Smooth Transition from Construction Phase to a Full Operation of LNG Carriers Using a Real-time Simulator

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Abstract

In offshore gas transportation business, the profitability is largely dependent on the vessel construction time as well as the overall cost. Reduction of the vessel construction time contributes to a favorable cash-flow (capital expenditure versus revenue return) to the ship-owner by making timely deployment of LNG carriers to the transportation service. However, amount of the required time from the start of the new shipbuilding to the commissioning and full operation can not be easily shortened in normal situation. Commissioning of highly complicated LNG carrier control system requires verifying every component and systems including the boil-off gas management, automatic boiler combustion control, most of which can only be tested during actual gas trial. For those who do not have previous LNG carrier operation experience, training their crew for the new vessel and/or the system is inevitable to ensure safe and economic operation. Daewoo Shipbuilding & Marine Engineering (DSME) has developed a state-of-the-art real-time simulator to verify the onboard control system, and to train operators for safe operation. The simulator covers most of the important cargo and machinery operation of LNG carriers such as boiler, turbine, boil-off gas management system, low duty compressor, cargo loading/ unloading, tank protection, and other safety functions. By using the dedicated simulator, transition from the construction phase to the full operation could be successfully implemented.

1. Introduction

Due to the demand for clean environment, many countries are expanding their LNG supply networks. LNG carriers take an important role in the LNG supply. Usually most of the countries are willing to transport at least some portion of the LNG by domestic shipping companies for the stable supply of national energy resources. With the reason, there is a tendency that a certain portion of LNG is transported by new domestic LNG shipping companies. Not only for the new shipping companies but also for the experienced shipping companies, the smooth transition from the LNG carrier construction phase to the full LNG carrier operation is important. In line with the rapid development in computer and control technologies, shipping companies need to prepare up to date technologies and train their crew for the new LNG carrier. The safety system training is also important for long term safety of the vessel. The operators should be able to cope with the emergency situations, and should be well trained for the circumstances, even though those situations are not encountered many times in normal operation. From the shipbuilders point of view, the commissioning of complex control system is also a difficult task and takes considerable time and efforts. To overcome the difficulties during the construction and operation stages, the LNG carrier dedicated simulation system can be utilized. Fig. 1 shows a typical LNG carrier.
2. Simulator System

2.1 Explanation on Simulator System

(1) LNG Carrier Control System

Central control system for LNG carrier is normally called as Integrated Automation System (IAS). The system is usually implemented by a Distributed Control System (DCS) technology. The control system enables operators control machinery and cargo systems through graphics on operator stations. As boil-off gas from cargo tanks is used for the fuel of the boiler, a coordinated control between the cargo tank pressure and the boiler load is important. At the same time, low duty compressors control system adjust the fuel to the boilers according to the fuel demand from the main boilers, and the boiler steam generation is linked to the main turbine system. The efficient control of the boiler system is indispensable to the overall LNG vessel performance. Not only for the control system check but also for the operator’s training purpose, a simulator system can be utilized.

![Image of LNG Carrier](image.png)

Fig. 1 Membrane Type LNG Carrier

(2) Simulator System

Fig. 2 shows a conceptual diagram of a typical simulator system. In order to be a very realistic simulation system, the modeling should be very precise, which call for much work and time, whereas if the modeling is too simple, it can not represent the exact responses of the ship behavior. Because it is sometimes unrealistic to have the exact same model as the actual ship in every component aspect, the scope and purpose of the simulation need be clearly defined in the design stage.
(3) Standalone Simulator
In the standalone simulator, the mathematical modeling of the ship and the control logic are implemented in the same workstation. Its hardware configuration is relatively simple, and the overall cost is low. However, the system only can be operated with a computer keyboard, or other simple input devices connected to the computer. Therefore, the operating environment is not exactly the same as onboard control system, and consequently the control system hardware familiarization and training can not be achieved. Nevertheless, the simulator is quite beneficial for the general understanding of control system and the LNG control characteristics. During the Gastech 2000 conference, the standalone simulator will be displayed in the DSME exhibition booth.

(4) Simulator Connected to an External Control System
Other type of the simulator system is the Simulator Connected to an External Control System. In this type of simulator, the LNG carrier mathematical model is resided in a workstation, but the control logic is implemented externally by the same hardware as onboard control system. As the control of the system is done by the same hardware, operators would feel exactly the same environment as onboard control room. The system can be used in two different phases. Firstly the system is implemented during the early construction stage of the vessel, typically in a laboratory. Secondly when onboard control system is ready, the simulator is directly connected to the control system. This provides almost the same environment as the actual ocean voyage. In the followings, the Simulator Connected to an External Control System will be mainly explained.

2.2 Simulator System Diagram
(1) System Hook-up
The simulator hook-up diagram is shown in Fig. 3. In the system, hardwire connections are used rather than communication means between the simulator and the control system. It requires additional works and costs, but it has an advantage in that the onboard control system program change is not necessary for the simulation test, by exchanging actual electric signals between two systems.

(2) Workstation
The simulator is implemented by a workstation or a powerful personal computer. The mathematical model of the whole LNG carrier is resided in the workstation. Each component of the equipment and piping is modeled by Fortran. The model is compiled and linked to libraries by using a simulation utility program called CASSIM, Cassiopeia, Canada. For the man-machine interface, Labview, National Instrument, USA is used. The simulator model parameter data is communicated to the I/O box.

(3) I/O Box
The I/O box links the workstation and the control system hardware. It receives communication data from the workstation, converts to actual electric signals (4-20 mA, Contact signal), and then transfers to the control system hardware, and vice versa.

Fig. 4 shows the actual simulator connections to onboard main control system hardware.

(4) Control System Hardware
The control system hardware is mainly composed of the control system hardware cabinet and the operator stations. The controllers in the cabinets and operator stations are connected with high-speed communication networks.

2.3 Mathematical Model of Simulator
(1) Modeling General
The important equipment, piping, and the cargo tanks are modeled. Each of the equipment models involves extensive work for acquiring related technical data as well as the modeling works themselves. The piping system
components and important valve characteristics are also modeled. DSME’s simulator is based on very
detail mathematical models, and it is a state-of-the-art real-time dynamic simulator, which can exactly
simulate most of important physical phenomena of the LNG carrier operation. The overview of the
simulator model is shown in Fig. 5. As an example of the modeling work, low duty (LD) compressor
diagram and input/output parameters of the model are shown in Fig. 6 and Table 1.

(2) Boiler
Each components of the boiler is precisely modeled based upon thermodynamic and relevant equations.
The model includes the boiler heat banks, drum level, pressure, temperature, steam flow, the calorific
heating values of the fuel, fuel mode choice, interfaces to turbine and so on. The model also contains the
burner management functions. The model can cover each mode of the operation encountered in real
situation, such as fuel mode change, fuel gas shutdown, and steam dump.

(3) Turbine
The turbine model includes the turbine characteristics, power to speed curve, and telegraph interface. This
allows the variation of the steam pressure and flow variation according to the turbine load. The effects on
the ship speed depending on the boiler conditions and the telegraph lever position also can be obtained.

(4) Cargo tank
The cargo tank model includes the boil-off gas generation, tank pressure, and cargo volume. With the
model, the cargo tank pressure variation according to the boil-off gas generation and consumption from
the boiler can be represented.

(5) Low Duty Compressor
The low duty compressor model includes the compressor performance and surge characteristics. Through
the model, the performance details, such as the fuel gas flow, pressure, required electric power in each
conditions of boil-off gas temperature and pressure can be obtained. From the compressor performance
curve based on inlet pressure, temperature, molecular composition, and inlet guide vane angle, normalized
performance curves are derived for the simulator modeling. The curve and related equations are shown in
Fig. 7 and below for an example of typical modeling works. Forcing vaporizer, and boil-off warm-up
heater are also modeled.
Table 1 Low Duty Compressor Model Input/Output Example

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
<th>Engineering Unit</th>
<th>Output</th>
<th>Description</th>
<th>Engineering Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGV</td>
<td>IGV angle</td>
<td>Degree</td>
<td>DP</td>
<td>Pressure Rise</td>
<td>kPa</td>
</tr>
<tr>
<td>RPM</td>
<td>Motor Speed</td>
<td>RPM</td>
<td>FDP</td>
<td>Final DP</td>
<td>kPa</td>
</tr>
<tr>
<td>M</td>
<td>Mass flow-rate</td>
<td>Kg/s</td>
<td>Tout</td>
<td>Outlet Temp.</td>
<td>–</td>
</tr>
<tr>
<td>T1</td>
<td>Inlet temperature</td>
<td>_</td>
<td>Run</td>
<td>Run/Stop signal</td>
<td>on/off</td>
</tr>
<tr>
<td>P1</td>
<td>Inlet Pressure</td>
<td>KPa</td>
<td>IGV</td>
<td>IGV angle</td>
<td>Degree</td>
</tr>
<tr>
<td>Run</td>
<td>Run/Stop signal</td>
<td>On/off</td>
<td>RPM</td>
<td>Motor Speed</td>
<td>Rpm</td>
</tr>
<tr>
<td>Coefficient</td>
<td>Description</td>
<td>Engineering Unit</td>
<td>S_cv</td>
<td>Surge Valve</td>
<td>Control</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------</td>
<td>------------------</td>
<td>------</td>
<td>-------------</td>
<td>---------</td>
</tr>
<tr>
<td>Tower</td>
<td>Time Constant</td>
<td>Sec</td>
<td>M</td>
<td>Mass Flow Rate</td>
<td>kg/s</td>
</tr>
<tr>
<td>K</td>
<td>C_p/C_v</td>
<td>S_m Surge Flow Rate</td>
<td>kg/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GAIN</td>
<td>Gain</td>
<td>EPC1 Normalized Error</td>
<td>%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RPT</td>
<td>Reset per time</td>
<td>OI Reset Derivative</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 7 Low Duty Compressor Performance Example**

\[ PR = \left( -1.689 + 5.762 \times 10^{-3} X_2 - 2.910 \times 10^{-6} X_2^2 \right) + \left( ??????? \right) \left( X_1 + \left( ??????? \right) \right) \left( IGV \right) \]

\[ PR = \frac{P_2}{P_1}, \quad X_2 = \frac{RPM}{\sqrt{T_1}}, \quad X_1 = \frac{m \sqrt{T_1}}{\sqrt{P_1}} \]

IGV : Inlet Guide Vane Angle(degree), RPM : Compressor Rpm(RPM),
M : Mass Flow Rate (10^3 kg/h), T1 : Compressor Inlet Temperature(K),
P1 : Compressor Inlet Pressure (Bar)

(6) Piping System
Each of the piping systems is modeled accurately. Not only the main piping but also the fittings and valves are modeled. If accurate calculations of pipe friction loss are required, those are made by other external process calculation packages such as HYSYS, Hyprotech, Canada, and the results are simplified and modeled to the main simulation model. The two stage calculations are sometimes necessary to be able to run the simulator in a real time base.

(7) Cargo Pumps
Cargo and stripping pump performance curves are modeled. Through the model, the cargo level and volume variation according to each operation mode can be obtained.
2.4 How the Simulator Works

(1) Program Development
After completion of modeling, the model is compiled, and linked with the CASSIM utility library. For the man-machine interface, the Labview graphics are generated. Separate window-based communication program, which links the external I/O box, is also prepared. The whole model is linked with Labview and the communication program. After compiling the program, the system is checked by running the whole simulation package. If any errors are found, the source program is corrected, re-compiled, and re-linked. However, once the programmed is completed, the simulator can be run without resorting to the source programming.

(2) Simulator Operation
After completion of the simulator programming, the simulator is handed over to the operators from the development engineers. The simulator is connected to the main control system through the interface I/O box. During the simulation operation, the control system functions are checked and the operator s training can be achieved.

3. Simulation Result

3.1 Gas Management System
Explanation of the gas management system is elaborated as an example of the simulator functions. As explained, naturally generated boil-off gas is used for the fuel of main boilers. In order to keep the cargo tank pressure within allowable ranges and to supply adequate fuel to boiler, the boiler master fuel gas control valve should be modulated accordingly. At the same time, the low duty compressor revolution and the inlet guide vane should be controlled to respond quickly enough for the boiler load change. Fig. 8 is the overview of the gas management system.
Numerous cases of the operation have been carried out in actual simulations in the laboratory and onboard. However, only typical simulation results of the related equipment are introduced in sections 3.2-3.6.

3.2 Boiler Operation
Following boiler functions have been checked during the simulation test.
- Initial Firing/Steam-up Control
- Burner Auto Increase Control
- Fuel Mode Change(FO, FG, Dual)
- FO Back-up Control / F.O. Boost-up Control
Boiler fuel mode change and fuel oil boost-up simulations are shown in Fig. 9. Fig. 10 shows the boiler fuel oil boost-up operation results obtained during onboard test (in quay) and gas trial. The simulation results showed similar trends and characteristics with the actual gas trial cases. The simulation reduced the boiler firing time for the adjustments of the control loops. The control loop programming verification could be done with the simulator, and similar range of PID parameters could be obtained during the simulation test. Therefore, it took relatively less time to adjust the tuning parameters during gas trails.

3.3 Turbine Operation
The steam consumption of the turbine and the corresponding ship speed could be simulated. Depending upon the telegraph lever position, the boiler pressure and the steam flow changes could be observed. Fig. 11 shows results for the gradual increase of the turbine revolution. During the operation, the number of burners is automatically increased up to the steam flow. The simulation would be helpful for operators to
understand the effect of boiler pressure, and flow due to the turbine revolution change. Following simulations have been carried out.
- Steam-up Control
- Telegraph Lever Increase / Decrease Control
- Crash Stop and Astern Control

Fig. 8 Gas Management System Overview

3.4 Cargo Compressor
Some of low duty compressor operation results are shown in Fig 12. The operators action for the low duty compressor can be learned from the simulations. Through the operation, the free flow operation of boil-off gas, compressor surge phenomena, and effect of the compressor control scheme could be also learned. Fig. 13 and Fig. 14 are illustrations of low duty compressor and related heater. Following low duty compressor related simulations have been carried out.
- Low Duty Compressor Start/Stop Control
- Free Flow Control
- Forcing Vaporizer Control
- Cargo Tank Vent Control

3.5 Cargo Tank Protection Mode
Tank protection control mode could be demonstrated in the simulator. In normal case, when the cargo tank inside pressure is sufficient, adequate boil-off gas is supplied to the boilers through the low duty compressor. However if the tank pressure goes below the predefined pressure, boil-off gas supply control up to boiler load requirements is no longer active to protect the cargo tank structure integrity. For the similar reason, if the tank pressure is higher than the predefined set pressure, the boil-off gas is burnt in boilers and the generated steam is dumped to the condenser. If this control does not work properly, the tank vent mode controller activates and vents the boil-off gas to the atmosphere. Following simulations have been carried out.
- Cargo Tank Vent Control / Operation

Fig. 9 Fuel Supply Mode Change and Boost-up Test

![Diagram of Fuel Supply Mode Change and Boost-up Test]

Fig. 10 Boiler F.O. Boost Up Mode between

(a) Simulator - Onboard Test  (b) Simulator - Gas Trial

3.6 Cargo Handling Operation

As the simulator system includes actual control system hardware, the operation functions such as the cargo valve opening/closing, the cargo pump starting/stopping, and cargo pump load adjustment can be done just the same manner as that used onboard. Through the simulation, the cargo unloading operation could be simulated, and the cargo operation training could be made. Cargo stripping pump can be used for the forced vaporizing function, and the system also could simulate the operation. Following cargo handling operation have been carried out.

- Cargo Pump Stating/Stopping Operation
- Cargo Valve Open/Close Operation
4. Effectiveness of the Simulator

4.1 Training of Operators

The advanced control system in LNG carriers can reduce the number of operators, and enhance the overall safety. However in order to achieve the goals, the training and familiarization of the modern control system have to be preceded. The best way to train operators would be on the job training. However, in LNG carriers, the training in sea-going LNG vessels would be difficult and inefficient. For shipping
companies, it would be good if the operator training can be done in line with the vessel construction. However, it is not feasible, because the ship control system can be alive in the final stage of the construction. Especially, the LNG cargo related operation is possible only during the gas trial stage, which is very late stage of the vessel construction. Therefore the training of the operator can be done only after the vessel construction is completed.

The training using a simulator would be an efficient and cost-effective solution. As the cargo containment works take relatively longer time in outfitting stage, the control system can be alive well before the completion of the containment system. During the time, by using the simulator and onboard control system, the cargo and machinery operation training can be carried out.

Adequate training of engineers and operators are necessary for LNG shipping companies, and recruiting qualified engineers and operators are difficult and expensive. Therefore, it is more effective and practical to train their crew internally. The training of the crew by using the simulator is very effective. The LNG carrier dedicated simulator with the same hardware as the ship that operators actually work in is strongly recommended considering the complexities in the operation scheme and the control system itself. This simulation based training would be very beneficial especially to those LNG shipping companies who do not have previous LNG operating experiences. The picture of onboard training for the operators is shown in Fig. 16.

4.2 Safety Related Training
The emergency state can happen in unexpected situations. Therefore every operators should be well prepared for the situations. However, it is very difficult to train and exercise the emergency measures, because making such situations involves substantial expense and also can be dangerous. For example, the operator s action training in the extremely dangerous high cargo tank pressure can not be made in a real situation. The simulator can be well used for the training of the emergency measures. Also the emergency related control functions should be thoroughly checked before the delivery of the vessel. Practically, the safety related dynamic control function verification could be achieved only by the simulation system.

4.3 Control System Familiarization
Modern control system is quite complex. The central I/O point quantity for a typical LNG carrier ranges between 3,000 —5,000. Even for the experienced LNG carrier operators, the complicated control system call for familiarization of the hardware and software of the control system. The DCS based control system is usually used in LNG carriers. The DCS based control system has a variety of functions and very
efficient, but at the same time it is very complicated and difficult to maintain without sufficient familiarization of the system. Therefore familiarization and a certain level of control system training is inevitable. Interactive training system based on actual LNG carrier specific control environment is more advisable and effective. Familiarization using the simulator will reduce the required transit time from the shipyard construction phase to operation phase of the vessel.

Fig. 15 Cargo Vent Operation Diagram

Fig. 16 Onboard Training of Operators

4.4 Control System Verification
As control functions are inter-related, verification of the control system requires enormous time and effort.
The control system should be verified in every component level. From the shipbuilders point of view, the control system should be checked and verified within a limited time during the shipyard commissioning. Some of the control system verification can only be done during the actual equipment operation stage, which does not allow enough time due to tight shipyard construction schedule.

For DSME case, the verification of onboard control system was one of the important motivations to develop the simulator system. By using the simulator system, the newly adopted control system can be verified effectively, which reduces any risks for inexperienced projects and consequently enhances the overall construction performance.

4.5 Shipyard’s Commissioning
By checking the control function with the simulator, any errors can be found and rectified beforehand. The application of new control system involves high risks of the commissioning time delay due to the repeated corrections and adjustments for the control system. The simulator can reduce the risk for the commissioning, and it can also contribute to the saving of LNG cargo consumption during the gas trial.

5. Conclusions and Recommendations
(1) Conclusions
Through the development and application of the simulator, following conclusion and observations could be obtained.
- A real time simulator is an effective tool for training ship operators.
- With the simulator, risks during the commissioning and operation of the vessel could be reduced,
- Safety training could be carried out and the overall safety is increased,
- The control system could be thoroughly checked,
- Amount of time taken for the commissioning could be reduced.
- Consequently, a timely deployment of the vessel could be achieved.

(2) Future Applications
The experience and technology acquired during the development of the simulator can easily be applied widely to developing simulators for offshore production platforms, natural gas liquefaction plants, and floating offshore plants. Simulators are useful tools when developing new process or projects, as they can be used as test beds for control function and safety check.

(3) Safety System Training
Simulator based regular and systematic safety training programs for a project will reduce the level of risks where the trainees are exposed to and consequently will enhance overall safety measure of the project. The effort for safety should be given at every level of company members; management, engineers, and operators. Providing a systematic training with a simulator can be regarded company’s sincere effort towards safe operation of LNG carriers.

6. Acknowledgement
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References