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(Research Article)

# Improving the efficiency of steam plant on LNG tankers

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## Abstract

This study seeks to investigate ways of improving the efficiency of a conventional steam plant, by converting to Ultra steam plant on an existing LNG Carrier. The design proposal is centered on existing technology. In this dissertation, the economic and environmental analyses of different means of propulsion were carried out, and reason the UST is the best available option.

**Keywords:** LNG Tankers; Conventional Steam Turbine (CST); Ultra Steam Turbine (UST); Boil-off Gas (BOG); Energy Efficiency; DFDE

## 1. Introduction

Propulsion means on LNG Tankers is constantly evolving, with emphasis on cost, reliability, efficiency. To remain competitive, Steam turbine which used to be the first choice because its boiler was the only one with the ability to use natural boil off gas from its cargo tanks efficiently, which by all means is a cleaner energy compared to marine diesel oil or heavy fuel oil and requires low maintenance cost compared to other forms of propulsion. But over time due to various reasons, some of which will be looked into in the course of this research, decline in the efficiency of the plant is inevitable (www.wartsila.com)

With renewed interest in design of marine diesel engine, which has the capacity to utilize the natural boil of, also with higher efficiency when compared to the steam turbine has make the DFDE technology attractive to ship-owners.

Gas turbine is well-known for having low efficiency, but with the latest “combined gas turbine electric and steam (COGES) system” by General electric. “By converting to a COGES power system, the fuel efficiency will be improved by 30%, which allows ship owners to increase chatter rate and win back opportunities dominated by duel fuel diesel engines” (www.geaviation.com)

This research tends to look into various ways to improve on the efficiency of a steam turbine on an existing LNG Tanker, using one of our fleet vessels LNG RIVER NIGER as a case study.

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*Aim*

The aim of this project is to look into various ways on how the efficiency of a steam turbine on an existing gas carrier can be improved, also the workability of new technology to be retrofitted on a gas carrier already in service.

*Objective*

To realize the aim of this project, I intend to review and study all available literatures, articles and journals, also available technology which can be retrofitted into an existing steam plant on an LNG Carrier

*Scope and limitation of study*

The scope of this project is to look at the best available solution, while the limitation will be the initial cost of implementing some of such solutions.

## 2. Literature Review

In this chapter we will be looking into the history and how the steam turbines as a means of propulsion on LNG Tankers has been in existence since the early sixties and how it has evolved over time, from the conventional steam to the ultra-steam plant.

### 2.1. Conventional Steam Plant Overview

The steam turbine plant consists of the two high pressure marine boiler, the high- and low-pressure turbine, condenser, vacuum pump or air ejector as the case maybe, low and high feed heaters, gland condenser, turbine feed pump, economizer and de- aerator.

#### *2.1.1. High Pressure Marine Boiler*

The marine boiler is a roof fire water tube; with an internal super heater and generating tube protected from the radiant heat by screen tubes, the furnace floor and wall are membrane constructed.

The super-heater has six passes with one to four been the primary, five and six been the secondary super heater. There are two de super-heaters which are located in the water and steam drum respectively for controlling the steam temperature. Circulation of water is done by the down comers which are outside the gas path

The boiler has the capacity of burning heavy fuel oil and natural boil off to generate superheated steam at 61.5Bar/515 degree Celsius and de- superheated steam of 61.5Bar/258 degree Celsius. Steam generated is led to the turbines for propulsion and electricity generation purpose and other consumers through the piping systems. (LNG River Niger Operating Manual Sec 3.3.1 pp2)

#### *2.1.2. Economizers*

An external surface feed heating system, placed in the gas path of exhaust from the boiler. The Condensate and Feed System

The feed water system takes condensate from the end user and back to the boiler. The pressure of the water is raised well enough above that of the boiler pressure by the feed pump creating a flow path.

#### *2.1.3. De-aerator*

The purpose de-aerator is the removal of dissolved oxygen and other condensable gases from the feed water. It also serves as the water heater and reservoir for the operation of the plant.

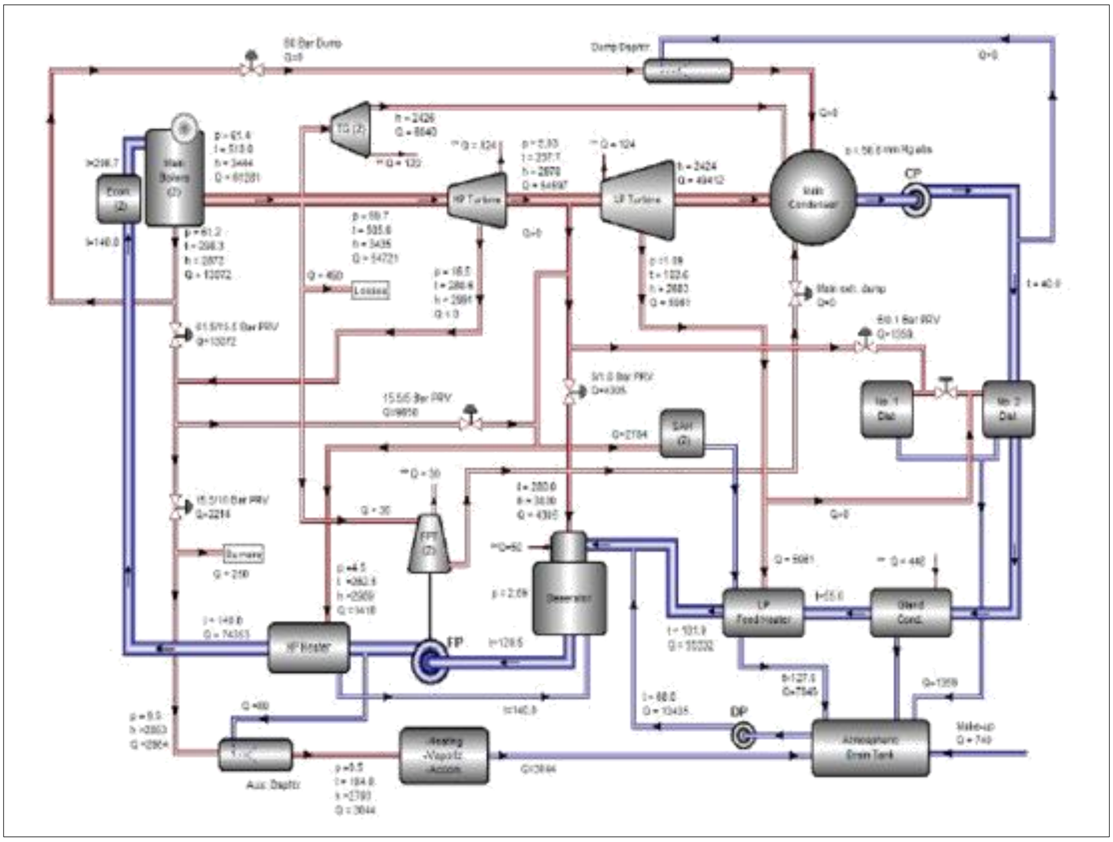


**Figure 1** Heat Balance diagram of a CST Plant

*2.1.4. Feed Pump*

It serves the purpose of helping to increase the pressure of the feed water to well above that of the steam drum pressure.

*2.1.5. Main Condenser*

The purpose of the condenser on a steam plant is the removal of latent heat out from the exhaust steam, through a regenerative process; the cooling is done by sea water. This allows the resultant so then the condensate can be pumped back into the system.

*2.1.6. Vacuum Pump/Air Ejector*

It is used on the steam plant for the removal of air from the condenser.

*2.1.7. Main Turbine*

The purpose of the turbine is the conversion of potential energy into a rotating kinetic energy. It's a cross compound impulse reaction type, comprising of the HP, LP and Astern turbine.

The HP is impulse single flow, which steam enters the turbine passing through the ahead stop valve which is attached straight to the turbine. It has five ahead nozzles with five groups of first stage nozzles which transfer its energy to the rotating body. The steam flows from the HP turbine to the LP turbine via a cross over pipe (LNG River Niger Operating Manual Sec 3 .4.1pp 2)

The LP turbine is a reaction type; energy is transferred to four rataue and four impulse stages before existing into the condenser. (LNG River Niger Operating Manual Sec 3 .4.1 pp 2)

Astern Turbine is gashed together on same shaft with the LP turbine, steam is administered via the astern guardian valve and astern maneuvering valve transferring energy to two Curtis row headed for the aft of the side and expend into the main condenser. (LNG River Niger Operating Manual Section 3 .4.1 pp 2)

Knowing the isentropic efficiency of the turbine (ŋt) = wa/ws

Where wa and ws is gotten from the energy equilibrium of the turbine

$$=-m\ (h2-h1)$$

$$(\eta t)= (h2a-h1)/\ (h2s-h1)$$

Where

- h1 = enthalpy at the inlet
- h2a=enthalpy of actual process at the exit
- h2s=enthalpy of isentropic process at the exit

### 2.2. Ultra Steam Plant Overview

The concept behind the ultra-steam turbines is to have a steam plant with same reliably, easy to maintain and operate but improved efficiency of about12- 15% compared to conventional steam plant. (www.mhi.co.jp)

The ultra-steam is the brain child of Mitsubishi heavy industries, with operating pressure of 100Bar and 560deg Celsius. The plant configuration is similar to that of a conventional steam plant with an improved high pressure reheat boiler, re-heater and the intermediate pressure (IP) turbine, all of which account for increase in efficiency of the new design. The design of the boiler allows the re heat burner to automatically ignites and extinguish itself at different plant condition to achieve the desired steam temperature.

The steam flow pattern is different from the conventional steam plant, from the boilers, it goes to the high pressure turbine, after which it goes through the re-heater before the IP turbine and passes to the LP turbine and exhaust into the main condenser. (www.mhi.co.jp)

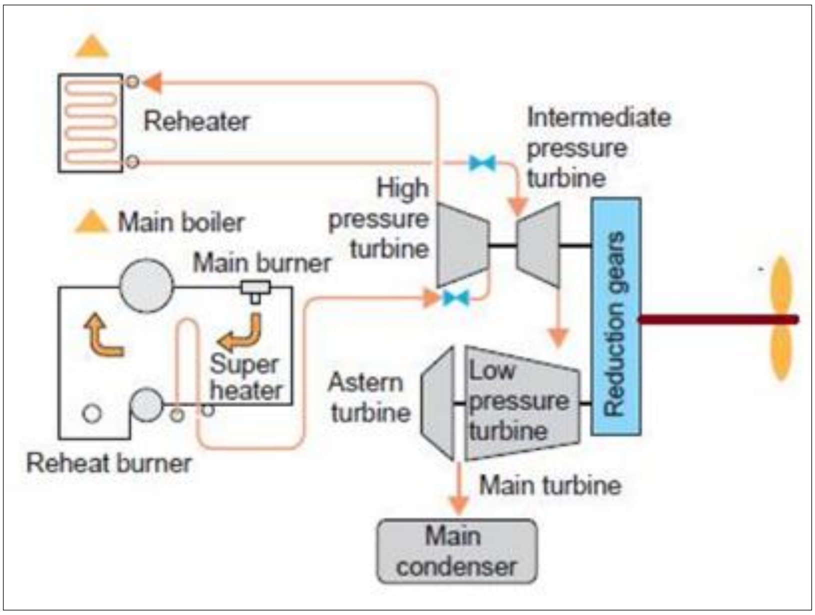


**Figure 2** Schematic of UST plant by MHI (reproduced from www.mhi.co.jp)

#### *2.2.1. Reheat Boiler*

The reheat boiler has been in use at shore plant, it has the ability to deliver super-heated steam at 560ºC temperature and 100Bar pressure, this is deployed for marine use and it is a major component of the UST plant. There are different types of reheat boiler available for marine use namely Dual furnace, Gas By-Pass and individual, but for the purpose of this project the dual furnace will be used(Reheat Boiler for Marine Reheat Cycle Plant)

*2.2.2. Dual Furnace Reheat Boiler*

This is a roof fired boiler, made from high temperature resistance and high strength carbon steel materials with a reheat burner and furnace at the lower part in ward way of the combustion gas. The re-heater is used to realise the precise steam temperature. Steam that flows through the re-heater do have a cooling effect on it, so that in low steam condition, it prevent the re-heater from burning out, that explains why it is located outward of the combustion gas where the temperature is low. The furnaces are gas tight. (Reheat Boiler for Marine Reheat Cycle Plant).

### 2.3. Summary

With the new regulation on emission coming fully in 2020, the ultra-steam plant will be fully compliant. The layout of both conventional and the ultra-steam plant have been reviewed in this chapter; the next chapter will look at the methodology.

## 3. Methodology

The aim of the project work is to look into ways of making the conventional steam plants on LNG Tanker more efficient in future working condition using an existing technology from Mitsubishi heavy industries. The new technology requires changing the system from the CST to UST.

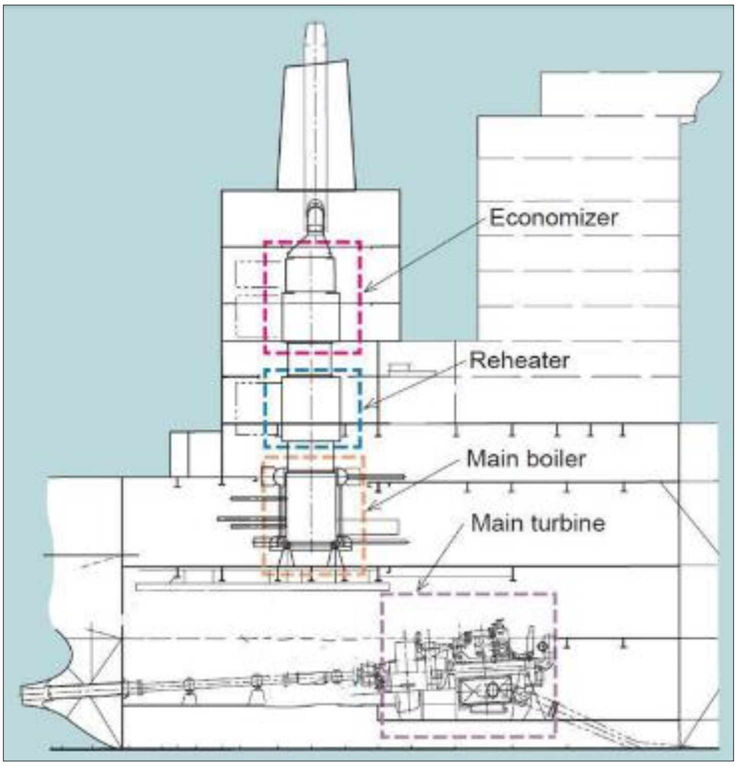


**Figure 3** Expanded view of UST Plant by MHI (reproduced from www.mhi.co.jp)

### 3.1. Design Assumptions

The design of the new system is based on the assumption of 100MCR and dual firing:

Boiler efficiency = 88.5%

Calorific value of fuel/gas =10280/13280kcal/kg

Design Super-heater Temperature/Pressure =560ºC/100Bar

Sea water temperature =27ºC

Boil off rate = 0.13%

Specific Gravity of Cargo = 0.46Ton/m3

(www.mhi-mme.com)

#### *3.1.1. Design Super- heater temperature/pressure*

The design super-heater steam temperature is 560ºC and pressure100Bar this will be achieved by reheating the steam to have dryness fraction of 0.86. By the aforementioned parameters, the thermal efficiency of the turbine will be increased a lower temperature might allow wet steam to be carried over into the turbine, thus eroding the turbine blade also reducing the efficiency of the turbine.

#### *3.1.2. Working fluid*

Just like the existing system, the working fluid in this new design is water.

### 3.2. Design Specification/Requirement

It is of uttermost importance that specification of the re-designed plant must

- Have good safety standard for both operator and the environment, conforming to all legislations.
- Extremely robust to last long
- Fit for the intended purpose.
- Adaptable into the existing CST design
- Able to use natural boil off from the cargo tanks
- Produce the power required for propulsion at 100% MCR of 26800kW and normal operation of 24120Kw
- Produce the required electrical need of the plant of 3200kW
- Improvement on the performance of the turbine to about 15% more compared to the existing CST system.

(www.mhi-mme.com)

### 3.3. Proposed Solution

For the purpose of this project, I am proposing a modification to the existing plant, by converting it from the conventional steam plant to an Ultra-steam plant. This can be achieved by deploying the MHI UST technology, which includes the reheat boiler3D stationary turbine blade, integrated shroud blade (ISB).

Most of the existing component on the existing plant will not be compatible because they are not designed to operate at the 560ºC and 100Bar which are the operating parameters for superheated steam, in the new re-design plant; as such they will be changed. The boiler, turbo feed pump, turbo alternator and turbines. Also all the pipe works including flanges will be changed, because the current arrangement will fail. From the available data from MHI, the modification will require the same amount of space as the CST. (www.mhi-mme.com)

**Table 1** Difference between CST and UST Plant

| | **Conventional Plant** | **Ultra-Steam Plant** |
|---|---|---|
| Steam Temp/Pressure(º/Bar) | 515/60 | 560/100 |
| Flow path | BLR-HP-LP-COND | BLR-HP-REHTR-IP-LP-COND |
| Flange | ANSI 900LB | ANSI 2500LB |

### 3.4. Fuel Efficiency Analysis

The amount of fuel used in determined by the amount of power used by the vessel, so calculating the specific fuel consumption = amount of fuel consumed/amount of power generated.

**Table 2** Fuel consumption at MCR Condition

| Power generated (kW) =29700 | Energy Supply (kW) = 90864.32 | |
|---|---|---|
| | **100% Fuel** | **Dual Fuel(BOG+ Fuel Oil)** |
| Fuel Consumption(Tonnes/hr) | 7.605 | 2.96 |
| Specific fuel | 256 | 100 |
| consumption(g/kW.h) | | |

**Table 3** Fuel consumption at NORMAL Condition

| Power generated (kW) =27020 | Energy Supply (kW) = 82646.97 | |
|---|---|---|
| | **100% Fuel** | **Dual Fuel(BOG+ Fuel Oil)** |
| Fuel Consumption(Tonnes/hr) | 6.92 | 2.27 |
| Specific fuel | 256 | 84 |
| consumption(g/kW.h) | | |

At plant conditions, the specific fuel consumption on 100% fuel mode, while on duel fuel mode, normal working condition has lower specific fuel consumption because the power demand is low in this condition.

### 3.5. Plant Efficiency

Calculating the entire efficiency of the plant is summing up the total amount of output power with ratio the amount of power input at normal working condition. Using system design requirement/assumptions, energy supply for normal working condition is 82646.97kW, power required for propulsion 24120kW and auxiliary power required is 3200kW.

$$\text{Plant Efficiency } (\eta) = (24120+3200) / 82646.97 = 0.330 \times 100 = 33.0\%$$

## 4. Results

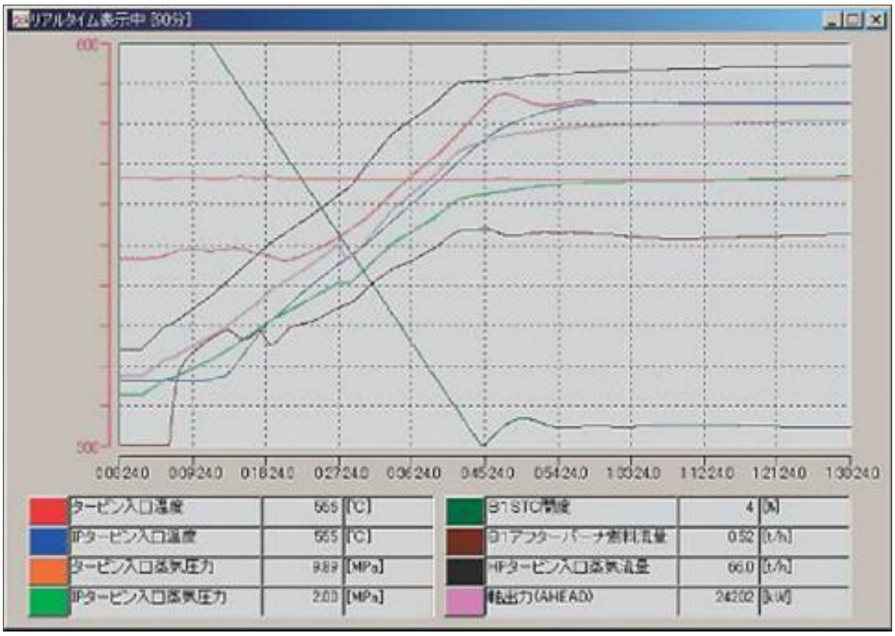


**Figure 4** Simulator Screen (www.mhi.co.jp)

Building a prototype for this project is not possible, but using the data obtained from MHI Nagasaki's R&D centre, which built a plant model and simulator to demonstrate all type of load condition, which help identify the dynamic performance of the UST. (www.mhi.co.jp)

I am proposing for implementation this project, on one of the fleet vessel "LNG River Niger" as pilot scheme, then subsequently all other steam vessel will be converted to UST.

### 4.1. Redundancy

The new designed Ultra steam plant is very reliable and available; there is installation of redundant equipment in case of unforeseen failure.

### 4.2. Commercial Analysis

The primary purpose of this project is to increase efficiency, making the ship competitive and increase profitability for the company. For the purpose of this project few assumptions were made some of which include the following

- Vessel is on long time chatter
- Chatter rate remains same.
- Bunker price of $460/ton
- Operating cost
- LNG price of $350/ton
- Vessel will operate 365days

According to projections made, when this design is implemented, it will reduce the current operating cost by 20% also extend the life cycle of the vessel by 10years. The operating cost includes the following which is estimated to be one third of the life cycle cost.

- Personnel Cost
- Stores/Spares
- Maintenance/Repair
- Insurance
- Bunkers/Lubricating oil

For this project to be implemented, the vessel will be out of service for about 6months, with a cost of conversion of $35-$40 million, with a good business plan, the charterers can also contribute to the cost of conversion to Ultra steam, because with better efficiency there will be savings on fuel. Currently an average fuel oil consumption 70tons/day and BOG consumption is 180ton/day, with the price assumptions, there will be a total savings of about $8million on fuel alone, the financial benefits to the chatterers will materialize over a long term if they choose to invest in the conversion.

The company has competent personnel with the required skill set and certification to man this vessel, it only required additional hands-on training to get familiar with the design, this can be done by liaising with the OEM for training sections to be organized for staffs.

### 4.3. Environment

At normal sea service, when the plant is on 100% gas mode, there is 0% Sulphur oxide emission from the plant, while the nitrogen and carbon oxide emission is the smallest compared to other means of propulsion system (Reheat Boiler for Marine Reheat Cycle Plant 2007).

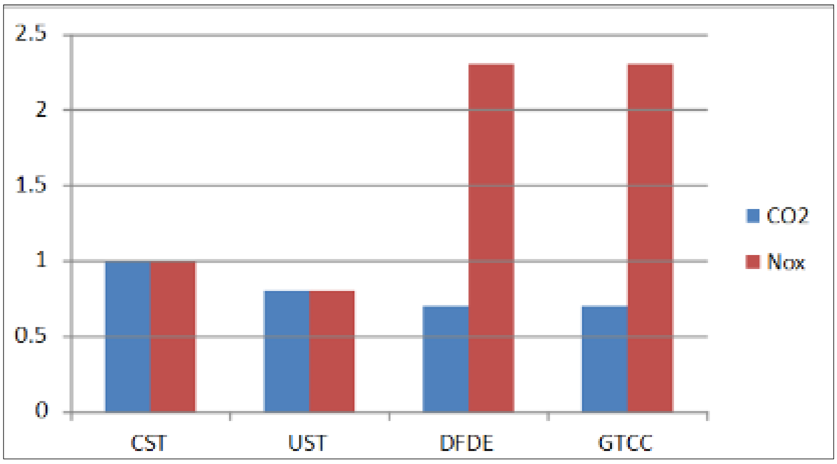


**Figure 5** Emission index at sea. (Reproduced from www.mhi.co.jp)

In harbor condition, Steam plant has the capacity to burn lesser fuel when compared to the DFDE making their Nitrogen oxide emission higher (Reheat Boiler for Marine Reheat Cycle Plant 2007)

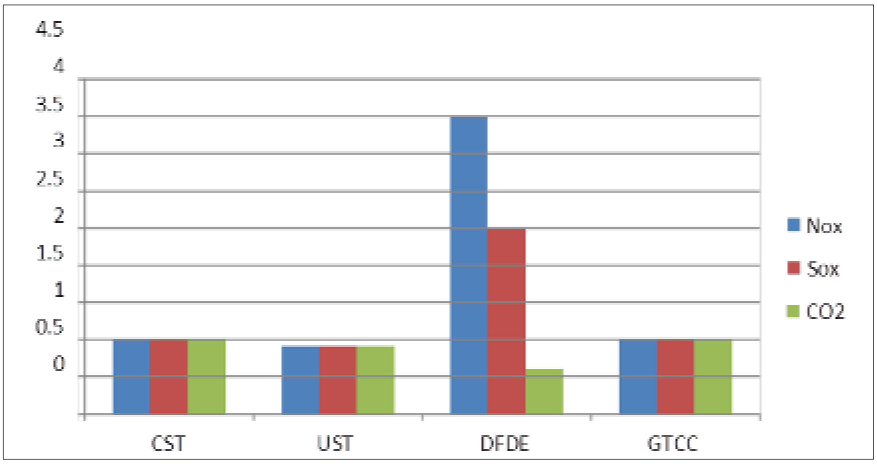


**Figure 6** Emission index in harbour condition (reproduced from www.mhi.co.jp)

## 5. Discussion

The efficiency of a steam plant is calculated by the amount of energy put into the system and the corresponding useful energy given out of the plant. Theoretically an ideal turbine should give out equal amount of energy put in, without any form of loss. But in practice this cannot be achieved due to heat and other forms of losses, some of which cannot be accounted for. There are various factors that determine the efficiency of a steam turbine, but are not limited to the following

- The temperature and pressure of steam
- Angle of guiding vanes
- Blade angle of the rotor
- Radius of rotor

$$\text{Efficiency } (\eta) = \text{work done} \div \text{input kinetic energy}$$

The input energy is dependent on the rate of steam going into the turbine, but the work done is determined by different factors within the system, some of which are difficult to calculate. The efficiency of the steam plant can be calculated either by calculating the efficiency of the blade ($\eta b$) or calculating the stage efficiency ($\eta s$). Reference turbineinfo.com

No matter the type of steam plant either the UST or CST, some things needs to be done in other to sustain the efficiency of the plant. The thermal efficiency of the plant can be improved by increasing the operating temperature and pressure, doing that will have effect on all materials used, including the super-heater tubes and materials used in the construction of the turbine in a CST plant. Most associated pipe works on a CST are made from alloys of steel, to avoid material failure; material used in the new system has been improved upon to materials with higher heat and corrosion resistance with high strength.

Maintaining good boiler hygiene is also a good way of improving the efficiency of the steam plant. (Marine Steam Turbines, Marine Engineering Design)

### 5.1. Feed Water Treatment

The quality of boiler and feed water is very important in the safe operation and overall efficiency of the steam plant. The purpose of water treatment is to prevent corrosion of the main boiler and the feed water systems, Scale formation and corrosion is a major threat to high pressure marine boilers, because they are made from different metal alloys, which are prone to corrosion especially in the presence of water or oxygen. Corrosion eats up some metal materials which in turn affect the strength integrity of the material making it to fail eventually. Scale deposit on the super-heater tube surface reduces the effect of heat transfer hereby reducing the efficiency of the boiler, also the affected area may overheat, which can lead to tube failure. Magnetite which is a by-product from corrosion forms a protective film

### 5.2. Fuel Oil System

The fuel oil and gas system is a very important aspect of the steam plant. Irrespective of plant design either UST or CST, the marine boiler is designed to run on fuel oil and natural boil off from the cargo tanks. The amount of natural boil off is determined by design and capacity of the cargo tanks either moss or membrane and the quality of fuel oil is determined by the type of bunker received.

For good combustion to be achieved, which in turn determines the efficiency of the plant, fuel oil must be at the right temperature, pressure, viscosity and good quality. If the quality of fuel oil is bad, good combustion cannot be archived which in turn forms slag on the surface of the tube thereby reducing the effect of heat exchange leading to reduction in the efficiency of the plant. To prevent this occurrence, fuel oil stabilizer, which is a chemical readily available in the market, is used to help recondition the fuel oil.

Also right quality and amount of air help inn prevent incomplete combustion, because incomplete combustion leads to discharge of carbon monoxide.

### 5.3. Steam Piping/Traps

A steam pipe and its internals inspection should be conducted, which is very important because it help to identify location of thermal efficiency is lost in the steam path.

The operating condition of steam trap on the steam line should checked, this should be done visually and ultrasonic listening, because temperature check does not give the accurate operating condition of the trap. If the trap is not operating correctly, it will also lead to loss of thermal efficiency.

*Nomenclature*

- LNG: Liquefied Natural Gas
- BOG: Boil off Gas
- MCR: Maximum continuous rating
- MHI: Mitsubishi Heavy Industries
- UST: Ultra Steam Turbine
- CST: Conventional Steam Turbine
- DFDE: Dual Fuel Diesel Engine
- COGES: Combine Gas Turbine Electric and Steam
- HP: High Pressure
- LP: Low Pressure
- IP: Intermediate Pressure
- ISB: Integrated Shroud Blade
- OEM: Original Equipment Manufacturer

## 6. Conclusion

In an increasingly harsh and aggressive market, ship-owner and managers are faced with the task of been competitive. From the study carried out, converting to UST will increase efficiency of the current plant configuration by 15%, compliant with latest regulation on emission and specific fuel consumption of 34g/kW.h. With improved efficiency, the operating cost will also be reduced and will make the vessel competitive. Converting to UST will give the vessel life extension of 10years

Sharing the cost of investment between owners and charterers is a rational negotiation.

### *Recommendations/future work and development*

There are other areas which was identified in the course of this project that can be researched further

- Instrumentation and controls
- Material composition of the reheat boiler

## Compliance with ethical standards

### *Acknowledgments*

Firstly I will like to express my appreciation to the project coordinator Dr Shikun Zhou and project supervisor Dr Hongwei Wang at University of Portsmouth for guidance and support during the course of this project.

I am grateful to my colleagues at work, who have contributed directly or indirectly to this project, also to Mitsubishi heavy industries.

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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