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A preliminary study on the application of thermal storage to merchant ships

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Abstract

The shipping industry is focusing more and more on reducing fuel consumption and greenhouse gas emissions. A non-negligible amount of fuel is consumed while ships are in port, waiting for loading or unloading, for heating up accommodation spaces and fuel tanks, while when at sea waste heat from engines exhaust is under-used because of low demand. In this paper we propose the use of thermal energy storage as a solution for the mismatch between heat availability and demand. A simplified system is proposed and the influence of design parameters (storage size, heat exchangers surface, secondary fluid mass flow rate, storage temperature) on the performance of the system is analyzed. The results of the application of a thermal energy storage system to a case study ship show that the installation of a storage tank of 1000 m^3 could reduce the fuel consumption from the boilers by 80%, which would lead to yearly savings of 268,000 USD. This preliminary analysis shows that there is potential of both economic and environmental benefits from the application of thermal energy storage to merchant vessels.

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Keywords: thermal energy storage; energy efficiency; low carbon shipping;

1. Introduction

The shipping industry is currently facing challenging times. Bunker fuel prices are today 3 times higher than in the 80's [1] and fuel costs have increased from 13% to more than 50% of total operating costs in the same period of time [2,3]. Limits for sulfur and nitrogen oxides emissions are being reduced, further increasing fuel-related costs [4]. Several solutions have been proposed for addressing this situation [5], but there is still a large potential for improvement in ship energy efficiency.

Merchant vessels are generally powered by Diesel engines, which provide energy for propulsion and electric auxiliaries. Thermal energy consumption onboard is mostly related to i) heating of fuel tanks and

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ii) heating of accommodation spaces, and is generally provided by recovering heat from the exhaust gas. In spite of the fact that the energy required for heating purposes generally only accounts for a minor part of the overall waste energy available in the exhaust [6] there is almost no record in the shipping industry of the utilization of additional systems to improve waste heat recovery [7,8]. On the hand, when waiting in port for loading, unloading, and other operations, auxiliary heat demand needs to be provided by auxiliary boilers which are generally dimensioned for operations in severe conditions and therefore often operated at off-design load.

Thermal Energy Storage (TES) systems are often applied in other sectors as a solution to similar situations of mismatching between supply and demand [9]. Although TES systems have been largely studied in other industrial sectors, both in connection with Diesel engines [10–12] and in transportation [13,14], there is no record of TES application to shipping in the scientific literature. The aim of this paper is that of partially filling this gap with a study on the potential of said application and on the influence of relevant parameters on the performance of the system.

2. Methodology

In this study the application of a TES to a case study vessel (a product tanker) for which extensive measurements are available is proposed. The ship is equipped with: two main engines (MaK 8M32C rated 3840 kW each) which generate the power required for propulsion; three auxiliary engines (rated 682 kW each) for auxiliary power generation; and two auxiliary boilers (with a design steam generation rate of 14,000 kg/h at 9 bar each) for fulfilling heat demand in port, for cargo tank cleaning and for heating highly-viscous cargo. In addition, a shaft generator (rated 3,200 kW) is used to convert mechanical energy generated by the main engines to electrical energy, while two exhaust gas boilers (rated 700 kg/h of steam at 9 bar each) is used to provide auxiliary heat when the main engines are running. Propulsion represents the largest energy demand on board; fuel heating, accommodation and operations of cargo-tank cleaning between laden voyages require auxiliary heat; operation of auxiliary machinery onboard, such as pumps, compressors, navigation equipment and electric motors, requires auxiliary power.

Propulsion power demand, auxiliary power demand, seawater temperature and ambient temperature are measured by a data logging system covering ship operations from March 2012 until October 2014 for a total of 31 months. Instantaneous heat demand is calculated using the ship heat balance as provided by the shipyard, where measured values for seawater and ambient temperature are used for the calculation of instantaneous heat losses to the environment. The heat flow in the engines exhaust is calculated by interpolating exhaust gas temperature and mass flow rate provided by the engine manufacturer as a function of engine load. Exhaust gas specific heat capacity is assumed constant at 1.08 kJ/kgK.

A TES system was designed and modelled in order to understand the effects of relevant design parameters on the performance of the system (see plant layout in Figure 1). A cylindrical storage tank was considered for the heat storage. The use of water as storage fluid would require a storage pressure of approximatively 10 bar in order to avoid evaporation. For this reason, thermal oil is often used in marine heat transfer application because of its high evaporation temperature at ambient pressure. We therefore assumed the utilization of thermal oil in the proposed TES. In order to simplify plant layout, the fluid from the storage tank is directly pumped to the heat recovery exchanger (HRE). The global heat exchange coefficient of the HRE is assumed equal to 40 W/m^2K, while the effects of different values for the exchange surface are discussed in the Results section. Heat losses from the storage tank are considered assuming a global heat exchange coefficient of 0.5 W/m^2K, which refers to an insulated tank. The conservative assumption is made of uniform storage temperature in the tank, since the effects of stratification depend on storage tank shape and are therefore not included in the modelling.

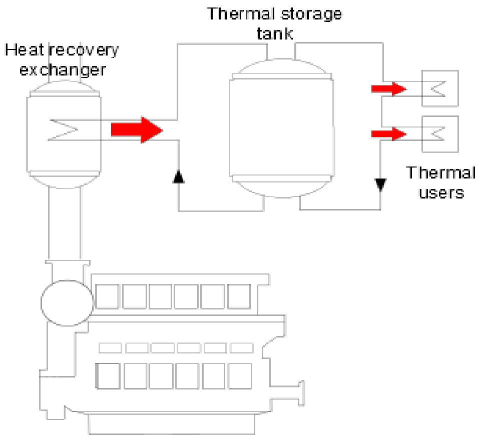


Figure 1: TES plant layout

With regards to storage cycles, it is assumed that:

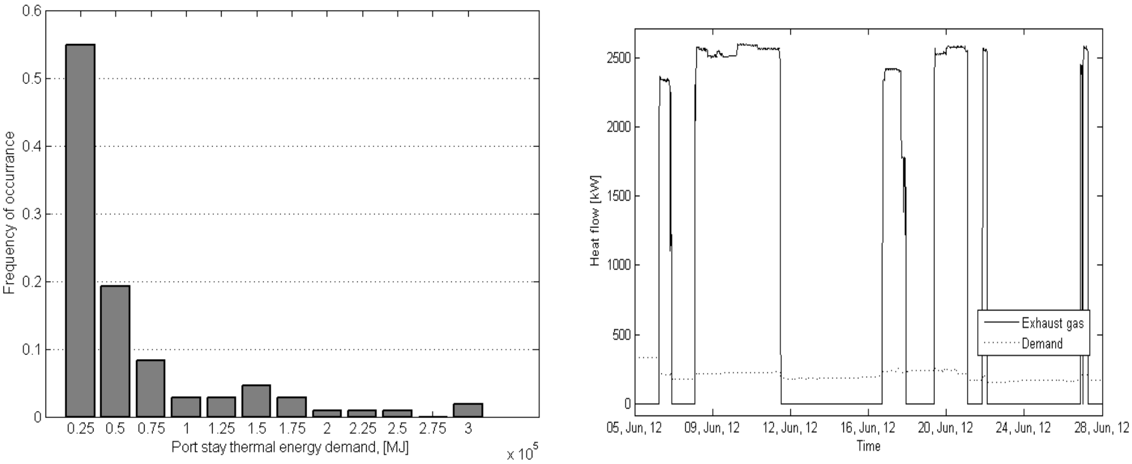
- During sea passage, the available thermal energy recovered from the exhaust gas that exceeds the heat demand is stored in the storage tank. When the maximum storage temperature is reached, excess heat is simply dumped.
- During port stays, the heat demand is fulfilled by the storage tank. When a minimum storage temperature of 100^{o}C is reached (based on the required temperature level of the thermal users) the auxiliary boilers are used instead for fulfilling the required auxiliary heat demand.

An efficiency of 80% for the auxiliary boilers is assumed because of the low load at which they are operated. For the economic evaluation, a price of 600 USD per ton of fuel is assumed, which reflects today fuel prices.

3. Results and discussion

In order to provide a starting guess for the storing capacity, the required amount of thermal energy during each port stay was calculated (see Figure 2a). The results suggests the amount of thermal energy to be stored in order to cover the whole auxiliary heat demand during port stays could be realistically evaluated between 200 and 300 GJ. A parametric investigation of the TES system is presented in Figures 3-4. Boiler yearly fuel consumption can be sensibly reduced already for relatively small storage tank capacities (70% reduction at roughly 1000 m^3, see Figure 3a) as expectable from the typical duration of port stays shown in Figure 2. As a term of comparison, the tanks storing water on board for maintaining stability when the ship is sailing with empty cargo tanks have a total capacity of approximately 20,000 m^3. A further reduction in boiler fuel consumption demands increasing storage size that is not justified by corresponding savings; in addition, the heat loss through tank walls becomes more and more relevant with increasing storage tank capacity. Reduction of the capacity of the heat storage can be achieved by increasing the allowed maximum temperature in the tank (see Figure 3b), even if increasing storage temperature decreases the efficiency of the heat exchange in the WHR boiler and increases heat losses.

The gas-thermal oil heat exchanger positioned on the exhaust gas line is a crucial element in the system given the low heat exchange properties of the gas side.

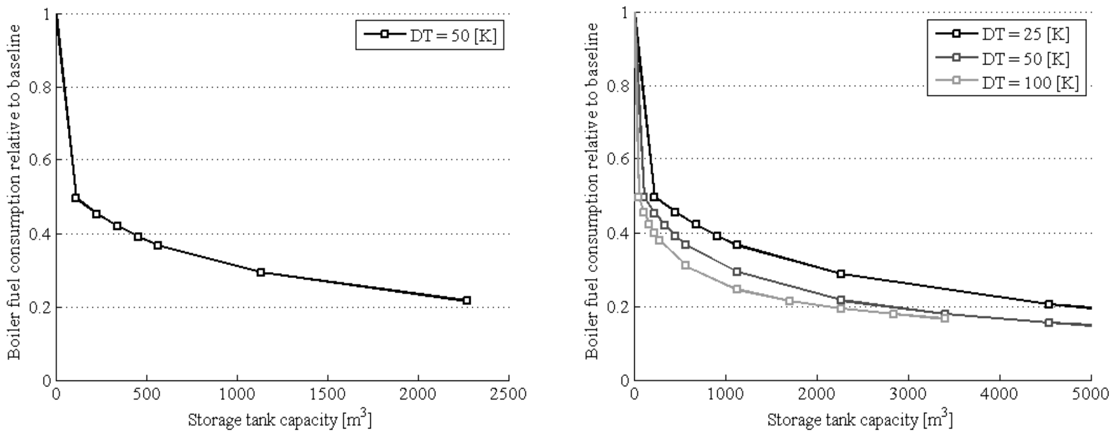


(a) (b)

Fig 2. (a) Distribution of port stay energy demand relative to the 31 months of available measurements; (b) Extract of available waste heat and heat demand for a 3 weeks period

Based on the assumption of a global heat exchange coefficient of 40 W/m^{2}K, a minimum exchange area of 75 m^2 should be accounted for if savings of the magnitude of 70% of yearly boiler fuel consumption are envisaged (see Figure 4a). A similar behavior is connected to the mass flow rate on the cold side of the HRE (Figure 4b) where decreasing the flow below 1 kg/s limits the potential for fuel savings. In both cases increasing area or mass flow rate over a certain boundary (respectively 75 m^2 and 2 kg/s) causes increased installation and operational costs without bringing correspondent improvement in the performance of the system.

Based on the considerations described in Figures 3 and 4 a storage capacity of 1000 m^3 was selected for the energetic and economic evaluation of the retrofitted system. The existing exhaust gas boilers are used as HREs, for a total heat exchange surface of 130 m^2; finally, a mass flow rate of 1.5 kg/s and a temperature range in the storage of 100 K were selected. The energetic and economic performances of the system are summarized in Table 1. Savings of approximately 268,000 USD/year were calculated when the proposed system is installed.



(a) (b)

Figure 2: (a) Influence of storage tank capacity and (b) allowed temperature range on boiler fuel consumption relative to baseline

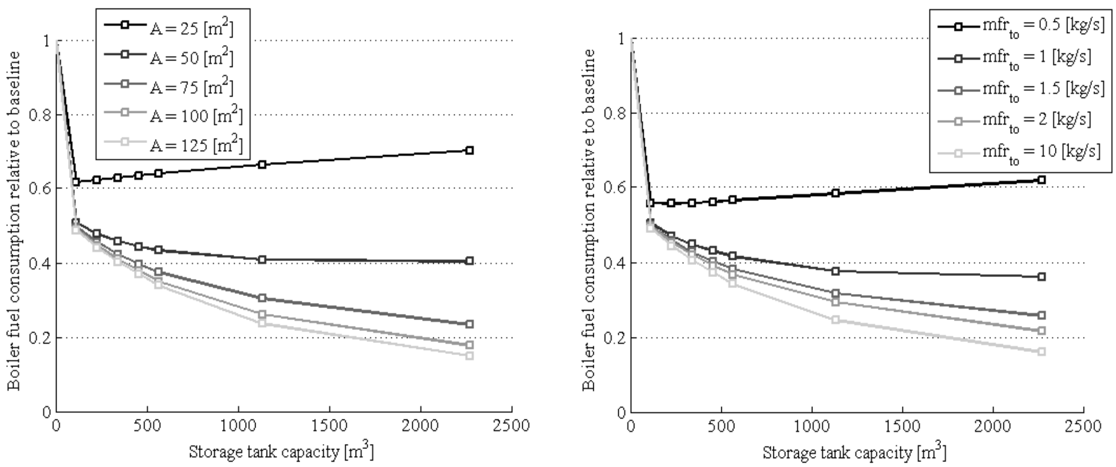


Figure 3: Influence of (a) global heat exchange coefficient and (b) thermal oil mass flow rate on boiler fuel consumption relative to baseline

Table 2: Comparison between system performance with and without TES system

	Baseline	With TES
Yearly boiler fuel consumption [ton]	216	74
Fuel consumption, relative to baseline	1	0.20
Yearly expense for boiler fuel [kUSD]	335	67
Yearly savings [kUSD]	0	268

4. Conclusions

In this paper we proposed the use of thermal energy storage (TES) as a solution for the mismatch between heat availability and demand on board of merchant ships. A TES system was applied to a case study vessel for which extensive measurements and technical documentation was available for the evaluation of waste heat availability and heat demand. The influence of the main design parameters on the performance of the system was analyzed. The storage tank capacity is the most crucial parameter, and should be included in a range of 500 m^3 to 2500 m^3 depending on the desired performance of the system (respectively reducing boiler fuel consumption by 60% and 90%). Increasing the maximum temperature in the storage tanks allows reducing the tank capacity, although improvements are minimal for a difference between minimum and maximum temperature of more than 100 K. The area of the heat exchanger on the exhaust gas line constitutes a limiting factor and should be of at least 50 m^2 in order to allow recovering sufficient heat from the exhaust. Similarly, the mass flow rate of thermal fluid in the heat exchanger on the exhaust gas line should be higher than 1 kg/s (and preferably higher than 1.5 kg/s) in order to warranty the extraction of a reasonable amount of heat from the exhaust.

The results showed that the installation of a storage tank of 1000 m^3 capacity could reduce the fuel consumption from the boilers by 80%, which would lead to yearly savings of 268,000 USD. Although this figure could be improved by a more detailed modelling and optimization of the TES system, this preliminary analysis shows that there is potential of both economic and environmental benefits from the application of thermal energy storage to merchant vessels.

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Biography

Francesco Baldi is a doctorate student at the department of Shipping and Marine Technology at Chalmers University of Technology, in Gothenburg. Educated at the University of Bologna in Energy Technology, his main focus lies in the analysis and modeling of ship energy systems.

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