The potential of Thermal Storage Tanks to assist in managing Peak Heat Loads on Naval Ships

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Synopsis

Thermal heat loading has become a burden on today's naval ships. Expanding operations in hot climate zones, increasing use of high energy systems (for example weapons) and maintaining the cooling of electronics that require fine temperature control have all contributed to a higher cooling demand. Designing cooling plant for a range of operating climates and varying equipment loads is a challenge due to high peaks in the thermal load that occur for short durations of time. Specification of a traditional chilled water system to meet peak load demands will result in a system that is oversized for normal operating loads and is likely to be deemed impractical.

The use of thermal storage tanks provides a potential solution to catering for these peak load demands. This consists of a tank filled with a medium that can be cooled so that it absorbs heat from the ships systems when cooling water is passed through the tank. The thermal storage medium can be used as a heat sink to smooth thermal load peaks and then be recharged during periods of lower demand. Various materials have shown potential for use as thermal storage mediums.

This paper summarises the operational advantages and integration challenges of thermal storage tanks, focusing on the use of water and wax as storage mediums. Relative tank sizes, cooling capacities and system scheme design solutions are presented for a range of thermal storage tank solutions.

Keywords: Heat loads, Thermal storage, Integration

1. Introduction: Intermittent, excessive heat loading on naval ships

Thermal management of peak heat loads is a familiar problem to most naval platforms. Increasing operations in tropical climates, the introduction of high power electronic equipment and the development of laser weapon and rail gun technology, all contribute to increased demand for cooling. Thermal management is critical to retaining and developing platform capability for both manned and unmanned platforms as humans, machinery and electronics all require cooling in order to preserve their functionality and fitness to fight.

Heat loads can be intermittent and create a cumulative demand on the cooling system if they occur simultaneously, resulting in potentially significant peak loads that may exceed the platform's cooling system capacity. These peak loads may be infrequent and occur for short periods. Environmental heat loads can be significant when operating in hot climates with high solar loading demands, but the peak heat load only occurs during a short period, as show in Figure 1. This is similar for laser weapons which create enormous heat demand for a very short transient time period. Thermal storage can offer a potential solution to providing instantaneous cooling during these periods of peak heat demand, be this by provision of additional cooling capacity during the tropical midday sun, or to cool a laser weapon during operation.

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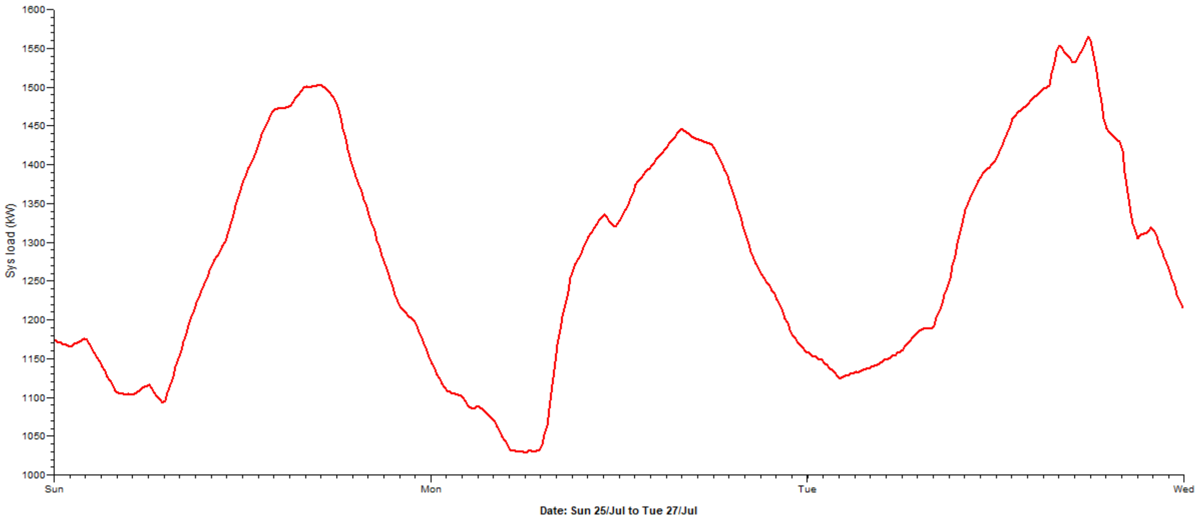

Figure 1: Chilled Water plant load variation from day to night (trials data from a Royal Navy Frigate)

The concept of thermal storage is to use the vessel's cooling system to slowly chill (charge) the thermal storage tank when extra capacity is available from the vessel's cooling system, for example during the night. The thermal storage can then be deployed, in addition to the vessel existing cooling system, for short periods when required. The design of this thermal storage solution can be tailored to suit the platform and heat load profile, with the possibility of both retrofit to existing vessels, or designed into new build.

2. Key Design Considerations

2.1. General

In order to assess the potential use of thermal storage for any particular scenario, and design a suitable solution, there are five key subjects that need to be considered. These encompass factors from investigation of the platform structure and operation to embody a thermal storage tank and ancillary components, to reviewing the type of technology and infrastructure that will be most suitable to the particular solution.

Key considerations are outlined as follows and discussed in the following paragraphs:

1. Thermal storage tank size and location
2. Thermal storage material
3. Delivery infrastructure
4. Thermal storage tank insulation
5. Creating a temperature inversion

Budget, integration complexity and maintenance interval will need to be considered in relation to each of the five aspects. Increasing capacity and complexity will increase budget and integration difficulty and a compromise may need to be made when developing a solution.

2.2. Thermal storage tank size and location

The use of thermal storage to assist in coping with peak heat loads can be considered for both retrofit to existing vessels and for the design of new vessels. The type of vessel and the arrangement of the ship's tanks will drive the design. A tank will be required to house the thermal storage material. Ships that have many ballast tanks, such as the UK Navy's Landing Platform Dock platforms (LPDs) are well suited to be fitted with thermal storage tanks. The selected tank should be usually full during normal operations to minimise any significant effect on stability. It is important that vessel tank usage is considered early in the design process and that a solution is developed around a tank that can feasibly be dedicated to thermal storage. On an existing vessel this will require some modification to the vessel ballasting plan. The ability to drain the tank in an emergency can be retained if a water based solution is used.

The tank volume available will determine the maximum capacity available from thermal storage. The chosen tank will need to be insulated.

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A proposal for the application of this technology for a laser weapon cooling system designed for specific vessels is presented in 'Advanced Cooling Methods for Naval Laser Directed Energy Weapons' [Hook A Dubey, L, 2020].

2.3. *Thermal storage material*

Two categories of thermal storage solutions can be considered; those using sensible heat and those using latent heat.

Sensible heat thermal storage is achieved simply by a volume of liquid such as water, absorbing heat by increasing its temperature. The sensible heat capacity that a thermal storage liquid can absorb is determined by its specific heat capacity and the total mass of liquid.

Latent heat thermal storage uses a Phase Change Material (PCM) which absorbs heat as it changes state. Ice and wax are examples of phase change materials. When they are heated and turn from solid to liquid, energy is required to break the bonds that retain their solid form, resulting in absorption of heat energy. A PCM must be chosen so that its melting temperature is within the correct range for the application. Various types of wax have melting temperatures of 10-20 ˚C, which is within a range that makes them suitable for use for cooling with a typical vessel chilled water system supply temperature of ~6 ˚C.

The latent heat properties of wax drastically increase the volume density of thermal capacity compared with the sensible heat thermal storage capacity of water. The relevant material properties for water and paraffin wax are compared below in Table 1. A basic calculation of heat capacity available from 1 m^3 for a 1 ˚C temperature rise at wax melting temperature, shows the huge potential of paraffin wax as a PCM. In reality, however, this figure is not obtainable, because some water volume is required within the thermal storage tank to transfer the heat from solid wax modules. This is achieved by pushing water through a lattice of wax filled containers, which retain the wax and allow for efficient heat transfer when it is a solid. The exact heat capacity figures will depend upon the type of wax module water flow arrangement used.

Table 1: Comparison of water and wax thermal properties at wax melt temperature [PCM Products]

Material	**Specific Heat Capacity** (J/g.K)	**Latent heat of melting** (kJ/kg)	**Thermal conductivity** (W/m.K)	**Density** (Kg/m3)	**Heat capacity (kJ) of 1m^3/1˚C**
Water	4.186	N/A	0.6	997	4.17
Paraffin wax	2.14	213	0.189	900	193.6

2.4. *Delivery infrastructure*

Cooling loop configuration options

There are a number of possible configurations for the way heat can be exchanged between the equipment or space to be cooled, the ship's Chilled Water (CW) plant and the thermal storage tank. A basic schematic showing the heat exchange interfaces can be seen in Figure 2.

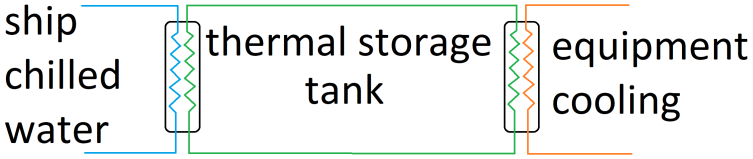

Figure 2: Basic schematic showing thermal storage tank heat transfer interfaces

The most appropriate solution type will depend upon which tank is chosen for thermal storage and what timescale is available for outfitting the tank. Heat exchangers are required to transfer heat from the ship's cooling supply to the thermal storage tank, and from the tank to the closed loop that feeds the equipment/space to be cooled. Heat exchangers can be located external to the tank with minimal modification to the tank itself. This is the preferred option if an existing tank is used which retains its original contents as it has minimal intrusion on the tank contents. Alternatively, heat exchanging interfaces can be located within the tank for minimal footprint outside the tank boundary. This is the preferred option if a dedicated tank is used and time is available to fully fit out the tank with the required equipment.

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Pumps are required to circulate the cooling medium and will need to be specified according to the required flow and pressure losses.

Temperature Control Mechanisms

Any design solution will require temperature control mechanisms. The design must ensure that demand on the ship's chilled water plant is not excessive during charging, causing chilled water return temperature to rise. If a minimum coolant feed temperature is required for the equipment, initial pre-heating of the coolant supply will need to be designed into the system. Once the system reaches design temperature, the supply temperature can be regulated by recirculating the feed water using a thermostatic control valve.

A flow limiting valve can be used to generate the specified flow rate. If the chilled water temperature exceeds the design temperature, then a thermostatic control valve measuring chilled water inlet temperature will be programmed to reduce the flow through the thermal storage heat exchanger and direct it through the bypass. The minimum tank temperature will also need to be regulated so it does not go below the minimum set point temperature. This can be achieved using a thermostatic control valve, measuring tank temperature and bypassing the chilled water supply to the heat exchanger when the tank temperature drops to the minimum set point. This will limit the heat lost from the tank structure to the surroundings and the set point value can be optimised to the external environment as a lower set point will give more thermal storage.

When the water in the tank is no longer cool enough to provide sufficient cooling to the equipment, a cut-off must be incorporated to detect that the supply temperature is out of specification and shut off supply to the equipment or warn the operator. Temperature sensors can be installed in the tank to keep the operator informed on the thermal storage 'charge' level that is available.

2.5. Thermal storage tank insulation

If it is assumed that the vessel is operating in 'worst case' extreme tropical conditions, the sea water temperature (surface temperature) is 36 ˚C [MoD, 2006], and for simplicity, ambient temperature outside of the tank is assumed to be 36 ˚C. A rectangular tank of 2.9 m x 3.5 m x 3.5 m has volume 35 m3 and surface area 69.3m2. This size has been arbitrarily selected as it represents a realistic tank size and provides a basis for comparison of the design solutions.

The overall heat transfer coefficient of a water/steel/water boundary has been estimated. This relies on making a number of assumptions when selecting the convective heat transfer coefficient for the water/steel boundary, as it varies depending on the magnitude of water turbulence at the boundary. Estimated tank thermal gain for uninsulated tanks are shown in Table 2.

Table 2: Thermal gain for rectangular tank of 35m^3 volume, 69.3m^2 surface area, internal and external temperature 20 ˚C and 36 ˚C respectively.

	Estimated overall heat transfer coefficient (U value)	**Thermal gain**
Uninsulated	86.3 W/m^{2}K	95.7 kW
Insulated (equivalent to 6mm mineral wool)	5.5 W/m^{2}K	8.2 kW

It is clear from the data in Table 2 that it is essential to insulate the tank in order to reduce heat conduction into the tank and decrease the cooling load on the ship's chilled water system if it is intended to use the thermal storage solution in warm climate conditions.

In cool climates the opposite effect can occur. If the temperature of the surroundings is less than the temperature of the tank, then heat is transferred from the tank, cooling it. This is beneficial and therefore insulation would increase heat load on the CW plant. Therefore it is important to consider the environmental conditions in which the vessel is intended to operate when specifying insulation. However in most cases, the vessel's CW plant is in greatest demand in hot climates, therefore this is when the least chilled water capacity is available, and therefore installing insulation will be essential.

The application of insulation to the tank is relatively unique because it is likely that it will be installed on the internal surface of the tank and submerged by the water in the tank. Therefore the insulation must be in a form that is fully waterproof. Traditional insulating Rockwool products work by trapping air in the wool and are porous and therefore cannot be used unless they are protected by a waterproof covering. Membrane tanks used in the Liquid Natural Gas (LNG) industry are insulated with a layers of insulating material that is encased within a membrane. This type of insulation would also be suitable for a thermal storage tank. If an equivalent insulation material to 6

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mm of mineral wool is fitted to the tank boundary, it will give an overall heat transfer coefficient of approximately 5.5 W/m^{2}K.

2.6. Creating a temperature inversion

A temperature inversion is created when warm water of slightly lower density rises and cool water of higher density sinks resulting in a temperature gradient. On a ship, motion will agitate the tank somewhat and cause a degree of mixing, weakening the effect of the temperature inversion. This sloshing and mixing will be dependent upon sea state and the temperature inversion will be more prominent in calm seas. Cool water for the equipment feed should be taken from the bottom of the tank and returned at the top. This will optimise the efficiency of the heat exchangers and also aid mixing. Warm water to be cooled by the ship chilled water will be taken from the top of the tank and returned at the bottom. This will take advantage of any thermal inversion that develops within the tank.

There is the option of installing a permeable plate in the thermal storage tank to encourage separation between the warm fluid at the top of the tank and the cool fluid at the base of the tank. This will limit mixing and enable the thermal storage tank to perform as desired for longer. The water can still penetrate through the plate but it will reduce the amount of convection between the warm and cool regions. However, for a seagoing ship, the wave motion and resultant sloshing of the tank contents may affect the way in which a permeable plate would function. This is an area that requires further research to determine if a membrane will have a positive effect on maintaining the temperature inversion or if it could actually drive greater turbulence in the tank, effectively mixing the warm and cool fluid.

3. Basic Design Solutions

3.1. General

Three design solutions have been developed to a basic level in order to allow for illustration of the concepts and to make comparisons:

1. External heat exchanger (water)
2. Internal heat exchangers (water)
3. Wax module PCM

All three solutions have been designed to provide 100kW of cooling to an item of equipment with a feed temperature of 20 ˚C. In each case the thermal storage tank is 35 m^3 with insulation applied on all boundaries with an overall heat transfer coefficient of 5.5 W/m^{2}K. The tanks are operating in extreme tropical conditions with ambient temperature of 36 ˚C, resultant thermal losses to the surroundings have been taken into account. Transportation heat losses through piping is considered negligible. For recharging of the tank with the ship's chilled water supply, 100kW is considered to be available with a supply of 6 ˚C and return of 12.5 ˚C. Instantaneous mixing of the tank contents is assumed with no thermal inversion which represents a worst case condition.

3.2. Solution 1 - external heat exchangers

This solution takes all of the system infrastructure outside of the tank for a minimally invasive solution. The water from the tank exchanges heat with the chilled water and equipment via heat plate exchangers located on the outside of the tank. This solution has minimal impact on the tank, and would be the simplest to install. The two heat exchangers will need to be located within the ship, each with a supply and return from the storage tank and one connected to a loop to supply the equipment and the other taking a feed/return form the CW plant. Three pumps are required to circulate water in each of the cooling stages. A schematic showing the fundamental components is shown in Figure 3.

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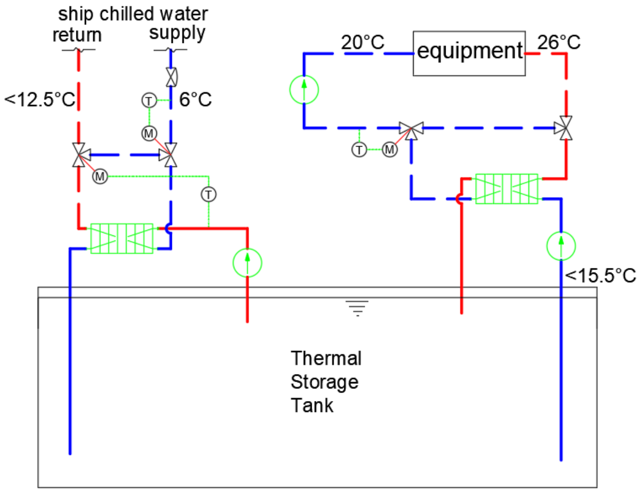

Figure 3: Schematic of solution 1 utilising heat exchangers positioned external to the tank.

For a dual external heat exchanger solution, a temperature difference between the fluids on either side of both heat exchangers must be maintained. This means that the maximum thermal storage temperature is 15.5 ˚C in order to maintain 100kW of cooling at the weapon with the specified heat exchangers and defined design conditions. This limits the longevity of the thermal storage usage when compared with solution 2, where thermal storage tank temperature can reach a higher temperature of 20 ˚C.

Table 3: Solution 1 calculated operating Timescales

Usage time at 100kW load	
Time to reach design temperature (12.5 – 15.5 ˚C)	1 hrs 07 min
Recharging time with 100 kW cooling supply	
Time to recharge tank (15.5 – 12.5 ˚C)	1 hrs 07 min

Comparison

The main advantage of solution one is that for a water tank, no modification to the contents of the tank will be required. Inlet and outlet pipework will need to be installed, and it will need to be ensured that the tank is filled when usage of the thermal storage system is required. The added mass from the system components is minimal compared with solutions 2 and 3. It is less effective as a thermal storage reservoir than solutions 2 or 3 due to the temperature difference that is required to be maintained across the two heat exchangers. The requirement for three pumps and two heat exchangers outside of the tank means that this solution will have a larger footprint and electrical power demand than solutions 2 or 3.

3.3. Solution 2 – Internal heat exchangers

This solution houses all heat exchange interfaces within the tank and has minimum space requirements outside of the tank boundary. It is designed for use with a repurposed tank and the contents will need to be dosed with corrosion inhibitor and antifreeze (depending on location). A single pump is required outside of the tank to circulate the cooling liquid through the equipment. Full access to the tank will need to be made in order to fit the array of plate heat exchangers, given the amount of work in way around most of the tanks, this will be a significant work package.

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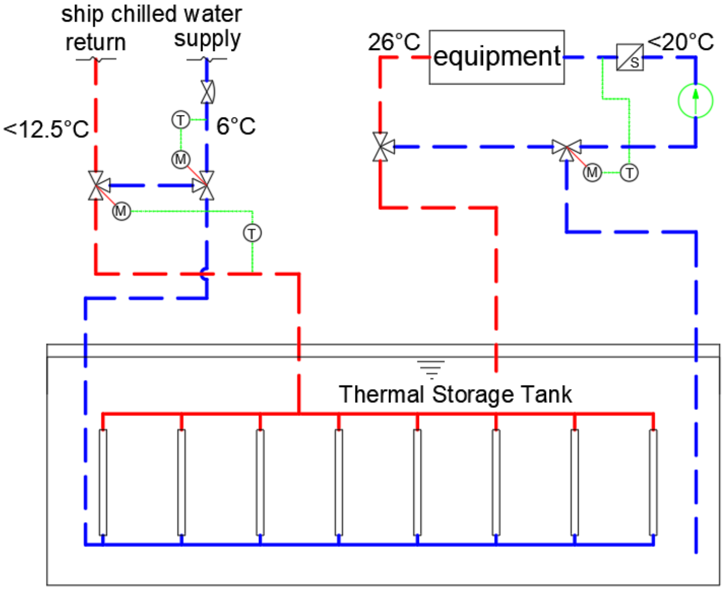

Figure 4: Schematic of solution 2 utilising heat exchangers positioned within the tank.

An array of heat exchanging plates will be installed submerged inside of the tank where water from the equipment and chilled water plant is pumped through these plates in the tank for heat exchange, as illustrated in Figure 4. Situating the heat exchangers inside of the tank means they will be more difficult to install and maintain than if they are situated outside of the tank. However, there is the advantage that they will not take up space outside of the tank boundary. Dimple plate heat exchangers (Figure 5) are designed to exchange heat between a circulating fluid and a stationary fluid so are well suited for use as heat exchangers within the tank. Agitation of the tank contents will significantly improve the heat transfer from the plate heat exchangers. Adding stirrers to the tank should be considered if this solution is implemented.

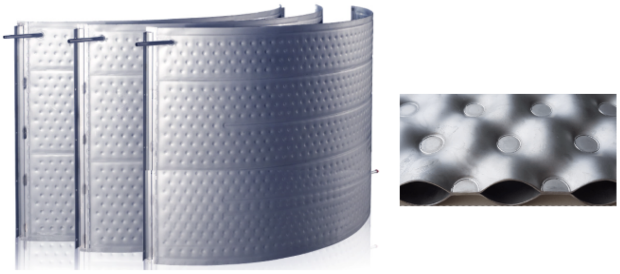

Figure 5: Dimple plate heat exchangers, overview and close-up of pillow pattern.

Water can be taken directly from the tank to feed the equipment. The removal of this heat exchanger interface means that tank temperature can reach 20 ˚C while still providing 100 kW cooling to the equipment heat exchanger interface which is beneficial for the efficiency of the heat exchanger. To use this configuration it may be important to ensure any sediment that forms/collects in the tank is not allowed to be pumped through the equipment and a filter may be required to protect the equipment. This solution can only be considered if the tank is repurposed, or if there is no concern over the contents causing corrosion or sediment problems.

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Table 4: Solution 2 calculated operating timescales

Usage time at 100kW load	
Time to reach design temperature (12.5 – 20 ˚C)	2 hrs 51 min
Recharging time with 100 kW cooling supply	
Time to recharge tank (20 – 12.5 ˚C)	3 hrs 21 min

Comparison

This option provides a longer period of cooling than solution 1. It is also simpler as it eliminates the requirement for an additional cooling loop and therefore reduces the electrical power requirements for pumps. However it does require a specifically designated tank, which will necessitate a change in the ship's tank filling arrangements and may require modification to the ballasting arrangements to retain stability. It should be noted that changing the fluid type in a large tank can be significant; the weight increase associated with filling a 35m3 tank with fresh water instead of diesel is approximately 6 tonnes.

The dimple plate heat exchangers are immersed in still fluid and are therefore do not have such high efficiency for their volume as the plate heat exchangers specified for option one where fluids are flowing on both sides of the thermal interface. Therefore, the dimple plate heat exchangers will be much heavier in total than the plate heat exchangers specified for solution 1, although the volume footprint of this solution is smaller because the heat exchangers are contained within the tank volume. Installing the dimple plate heat exchangers into the tank will require an invasive work package.

3.4. Solution 3 - wax modules

An alternative solution to using a water tank is to fill a water tank half full by volume with stacked paraffin wax modules. This solution will exploit the phase change characteristics and the latent heat of the wax. These modules will be submerged within the tank, acting as a heat exchanger with the surrounding water. The water transfers heat to/from the surfaces of the wax modules, as the thermal conductivity of wax itself is relatively poor. The tank will need to be outfitted with the wax modules from build or during refit. A concept schematic of this configuration is presented in Figure 6.

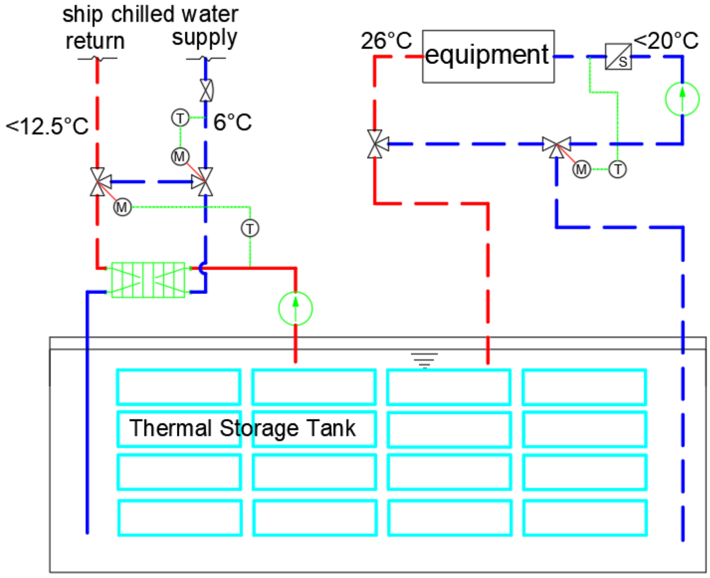

Figure 6- Concept schematic wax cooling

Various different wax type compounds can be used for thermal storage. For this solution a specific paraffin wax grade has been selected with a 17 ˚C melting point. The paraffin wax will need to be encapsulated within modules so that water can flow through the modules to transfer heat from the solid wax. The modules retain the wax within a sealed unit, ensuring safe and reliable operation that requires minimal maintenance. FlatICE modules

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from PCM Products UK are one such example of this, and when immersed in water the matrix of FlatICE units have a specified capacity of 46 kWh/m3 [PCM Products, 2020]. Calculations have been undertaken based on the data for the S17 modules supplied by PCM Products Ltd fitted to a 35 m3 tank with a 50/50 volume ratio of modules to water. An image of the FlatICE product is presented in Figure 7.

Figure 7- PCM Products Limited FlatICE Product [PCM Products]

Table 5: Solution 3 calculated operating timescales

Usage time at 100kW load	
Time to reach design temperature (12.5 – 20 ˚C)	10 hrs 45 min
Recharging time with 100 kW cooling supply	
Time to recharge tank (20 – 12.5 ˚C)	12 hrs 36 min

Comparison

The results in Table 5 show that using paraffin wax is revolutionary compared with water based thermal storage. It offers huge benefits in the capacity density of thermal storage over water, with a much longer usage period. Additionally, minimal ancillary components are required outside of the tank so the footprint of this solution is small. Successful use of phase change materials for thermal storage has been demonstrated in cold storage warehouse facilities to smooth peak daytime loads and improve cooling efficiency [Viking Cold Storage, 2020]. The use of phase change materials is still novel to naval applications and warrants further investigation. Modelling and testing of different products would enable a better understanding of the performance and implications around the arrangement of the wax modules and will provide assurance of performance. Further work needs to be conducted in order to fully investigate different products that are available for thermal storage. This will involve undertaking small scale testing of promising wax module products.

4. Conclusions

This paper demonstrates by simple basic calculation and design concept that there is great potential in developing thermal storage solutions to assist with thermal management of peak loads on naval platforms. The first step when investigating the feasibility of installing thermal storage on a specific vessel is to determine the suitability of adapting tank space. The available tank space, the thermal load requirement and budget for invasive modification (if retrofitting) will then direct the design towards a particular solution. The three design solutions presented demonstrate the variety of ways that thermal storage can be adapted to suit different individual requirements. Wax has great benefits compared to water in terms of thermal energy absorption density, but is more challenging to integrate. Further research and testing is required to investigate wax module products as they are still a relatively novel solution to this application. However, the concept is simple, and it could be implemented in the near future.

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