Fuel Savings on Propulsion by Recovery of Thermal Energy – the Most Efficient Opportunity to Protect the Enviroment (shortened version)

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SYNOPSIS

As well as the continuous growth in shipping activities worldwide - the related pollution of air is permanently increasing. Unfortunately up to now there was no parallel development to that on land based sources of air pollution which has demonstrated remarkable reductions since year 2000. This may change now with the coming into force of the IMO Rules Annex 6.
As thereis a substantial demand on the power installed aboard large (reefer) container vessels, much more than that required before, a modified propulsion plant alternative is proposed in this paper. One of their targets is to save energy, i.e.minimise fuel consumption as well as emissions. Another is to give the ship additional power and, by means of a so-called booster device, to increase her speed or to have a supplementary "Sea Margin". This is particularly important for container ships operated under strict time schedules. To reach these goals, three main components have been chosen for the proposed alternatives: The Waste Heat Recovery (WHR) plant, the electrical motor concentric on the propeller shaft (Booster), and the Power Management System (PMS). Under the leadership of Siemens AG, a group of renowned suppliers has been organised to deliver offers to shipping companies open to such innovations. The group members are: Aalborg Industries (DK), Peter Brotherhood Ltd. (GB) and Siemens AG (D). Additionally, Wärtsilä Switzerland Ltd. (CH) and MAN-B&W Diesel A/S are associate partners of this group.

Authors' Biographies

Kay Tigges was born in Duisburg in 1961. He studied at the University of Duisburg and graduated with an MSc in Naval Architecture in 1984. From 1985 to 1989 he was responsible for basic design of container feeder ships and RoRo-vessels at the Schiffswerft Sietas in Hamburg. Since 1989, Mr. Tigges has been employed by Siemens AG in Hamburg, where he is in charge of project management and sales of diesel electric propulsion plants, as well as of complete ship electrical installations. His present interest and area of activities are special applications like POD-drives, shaft generator/motor systems and waste heat recovery systems.

1. LIST OF CONTENTS

2. INTRODUCTION

2.1 Background

The worldwide shipping activities are still growing wherein the container business covers the lion's share so far. Moreover, the percentage of refrigerated containers transported by one vessel has risen as well. These types of reefer container vessels are part of the market trend. A consequence of these developments is a substantial demand on the power installed aboard container ships. It is therefore easy to understand the efforts of naval architects and marine engineers to create and propagate new solutions in that direction, such as WHR plants plus Booster, as well as Power Management Systems (PMS).

2.2 Waste Heat Recovery (WHR)

Total efficiencies of diesel engines of about 50%, which were seen as practically impossible up to that date, were attained. Nevertheless, a target still remained: To recover the majority of energy lost through the exhaust gases.

Part of this energy had already been used on diesel engines to drive their own turbo chargers or for water heating purposes, but the rest of about 10% of the total nominal energy of the main engine was still being wasted. Thus, the idea to use WHR on ships was the order of the day at the beginning of the eighties. The original concept envisaged replacing one diesel generator with a supplementary turbo generator. One diesel generator less means less investment as well as reduced maintenance work and noise disturbance.

Another possibility was offered then too, namely to keep the number of diesel generators on board constant and to use the additional, economical electrical energy delivered by the WHR turbo generator, via a power take in plant (PTI), for the ship's propulsion purposes.

New products were launched on the market under such names as "Efficiency Booster System (EBS)" by Sulzer of Winterthur or "Turbo Compound Systems (TCS)" by MAN B&W of Copenhagen. However, in order to use WHR for the ship's propulsion, PTI installations were needed. These PTIs included complicated epicyclical gears. The recovered energy was fed directly to the engine shaft, allowing the engine to be run at a correspondingly reduced output and to deliver the same CSR power to the propeller shaft, with a correspondingly lower specific fuel consumption.

However, reality even surpassed the trend. In spite of the sophisticated vibration calculations, supplied as part of the package, the evidence and intensity of torque fluctuations coming from propeller, plus vibration impulses coming from the diesel engine itself, repeatedly caused unpleasant operational difficulties. The confidence of the buyers and users of such products had been damaged. The evident conclusion of all these developments is that even if the plant is more expensive, the safest choice of all the proposals until now is to connect electrically a WHR turbo generator with a SM/SG plant of a gearless type.

2.3 Present WHR Proposals

Three companies, each expert in its own field, have started a joint venture for the development and application of WHR plants on ships, particularly medium-sized and large container vessels.

They form a working group whose members are:

Aalborg Industries (DK)
Peter Brotherhood Ltd. (GB)
Siemens AG (D)

including, as partners,

Wärtsilä Switzerland (CH)
MAN-B&W Diesel A/S (DK).

The present WHR system is designed and manufactured according to the latest technical achievements. Its principle scheme is displayed in Fig. 1.

The turbo compound system consists of a power turbine, a steam turbine and a generator. The gas turbine is usually driven by exhaust gas separated from the main flow. The steam turbine is of dual pressure type (HP + LP). Exhaust gas outlets from the main engine turbo chargers are connected to the exhaust gas boiler.

The turbo generator can operate as single generator or in parallel with other generators depending on available exhaust gasses and the load situation.

2.4 Additional Power Availability and Application

The waste heat recovery system recovers substantial energy otherwise lost in the exhaust gases. This facility has been extremely important in the recent times due to a steady and persistent rise in fuel prices.

The resulting questions are: What can be done with the additional power (round 10%) available on board the ship and what would be its best application? An example of such an investigation is shown in figure 2. In principle, there are four distinct modes of applicability. (The order of these , as stated below, is not significant.)

1) Assuming a constant ship's speed, i.e. total propulsion power required, the continuous service rating of the main engine (ME) could be reduced by the same amount as delivered by the WHR plant. This means less fuel consumption, i.e. operational costs.

2) Alternatively, the installed output of the ME, i.e. number of cylinders, could be correspondingly reduced.

3) The power contribution of the WHR plant could be considered as a reserve (supplementary Sea Margin) in order to keep the ship's service speed constant, also under heavily adverse weather and sea conditions or to recover already caused delays. This applicability mode of additional available power is essential for large container ships working in pools and under strictly fixed time schedules.

4) The additional power obtained through the WHR plant could be used to reduce or eliminate the need to use the auxiliary engines (AE) during sea passages. As is well-known, the medium or fast diesel AE of the gen. sets have a higher specific fuel consumption and need more maintenance than the two stroke diesel ME of the ship. The already-mentioned trend towards reefer container vessels makes the elimination of the requirement to use the AE during navigation on open sea, due to the WHR power supply, even more attractive. However, the number of gen. sets installed on board remains the same as before, being dictated by the power demand for manoeuvring conditions.

N.B.: The modes described in Items 1 and 4 can also be applied in combination, thus reaping even higher economical benefits.

All the applicability modes described above imply the necessity of an electrical motor, installed on the propeller shaft of the ship and fed with energy, via a converter, by the electrical board net. Normally, such a shaft motor (SM), usually called “Booster”, can also be used as a shaft generator (SG). The Booster must also function as a buffer during cases when the energy of the WHR is not entirely absorbed by the variable consumers on board. The design principle of the Booster and the WHR systems are displayed in Fig. 3,4,5,6.

3. MAIN COMPONENTS OF THE SYSTEM

3.1 ME-tuning and PT layout

As the source of thermal energy is of course directly influence by the quality of combustion, i.e. the temperature level and flowrate of the exhaust gas, special attention has to be spend to a flexible tuning of the injection system and the efficiency of the turbocharger(s).)
From the very beginning, the air intake (combustion air) can be feed to the turbochargers from outside the engine room via separate air ducting. This enables a higher exhaust gas temperature after the burning process without escalating the thermal load at the critical engine parts. See Figure 7,8.

Modern high efficient turbochargers from makers MHI or ABB no longer require the full exhaust gas flow of the ME to drive the compressor part with sufficient power. Therefore it became common to utilize the non-required flow rate from a bypass at the exhaust gas receiver to drive the power turbine directly. The power turbine (PT) is designed specifically to the available bypass flow.(Usually between 7,5 %and 10% of the total exhaust gas flow rate). Heat is also recovered from the engine’s jacket cooling water and scavange air cooler to preheat the boiler’s feed water. See Figure 9,10.

3.2 Exhaust gas boiler plant

Dual pressure exhaust gas boilers for marine combined cycle plants were supplied for a series of ships entering service in the early 1980’s. The extensive operation experience of these plants is the important background for the development, design and configuration of the latest generation of large waste heat recovery plants like those having recently entered operation.

Steam for the turbo generator is evaporated and superheated in two pressure stages (see figures 11 and 12). Each stage comprises a forced circulation evaporator, a steam separation drum, and a superheater. The steam output is boosted by preheating of the feed water in two stages by means of other main engine waste heat sources, namely jacket water and scavenge air.

The extended heating surfaces are of the well-known and proven double finned tube design with optimized fin density providing compact design while still maintaining low fouling rates.

Much attention has been paid to improve the safe and reliable operation of the boiler plant by eliminating the major operational hazards related to exhaust gas boilers, namely the risk of soot fires and corrosion:

- Circulation pumps of the canned motor type (with external cooling) and flow monitoring equipment enhance reliability and secure the continuous circulation of boiler water and the vital cooling of the evaporator heating surfaces. Stand-by pumps are always included and arranged for automatic start in case of trouble with the operating pumps.
- Automatically operated steam soot-blowers with improved cleaning efficiency ensure effective on-load cleaning of the boiler tubes.
- Monitoring of exhaust gas parameters provides the operator with continuous information about the boiler fouling conditions, and temperature sensors arranged in grids above each section provide warning and indicate location of a possible soot fire.
- A by-pass and exhaust gas dampers enable automatic by-passing of exhaust gas during low load operation where fouling rates is increasing due to poorer combustion quality and reduced exhaust gas velocity.
- Dosing of the fuel oil additive “Ferrocene” improves the quality of the main engine combustion and reduces fouling rate of the boiler (and turbochargers).

- An automated feed and boiler water treatment system monitors the water quality and adjusts dosage of water treatment chemicals accordingly, thus securing adequate conditions for avoiding problems of water side corrosion and water carry-over from steam drums to superheaters and steam turbine.
- The operating pressure of the LP section is selected and adjusted suitably high to avoid condensation of sulphuric acid that would immediately create excessive fouling problems and on a longer term also corrosion damages.

The exhaust gas boiler allows sliding pressure operation, and control logic within the steam turbine control system automatically adjust the HP operation pressure to secure the highest possible power output in all operating conditions.

3.3 TCS (turbo compound system)

The TCS consists of dual pressure multi-stage steam turbine, a power turbine designed to the bypass flowrate, two reduction gears, a self shifting coupling to the PT and a standard 4-pole generator operating at60Hz. All of the major components are of proven design but are assembled together in an innovative arrangement that maximises the electrical output available from the steam and gas in a cost effective (Euro/kW) solution.
See figures 13,14,15,16
The HP part of the ST is designed to be controllable for speed and load. This enables a limited range for load control and enables synchronizing to the frequency of the ship's mains. The LP part of the ST is as well as the power turbine is uncontrolled in matters of speed or power. All components are built up on a common bedframe which contents as well the necessary lub-oil tanks, pumps, valves etc.

3.4 Gearless Shaft Motor/Generator (SM/SG)

In principle, the Gearless Shaft Motor/Generator (SM/SG) consists of an electric shaft motor (SM), which can also be used as a generator (SG). The main function of a shaft motor (SM), also called a "booster" plant, is, as its short name implies, to boost the propulsion of ships.

The SM produces the additional propeller torque, which leads to the boost of the ship's speed, whereas while working in generator mode (SG) the SM/SG plant can supply electrical energy for the board needs and the refrigeration process. The "SM/SG" unit can be concentrically installed on the propeller shaft, driving it directly without the help of any gears.

For the propulsion plants of very large and ultra large container ships, the highest priority is given to the reliability of the components, synonymous with simplicity. Therefore, it is no surpriseto see that for those types of ships, the SM/SG concentric configuration on the propeller shaft has been mostly adopted. Truly speaking, the "Gearless SM/SG" is the most expensive solution, but as it is often the case in real life, it is also the most recommendable one. This is the reason why only this type of SM/SG has been considered in this study.

In general, a ship propeller generates torque vibrations, because it works in the non-homogenous wake field behind the ship's hull. The torque vibrations are even aggravated by bad weather conditions, when the propeller immersion varies with the encountered sea waves, respectively the pitch movements of the ship.

This is why converters, in spite of their non-negligible price, should always be fitted in the electrical part of the power transmission. The Gearless SG/SM must be controlled by speed or torque, respectively for constant ship's operation or for lower load of the ME.

In terms of the Classifications Society rules and regulations, the booster drive is considered as a non-vital accessing drive. If defect, the SM/SG can be electrically disconnected from the board net and turn idly, whereas the main diesel engine can drive the ship's propeller further, undisturbed.

From the perspective of the ship designer, the small dimensions of a Gearless SM/SG Unit, and its concentric location on the propeller shaft, lead to the great advantage that the installation does not change the dimensions of the ship and her cargo capacity remains intact.

As known, in medium-sized container vessels, the engine room is located in the aft ship. Naval architects and hydrodynamic experts, designing the underwater hull form of the ship, strive to obtain uniform water flow to the propeller in order to avoid vibrations and to obtain the highest possible propulsion efficiency. Thus, they choose

U-shaped contours of the frames and very often a stern bulb, too. Such a modern hull design indeed enables the Gearless SM/SG device to be pushed far aft in the ship.

On very large container vessels, with the engine room arranged between 1/4 and 2/3 of the ship's length, the Gearless SM/SG unit can be located aft, anywhere in the tunnel of the propeller shaft.

3.5 Power Management System (PMS)

The Power Management System (PMS) is designed to ensure uninterrupted and sufficient electrical power flow to the ship's systems. The PMS controls the amount of electrical power, as demanded by the various consumers, in an efficient way under all normal operating conditions of the ship. Furthermore, a power plant fitted with PMS enables the ship to take full advantage of the waste heat recovery. See figure 17.

The PMS is normally set to economical load sharing (ELS) mode that loads the turbo generator as much as possible and feeds surplus power to the propeller shaft whenever possible.
The PMS functions are also essential for the undisturbed operation of the vessel in normal and in emergency conditions. A single failure of one component has no negative effect on the functioning of the entire PMS system. Important attributes of the PMS units are high reliability and availability. Moreover, they relieve the crew from tiresome and sometimes risky tasks.

3.6 Shore connection

Air pollution in ports have become an important issue at least in the Baltic Sea. Actually the NEW HANSA (Union of the Baltic cities) have committed themselves to support and require a shore connection while the port stays of the vessels. The voltage level for those shore connections has been selected as 10KV. This requires accordingly transformers on the ship's side. When the ships load shall be transferred to shore connection normally the ship's mains voltage and frequency as well as phases have to be synchronised to the shore-side. This could cause problems in the stability (safety against blackout) of the ships system while load shifting.
An existing converter system with sufficient size could easily be utilize to synchonise the shore supply to the stable ship's mains without disturbing this. A booster/shaft-generator converter can easily made suitable to this additional feature.

4. ENVIRONMENTAL ASPECTS

4.1 Actual Scenario

Protecting the environment, by minimising the impact of growing industrial activities on it, Has been finally deeply recognised as essential for the well-being of life on our planet. It is on the agenda of international organisations, governments, political parties, customers and suppliers of goods of any kind.
Climatic changes and protection of the atmosphere against the harmful gases emitted by diesel engines on board of ships are important items in this train of thought. Of such gases, the main ones are oxides of nitrogen (NOx), sulphur (SOx) and carbon (COx). See figure 24,25.

The most important forum for rules and regulations in the maritime world today is the "International Maritime Organisation (IMO)", an institution of the United Nations in London and its members are all the maritime nations of the world. Another authority involved in the matter is the Commission of the European Union (EU) in Brussels.

The two main bodies of the IMO which deal with the environmental affairs are:

- Maritime Safety Committee (MSC) and
- Maritime Environment Protection Committee (MEPC).

The two committees mentioned above, as a rule, meet once or twice a year with 500-600 participants from 80-90 countries. The preparations for the meetings and concepts for recommendations, rules or conventions are executed by Sub-Committees and Working Groups. The decisions taken during the MSC and MEPC meetings are submitted for approval to the General Assembly of the IMO.
The rules, recommendations or conventions approved by the General Assembly are forwarded to the IMO member states, and they may become laws after a certain number of states with a given percentage of the world's fleet have agreed to them. The normal duration of all the procedure described above can take many years, such as was the case with the "MARPOL" Convention, dealing with maritime pollution.

The MARPOL Convention consists of a number of Annexes, each is about a certain topic. For the present study, the most important is in Annex VI, entitled "Regulations for the Prevention of Air Pollution from Ships" which was approved by IMO in September 1997, but first coming into force in May 2005. This could only happen when at least 15 states (there were 20) with no less than 50% of the world's merchant shipping tonnage (it was 62%) adopted the Annex VI, too. Annex IV, in its turn, is composed of various Chapters and Rules. For the present study, Chapter III "Requirements for Emission Control" is of special interest.

On ships, the sources of emission are the diesel engines, which deliver propulsion and auxiliary power. Unfortunately, all devices and measures used to reduce emissions cost money to be installed and operated.

Until now, owners and operators of ships, with few exceptions, paid only lip service to the necessity of emissions reduction on their ships, because they were aware that it normally takes a long time for the IMO Conventions to come into force and were afraid of the financial consequences involved. This situation is changing, because recommendations of the past are becoming current laws now. These days, everybody already speaks about "green ships" and conferences, such as this one,on this subject are being held. Several shipping companies are taking advantage of this environmental service and an increasing number of ships carry an Environmental Passport on board issued by Classification Societies.

4.2 WHR-Contribution

In this scenario, ship propulsion plants including WHR plants are becoming even more attractive. Emissions from diesel engines are generated during the burning process of the fuel in the combustion chambers of their cylinders. This mainly depends on how much fuel is being burnt and is a function of the propulsion and auxiliary power required on the ship. For large (reefer) container ships, the amount of power, respectively emissions, can be impressive. Then logically: A WHR plant adopted primarily to reduce the fuel consumption i.e. operational costs by say 10%, will have **a costs free benefit as by-product**, consisting of approximately the same amount of emissions reduction. See figure 26.

With reference to the available practical measures for the reduction of each of the normal gases mentioned earlier, the impact of the WHR systems is as follows:

* Regarding NOX, a lot of research has already been carried out and progress has already been achieved by the engine manufacturers. Their diesel engines are now complying with the requirements of MARPOL 73/78 Annex VI. The diesel engines are provided with Technical Files for this purpose. The WHR contribution through the reduction of the quantity of fuel burnt is realistic in this case too.

* With reference to the SOx, the benefits brought by the WHR in this case are even more interesting and should be appreciated, because SOx can only be limited through the chosen quality of a more expensive fuel and the burnt quantity of it.

  The contribution of a WHR plant to emissions reduction will be roughly proportional to the fuel quantity saved.

  Regarding the percentage of sulphur content in the fuel , there are three limits to be considered, as prescribed by the Sulphur Directive 1999/32 issued by the EU:

  - Maximum allowed of 4.5 % (in force since 2005)
    (in practice, around 2.8% is mostly used)
  - A limit of 1.5% for regular ferries (by 2007)
  - A limit of 0.2% (later 0.1%, by 2008) for ships in EU ports

  The question arising from these restrictions is whether "one fuel ships" (same fuel for main engine and gen. sets) can still survive.

* In the case of COx, respectively CO_2, some activities have been initiated and performed by IMO and the EU as well. On 1st August 2005, the Marine Environment Protection Committee (MEPC) issued "Interim Guidelines for Voluntary Ship COx Emissions Indexing for use on Trials". It can be expected that the "Policies and Practices Related to the Reduction of Greenhouse Gas Emissions from Ships" (IMO Assembly Resolution A 963/23 of November 2003) will be further pursed and improved.

Consequently, the contribution of the WHR systems in this direction will gain ground too. But the number of indexed applications has to grow too in order to facilitate the quantification of the benefits and such developments may take years to be accomplished.

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