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Potential of thermal storage for hot potable water distribution in cruise ships

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Abstract

Hot potable water preparation in ships requires lots of energy from the power plant; this is particularly true in modern cruise ships with a high demand of potable water for people, restaurants, spa and pools. Usually the required amount of hot water is instantly produced using a number of different energy sources available on board. However, the use of direct heaters on peak demand conditions increases fuel consumption and greenhouse gas emissions. This is especially important in the case of ship in port configuration, due to the reduced number of active engines and therefore the reduced amount of waste heat from the cooling line usually employed for this task.

This paper investigates possible solutions to size a hot water thermal storage in order to compensate the mismatch between heat generation during cruise and heat required during ship in port configuration. The performances of different solutions are compared using dynamic thermal simulations of the ship's hot water distribution system with different regimes and time dependent heat requirements. Moreover it will be introduced the use of PCM materials with the aim to further improve system's performance.

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1. Introduction

Cruise Ship (CS) industry is nowadays facing a challenge due to the stricter energy limits and the requirement to reduce greenhouse gas emissions. The International Maritime Organization (IMO) introduced the Energy Efficiency Design Index, EEDI [1], aiming at promoting the use of less pollutant equipment and engines on ships. The introduction of lower limits for pollutants drives the industry to explore new systems with increasing efficiencies. Traditional measures considered the properties of the ship's hull and to increase the efficiency of the propulsion, however, some researches started looking for more efficient utilization of ship's power plant. Rami et al. [2] assess how novel systems affect the energy efficiency of a ship, among the tested ones there is the effect of introducing micro steam turbines and ORCs powered by steam and hot water; other measures considers the use of heat pumps to extract energy from the low temperature (LT) engine cooling line. Additional measures are described in [3] with usage of water in cabins using novel types of showers. Use of renewable sources to reduce the energy footprint is also of interest, for example in [4] the authors investigated the benefits obtainable by the installation of solar-thermal collectors on board on a CS during a voyage in the Black Sea.

In order to decrease the energy consumption and to optimally exploiting the multiple energy sources present in this type of environment, numerical models of the complex systems have been presented in literature. Marty et al. [5] developed a ship modelling platform in order to simulate the time dependent energy flows and energy systems on board of a CS; they also compared the results with field measurements during four cruises demonstrating reasonable estimations of fuel's consumption. An optimization method, based on genetic algorithms, has been proposed in [6] to maximize the energy efficiency in this environment; five different strategies have been developed and compared to actual cruise operation for a medium sized CS, showing significant improvements in fuel consumption if thermal energy storage is considered.

Thermal energy storage is one of the measures proposed to increase energy efficiency on this type of ship [6,7]. Production of fresh and hot water is a key component for such ships, which have to provide hotel facilities to passengers. In a classical layout hot steam produced by the engine exhaust cooling system provides the energy for fresh water production and hot water heating, however in some situations, namely for the ship in port situation, the energy available from the engines is reduced, and additional energy must be provided by dedicated boilers.

In the present paper, a sizing procedure is applied in order to study how the thermal storage for hot potable water affects the heating power required to produce that same water.

2. Potable water heating on cruise ships

The main source of thermal energy onboard is the integrated engine cooling system. The recovered heat is usually divided in steam line, High Temperature Cooling System (HTCS) and Low Temperature Cooling System (LTCS) [5, 6], usually no fuel consumption from additional boilers is required [6]. However, the use of auxiliary boilers can be called in when the heat load is greater than the heat provided by the cooling line system. The amount of hot water required must cover the needs for cabin utilities, such as showers and sinks, but it's also used for services such as laundries and kitchens. Ship in port is a typical situation in which the heat provided by the cooling systems is not able to satisfy the power needed to heat the potable water at the required temperatures. Indeed, in this situation usually only one engine is active, furthermore, the heat called in by hot water preparation shows strong changes with peaks in correspondence of the morning, when the passengers leave the ship, and in the afternoon when they return on board.

Nomenclature

c_{PCM}	PCM specific heat [J/(kg K)]
c_W	water specific heat [J/(kg K)]

L_{PCM}	PCM latent heat [kJ/kg]
λ_{PCM}	PCM conductivity [W/(m K)]
$\dot{m}_{HW}$	requested hot water flow [kg/s]
$\dot{m}_{mix}$	water flow at t_f needed to obtain t_{HW} for the users [kg/s]
$\dot{m}_{rec}$	recirculation water flow [kg/s]
$\dot{m}_s$	hot water flow from HX to tank [kg/s]
$\dot{m}_{TES}$	water flow circulating in the tank [kg/s]
P_{DRAW}	mean heating power required by users during tank recharge [W]
P_{HX}	heat exchanger heating power [W]
ρ_{PCM}	PCM density [kg/m^3]
ρ_W	water density [kg/m^3]
t_c	cold water temperature [°C]
t_f	temperature of water initially at t_c and warmed up through mixing with water at t_{rec} [°C]
t_{HW}	requested hot water temperature [°C]
t_{PHC}	PCM solidification temperature [°C]
t_{rec}	temperature of water returning from recirculation's loops [°C]
t_{TES}	storage water temperature [°C]
τ_{hl}	heat peak load time period [s]
τ_{ph}	preheat time [s]
V_{TES}	thermal energy storage volume [m^3]

2.1. Hot water distribution and storage system

Fig.1a) presents the classical system used to prepare hot water on a ship: water is heated using LTCL and the Steam Line. Seeing the layout it is clear that the maximum heating power corresponds to the peak hot water demand since water is instantly heated. Fig.1b) presents an alternative solution with a Thermal Energy Storage (TES) system. Hot water is stored when heat from the engine's cooling system is available and it's delivered when needed, as common with TES the heating power required is lower than the maximum one called in by the users.

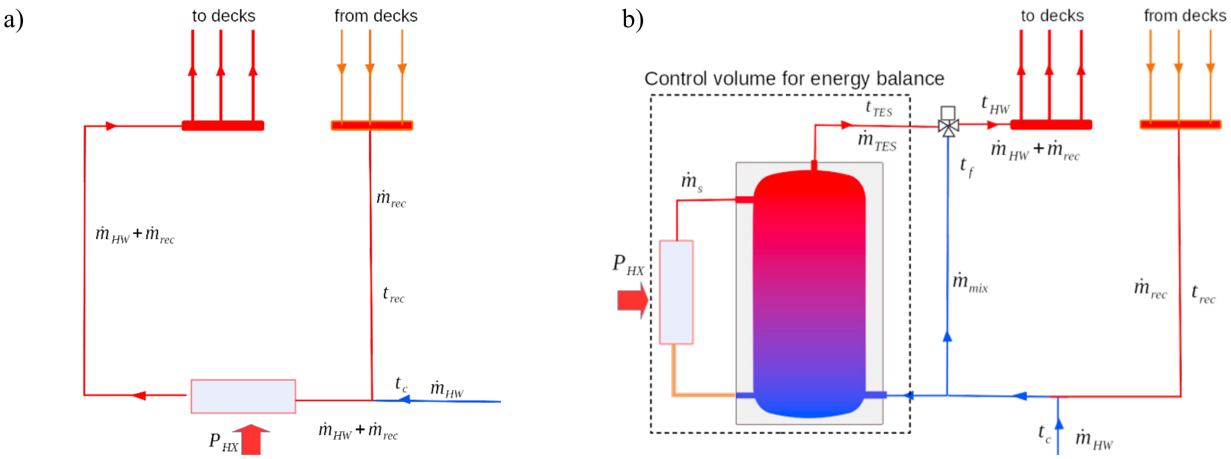

Fig. 1: Hot water preparation on a cruise ship with a) standard hot water preparation without TES and b) modified system with TES.

2.2. Cruise ship water draw

The first problem to face about TES, since it must provide the required hot water and must have the time to be recharged by heating sources, is its sizing procedure. This problem is linked to the peak power required and to the amount of time it lasts to provide hot water to utilities. In this configuration a CS, as far as the use of hot water is concerned, can be assimilated to a hotel, with peak demands characterized by high flows of hot water. In order to assess the viability of a TES system, hot water profiles are required. Unfortunately, in literature standard profiles are usually only available for domestic hot water [8], however some studies target hotels too [9]. The profiles presented in literature show the peak values in the morning and in the afternoon; in order to size the TES for a CS an usability profile which mimic hotel requirements has been developed, but with different timings. The reference case is a CS with about 5000 persons on board considering both passengers and crew; the amount of daily hot water required for this configuration, has been estimated in 540 m^3. Fig. 2 presents the hot water utilization profile and it has been created by superimposition of three normal curves obtained using estimated maximum draw profiles at three different hours.

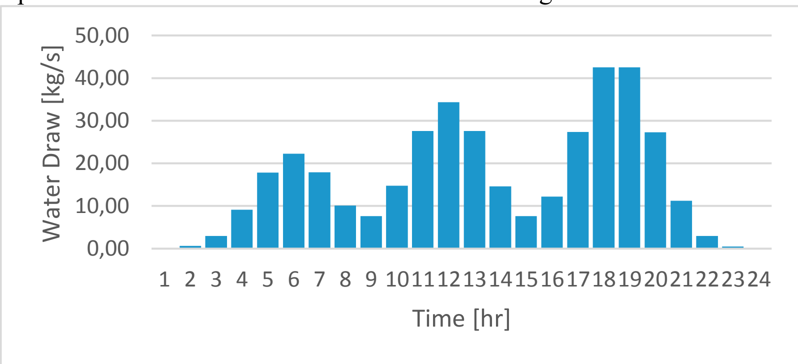

Fig. 2: Cruise ship water draw distribution.

3. TES sizing

In order to size the tank the method provided in [10] was first applied; the water volume is then computed on the basis of the peak utilization time and the required mass flow. For the water draw presented in Fig.2 the peak draw lasts two hours, but the recharge time is not well defined, since the water is withdrawn from the tank with continuity. However, numerical simulation carried on using ESP-r showed that the TES is undersized and the system is not able to provide water at the required temperature as it can be seen in Fig. 3 below, so a new sizing approach has been developed.

3.1. Tank sizing with continuous draw

As it appears from the inspection of Fig. 3 the application of said method failed because the recharge period between the two peak values at 12:00 and 18:00 is characterized by a continuous water draw. The sizing approach must take into account along with the heating power to recharge the water tank also the energy withdrawn from it in the same period.

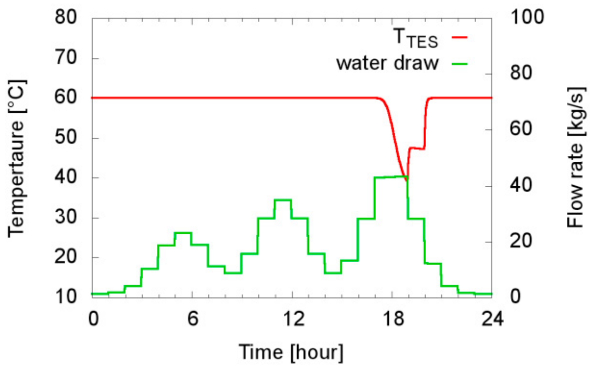

Fig. 3: Temperature distribution of TES system sized with Eqn. (1) and (2).

Following the approach used in [10] a new energy balance on the domain of Fig. 1b) has been developed. Neglecting recirculation and taking into account the draw during recharge time yields:

$$\dot{m}_{TES} \cdot c_W \cdot t_{TES} \cdot \tau_{hl} = \dot{m}_{TES} \cdot c_W \cdot t_C \cdot \tau_{hl} + P_{HX} \cdot \tau_{hl} + 0.9 \cdot V_{TES} \cdot \rho_W \cdot c_W \cdot (t_{TES} - t_C) \quad (1)$$

$$P_{HX} \cdot \tau_{ph} = 0.9 \cdot V_{TES} \cdot \rho_W \cdot c_W \cdot (t_{TES} - t_C) + P_{draw} \cdot \tau_{ph} \quad (2)$$

$$\dot{m}_{TES} = \dot{m}_{HW} \cdot \frac{t_{HW} - t_C}{t_{TES} - t_C} \quad (3)$$

Inserting Eqn. (2) and (3) into Eqn. (1) and rearranging the terms, TES volume can be evaluated as:

$$V_{TES} = \frac{1}{0,9} \cdot \frac{1}{\rho_W} \cdot \dot{m}_{HW} \cdot \tau_{hl} \cdot \frac{t_{HW} - t_C}{t_{TES} - t_C} \cdot \frac{\tau_{ph}}{\tau_{ph} + \tau_{hl}} - \frac{P_{draw} \cdot \tau_{hl}}{0,9 \cdot \rho_W \cdot c_W \cdot (t_{TES} - t_C)} \cdot \frac{\tau_{ph}}{\tau_{ph} + \tau_{hl}} \quad (4)$$

While the heating power required is obtained as:

$$P_{HX} = \frac{V_{TES} \cdot \rho_W \cdot c_W \cdot (t_{TES} - t_C)}{\tau_{ph}} + P_{draw} \quad (5)$$

The mean heating power required between 12:00 and 18:00 has been computed as P_{draw} = 2994,54 kW; Table 1 reports the sizing of the TES using Eqn. (4) for two water storage temperatures, the first line reports the maximum heating power required without thermal storage. As it can be seen the maximum heating power required decreases by 39 % in the first case and by 21 % with a storage temperature of 85 °C. In the latter case however, the TES volume is lower than the previous one.

Table 1. Solutions for heat transfer.

t_{TES} [°C]	V_{TES} [m^3]	P_{HX} [kW]	ΔP_{HX} [%]
-	-	7122.9	-
60	142.58	4304.9	39.56
85	60.59	5582.2	21.62

4. Numerical simulation

To model the performance of the TES two dynamic models have been developed; two established numerical codes for plant thermal simulation have been used: TRNSYS v16 and ESP-r. The base system is the one used for the sizing and represented in Fig. 1b) where the heating system charges the TES. The water is withdrawn from the TES and mixed with the return line to provide water at temperature t_{HW} to the decks, part of the water is recirculated and mixes with the fresh water before entering the tank.

4.1. TRNSYS simulation

Fig. 4 shows the time history of the two analyzed cases, with TES temperature of 60 °C and 85 °C (with the size of TES and maximum heating power reported in Tab.1). As it can be seen, the solutions show that the system is fully capable of providing water at the required temperature for the analyzed period. It can be identified only one short period when water's temperature falls slightly below the required value corresponding to the period of high water requirement.

4.2. ESP-r simulation

ESP-r is an open-source building simulation code with also plant system simulation capability. It has been modified [11, 12] to deal with Thermal Storages with embedded Phase Change Materials (PCM). The same simulations with TRNSYS have been replicated with ESP-r; Fig. 5 presents the time plot of the water temperature for one-day simulation (Fig. 5a refers to the solution with thermal storage temperature of 60 °C while Fig. 5b with a storage temperature of 85 °C). As it can be seen, both solutions perform well with results similar to the ones obtained with the TRNSYS code. The temperature distribution inside the tank, or thermocline, for different times is also of interest, since it highlights how the energy is stored. Fig. 6 presents the time history of the vertical distribution of temperature, or thermocline, for $t_{TES} = 60$ °C and $t_{TES} = 85$ °C.

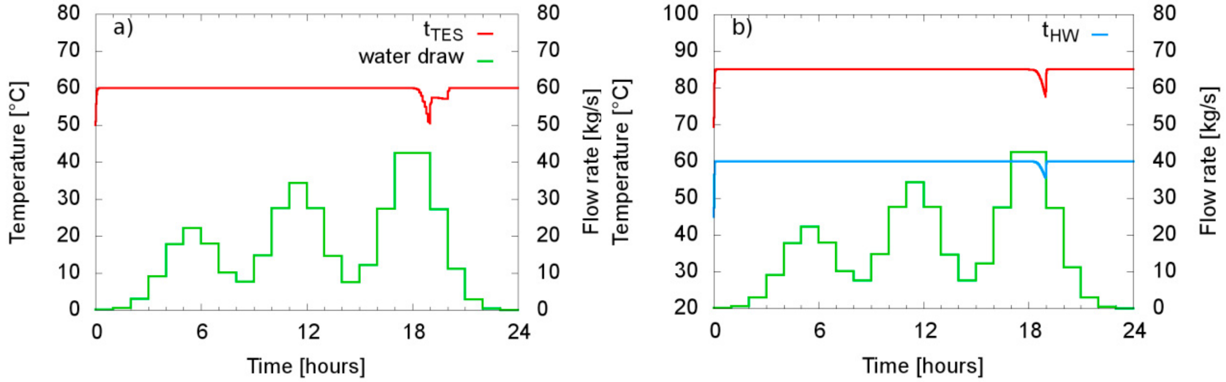

Fig. 4: TRNSYS time distribution of temperature and mass flow for a) storage temperature $t_{TES} = 60°C$ and b) $t_{TES} = 85°C$.

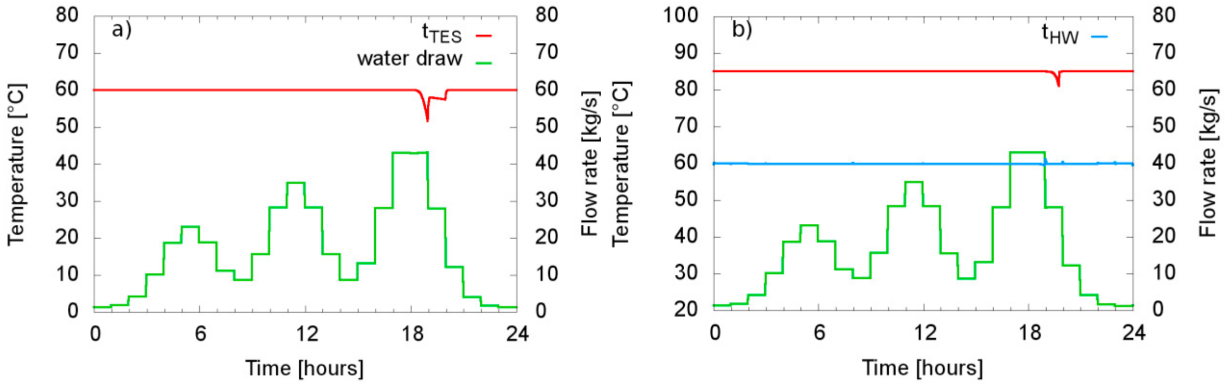

Fig. 5: ESP-r time distribution of temperature and mass flow for a) storage temperature $t_{TES} = 60°C$ and b) $t_{TES} = 85°C$.

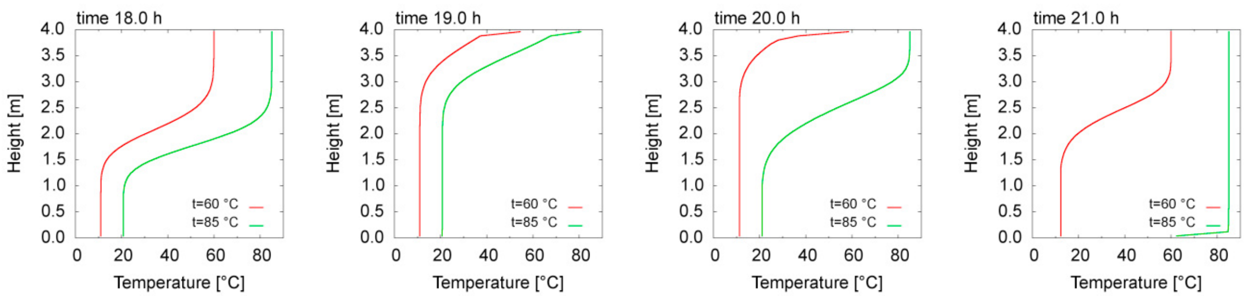

Fig. 6: ESP-r isocline history comparison between $t_{TES} = 60$ °C and t_{TES}=85 ° case.

5. A solution for TES performance improvement: use of PCM materials

5.1. PCM materials

Phase Change Materials (PCM) is a viable option for enhancing thermal storage by exploiting the latent effect during phase change. In order to highlight the performance of a latent enhanced TES the same simulation performed with water heated at 60 °C have been reproduced. A validated modified version of ESP-r which considers the possibility of embedding PCM filled vertical cylindrical bars in the TES has been used [11,12]. Phase change phenomena is modelled using an enthalpic approach solving the problem using an axisymmetric two dimensional grid. The selected PCM is a commercial hydrated salt with characteristics reported in Table 2, the most critical parameter in selecting PCM material is the phase change temperature and in this case, the material has been selected since it has a phase change temperature slightly lower than TES temperature.

Table 2. PCM S58S characteristics

t_{PHC} [°C]	ρ_{PCM} [kg/m^3]	L_{PCM} [kJ/kg]	c_{PCM} [J/(kg K)]	λ_{PCM} [W/(m K)]
58	1505	145	2550	0.69

5.2. Simulation and results

To evaluate how PCM materials affect TES's performances the analysis with $t_{TES} = 60$ °C has been repeated considering a PCM volume of 20 m^3 leaving unchanged all other parameters. With this configuration the upper part of the TES has been filled with 1192 cylindrical bars with the lower part positioned at 2.8 m from the bottom.

Results of this simulation and a comparison between PCM and no-PCM cases are reported below in Fig. 7. In Fig. 7 a) is reported the comparison between the two solutions during a 24 hours period. In Fig. 7 b) attention is focused on the evening peak draw. The effect of the PCM is clearly visible, since the temperature decreases less respect the sensible only solution, confirming the capacity of the PCM to enhance thermal stratification.

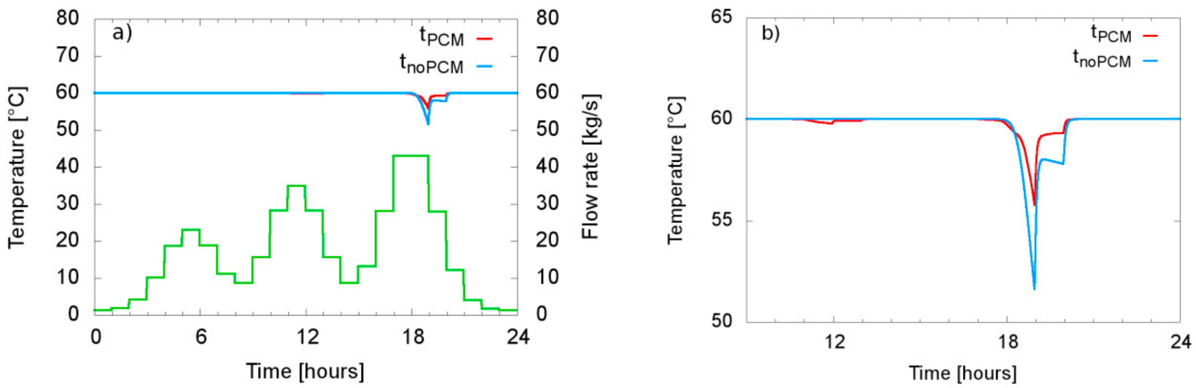

Fig. 7: ESP-r comparison of temperature between PCM and no-PCM case during a) 24 hours period and b) evening peak draw.

The PCM insertion allows a higher temperature in the top part of the tank when water demand is higher at 19:00 and 20:00, as presented in Fig. 8, which represents a comparison between the time history of thermoclines obtained with and without PCM.

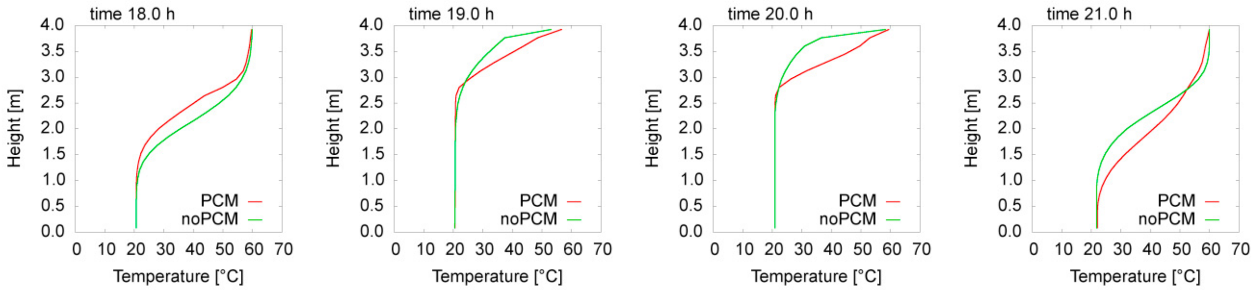

Fig. 8: ESP-r isocline history comparison between TES with and without PCM.

6. Conclusions

Thermal storage in Ship applications and especially for Cruise ships appears to be a viable solution to increase energy efficiency. The ship in port situation is always problematic in providing thermal energy to the hotel facilities. This is especially true for hot water preparation since the main source of energy, the engine cooling system, is working at reduced rates. The classical way to deal with the problem is to activate additional boilers with an increase of fuel consumption and environmental issues. The solutions presented in the present paper show that, by using a thermal storage system, the heating power required for hot water preparations can be reduced up to 39 % thus decreasing the need of additional heating sources.

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