 12 MNm^3 simulation – Unloading Phase

At the end of the loading phase the cylinders reach a temperature of 57°C and, therefore, the temperature of the hold tends to reach this value. The high temperature in the hold facilitates the unloading process but a temperature too high in the hold is not acceptable due to safety reasons.

During navigation, in a first phase, it is necessary to cool down the hold to maintain a temperature of about 40°C so that the hold can be accessible by operators equipped with the appropriate protections in case of emergency operations. Once this temperature is reached, it is kept constant until the beginning of the unloading phase by supplying heat, if necessary, using two boilers of 3 MW each. For the unloading phase, an initial hold temperature of 40°C was considered. If at the time of discharge the gas temperature is still higher than 40°C it is better for the process.

Table 6.4 – Simulation data – Unloading phase – 12 MNm^3 – Mediterranean Sea

Unloading Phase		
Initial On–Shore Storage Pressure	bar	80
Initial Cylinders Pressure	bar	301
Initial Cylinders Temperature	°C	40
Initial Cylinder Density	kg/m^3	199
Final On–Shore Storage Pressure	bar	80
Final Cylinders Pressure	bar	20
Final Cylinders Temperature	°C	32
Final Cylinder Density	kg/m^3	13
Unloading Time	h	69
Unloading compressors consumption	ton	18

Unloading Phase		
Average Flow Rate	kg/s	36
	Nm^3/h	179,130
Maximum Flow Rate	kg/s	85
	Nm^3/h	427,951
Remaining Mass Inside Cylinders	ton	621
	Nm^3	865,032
Unloaded Mass	**ton**	**8,818**
	Nm^3	**12,290,938**

The unloading phase lasts 69 hours, 19 hours of free unloading and 50 hours of forced unloading. During the process 12,290,938 Nm^3 of gas are unloaded. In assessing the quantity of gas unloaded, the gas consumed by the compressors was taken into account.

In this case it is possible to unload 687,581 Nm^3 more than the minimum time strategy.

The figures from Figure 6.22 to Figure 6.28 show the graphs of the main parameters of the unloading phase.

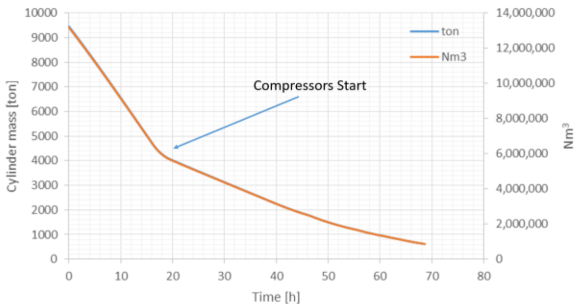

Figure 6.22 – Unloaded mass – Unloading phase – 12 MNm^3 – Mediterranean Sea

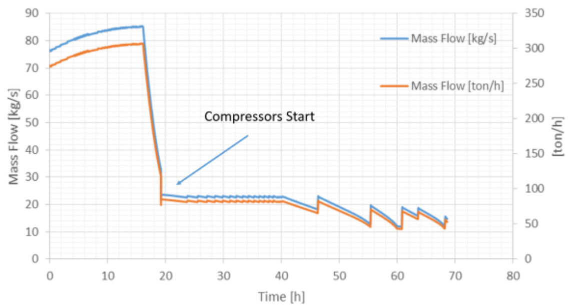

Figure 6.23 – Flow rate – Unloading phase – 12 MNm^3 – Mediterranean Sea

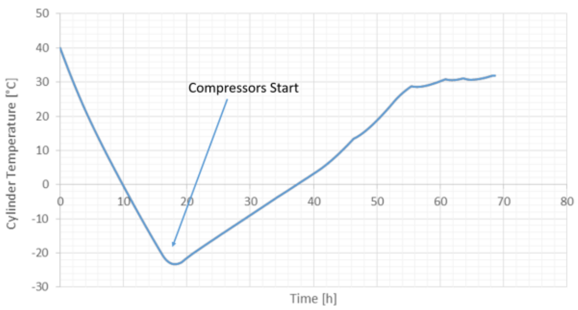

Figure 6.24 – Cylinder temperature – Unloading phase – 12 MNm^3 – Mediterranean Sea

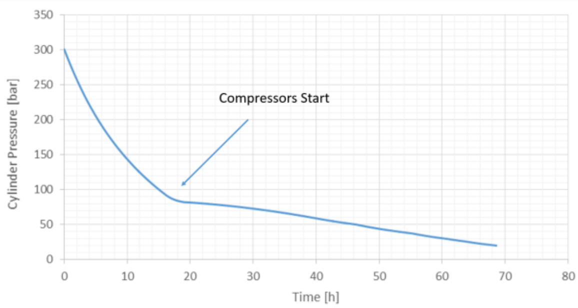

Figure 6.25 – Cylinder pressure – Unloading phase – 12 MNm^3 – Mediterranean Sea

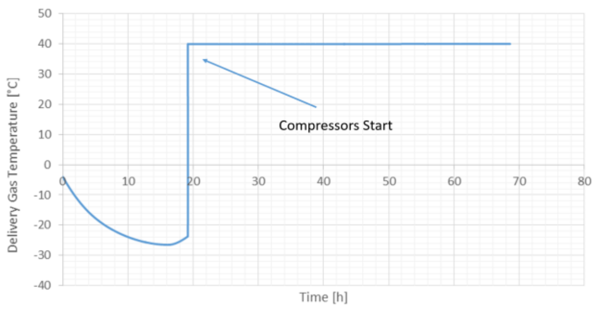

Figure 6.26 – Delivery gas temperature – Unloading phase – 12 MNm^3 – Mediterranean Sea

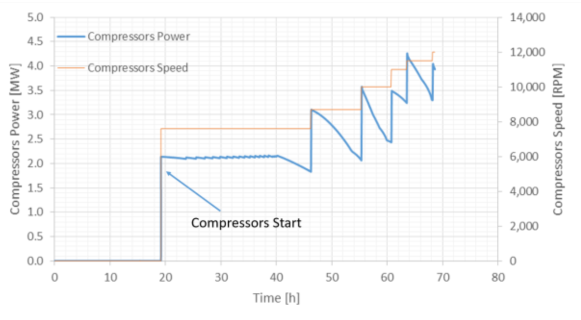

Figure 6.27 – Compressors power – Unloading phase – 12 MNm^3 – Mediterranean Sea

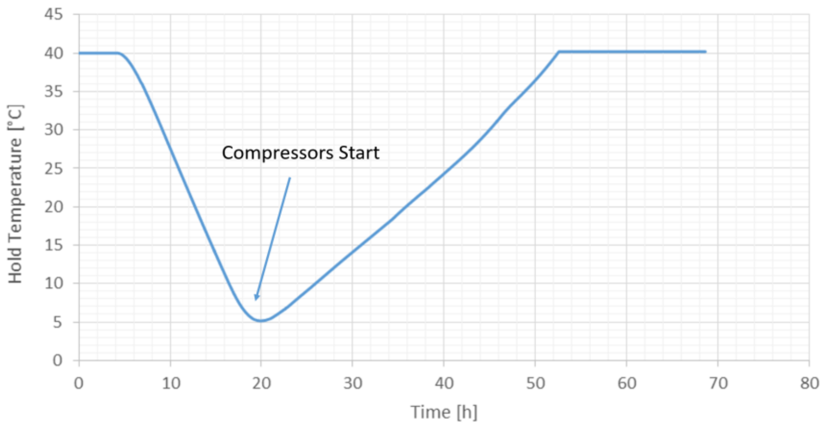

Figure 6.28 – Hold temperature – Unloading phase – 12 MNm^3 – Mediterranean Sea

Figure 6.22 shows the decrease of the gas quantity contained in the pressure cylinders. In the free unloading phase the flow rate (Figure 6.23) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow rate increases thanks to the decrease of the gas density upstream of the valve and in the cylinders.

When the pressure difference between the cylinders and the storage is small, the flow rate drops and the compressors are started. In the first part of the flow rate curve, since from the start of the compressors there are oscillations related to the opening of the throttle valves of the compressors. In the second part of the curve, some peaks corresponding to the change of the speed of the compressors can be observed.

Figure 6.24 and Figure 6.25 show the temperature and pressure trends inside the cylinders.

The delivery gas temperature is shown in Figure 6.26 with a minimum temperature, during the free unloading phase, of -26°C. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler.

Figure 6.27 shows the power absorbed by the compressors with a maximum of 4.3 MW at 11,500 rpm. The maximum compression ratio is 4. The temperature of the hold is shown in

Figure 6.28 with a maximum value of 40°C and a minimum of 5°C.

6.5 Fuel consumption for specific scenarios of Mediterranean Sea

Once again macro areas were considered instead of the specific locations due to the limited differences of the characteristic ambient conditions for what concerns the dynamics of the loading and unloading processes.

By the way in order to evaluate the quantity of discharged gas at the unloading point the specific routes have to be considered because a different length of the route leads to a different fuel consumption which affects directly the amount of the gas that can be discharged.

Table 6.5 – Shipping time for specific scenarios of Mediterranean Sea

Mediterranean Sea Routes		**DISTANCE**	**TIME**	**TIME (+20%)**
Loading point	**Unloading point**	**km**	**days**	**days**
Vasilikos (Cyprus)	Lebanon	200	0.3	0.34
Vasilikos (Cyprus)	Linoperamata (Crete)	910	1.2	1.5
Vasilikos (Cyprus)	Egypt	530	0.7	0.85

The Table 6.5 shows the loading and unloading points with the estimated distance between these two points followed by the navigation days plus a column where the days spent at sea has been increased by the 20% to take into account the real conditions (e.g. real route, sea conditions, manoeuvring time). This is the time which was taken into account for the evaluation of the gas discharged.

With such data an assessment of the quantity of the discharged gas, closer to the real value, can be carried out.

Table 6.6 – Estimated gas unload for Vasilikos (Cyprus) – Lebanon scenario

Transport consumption Vasilikos (Cyprus) – Lebanon		
Sailing time	days	0.34
Speed	Knot	17
Specific Fuel Consumption	g/kWh	143
Total fuel consumption	ton	14
Unloading Phase		
Remaining Mass Inside Cylinders	ton	621
	Nm^3	865,032
Unloaded Mass	ton	8,804
	Nm^3	12,271,459

Table 6.7 – Estimated gas unload for Vasilikos (Cyprus) – Linoperamata (Crete) scenario

Transport consumption Vasilikos (Cyprus) – Linoperamata (Crete)		
Sailing time	days	1.50
Speed	Knot	17
Specific Fuel Consumption	g/kWh	143
Total fuel consumption	ton	61
Unloading Phase		
Remaining Mass Inside Cylinders	ton	621
	Nm^3	865,032
Unloaded Mass	ton	8,757
	Nm^3	12,205,766

Table 6.8 – Estimated gas unload for Vasilikos (Cyprus) – Egypt scenario

Transport consumption Vasilikos (Cyprus) – Egypt		
Sailing time	days	0.85
Speed	Knot	17
Specific Fuel Consumption	g/kWh	143
Total fuel consumption	ton	35
Unloading Phase		
Remaining Mass Inside Cylinders	ton	621
	Nm^3	865,032
Unloaded Mass	ton	8,784
	Nm^3	12,242,577

The assessment of the real discharged gas was carried out referring to the 12 MNm^3 simulations. It has to be highlighted that the results come from an approximation of the real case because of the uncertainties about the route, furthermore the assessment of the discharged gas was made by considering the 12 MNm^3 simulations of the macro areas and subtracting the fuel used for the navigation.

In Table 6.6, Table 6.7 and Table 6.8 is possible to observe that the decrease in the delivered gas due to the fuel consumption of the ship does not affect in a relevant way the amount of gas discharged that is in any case higher than 12 MNm^3.

The gas used during the navigation represent in the worst case only the 0.70% of the overall unloadable gas.

7. Black Sea conditions

7.1 Minimum loading time simulation – Loading Phase

For the loading phase it was considered an initial hold temperature of 15°C because the low temperature facilitates the loading process. This temperature is obtained by cooling down the hold with fan coils during navigation with the empty vessel. The cold power is provided by four chillers of 1.4 MW each. The remaining initial parameters for the simulation are shown in the Table 7.1.

Table 7.1 – Simulation data – Loading phase – Min. Time – Black Sea

Loading Phase		
Initial On–Shore Storage Pressure	bar	240
Initial On–Shore Storage Temperature	°C	25
Initial Cylinders Pressure	bar	20
Initial Cylinders Temperature	°C	15
Initial Cylinder Density	kg/m^3	14
Final On–Shore Storage Pressure	bar	240
Final On–Shore Storage Temperature	°C	25
Final Cylinders Pressure	bar	336
Final Cylinders Temperature	°C	69
Final Cylinder Density	kg/m^3	189
Loading time	h	28
Loading compressors consumption	ton	6
Average Flow Rate	kg/s	81
	Nm^3/h	408,216
Maximum Flow Rate	kg/s	128
	Nm^3/h	640,595
Mass Inside Cylinders	ton	8,979
	Nm^3	12,515,008
Loaded Mass	**ton**	**8,315**
	Nm^3	**11,590,107**

The loading phase lasts 28 hours, 22 hours of free loading and 6 hours of forced loading. As shown in Table 7.1, the cylinder temperature at the end of the process is 69°C. In these conditions the total mass of gas, at a pressure of 335 bar, which can be stored in the cylinders is 12,515,008 Nm^3 and the mass loaded during the process is 11,590,107 Nm^3.

The figures from Figure 7.1 to Figure 7.7 show the graphs of the main parameters of the loading phase.

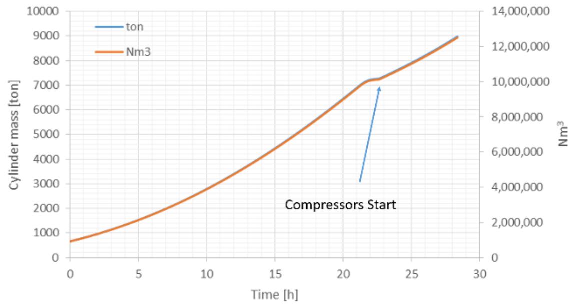

Figure 7.1 – Loaded mass – Loading phase – Min. Time – Black Sea

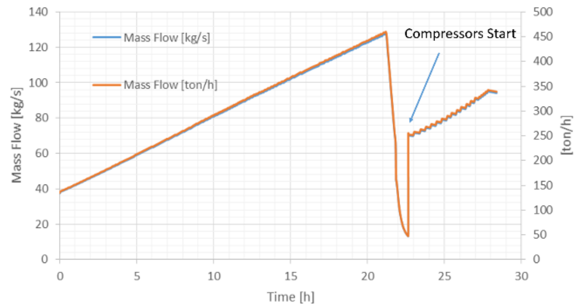

Figure 7.2 – Flow rate – Loading phase – Min. Time – Black Sea

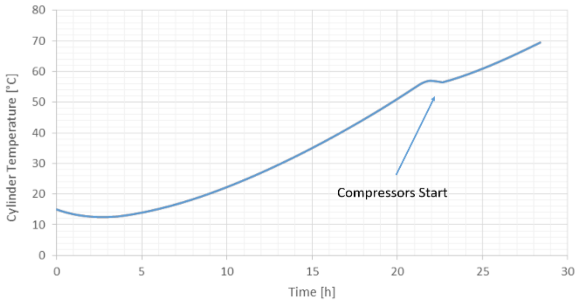

Figure 7.3 – Cylinder temperature – Loading phase – Min. Time – Black Sea

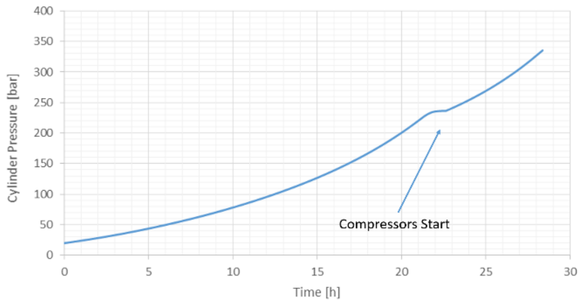

Figure 7.4 – Cylinder pressure – Loading phase – Min. Time – Black Sea

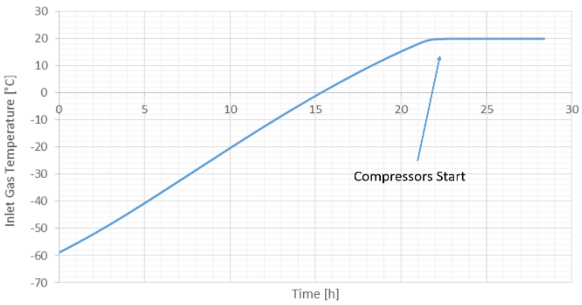

Figure 7.5 – Gas temperature at cylinder inlet – Loading phase – Min. Time – Black Sea

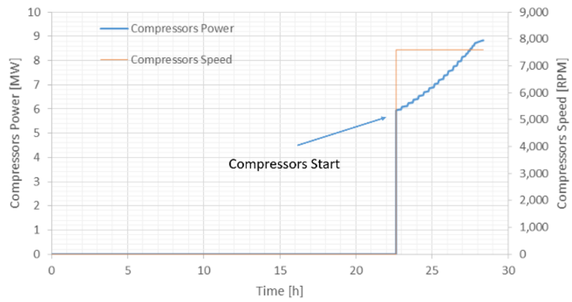

Figure 7.6 – Compressors power – Loading phase – Min. Time – Black Sea

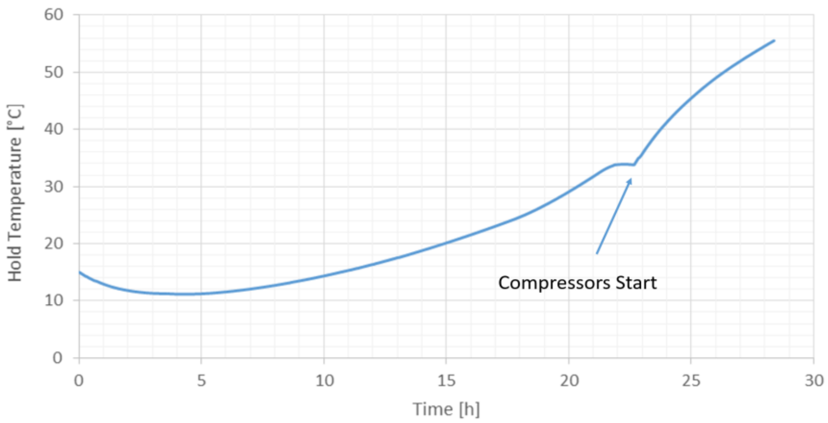

Figure 7.7 – Hold temperature – Loading phase – Min. Time – Black Sea

Figure 7.1 shows the increasing of the gas quantity contained in the pressure cylinders. In the free loading phase the flow rate (Figure 7.2) is controlled by the regulating valve in order to limit the gas speed in the pipes. At the beginning the flow rate increases thanks to the increase of the gas density downstream of the valve and in the cylinders. When the pressure difference between the storage and the cylinders is small, the flow rate drops and the compressors are started. The oscillatory course of the flow curve and the curve of the power absorbed by the compressors (Figure 7.6) are related to the opening of the throttle valves of the compressors.

Figure 7.3 and Figure 7.4 show the increasing trend of temperature and pressure inside the cylinders. The temperature of the gas at the cylinders inlet is shown in Figure 7.5 with a minimum temperature of –59°C at the beginning of the process. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler. Figure 7.6 shows the power absorbed by the compressors with a maximum of 8.9 MW at 7600 rpm. The temperature of the hold is shown in Figure 7.7 with a maximum value of 55°C.

7.2 Minimum loading time simulation – Unloading Phase

At the end of the loading phase the cylinders reach a temperature of 69°C and, therefore, the temperature of the hold tends to reach this value. The high temperature in the hold facilitates the unloading process but a temperature too high in the hold is not acceptable due to safety reasons.

During navigation, in a first phase, it is necessary to cool down the hold to maintain a temperature of about 40°C so that the hold can be accessible by operators equipped with the appropriate protections in case of emergency operations. Once this temperature is reached, it is kept constant until the beginning of the unloading phase by supplying heat, if necessary, using two boilers of 3 MW each. For the unloading phase, an initial hold temperature of 40°C was considered. If at the time of discharge the gas temperature is still higher than 40°C it is better for the process.

Table 7.2 – Simulation data – Unloading phase – Min. Time – Black Sea

Unloading Phase		
Initial On–Shore Storage Pressure	bar	80
Initial Cylinders Pressure	bar	279
Initial Cylinders Temperature	°C	40
Initial Cylinder Density	kg/m^3	13
Final On–Shore Storage Pressure	bar	80
Final Cylinders Pressure	bar	20
Final Cylinders Temperature	°C	32
Final Cylinder Density	kg/m^3	13
Unloading Time	h	66
Unloading Compressors Consumption	ton	17
Average Flow Rate	kg/s	35
	Nm^3/h	175,684
Maximum Flow Rate	kg/s	84

Unloading Phase		
	Nm^3/h	421,222
Remaining Mass Inside Cylinders	ton	620
	Nm^3	864,839
Unloaded Mass	**ton**	**8,341**
	Nm^3	**11,626,190**

The unloading phase lasts 66 hours, 18 hours of free unloading and 48 hours of forced unloading. During the process 11,626,190 Nm^3 of gas are unloaded. To assess the quantity of gas unloaded, the gas consumed by the compressors was taken into account.

The figures from Figure 7.8 to Figure 7.14 show the graphs of the main parameters of the unloading phase.

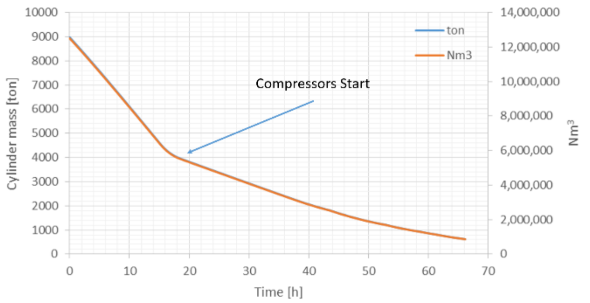

Figure 7.8 – Unloaded mass – Unloading phase – Min. Time – Black Sea

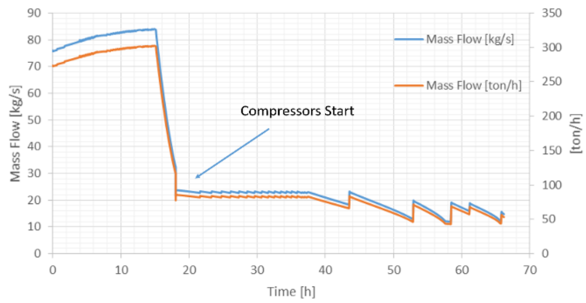

Figure 7.9 – Flow rate – Unloading phase – Min. Time – Black Sea

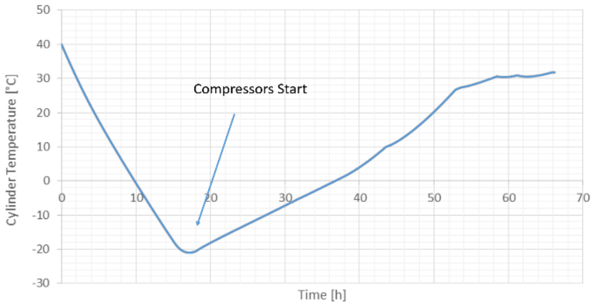

Figure 7.10 – Cylinder temperature – Unloading phase – Min. Time – Black Sea

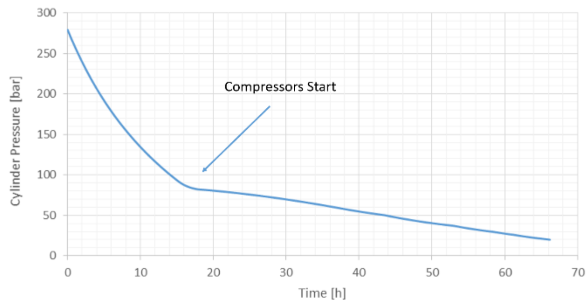

Figure 7.11 – Cylinder pressure – Unloading phase – Min. Time – Black Sea

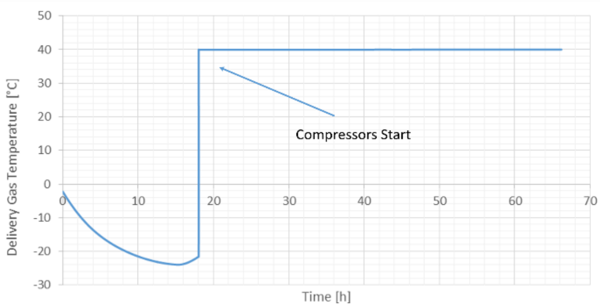

Figure 7.12 – Delivery gas temperature – Unloading phase – Min. Time – Black Sea

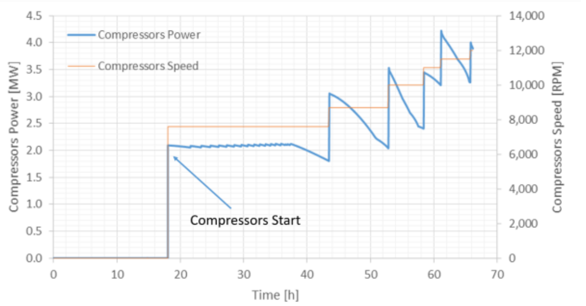

Figure 7.13 – Compressors power – Unloading phase – Min. Time – Black Sea

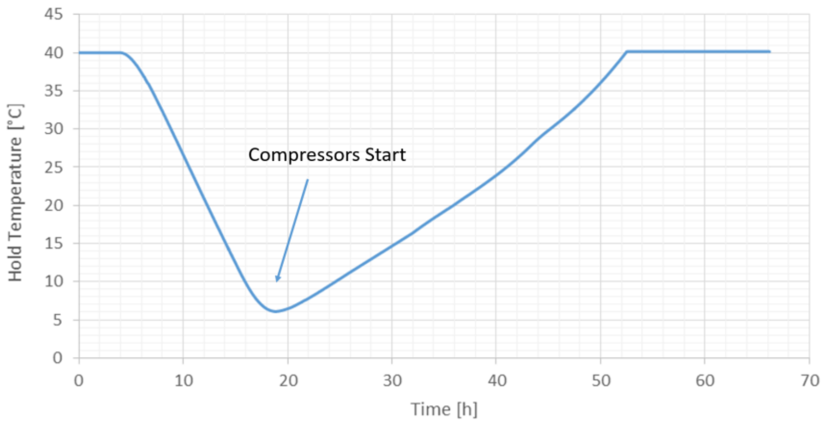

Figure 7.14 – Hold temperature – Unloading phase – Min. Time – Black Sea

Figure 7.8 shows the decrease of the gas quantity contained in the pressure cylinders. In the free unloading phase the flow rate (Figure 7.9) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow increases thanks to the decrease of the gas density upstream of the valve and in the cylinders.

When the pressure difference between the cylinders and the storage is small, the flow rate drops and the compressors are started. In the first part of the flow rate curve, from the start of the compressors there are oscillations related to the opening of the throttle valves of the compressors. In the second part of the curve, some peaks corresponding to the change of the speed of the compressors can be observed.

Figure 7.10 and Figure 7.11 show the temperature and pressure trends inside the cylinders.

The delivery gas temperature is shown in Figure 7.12 with a minimum temperature, during the free unloading phase, of –24°C. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler.

Figure 7.13 shows the power absorbed by the compressors with a maximum of 4.2 MW at 11,500 rpm. The maximum compression ratio is 4. The temperature of the hold is shown in Figure 7.14 with a maximum value of 40°C and a minimum of 6°C.

7.3 12 MNm^3 simulation – Loading Phase

For the loading phase it was considered an initial hold temperature of 15°C because the low temperature facilitates the loading process. This temperature is obtained by cooling down the hold with fan coils during navigation with the empty vessel. The cold power is provided by four chillers of 1.4 MW each. The remaining initial parameters for the simulation are shown in the Table 7.3.

Table 7.3 – Simulation data – Loading phase – 12 MNm^3 – Black Sea

Loading Phase		
Initial On–Shore Storage Pressure	bar	240
Initial On–Shore Storage Temperature	°C	25
Initial Cylinders Pressure	bar	20
Initial Cylinders Temperature	°C	15
Initial Cylinder Density	kg/m^3	14
Final On–Shore Storage Pressure	bar	240
Final On–Shore Storage Temperature	°C	25
Final Cylinders Pressure	bar	335
Final Cylinders Temperature	°C	56
Final Cylinder Density	kg/m^3	199
Loading Time	h	47
Loading Compressors Consumption	ton	5
Average Flow Rate	kg/s	52
	Nm^3/h	262,341
Maximum Flow Rate	kg/s	128
	Nm^3/h	640,595
Mass Inside Cylinders	ton	9,455
	Nm^3	13,177,894
Loaded Mass	**ton**	**8,791**
	Nm^3	**12,252,993**

The loading phase lasts 47 hours, 19 hours more than the minimum time strategy simulation. The cylinder temperature at the end of the process in this case is 56°C and therefore lower than the previous case by 13°C. The total mass of gas in the cylinders, at the pressure of 335 bar, is 13,177,894 Nm^3 and the loaded mass is 12,252,993 Nm^3, therefore higher than the previous case of 662,886 Nm^3.

The figures from Figure 7.15 to Figure 7.21 show the graphs of the main parameters of the loading phase.

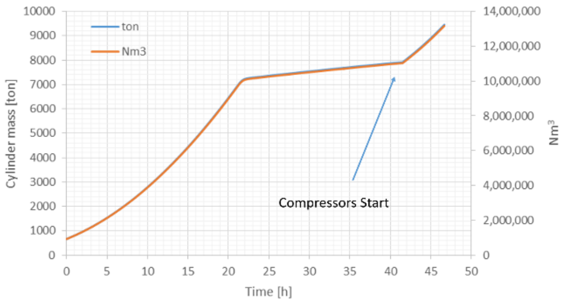

Figure 7.15 – Loaded mass – Loading phase – 12 MNm^3 – Black Sea

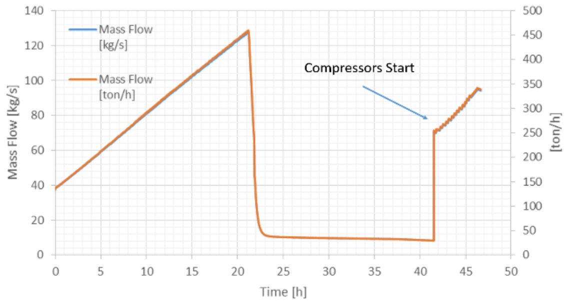

Figure 7.16 – Flow rate – Loading phase – 12 MNm^3 – Black Sea

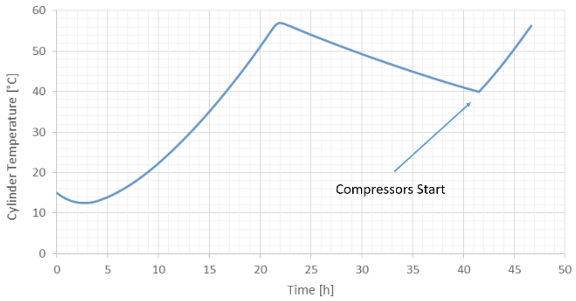

Figure 7.17 – Cylinder temperature – Loading phase – 12 MNm^3 – Black Sea

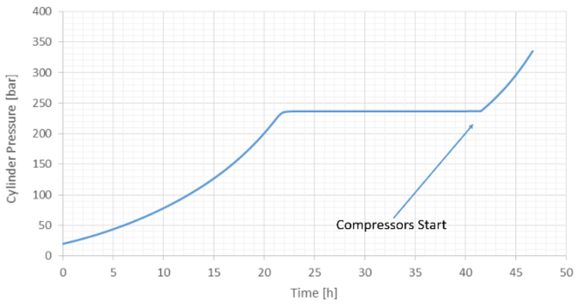

Figure 7.18 – Cylinder pressure – Loading phase – 12 MNm^3 – Black Sea

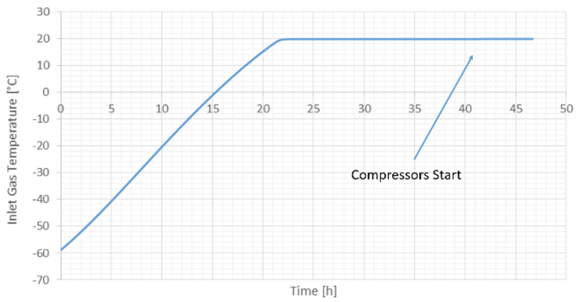

Figure 7.19 – Gas temperature at cylinder inlet – Loading phase – 12 MNm^3 – Black Sea

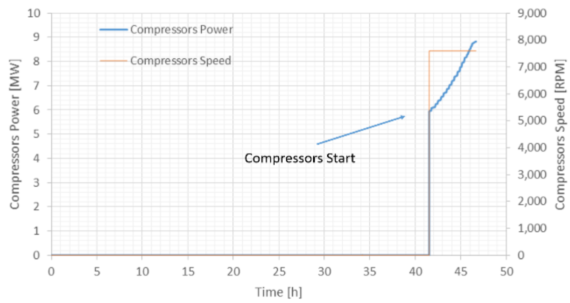

Figure 7.20 – Compressors power – Loading phase – 12 MNm^3 – Black Sea

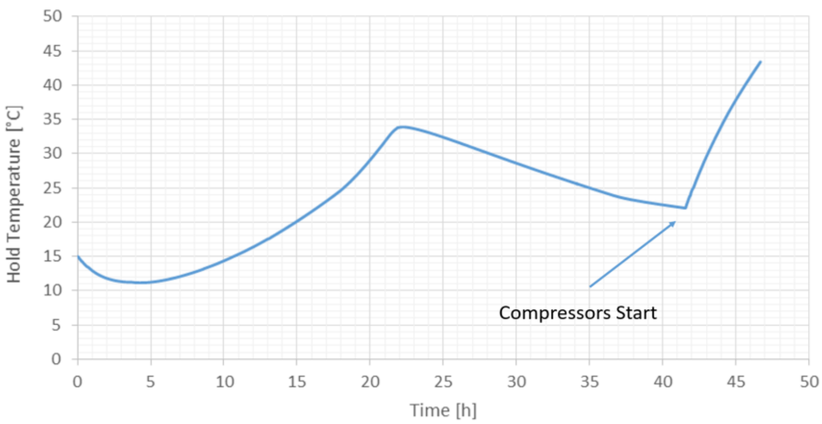

Figure 7.21 – Hold temperature – Loading phase – 12 MNm^3 – Black Sea

Figure 7.15 shows the increasing of the gas quantity contained in the pressure cylinders. In the free loading phase the flow rate (Figure 7.16) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow rate increases thanks to the increase the density of the gas downstream of the valve and in the cylinders. When the pressure difference between the storage and the cylinders is small, the flow rate drops, but in this case, the compressors start when the cylinder temperature to drop to 40°C, carrying out the free loading phase with a minimum flow rate. If the temperature of the gas in the cylinders is brought to this temperature before starting the compressors, a commercial mass of gas of about 12 MNm^3 is guaranteed. When the compressors

are started, the flow rate curve shows oscillations related to the opening of the throttle valves of the compressors.

Figure 7.17 and Figure 7.18 show the trend of temperature and pressure inside the cylinders. The temperature of the gas at the cylinders inlet is shown in Figure 7.19 with a minimum temperature of -59°C at the beginning of the process. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressors and must be cooled down in the post cooler. Figure 7.20 shows the power absorbed by the compressors with a maximum of 8.9 MW at 7600 rpm. The temperature of the hold is shown in Figure 7.21 with a maximum value of 43°C.

7.4 12 MNm^3 simulation – Unloading Phase

At the end of the loading phase the cylinders reach a temperature of 56°C and, therefore, the temperature of the hold tends to reach this value. The high temperature in the hold facilitates the unloading process but a temperature too high in the hold is not acceptable due to safety reasons.

During navigation, in a first phase, it is necessary to cool down the hold to maintain a temperature of about 40°C so that the hold can be accessible by operators equipped with the appropriate protections in case of emergency operations. Once this temperature is reached, it is kept constant until the beginning of the unloading phase by supplying heat, if necessary, using two boilers of 3 MW each. For the unloading phase, an initial hold temperature of 40°C was considered. If at the time of discharge the gas temperature is still higher than 40°C it is better for the process.

Table 7.4 – Simulation data – Unloading phase – 12 MNm^3 – Black Sea

Unloading Phase		
Initial On–Shore Storage Pressure	bar	80
Initial Cylinders Pressure	bar	301
Initial Cylinders Temperature	°C	40
Initial Cylinder Density	kg/m^3	13
Final On–Shore Storage Pressure	bar	80
Final Cylinders Pressure	bar	20
Final Cylinders Temperature	°C	32
Final Cylinder Density	kg/m^3	13
Unloading Time	h	69
Unloading Compressors Consumption	ton	18
Average Flow Rate	kg/s	35
	Nm^3/h	177,979
Maximum Flow Rate	kg/s	86
	Nm^3/h	429,101
Remaining Mass Inside Cylinders	ton	619
	Nm^3	863,449
Unloaded Mass	**ton**	**8,817**
	Nm^3	**12,289,374**

The unloading phase lasts 69 hours, 19 hours of free unloading and 50 hours of forced unloading. During the process 12,289,374 Nm^3 of gas are unloaded. In assessing the quantity of gas unloaded, the gas consumed by the compressors was taken into account.

In this case it is possible to unload 663,184 Nm^3 more than the minimum time strategy.

The figures from Figure 7.22 to Figure 7.28 show the graphs of the main parameters of the unloading phase.

Figure 7.22 shows the decrease of the gas quantity contained in the pressure cylinders. In the free unloading phase the flow rate (Figure 7.23) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow rate increases thanks to the decrease of the gas density upstream of the valve and in the cylinders.

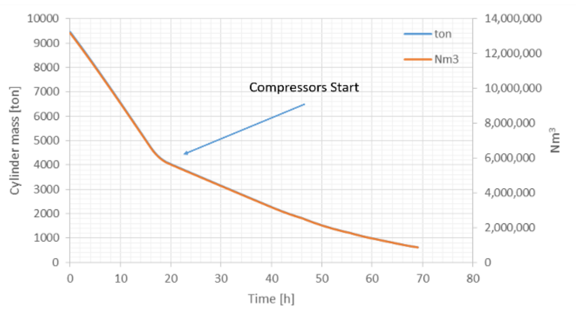

Figure 7.22 – Unloaded mass – Unloading phase – 12 MNm^3 – Black Sea

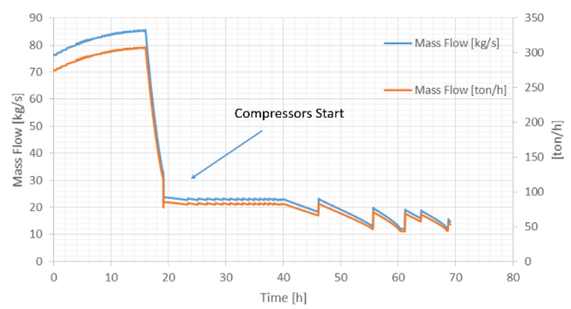

Figure 7.23 – Flow rate – Unloading phase – 12 MNm^3 – Black Sea

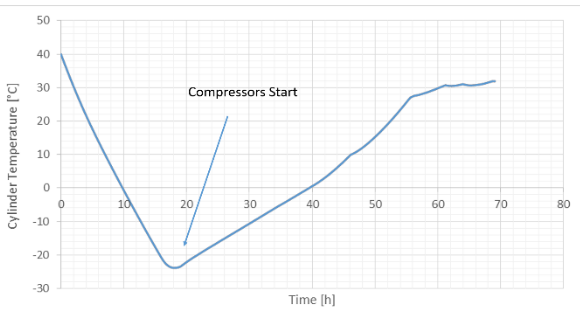

Figure 7.24 – Cylinder temperature – Unloading phase – 12 MNm^3 – Black Sea

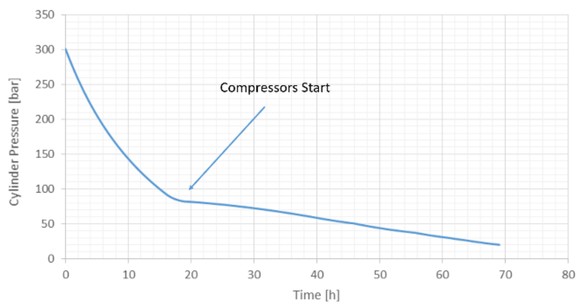

Figure 7.25 – Cylinder pressure – Unloading phase – 12 MNm^3 – Black Sea

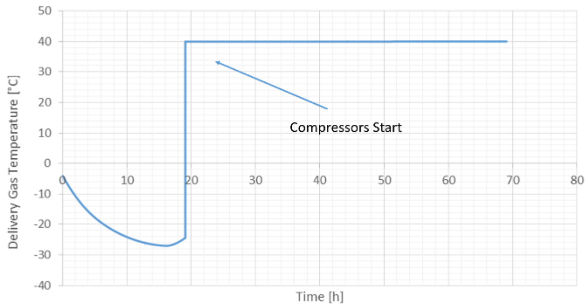

Figure 7.26 – Delivery gas temperature – Unloading phase – 12 MNm^3 – Black Sea

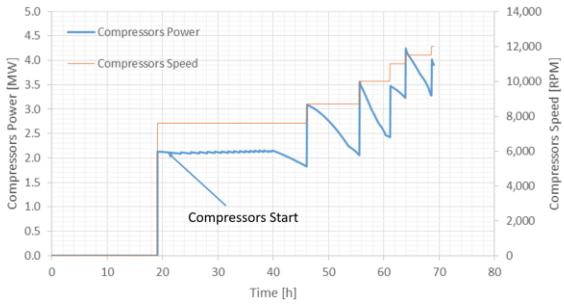

Figure 7.27 – Compressors power – Unloading phase – 12 MNm^3 – Black Sea

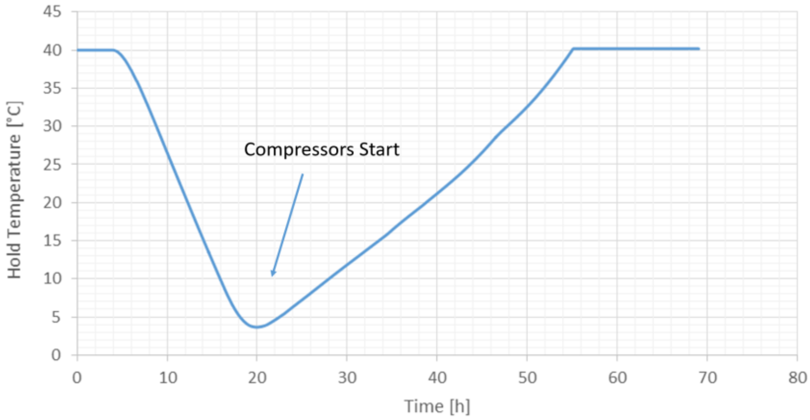

Figure 7.28 – Hold temperature – Unloading phase – 12 MNm^3 – Black Sea

When the pressure difference between the cylinders and the storage is small, the flow rate drops and the compressors are started. In the first part of the flow rate curve, since from the start of the compressors there are oscillations related to the opening of the throttle valves of the compressors. In the second part of the curve, some peaks corresponding to the change of the speed of the compressors can be observed.

Figure 7.24 and Figure 7.25 show the temperature and pressure trends inside the cylinders.

The delivery gas temperature is shown in Figure 7.26 with a minimum temperature, during the free unloading phase, of -27°C. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler.

Figure 7.27 shows the power absorbed by the compressors with a maximum of 4.2 MW at 11,500 rpm. The maximum compression ratio is 4. The temperature of the hold is shown in Figure 7.28 with a maximum value of 40°C and a minimum of 4°C.

7.5 Fuel consumption for specific scenarios of Black Sea

As already said macro areas were considered instead of the specific locations due to the small differences of their ambient conditions. It has however to be noted that in order to evaluate the quantity of discharged gas at the unloading point the specific routes have to be considered because a different length of the route leads to a different fuel consumption which affects directly the amount of the gas that can be discharged.

Table 7.5 – Shipping time for specific scenario of Black Sea

Black Sea Routes		**DISTANCE**	**TIME**	**TIME (+20%)**
Loading point	**Unloading point**	**km**	**days**	**days**
Poti (Georgia)	Yuzne (Ukraine)	1000	1.3	1.7

The Table 7.5 shows the loading and unloading points with the estimated distance between these two points followed by the navigation days plus a column where the days spent at sea has been increased by the 20% to take into account the real conditions (e.g. real route, sea conditions, manoeuvring time). This is the time which was taken into account for the evaluation of the gas discharged.

With such data an assessment of the quantity of the discharged gas, closer to the real value, can be carried out.

The assessment of the real discharged gas was carried out referring to the 12 MNm^3 simulations. It has to be highlighted that the results come from an approximation of the real case because of the uncertainties about the route, furthermore the assessment of the discharged gas was made by considering the 12 MNm^3 simulations of the macro areas and subtracting the fuel used for the navigation.

Table 7.6 – Estimated gas unload for Poti (Georgia) – Yuzne (Ukraine) scenario

Transport consumption Poti (Georgia) – Yuzne (Ukraine)		
Sailing time	days	1.7
Speed	Knots	16.5
Specific Fuel Consumption	g/kWh	142.6
Total fuel consumption	ton	69
Unloading Phase		
Remaining Mass Inside Cylinders	ton	619
	Nm3	863,449
Unloaded Mass	**ton**	**8,748**
	Nm3	**12,193,083**

In Table 7.6 is possible to observe that the decrease in the delivered gas due to the fuel consumption of the ship does not affect in a relevant way the amount of gas discharged that is in any case higher than 12 MNm^3. The gas used during the navigation represent only the 0.79% of the overall unloadable gas.

8. Barents Sea

8.1 Minimum loading time simulation – Loading Phase

For the loading phase it was considered an initial hold temperature of 15°C because the low temperature facilitates the loading process. This temperature is obtained by cooling down the hold with fan coils during navigation with the empty vessel. The cold power is provided by four chillers of 1.4 MW each. The remaining initial parameters for the simulation are shown in the Table 8.1.

Table 8.1 – Simulation data – Loading phase – Min. Time – Barents Sea

Loading Phase		
Initial On–Shore Storage Pressure	bar	240
Initial On–Shore Storage Temperature	°C	20
Initial Cylinders Pressure	bar	20
Initial Cylinders Temperature	°C	15
Initial Cylinder Density	kg/m^3	14
Final On–Shore Storage Pressure	bar	240
Final On–Shore Storage Temperature	°C	20
Final Cylinders Pressure	bar	336
Final Cylinders Temperature	°C	68
Final Cylinder Density	kg/m^3	190
Loading Time	h	28
Loading Compressors Consumption	ton	6
Average Flow Rate	kg/s	84
	Nm^3/h	419,132
Maximum Flow Rate	kg/s	129
	Nm^3/h	644,811
Mass Inside Cylinders	ton	9,045
	Nm^3	12,607,282
Loaded Mass	**ton**	**8,382**
	Nm^3	**11,682,381**

The loading phase lasts 28 hours, 22 hours of free loading and 6 hours of forced loading. As shown in Table 8.1, the cylinder temperature at the end of the process is 68°C. In these conditions the total mass of gas, at a pressure of 335 bar, which can be stored in the cylinders is 12,607,282 Nm^3 and the mass loaded during the process is 11,682,381 Nm^3.

The figures from Figure 8.1 to Figure 8.7 show the graphs of the main parameters of the loading phase.

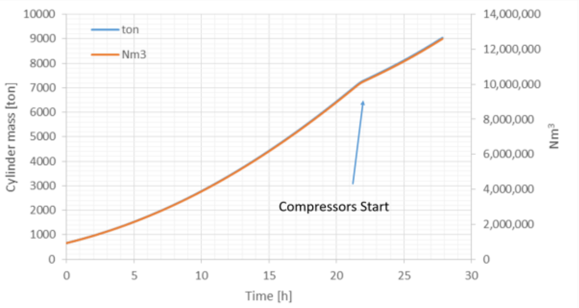

Figure 8.1 – Loaded mass – Loading phase – Min. Time – Barents Sea

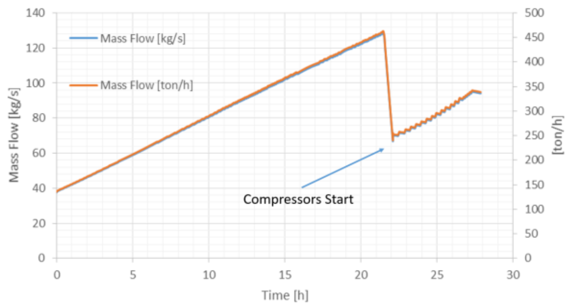

Figure 8.2 – Flow rate – Loading phase – Min. Time – Barents Sea

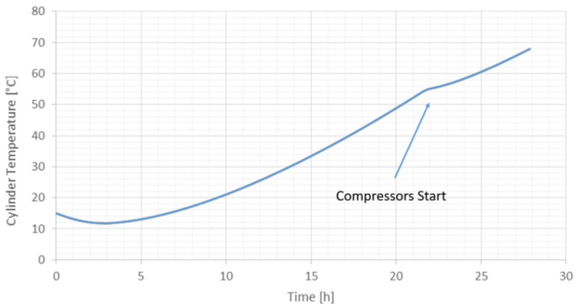

Figure 8.3 – Cylinder temperature – Loading phase – Min. Time – Barents Sea

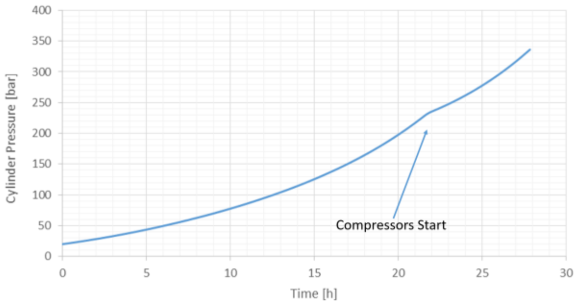

Figure 8.4 – Cylinder pressure – Loading phase – Min. Time – Barents Sea

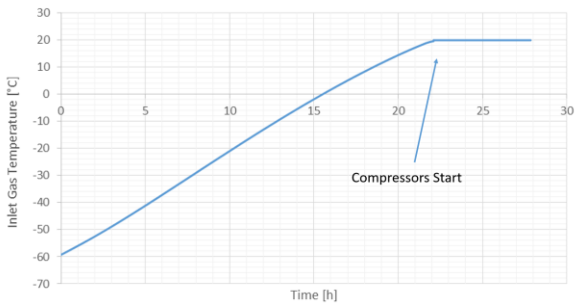

Figure 8.5 – Gas temperature at cylinder inlet – Loading phase – Min. Time – Barents Sea

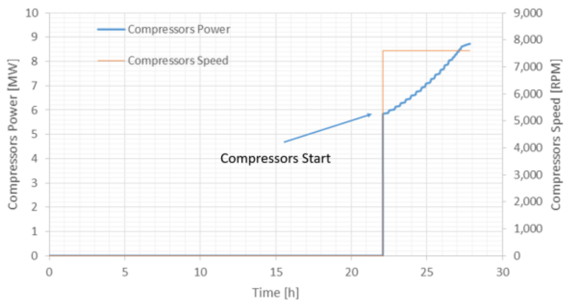

Figure 8.6 – Compressors power – Loading phase – Min. Time – Barents Sea

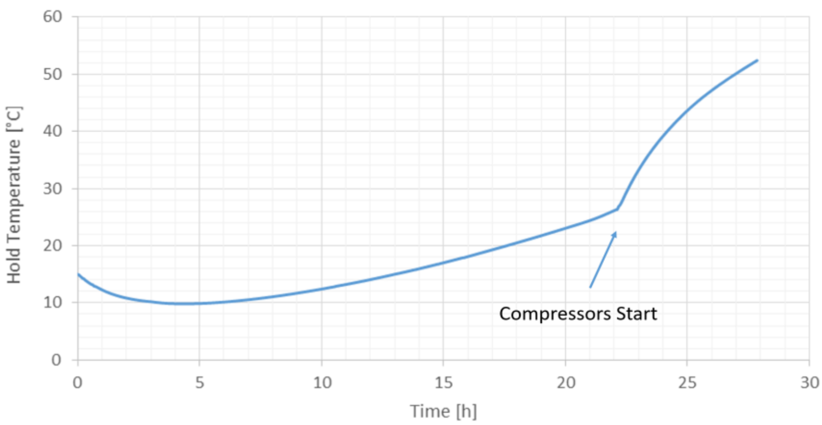

Figure 8.7 – Hold temperature – Loading phase – Min. Time – Barents Sea

Figure 8.1 shows the increasing of the gas quantity contained in the pressure cylinders. In the free loading phase the flow rate (Figure 8.2) is controlled by the regulating valve in order to limit the gas speed in the pipes. At the beginning the flow rate increases thanks to the increase of the gas density downstream of the valve and in the cylinders. When the pressure difference between the storage and the cylinders is small, the flow rate drops and the compressors are started. The oscillatory course of the flow curve and the curve of the power absorbed by the compressors (Figure 8.6) are related to the opening of the throttle valves of the compressors.

Figure 8.3 and Figure 8.4 show the increasing trend of temperature and pressure inside the cylinders. The temperature of the gas at the cylinders inlet is shown in Figure 8.5 with a minimum temperature of -59°C at the beginning of the process. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler. Figure 8.6 shows the power absorbed by the compressors with a maximum of 8.7 MW at 7600 rpm. The temperature of the hold is shown in Figure 8.7 with a maximum value of 52°C.

8.2 Minimum loading time simulation – Unloading Phase

At the end of the loading phase the cylinders reach a temperature of 68°C and, therefore, the temperature of the hold tends to reach this value. The high temperature in the hold facilitates the unloading process but a temperature too high in the hold is not acceptable due to safety reasons.

During navigation, in a first phase, it is necessary to cool down the hold to maintain a temperature of about 40°C so that the hold can be accessible by operators equipped with the appropriate protections in case of emergency operations. Once this temperature is reached, it is kept constant until the beginning of the unloading phase by supplying heat, if necessary, using two boilers of 3 MW each. For the unloading phase, an initial hold temperature of 40°C was considered. If at the time of discharge the gas temperature is still higher than 40°C it is better for the process.

Table 8.2 – Simulation data – Unloading phase – Min. Time – Barents Sea

Unloading Phase		
Initial On–Shore Storage Pressure	bar	80
Initial Cylinders Pressure	bar	282
Initial Cylinders Temperature	°C	40
Initial Cylinder Density	kg/m^3	190
Final On–Shore Storage Pressure	bar	80
Final Cylinders Pressure	bar	20
Final Cylinders Temperature	°C	32
Final Cylinder Density	kg/m^3	13
Unloading Time	h	67
Unloading Compressors Consumption	ton	18
Average Flow Rate	kg/s	35
	Nm^3/h	174,592
Maximum Flow Rate	kg/s	85

Unloading Phase		
	Nm^3/h	424,182
Remaining Mass Inside Cylinders	ton	620
	Nm^3	864,496
Unloaded Mass	**ton**	**8,407**
	Nm^3	**11,718,274**

The unloading phase lasts 67 hours, 18 hours of free unloading and 49 hours of forced unloading. During the process 11,718,274 Nm^3 of gas are unloaded. To assess the quantity of gas unloaded, the gas consumed by the compressors was taken into account.

The figures from Figure 8.8 to Figure 8.14 show the graphs of the main parameters of the unloading phase.

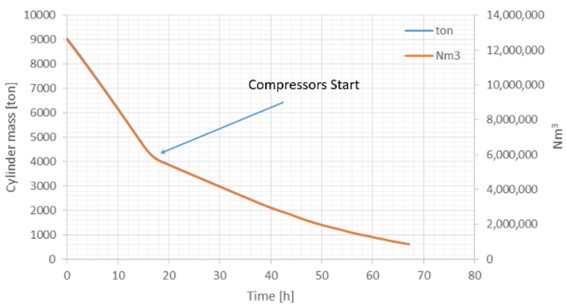

Figure 8.8 – Unloaded mass – Unloading phase – Min. Time – Barents Sea

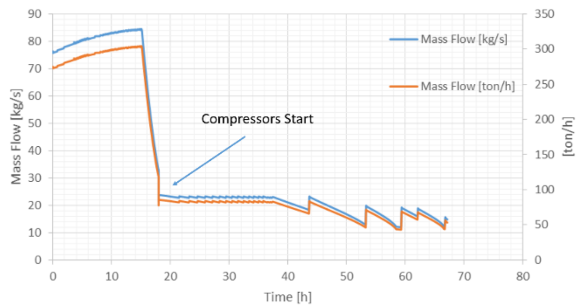

Figure 8.9 – Flow rate – Unloading phase – Min. Time – Barents Sea

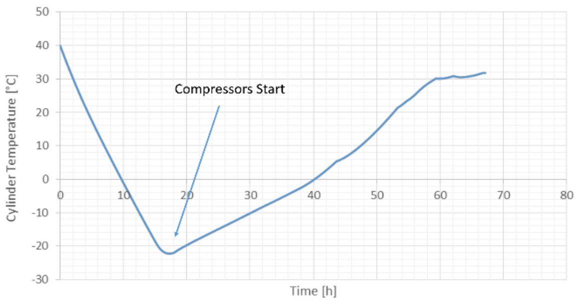

Figure 8.10 – Cylinder temperature – Unloading phase – Min. Time – Barents Sea

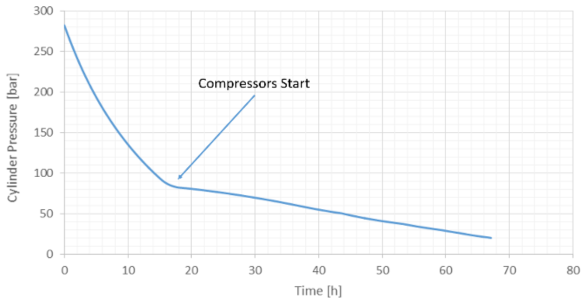

Figure 8.11 – Cylinder pressure – Unloading phase – Min. Time – Barents Sea

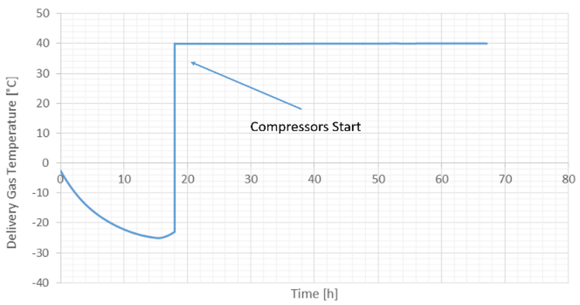

Figure 8.12 – Delivery gas temperature – Unloading phase – Min. Time – Barents Sea

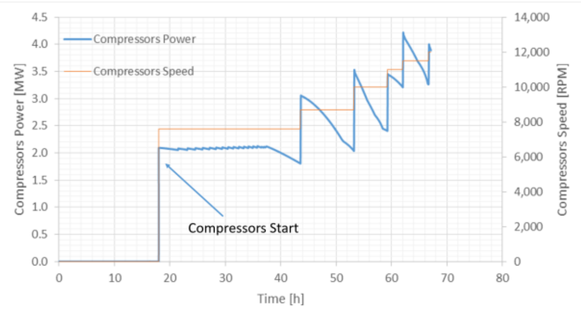

Figure 8.13 – Compressors power – Unloading phase – Min. Time – Barents Sea

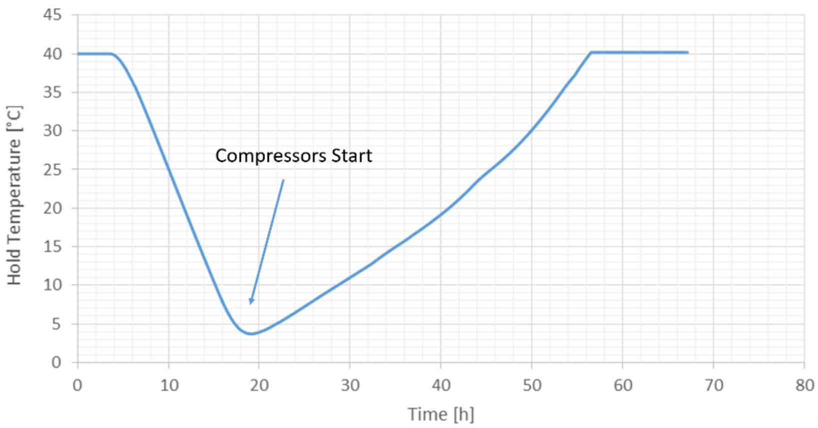

Figure 8.14 – Hold temperature – Unloading phase – Min. Time – Barents Sea

Figure 8.8 shows the decrease of the gas quantity contained in the pressure cylinders. In the free unloading phase the flow rate (Figure 8.9) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow increases thanks to the decrease of the gas density upstream of the valve and in the cylinders.

When the pressure difference between the cylinders and the storage is small, the flow rate drops and the compressors are started. In the first part of the flow rate curve, from the start of the compressors there are oscillations related to the opening of the throttle valves of the compressors. In the second part of the curve, some peaks corresponding to the change of the speed of the compressors can be observed.

Figure 8.10 and Figure 8.11 show the temperature and pressure trends inside the cylinders.

The delivery gas temperature is shown in Figure 8.12 with a minimum temperature, during the free unloading phase, of -25°C. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler.

Figure 8.13 shows the power absorbed by the compressors with a maximum of 4.2 MW at 11,500 rpm. The maximum compression ratio is 4. The temperature of the hold is shown in Figure 8.14 with a maximum value of 40°C and a minimum of 4°C.

8.3 12 MNm^3 simulation – Loading Phase

For the loading phase it was considered an initial hold temperature of 15°C because the low temperature facilitates the loading process. This temperature is obtained by cooling down the hold with fan coils during navigation with the empty vessel. The cold power is provided by four chillers of 1.4 MW each. The remaining initial parameters for the simulation are shown in the Table 8.3.

Table 8.3 – Simulation data – Loading phase – 12 MNm^3 – Barents Sea

Loading Phase		
Initial On–Shore Storage Pressure	bar	240
Initial On–Shore Storage Temperature	°C	20
Initial Cylinders Pressure	bar	20
Initial Cylinders Temperature	°C	15
Initial Cylinder Density	kg/m^3	14
Final On–Shore Storage Pressure	bar	240
Final On–Shore Storage Temperature	°C	20
Final Cylinders Pressure	bar	337
Final Cylinders Temperature	°C	56
Final Cylinder Density	kg/m^3	200
Loading Time	h	44
Loading Compressors Consumption	ton	5
Average Flow Rate	kg/s	56
	Nm^3/h	281,626
Maximum Flow Rate	kg/s	129
	Nm^3/h	644,811
Mass Inside Cylinders	ton	9,499
	Nm^3	13,239,734
Loaded Mass	**ton**	**8,835**
	Nm^3	**12,314,833**

The loading phase lasts 44 hours, 16 hours more than the minimum time strategy simulation. The cylinder temperature at the end of the process in this case is 56°C and therefore lower than the previous case by 12°C. The total mass of gas in the cylinders, at the pressure of 335 bar, is 13,239,734 Nm^3 and the loaded mass is 12,314,833 Nm^3, therefore higher than the previous case of 632,452 Nm^3.

The figures from Figure 8.15 to Figure 8.21 show the graphs of the main parameters of the loading phase.

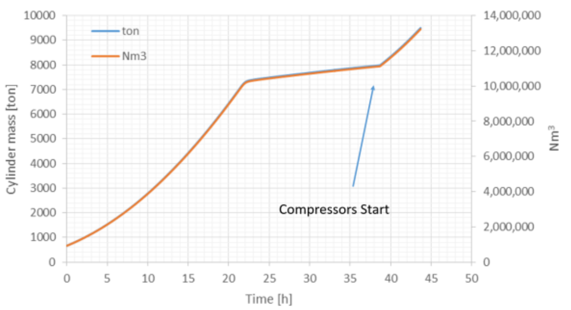

Figure 8.15 – Loaded mass – Loading phase – 12 MNm^3 – Barents Sea

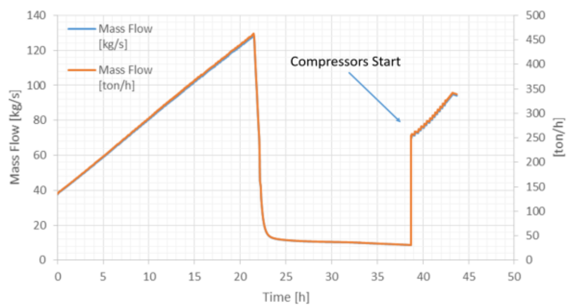

Figure 8.16 – Flow rate – Loading phase – 12 MNm^3 – Barents Sea

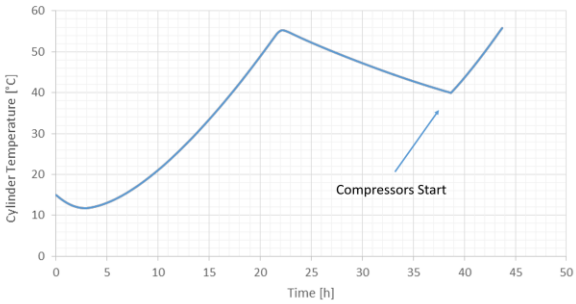

Figure 8.17 – Cylinder temperature – Loading phase – 12 MNm³ – Barents Sea

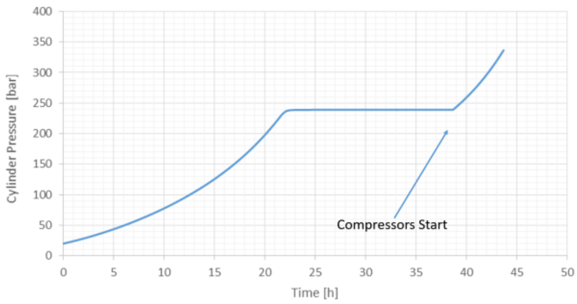

Figure 8.18 – Cylinder pressure – Loading phase – 12 MNm³ – Barents Sea

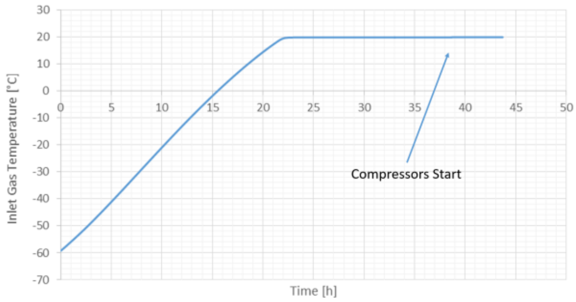

Figure 8.19 – Gas temperature at cylinder inlet – Loading phase – 12 MNm³ – Barents Sea

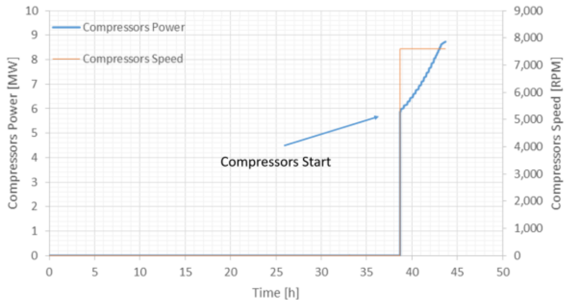

Figure 8.20 – Compressors power – Loading phase – 12 MNm³ – Barents Sea

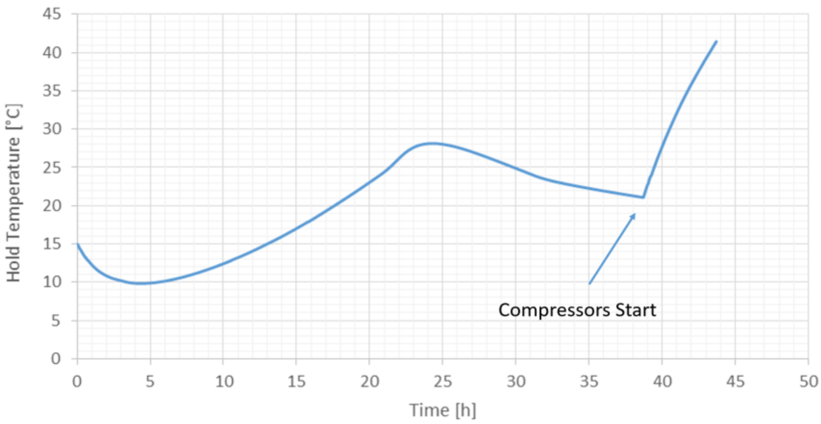

Figure 8.21 – Hold temperature – Loading phase – 12 MNm³ – Barents Sea

Figure 8.15 shows the increasing of the gas quantity contained in the pressure cylinders. In the free loading phase the flow rate (Figure 8.16) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow rate increases thanks to the increase the density of the gas downstream of the valve and in the cylinders. When the pressure difference between the storage and the cylinders is small, the flow rate drops, but in this case, the compressors start when the cylinder temperature to drop to 40°C, carrying out the free loading phase with a minimum flow rate. If the temperature of the gas in the cylinders is brought to this temperature before starting the compressors, a commercial mass of gas of about 12 MNm³ is guaranteed. When the compressors

are started, the flow rate curve shows oscillations related to the opening of the throttle valves of the compressors.

Figure 8.17 and Figure 8.18 show the trend of temperature and pressure inside the cylinders. The temperature of the gas at the cylinders inlet is shown in Figure 8.19 with a minimum temperature of –59°C at the beginning of the process. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressors and must be cooled down in the post cooler. Figure 8.20 shows the power absorbed by the compressors with a maximum of 8.7 MW at 7600 rpm. The temperature of the hold is shown in Figure 8.21 with a maximum value of 41°C.

8.4 12 MNm^3 simulation – Unloading Phase

At the end of the loading phase the cylinders reach a temperature of 56°C and, therefore, the temperature of the hold tends to reach this value. The high temperature in the hold facilitates the unloading process but a temperature too high in the hold is not acceptable due to safety reasons.

During navigation, in a first phase, it is necessary to cool down the hold to maintain a temperature of about 40°C so that the hold can be accessible by operators equipped with the appropriate protections in case of emergency operations. Once this temperature is reached, it is kept constant until the beginning of the unloading phase by supplying heat, if necessary, using two boilers of 3 MW each. For the unloading phase, an initial hold temperature of 40°C was considered. If at the time of discharge the gas temperature is still higher than 40°C it is better for the process.

Table 8.4 – Simulation data – Unloading phase – 12 MNm^3 – Barents Sea

Unloading Phase		
Initial On–Shore Storage Pressure	bar	80
Initial Cylinders Pressure	bar	303
Initial Cylinders Temperature	°C	40
Initial Cylinder Density	kg/m^3	200
Final On–Shore Storage Pressure	bar	80
Final Cylinders Pressure	bar	20
Final Cylinders Temperature	°C	32
Final Cylinder Density	kg/m^3	13
Unloading Time	h	69
Unloading Compressors Consumption	ton	18
Average Flow Rate	kg/s	35
	Nm^3/h	177,941
Maximum Flow Rate	kg/s	86
	Nm^3/h	431,099
Remaining Mass Inside Cylinders	ton	620
	Nm^3	864,648
Unloaded Mass	**ton**	**8,861**
	Nm^3	**12,350,005**

The unloading phase lasts 69 hours, 19 hours of free unloading and 50 hours of forced unloading. During the process 12,350,005 Nm^3 of gas are unloaded. In assessing the quantity of gas unloaded, the gas consumed by the compressors was taken into account.

In this case it is possible to unload 631,731 Nm^3 more than the minimum time strategy.

The figures from Figure 8.22 to Figure 8.28 show the graphs of the main parameters of the unloading phase.

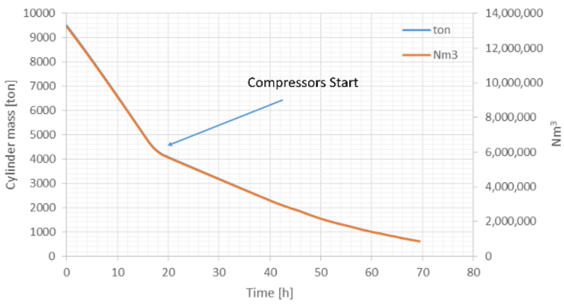

Figure 8.22 – Unloaded mass – Unloading phase – 12 MNm^3 – Barents Sea

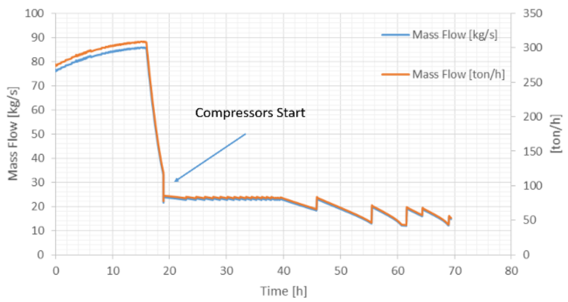

Figure 8.23 – Flow rate – Unloading phase – 12 MNm^3 – Barents Sea

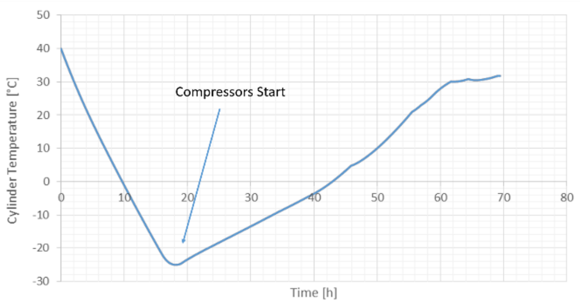

Figure 8.24 – Cylinder temperature – Unloading phase – 12 MNm3 – Barents Sea

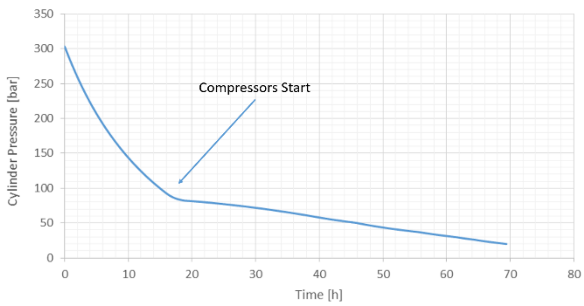

Figure 8.25 – Cylinder pressure – Unloading phase – 12 MNm3 – Barents Sea

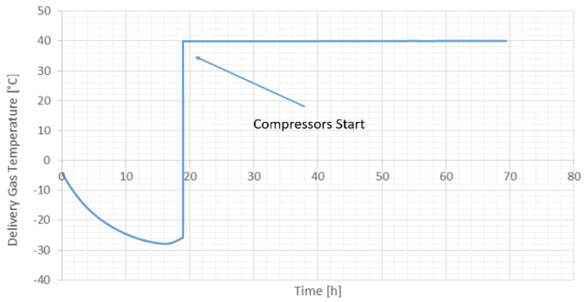

Figure 8.26 – Delivery gas temperature – Unloading phase – 12 MNm^3 – Barents Sea

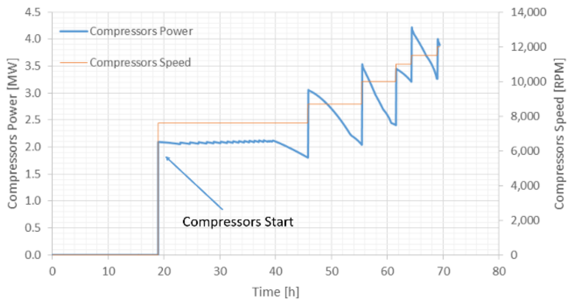

Figure 8.27 – Compressors power – Unloading phase – 12 MNm^3 – Barents Sea

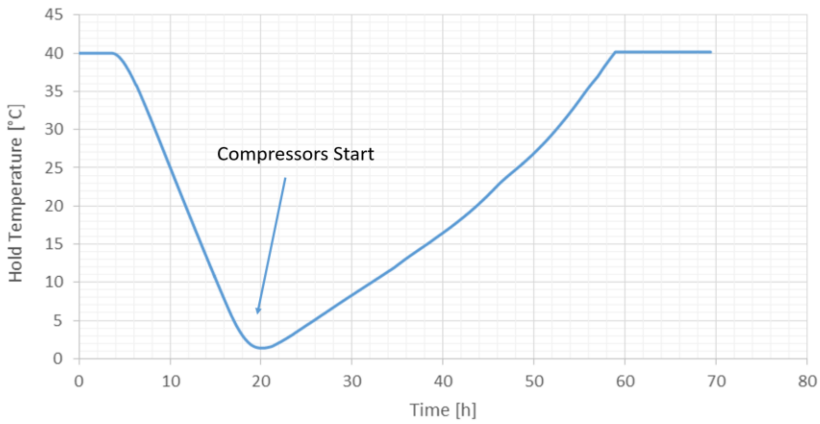

Figure 8.28 – Hold temperature – Unloading phase – 12 MNm^3 – Barents Sea

Figure 8.22 shows the decrease of the gas quantity contained in the pressure cylinders. In the free unloading phase the flow rate (Figure 8.23) is controlled by the regulating valve in order to limit the speed in the pipes. At the beginning the flow rate increases thanks to the decrease of the gas density upstream of the valve and in the cylinders.

When the pressure difference between the cylinders and the storage is small, the flow rate drops and the compressors are started. In the first part of the flow rate curve, since from the start of the compressors there are oscillations related to the opening of the throttle valves of the compressors. In the second part of the curve, some peaks corresponding to the change of the speed of the compressors can be observed.

Figure 8.24 and Figure 8.25 show the temperature and pressure trends inside the cylinders.

The delivery gas temperature is shown in Figure 8.26 with a minimum temperature, during the free unloading phase, of –28°C. When the compressors are started the graph shows a discontinuity since in the forced loading phase the gas warms up through the compressor and must be cooled down in the post cooler.

Figure 8.27 shows the power absorbed by the compressors with a maximum of 4.2 MW at 11,500 rpm. The maximum compression ratio is 4. The temperature of the hold is shown in Figure 8.28 with a maximum value of 40°C and a minimum of 1°C.

8.5 Fuel consumption for specific scenarios of Barents Sea

As already said macro areas were considered instead of the specific places because of the little differences in the ambient conditions.

By the way in order to evaluate the quantity of discharged gas at the unloading point the specific routes have to be considered because a different length of the route leads to a different fuel consumption which affects directly the amount of the gas that can be discharged.

Table 8.5 – Shipping time for specific scenarios of Barents Sea

Barents Sea Routes		DISTANCE	TIME	TIME (+20%)
Loading point	**Unloading point**	**km**	**days**	**days**
Johan Castberg Platforms (Norway)	Aasta Hansteen (Norway)	800	1.1	1.3
Johan Castberg Platforms (Norway)	Nyhamna Gas Plant (Norway)	1200	1.6	1.9

The Table 8.5 shows the loading and unloading points with the estimated distance between these two points followed by the navigation days plus a column where the days spent at sea has been increased by the 20% to take into account the real conditions (e.g. real route, sea conditions, manoeuvring time). This is the time which was taken into account for the evaluation of the gas discharged.

With such data an assessment of the quantity of the discharged gas, closer to the real value, can be carried out.

The assessment of the real discharged gas was carried out referring to the 12 MNm^3 simulations. It has to be highlighted that the results come from an approximation of the real case because of the uncertainties about the route, furthermore the assessment of the discharged gas was made by considering the 12 MNm^3 simulations of the macro areas and subtracting the fuel used for the navigation.

Table 8.6 – Estimated gas unload for Johan Castberg Platforms (Norway) – Aasta Hansteen (Norway) scenario

Transport consumption Johan Castberg Platforms (Norway) – Aasta Hansteen (Norway)		
Sailing time	days	1.30
Speed	Knot	17
Specific Fuel Consumption	g/kWh	143
Total fuel consumption	ton	53
Unloading Phase		
Remaining Mass Inside Cylinders	ton	620
	Nm^3	864,648
Unloaded Mass	**ton**	**8,808**
	Nm^3	**12,276,376**

Table 8.7 – Estimated gas unload for Johan Castberg Platforms (Norway) – Nyhamna Gas Plant (Norway) scenario

Transport consumption Johan Castberg Platforms (Norway) – Nyhamna Gas Plant (Norway)		
Sailing time	days	1.90
Speed	Knot	17
Specific Fuel Consumption	g/kWh	143
Total fuel consumption	ton	77
Unloading Phase		
Remaining Mass Inside Cylinders	ton	620
	Nm^3	864,648
Unloaded Mass	**ton**	**8,783**
	Nm^3	**12,242,397**

In Table 8.6 and Table 8.7 it is possible to observe that the decrease in the delivered gas due to the fuel consumption of the ship does not affect in a relevant way the amount of gas discharged that is in any case higher than 12 MNm^3.

The gas used during the navigation represent in the worst case only the 0.88% of the overall unloadable gas.

9. Summary of simulation results

To summarise, the simulation of the two extreme cases of WINTER and SUMMER conditions have been illustrated, primarily to verify the capacity of the loading and unloading system. Moreover, the simulation of the complete loading and unloading processes for the three geographical areas of interest have been presented distinguishing between the minimum time strategy (that does not maximize the useful commercial load) and a maximum commercial load strategy (that does not optimize the loading and unloading time).

The Table 9.1 and the Table 9.2 illustrated the summary data regarding the loading and unloading phases of the simulations related to the three macro-scenarios. The table of the loading phase shows that for each macro scenario there is a clear difference between the minimum time strategy and the one that aims to load about 12 MNm^3 in terms of time and loaded gas.

Comparing the different macro scenarios it can be noted that, with the same strategy, the differences are remains rather limited. Comparing, for instance, the scenarios "Mediterranean Sea" and "Barents Sea" it can be noted that the amount of loaded gas is almost the same but with a difference in the loading time of about 4 hours.

The Table 9.2 shows summarizes the data of the unloading phase for the three macro scenarios. The differences between the two strategies applied to the same macro scenario is only due to different quantity of gas contained in the cylinders at the start of unloading phase. Once again, comparing the simulation data for the various macro scenarios by adopting the same loading strategy the difference remains rather limited.

The model is now ready to support the investigation of other scenarios, especially other strategies that could be necessary to minimize the operational costs as well as to minimize the operational risks.

Table 9.1 – Summary of simulation results - Loading Phase

Loading Phase		Mediterranean Sea		Black Sea		Barents Sea	
		Min. Time	12 MNm^3	Min. Time	12 MNm^3	Min. Time	12 MNm^3
Initial On-Shore Storage Pressure	bar	240	240	240	240	240	240
Initial On-Shore Storage Temperature	°C	25	25	25	25	20	20
Initial Cylinders Pressure	bar	20	20	20	20	20	20
Initial Cylinders Temperature	°C	15	15	15	15	15	15
Initial Cylinder Density	kg/m^3	14	14	14	14	14	14
Final On-Shore Storage Pressure	bar	240	240	240	240	240	240
Final On-Shore Storage Temperature	°C	25	25	25	25	20	20
Final Cylinders Pressure	bar	336	336	336	335	336	337
Final Cylinders Temperature	°C	70	57	69	56	68	56
Final Cylinder Density	kg/m^3	188	199	189	199	190	200
Loading Time	h	28	48	28	47	28	44
Loading Compressors Consumption	ton	6	5	6	5	6	5
Average Flow Rate	kg/s	82	51	81	52	84	56
	Nm^3/h	408,984	254,743	408,216	262,341	419,132	281,626
Maximum Flow Rate	kg/s	128	128	128	128	129	129
	Nm^3/h	641,560	641,560	640,595	640,595	644,811	644,811
Mass Inside Cylinders	ton	8,962	9,457	8,979	9,455	9,045	9,499
	Nm^3	12,491,833	13,180,834	12,515,008	13,177,894	12,607,282	13,239,734
Loaded Mass	**ton**	**8,299**	**8,793**	**8,315**	**8,791**	**8,382**	**8,835**
	Nm^3	**11,566,932**	**12,255,933**	**11,590,107**	**12,252,993**	**11,682,381**	**12,314,833**

Table 9.2 – Summary of simulation results - Unloading Phase

Unloading Phase		Mediterranean Sea		Black Sea		Barents Sea	
		Min. Time	12 MNm^3	Min. Time	12 MNm^3	Min. Time	12 MNm^3
Initial On-Shore Storage Pressure	bar	80	80	80	80	80	80
Initial Cylinders Pressure	bar	279	301	279	301	282	303
Initial Cylinders Temperature	°C	40	40	40	40	40	40
Initial Cylinder Density	kg/m^3	188	199	13	13	190	200
Final On-Shore Storage Pressure	bar	80	80	80	80	80	80
Final Cylinders Pressure	bar	20	20	20	20	20	20
Final Cylinders Temperature	°C	32	32	32	32	32	32
Final Cylinder Density	kg/m^3	13	13	13	13	13	13
Unloading Time	h	66	69	66	69	67	69
Unloading Compressors Consumption	ton	17	18	17	18	18	18
Average Flow Rate	kg/s	35	36	35	35	35	35
	Nm^3/h	175,312	179,130	175,684	177,979	174,592	177,941
Maximum Flow Rate	kg/s	84	85	84	86	85	86
	Nm^3/h	419,957	427,951	421,222	429,101	424,182	431,099
Remaining Mass Inside Cylinders	ton	620	621	620	619	620	620
	Nm^3	864,171	865,032	864,839	863,449	864,496	864,648
Unloaded Mass	**ton**	**8,325**	**8,818**	**8,341**	**8,817**	**8,407**	**8,861**
	Nm^3	**11,603,357**	**12,290,938**	**11,626,190**	**12,289,374**	**11,718,274**	**12,350,005**

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