Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2018, 55 (127), 44–50
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/300

Received: 03.07.2018
Accepted: 16.09.2018
Published: 17.09.2018

Experiences with gas engines during practical ship operations – impact of load fluctuations during generator operations on the ship's power grid

Stefan Rother, Holger Watter

Centre for Maritime Studies at Flensburg University of Applied Sciences
Kanzleistr. 91-93, 24943 Flensburg, Germany
e-mail: {stefan.rother; holger.watter}@hs-flensburg.de
corresponding author

Key words: LNG, gas engine, dual-fuel engine, load fluctuation, MODELICA, simulation, fluid dynamics, thermodynamics, practical advice, ship operation

Abstract

Liquefied natural gas (LNG) qualifies as sustainable and secure marine fuel that is reliable in supply. The international standards (IGF Code) and classification regulations have been aligned. First experiences in ship operations and design are now available. Initial reports from the practical ship operations show that the lack of knowledge and misjudgements of original equipment manufacturers (OEM's), suppliers, consulting services and flag state authorities have led to operational restrictions or expensive retrofitting. The aim of this paper is to illustrate first experiences and operating instructions using this new and different marine fuel; derive recommendations for instructions for education and training programmes at maritime colleges, universities and business partners; present action recommendations for future operational concepts.

Objective

Liquefied natural gas (LNG) qualifies as a sustainable and secure marine fuel that is reliable in supply. Recently, the international standards (IGF Code) and classification regulations have been aligned (Watter, 2013) and first experiences in ship operations and design are now available (Renz, 2018).

Initial reports from the practical ship operations show that the lack of knowledge and misjudgements by the original equipment manufacturers (OEM's), suppliers, consulting services and flag state authorities have led to operational restrictions or expensive retrofitting.

The aim of this paper is to

- illustrate first experiences and operating instructions for new and different marine fuel;
- derive recommendations for educational instructions and training programs at maritime colleges, universities, and business partners;
- present action recommendations for future operational concepts.

During the course of this study, a special focus is placed on load variations by means of engine-driven consumer applications or load shedding, and both their repercussions on the fuel control in the gas engines. Unlike diesel or dual fuel engines, pure gas engines are not as good at compensating these load variations, which can give rise to operational and constructional problems. Project-related and operational errors have given cause for the subsequent overview and the subsequent action recommendations.

Characteristics of gas engines

Due to the varying operational characteristics of gas engines, and in order to establish a standardized nomenclature, a distinction between gas and dual fuel engines (DF engines) is necessary.

For the ship's crew, the ship operational requirements based on the propulsion engines that run on gaseous fuels are diverse, which is why the knowledge of gas as a marine fuel is required. First and foremost, the selection criteria of the main and auxiliary engines have to be taken into account during the initial planning phase of the ship's design. Even though all engines in question fall under the umbrella term "gas engines", the combustion processes can vary significantly.

Medium-speed four-stroke engines or low-speed two-stroke engines are often used as so-called dual fuel engines (DF) for the propulsion of the propeller. Supplying the ship system with electrical power can be accomplished via DF engines, as well or alternatively by means of high-speed auxiliary engines, which are equipped with an external carburetion and whose cylinder charging can be ignited via a spark plug.

Therefore, depending on the application field and the load profile of the ship, there is a wide variety of possible combinations. The following examples of combinations utilizing the main or auxiliary engines are conceivable (Table 1).

Table 1. Common possible combinations of gas and dual fuel engines (DF engines)

Main engine	Generator drive	
	Four-stroke DF engine	Four-stroke gas engine
Two-stroke gas engine	X	X
Four-stroke DF engine	X	X
Four-stroke gas engine		X

The requirement profile of the ship determines the fundamental design criteria during the selection of the engines. These are:

- main engines with fixed propellers and power take-off operation (PTO) as the ships power supply;
- main engines with controllable pitch propellers and PTO operation as the ship's power supply;
- diesel-electric drives with gas engines;
- diesel-electric drives with DF engines.

As not every gas engine is the same, the differences in operating behaviour and in the load impact must be considered during the project-planning phase. To differentiate between these engines, the following depiction is used to clarify the terminology:

- Otto gas engines with direct external ignition via a spark plug;
- Otto gas engines with pre-combustion chamber ignition;
- diesel igniting beam engines;
- diesel pilot-igniting beam engines.

Furthermore, terms such as "lean-burn engines" or "lambda 1 engines" are used, which can lead to confusion. These terms refer to the control concepts underlying these engines (λ – air-fuel ratio). Thus, for the case of a lambda 1 engine, a stoichiometric combustion is aimed for, i e. the ideal state of the air-fuel mixture during the combustion. Lambda < 1 signifies an air deficiency, standing for a rich mixture. Lambda > 1 signifies an excess air up to the lack of ignitability. Lambda 1 engines can be used as naturally aspirated engines or as supercharged engines with exhaust gas recirculation (Herdin, 2012).

Operating experience

A consequence of the different mixture formation procedures or the control concepts for the mixture formation, individual engine types behave differently within the context of the respective handling of the load. Aside from this, the general use of gaseous fuels in comparison to liquid ones must be noted.

These considerations during the project-planning phase are essential for the installation of a ship propulsion drive or generating electrical energy in the ship's power grid.

A supercharged DF engine with pilot fuel injection possesses another type of load handling other than an Otto gas engine with external spark ignition. If these engines are supposed to operate within a joint ship's power grid, not only has the plain engine layout got to be considered, but also the rated power of the engines or the differences in power with regards to the power distribution requirements of the vessel. Especially if larger consumer applications, such as DP thrusters (DP – dynamic positioning) or thruster units, are to be operated. The time function for the impact load or handling of the load within the power grid is very important. Figures 1 and 2 are schematic representations of the processes.

In the case of load variations and load shedding, the fuel supply system has to be adapted immediately. Newton's Laws of Motion states:

$$\sum M = J \cdot \ddot{\varphi} \tag{1}$$

This leads to a inhomogeneous second-order differential equation

$$J \cdot \ddot{\varphi} + b \cdot \dot{\varphi} + c \cdot \varphi \sim p_{mi} \sim m_{BZ} \tag{2}$$

where:

J – mass moment of inertia for the rotating masses (engine and generator or propeller),

$\ddot{\varphi}$ – angular acceleration,
$\dot{\varphi} = 2 \cdot \pi \cdot n$ – angular velocity (revolutions per minute: n),
φ – twist angle,
b – extent of damping (e.g. friction losses),
c – elastic properties (e.g. torsional rigidity),
p_{mi} – indicated medium pressure,
m_{BZ} – fuel mass in the cylinder.

Due to the mechanic inertia from the oscillating weight of the machine and the transmission elements of the actuators, the filling adjustment occurs time-delayed and asymptotically in the form of an exponential function (Figure 2).

In contrast to pure diesel engines, an approximate 600-fold lower density of the gas requires an approximate 600-fold larger volumetric flow rate adjustment, within the gas control system, see Figure 1.

$$\dot{m}_{BZ} = \dot{V} \cdot \rho \tag{3}$$

The same applies to the fuel input in the cylinder:

$$m_{BZ} = V \cdot \rho \tag{4}$$

if the same quantity of energy is to be supplied for the actual power demand.

$$\dot{Q}_{zu} = \dot{m}_{BZ} \cdot H_U = \dot{V} \cdot \rho \cdot H_U \tag{5}$$

Hence, in comparison to a pure diesel operation, significantly larger fluctuations in the volumetric flow rate and the pressure will have to be controlled.

The adjustment of the volumetric flow rate for the fuel input is carried out by means of the gas valve unit (GVU). However, according to the orifice equation for gas flow (Watter, 2017), a non-linear flow behaviour with a high degree may occur. According to the laws of gas dynamics, the following equation applies to the mass current density at the gas valve unit (GVU):

$$\frac{\dot{m}}{A} = c\rho = \alpha\zeta p_1 \sqrt{\frac{2}{R \cdot T_1}} \sqrt{\frac{\kappa}{\kappa - 1}\left[\left(\frac{p_2}{p_1}\right)^{\frac{2}{\kappa}} - \left(\frac{p_2}{p_1}\right)^{\frac{\kappa+1}{\kappa}}\right]} \tag{6}$$

where:
A – the released cross-sectional area of the valve,
c – the flow rate,
ρ – the density of the gas,
α – the discharge coefficient (flow constriction),
ζ – the loss coefficient (flow losses, turbulence),
p_1, T_1 – pressure and temperature in front of the valve,
R – the gas constant of the volumetric flow rate of the fuel input,

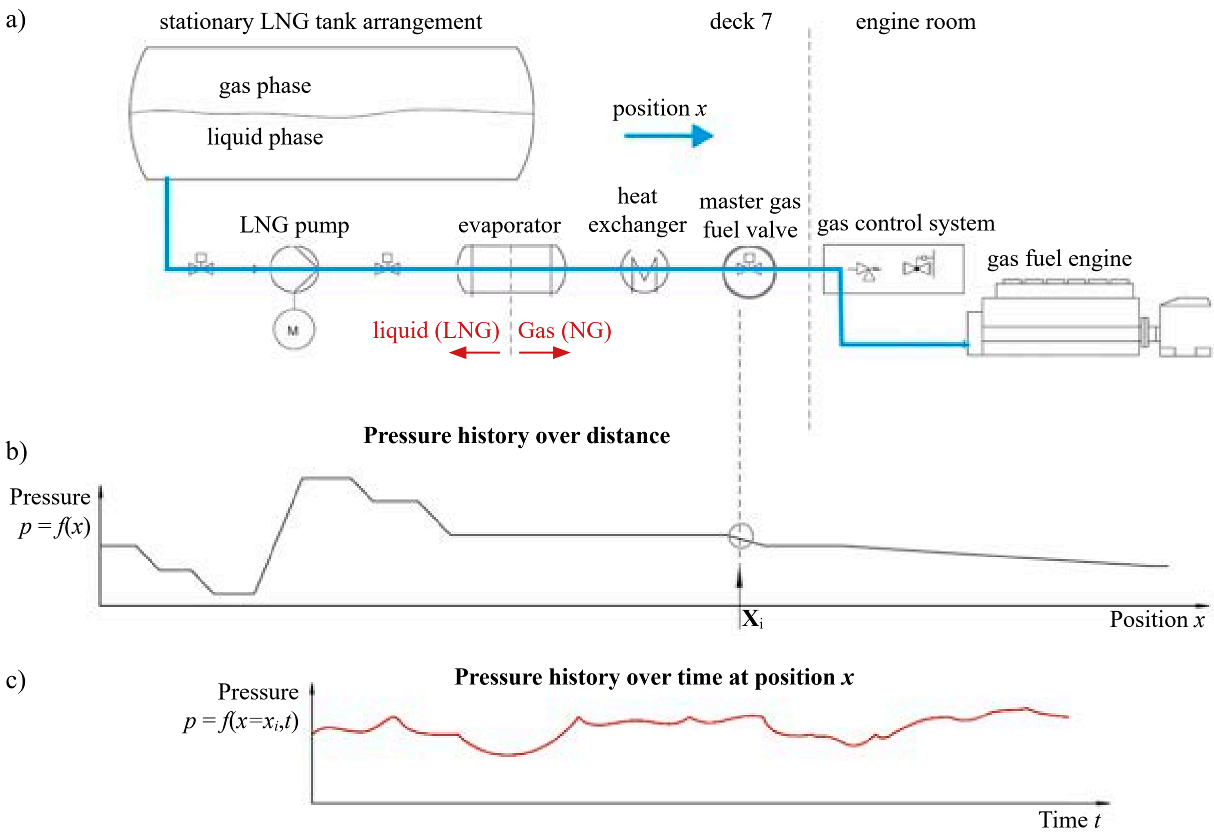


Figure 1. Schematic pressure history over distance and time within an LNG fuel system (Renz, 2018)

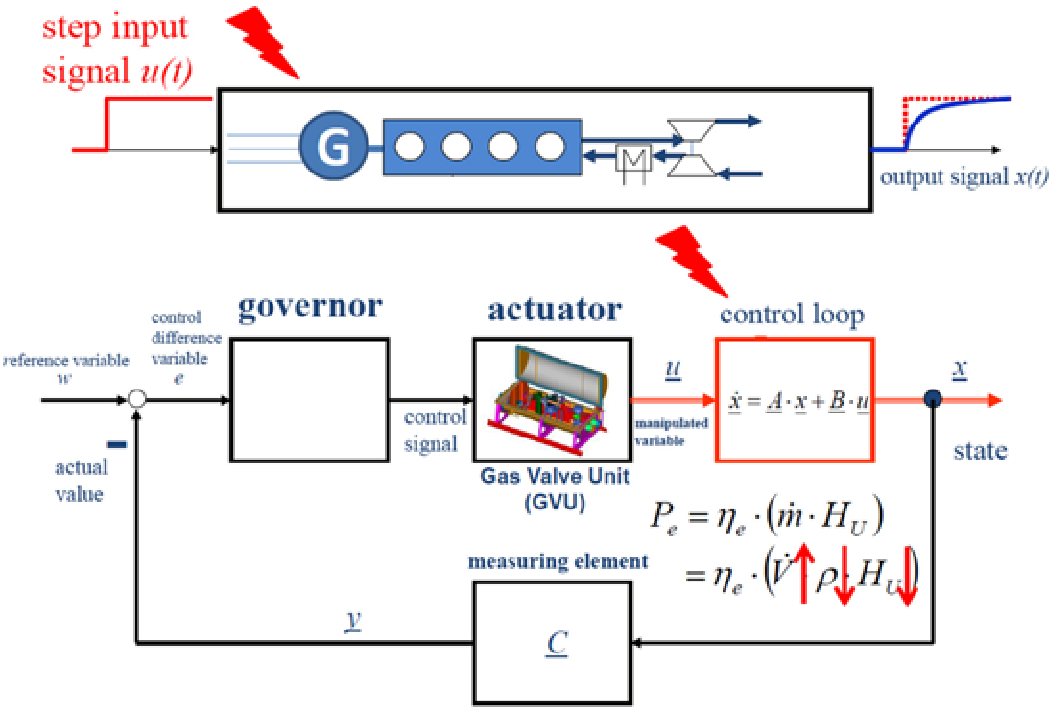


Figure 2. Closed-loop system of load variations within a fuel system (Watter, 2013)

κ – isentropic exponent of the gas,
(p_2/p_1) – the pressure ratio between the downstream and upstream pressure at the valve.

Especially in the second root equation, the flow rate function hampers the control-based treatment of the valve. Depending on the pressure ratio at the control valve, two effects may occur:

- When exceeding a critical pressure ratio of 1:2 in front of and behind the control valve, the flow rate is limited to the acoustic velocity. Regardless of the pressure ratio, the flow occurs at the maximum mass current density at acoustic velocity.
- On falling below, the critical pressure ratio, the flow rate function complies with a root function and is therefore non-linear.

Consequently, this means that load variations can be absorbed significantly slower than in the case of dual fuel engines or pure diesel engines, see Figure 2. Safe operations are the result of new operational and constructional concepts designed for the purpose of pure gas operations.

Simulation analysis

As previously shown, complex theoretical analyses and simulation tools are necessary and helpful for the engineering process. RENZ has conducted numerical simulations of transient flow conditions in the ships' power grid LNG system by using MODELICA® (Renz, 2018). Figure 3 shows a simple model layout. MODELICA® is a non-proprietary, object-oriented, equation-based language to conveniently model complex physical systems containing, e.g., mechanical, electrical, electronic, hydraulic, thermal, control-based, electric power, and process-oriented subcomponents (Modelica, 2018).

Practical considerations

In the case of load variations, it is imperative to mind the performance-based curves for revolutions per minute and torques that are both specified by the engine manufacturer. The operational characteristics of gas engines vary considerably from the load variations of diesel or DF engines (Rother, 2015; 2017).

Consequently, this varying engine behaviour, may lead to a significantly prolonged handling of the load, which may then result in operational restrictions due to the load impact of larger consumer applications. When comparing gas to diesel operations, a difference of 10 seconds for a start-up of various load points is feasible and has to be taken into account (Figure 4).

In the load step diagrams, the permitted load acceptance and load shedding of the engines are given as curves. On the x-axis, the active load of the engines is indicated, while the y-axis shows the possible load application, or the possible load shedding related to the active engine load. The following operating parameters influence the height of the load steps:

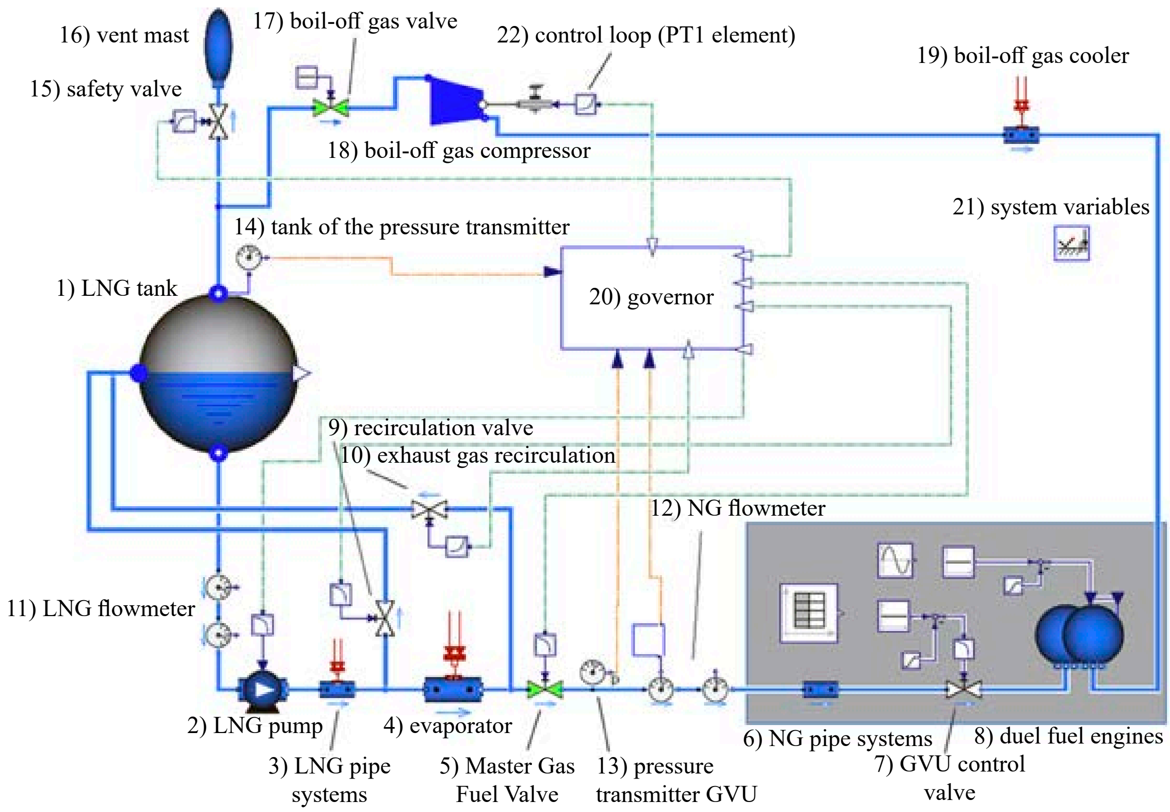
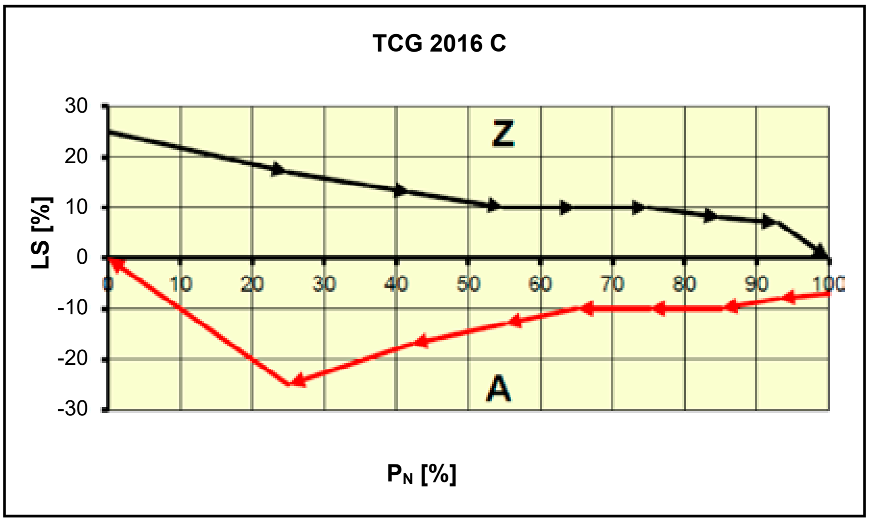


Figure 3. MODELICA model of an LNG ship power grid system (Renz, 2018)

Load appication		
P_N [%]	$t_{f,in}$ [s]	n [%]
0 – 25	15	13
25 – 42	15	11
42 – 55	15	10
55 – 65	15	10
65 – 75	12	9
75 – 85	12	9
85 – 93	10	6
93 – 100	8	6

Load shedding		
P_N [%]	$t_{f,in}$ [s]	n [%]
100 – 93	8	6
93 – 85	10	6
85 – 75	12	9
75 – 65	12	9
65 – 55	15	10
55 – 42	15	10
42 – 25	15	11
25 – 0	15	13



P_N	Active load	$t_{f,in}$	Recovery time
LS	Load step	n	Speed drop
Z	Load application	A	Load shedding

Figure 4. Examples of load curves and manufacturer specifications for gas engines (MWM, 2016)

- air filter – clean / contaminated;
- increased exhaust counter-pressure;
- lower calorific value of the fuel gas;
- engine wear;
- installation height;
- air inlet temperature;
- NOx emissions requirements.

The following are action recommendations for the design of the engine:

- exact specifications of the engine and the ship's power grid;
- specification of the engine type and the release of the performance-based curves in revolutions per minute and torque at the hands of the operator;
- specification of the necessary parallel operation of engines and the possible load impact or load shedding – which consumer applications must be operated under a time availability? How fast can these loads be managed for the generator operations?
- specification of the engine technology, i.e. high-pressure systems (up to 300 bar) or low-pressure systems featuring pressure build-up units (< 5 bar)?
- consideration of the interfaces between engines and the ship (gas control system and gas supply system);
- which concept should be realized (gas safe machinery space or engine shut-down (ESD) protected machinery space or a combination of both)?
- specification of tank types (e.g. C tanks), dry clutches, pumps, evaporators etc.;
- specification of gas qualities (boil-off gas or evaporated gas);
- methane number of the used gas, the specifications of the gas, depending on the gas origin, this may vary and support the knocking tendency of the engine;
- constructional design of the engine room and the bunker system, i.e. division of the hazardous zones, location and equipment of the bunker station, protective measures against the leaking of cryogenic and liquid LNG, ventilation, gas detection and explosion protection measures;
- initiation concepts for bunkering procedures and emergency facilities.

The Figure 5 emphasizes the conceptual possibilities of an LNG propulsion unit.

Both the training for the following fields, and their integration into the subsequent research for the operating staff, are to be recommended (Figure 6):

- Conducting a risk analysis for the ship operation and the integration into the ISM system;
- Basic training regarding physical and chemical properties of gaseous and cryogenic fuels;
- Use and alignment of drip trays and water curtains for liquidly leaking LNG with the objective of protecting people and the steel structures on the ship;
- Fire protection and extinguishing technology in the case of gas leakages;
- Prevention of rapid phase transitions in the case of gas leakages or roll-overs in tanks;
- Personal safety equipment for the operating staff (cryogenic equipment).

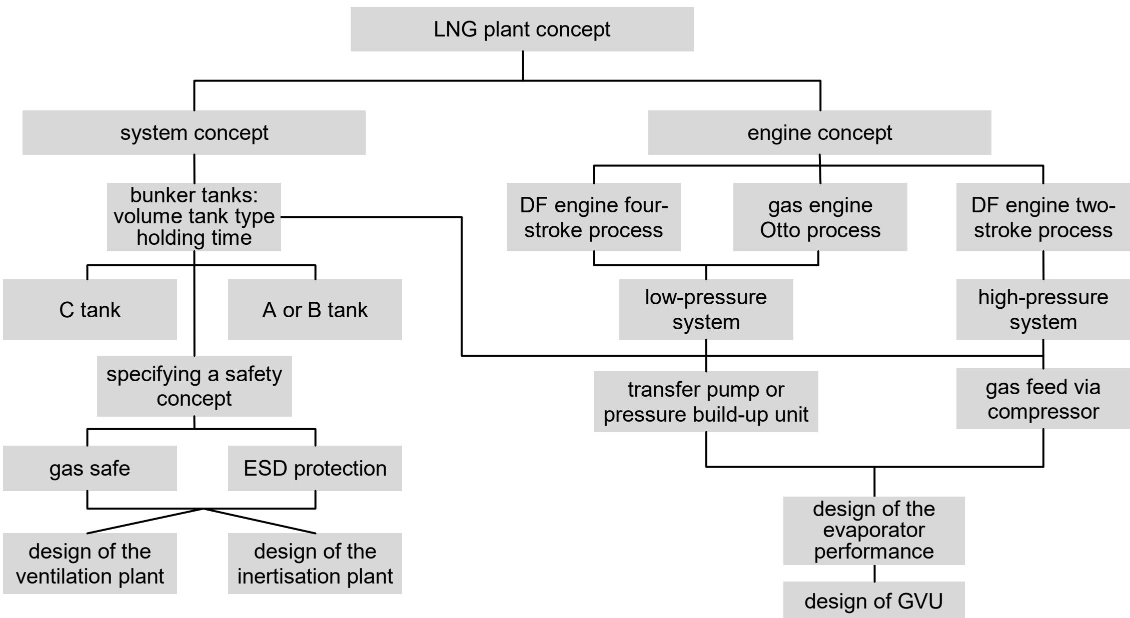


Figure 5. LNG concepts (an overview)

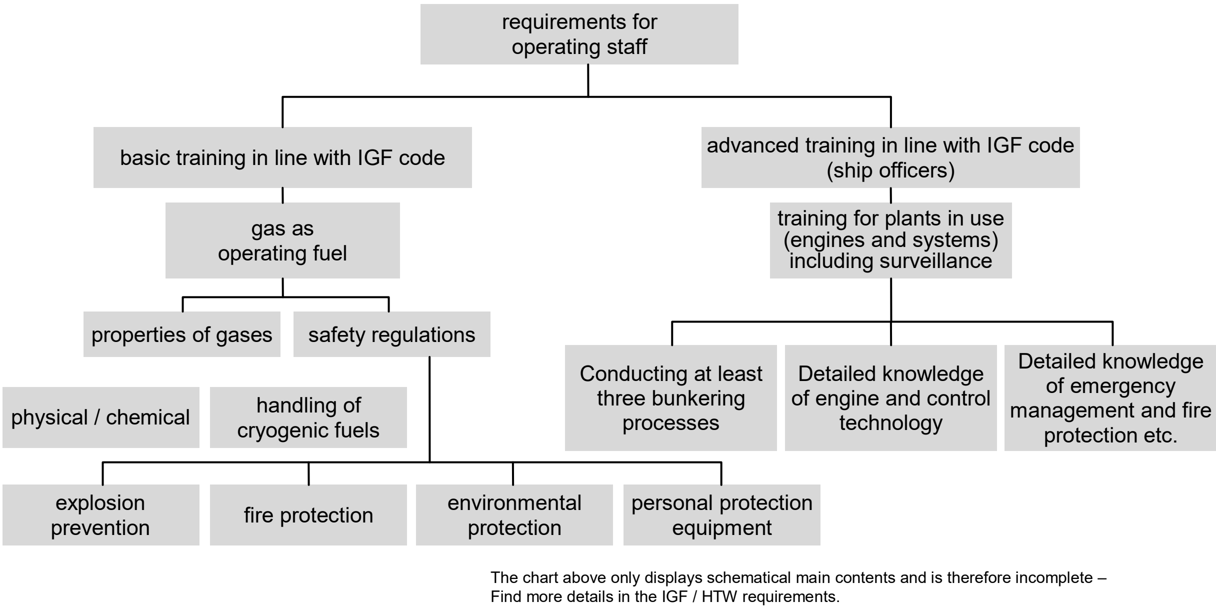


Figure 6. Requirements for operational and advanced training

Conclusions

This scientific research has shown that:

- new operating fuels such as LNG also require new constructional and operational concepts (Watter, 2015);
- different physical limits are created and have to be managed accordingly;
- initial experiences and new problems indicate the necessity for a "planned and fail-safe learning curve";
- recommendations for engineering and for future operational concepts must be derived from these experiences.

References

1. Herdin, G. (2012) *Grundlagen Gasmotoren*. PGES GmbH [Online] Available from: https://www.yumpu.com/de/document/view/10843237/grundlagen-gasmotoren-dr-di-gunther-herdin-prof-gescom [Accessed: September 16, 2018].
2. Modelica (2018) [Online] Available from: https://www.modelica.org [Accessed: June 25, 2018].
3. MWM (2016) *Power plants layout with Gas Engines – Planning and Installation Notes*. [Online] Available from: https://www.mwm.net/files/upload/mwm/issuu/power_plants_layout_MWM_06-16_EN.pdf [Accessed: June 25, 2018].
4. Renz, J.-P. (2018) *Numerische Simulation von instationären Betriebszuständen eines LNG-Brennstoffsystems auf einem RoPax-Schiff*. Master's thesis in the study programme Systems Engineering, Flensburg University of Applied Sciences, Flensburg.
5. Rother, S. (2015) *Ausbildungsanforderungen für den Schiffsbetrieb mit LNG*. Schiffsbetriebstechnische Gesellschaft Flensburg.
6. Rother, S. (2017) *Schiffsbetrieb mit LNG versus Schweröl.* Schiffsbetriebstechnische Gesellschaft Flensburg.
7. Watter, H. (2013) Gas als Schiffsbrennstoff – Neue Anforderungen an die Qualifikation der Besatzungen. *Ingenieurspiegel* 2, pp. 76–78.
8. Watter, H. (2015) *Regenerative Energiesysteme – Grundlagen, Systemtechnik und Analysen ausgeführter Beispiele nachhaltiger Energiesysteme*. 4th edition. Wiesbaden: Springer-Verlag.
9. Watter, H. (2017) *Hydraulik und Pneumatik – Grundlagen und Übungen – Anwendungen und Simulation*. 5th edition. Wiesbaden: Springer-Vieweg-Verlag.