The use of Absorption Chiller Plant to support the cooling of High Energy Mission System Equipment

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Synopsis

There has been much development into high energy sensors and weapons in recent years to enhance the self-defence capability of warships. The impact of the short-term high energy demands on the ships' electrical systems have been much reviewed but there are also requirements to adapt the ships' cooling systems to match the needs of the finely-tuned lasers and other associated equipment. Although the use of water buffer tank (WBT) as heat storage with Phase Change Materials (PCM) has been considered, the increase in power generation may also allow increased cooling capacity from the Diesel generator set waste heat. Using an absorption chiller plant (ACP), this heat can be used to create additional short-term Chilled Water (CW) capacity which can then cool the WBT.

Such a CW booster may enable the WBT size to be smaller and/or may allow for longer sustained use of the mission systems without any limitation due to the equipment's cooling requirements.

The paper reports on studies to develop a mathematical model of the thermal behaviour of the cooling systems and the associated set of equipment for an indicative system. The Matlab model allowed a time-based analysis of the power generation and cooling system to be assessed using data which had been gathered on the time-variant behaviour of the DG sets, and the ACP. Qualified assumptions based on scientific models are made about the behaviour of the heat transfer systems.

The results show the degree to which a DG set, an ACP and a PCM-based heat storage arrangement can be matched to achieve a sustained performance to meet both Laser Direct Energy Weapons(LDEW) power supply and thermal management requirements.

Keywords: Absorption Chiller Plant, Phase Change Materials, Laser Direct Energy Weapons

1. Introduction

The threat from small, fast, manned or unmanned craft or airborne platforms now makes surface naval vessels increasing vulnerable to hostile action from a wider variety of potential adversaries. Whilst medium to large missiles and such like are likely to be delivered by state actors in more predictable and anticipated periods of tension, smaller weapons may come from shore or small craft with little or no warning at virtually any place in the world.

There is a need for a fast reaction, Close In Weapons System (CIWS) which is wholly defensive in nature, and which minimises the risk of collateral damage to non-combatants. The laser-based direct energy weapon (LDEW) has been developed to address this need. It makes best use of the increasingly improved power, quality, and efficiency of commercial laser systems. In the past twenty years, the rating of commercial lasers has increased to power ratings that make them a credible means of destroying targets. Their efficiency has also improvement to ~20% thus there is a reduced power and thermal cooling demand. These two aspects have allowed the concept of a LDEW for CIWS duties to become an increasingly realistic prospect.

The first seaborne Laser Weapons System, called LaWS, was fitted to the USS PONCE as a trials platform in 2014 and the ship continues to have a LDEW fitted, Ref i. The USN has now fitted a 30kW LDEW systems to its vessels and continues to develop larger rated systems.

In January 2017, the UK MoD announced a £30m programme to develop a protype LDEW, Refs ii, iii. The project, called Dragonfire, is a collaborative team led by MBDA which has developed an initial concept design. The UK has funded recent studies into the shipboard impact of the retrofit of LDEW such as Dragonfire, chiefly relating to the power supply provisions and the cooling arrangements.

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The provision of quality power to the LDEW in the necessary salvo rate of either short bursts, or enduring fire at a multiple swarm of drones is a considerable challenge. Energy storage devices such as flywheels, Ref iv and super-capacitors have been considered together with more conventional battery storage (i.e. lithium ion or nickel-zinc chemical) which is now commercially available at competitive prices. Companies have developed combined power and thermal management systems for equipment testing, Ref v but these are so far at smaller scales that the likely in-service equipment requires.

2. Cooling Requirements

The cooling requirement is no less considerable and critical if the laser is to continue to be an effective tool at disarming the threat. To operate reliably and accurately for a sustained period of time, the laser needs to be maintained within the internal temperature specification which usually refers to an acceptable supply temperature range. If the coolant supply temperature passes outside this range the laser can be less efficient and may be less effective.

As the laser's efficiency is of the order of 20% this clearly requires the removal of a heat load which is four times the optical power delivered . Considering a commercial laser specification, Ref vi offers the following considerations which could apply to the Original Equipment Manufacturers' (OEM) own Laser Cooling System (LCS):

a. During laser operations, the LCS Fresh Water (FW) cooling flows are to be constant with a fine tolerance of variation;
b. The stated maximum design flow is not to be exceeded to avoid inducing laser head vibrations;
c. The LCS cooling flow is not to fall below the minimum design flow to avoid over-heating;
d. The cooling water temperature at the inlet to the laser can be in the range 10 to 35 °C. With a nominal target steady LCS supply temperature of 22°C, this can be cooled by a FW cooling system at 18°C nominal.
e. The maximum allowable supply LCS FW cooling temperature is 25°C;
f. Although a higher LCS supply temperature of 30°C could be used to avoid potential condensation issues this leaves relatively little margin for a temperature increase during long salvoes.
g. The OEM LCS circuit is to meet very specific cleanliness standards and there are to be no additives (so standard Chilled Water (CW) cannot be used);
h. Materials compatibility for LCS to be considered when choosing the heat exchangers (HXE) to cool the LCS. Stainless steel is a likely choice for the plate-heat exchanger baffles;
i. The HXE and the tank allows more flexibility in respect of back-up systems if the Chilled Water Plant (CWP) fails;
j. The minimum temperature difference between LCS & CW/FW side is to be 5°C.

3. Potential Cooling Solutions

From these requirements it appears that a combined HXE and tank-type solution with variable flows would allow greater control over the LCS supply temperature to the laser head. However, the Variable Speed Drives (VSD) may arguably give another source of failure. Therefore, this study considers steady flow conditions for the principal cooling circuits and uses a WBT to manage the temperature changes with time.

The FW cooling system, supported by a WBT, can then either be cooled by a CW system with supply and return temperatures of 7/14°C, or a direct SW cooling system in cold and temperate climates. Where the SW temperature is at higher values, there is the potential for an in-series CW cooling top-up of the FW circuit.

As stated above, the commercial OEM-supplied LCS is normally rated to operate over a range of temperatures with water flows sized to ensure the laser head is suitably cooled. In this study it is assumed the temperature of the LCS supply to the LDEW is to be within a given temperature range of 21 to 25°C with a nominal design temperature of 22°C. This gives a good margin below 30°C and allows a good temperature match with the FW cooling system and the CW that cools that.

The temperature of the LCS supply to the laser can be controlled using a combination of variable speed pumps and thermostatic flow divider valves to achieve the required fine tolerances for supply conditions. To avoid the reliance on such fine controls, this study considers how a cooling arrangement can be devised which keeps the LCS supply temperature to within a safe working range by adopting a WBT and a fixed coolant flow rate.

Figure 1 shows the conceptual arrangement of the LCS, the WBT, its two FW branches and the CW cooling section.

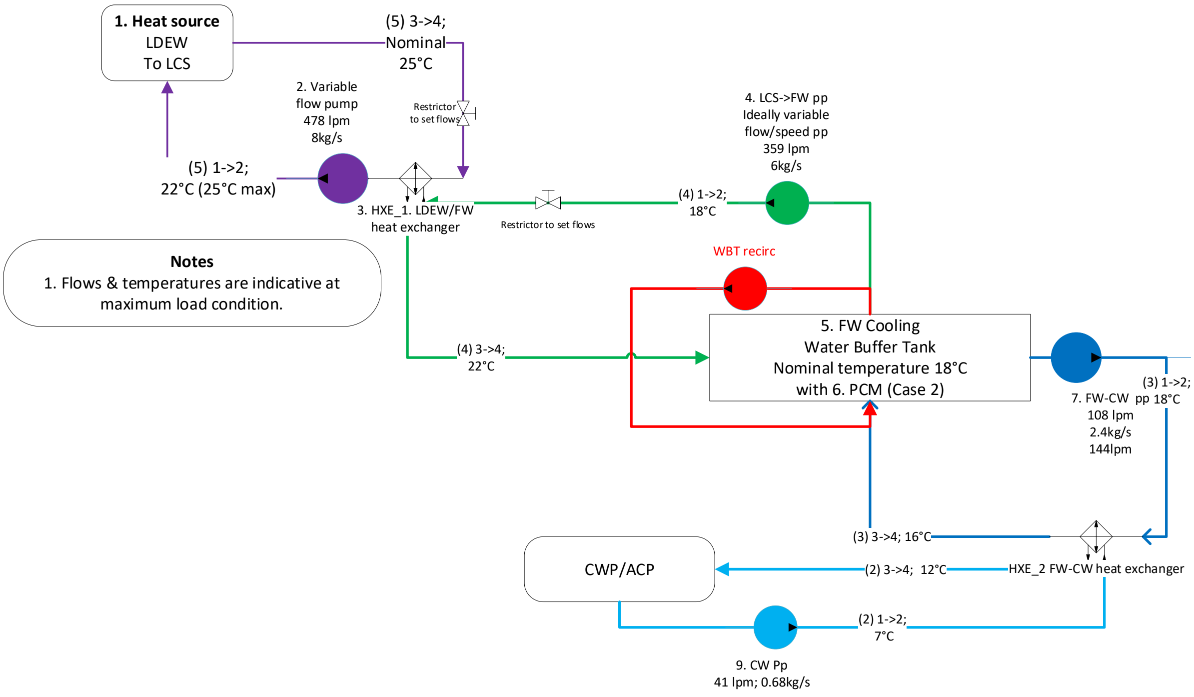

Figure 1. Cooling System Layout

Figure 1 shows the design flows in each pipe section with each individual sub-system numbered with an identifier in brackets. There are two principal heat exchangers (HXE_1 and HXE_2) assumed conservatively to have an effectiveness of 0.58.

4. Solution Analysis

The network was analysed by creating a Matlab model which captured the temperature difference time delay of flows passing through the 10m pipework sections. It also calculates the heat transfer at each principal heat exchanger and the flows entering and leaving the 770 litre FW WBT (item 5) which is at a design temperature of 18°C. Perfect mixing amongst the water and the PCM was assumed within the tank as this is facilitated by the two supply and return flows between the two principal heat exchangers and a recirculating line which ensures mixing when the LDEW is not in use.

In Case 1, the laser starts to operate after 10s and continues for a period until 100s have elapsed. The individual branch lines in Figure 1 show the target design temperatures for steady state operation of the system with a 100kW thermal load at the heat source (item 1) which gives the LCS, system (5), a nominal supply temperature of 22°C (1->2) and a return temperature of 25°C (3->4). The CW cooling supply is nominally off, so the system temperatures will go up with sustained operation.

Figure 2 shows how the Case 1 temperature and heat flows vary when the LCS heat source is turned on and kept on. The tank temperature rises to 21.1°C and consequently, the temperature of the LCS supply to the laser rises to the limit value of 25°C after 98s.

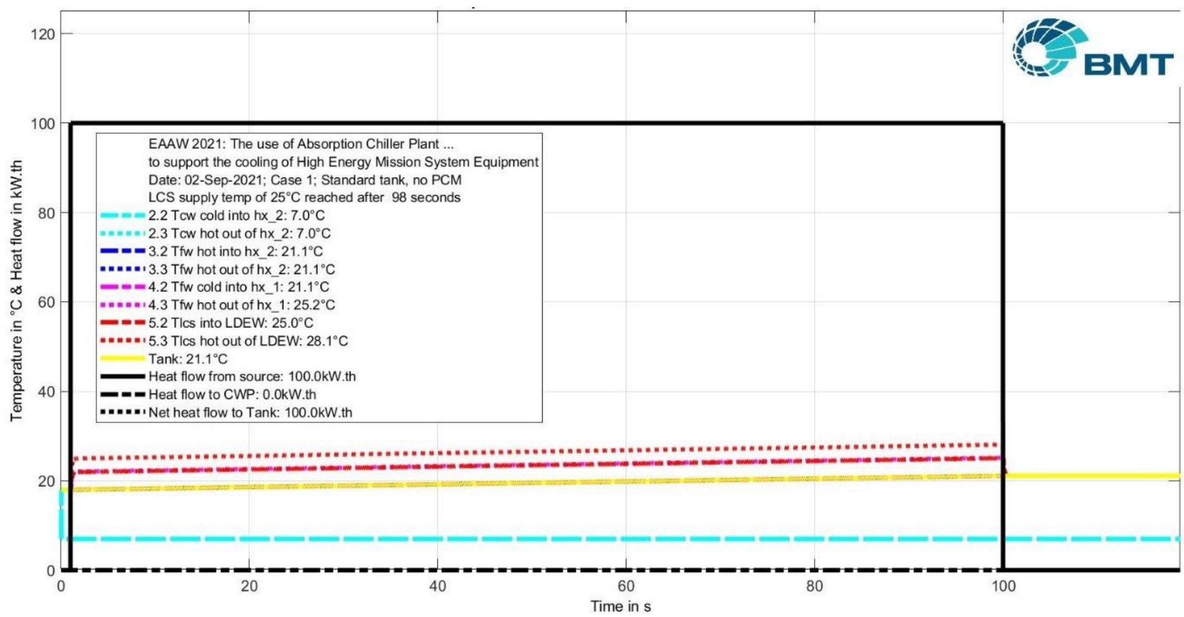

Figure 2. Case 1. No PCM in WBT: Temperature & heat flow v time

Clearly there are options such as variable speed pumps to provide more flow in each leg but fundamentally the system will heat up without a means of increasing the buffer storage of heat in the tank. One obvious way would be to increase the size of the tank, but an alternative is to increase its heat capacity in the vicinity of its key temperature region.

5. Phase Change Materials

Phase Change Materials (PCM) have a large latent heat capacity at the range of temperatures where they change from liquid to solid, or reverse. There are numerous materials that can be used for this duty but in practice paraffin wax or a safer derivative with a much higher flash point temperature (over 200°C) can be used. The use of PCM as a buffer enhancing material has already been explored by designers of cooling systems for commercial warehouses which see a diurnal cycle of solar heating and cooling, Ref vii. The PCM heat store absorbs heat during the day to keep the building temperature below a required threshold and this heat is then released at night to maintain the temperature above a required threshold.

The application of PCM to this application is presented by Dawe, Dubey and Hook in INEC 2020, Refs viii & ix. Dubey and Hook endorse the approach of using PCM to provide an enhanced capacity of the thermal storage buffer and identify that the diurnal loading of the CWP onboard can also support the cooling cycle. However, when in conflict there is unlikely to be a standard 24-hour watch-keeping cycle and the ship's activities may be consistent with a high alert status whereby the CWP is always highly loaded and spare capacity is marginal. This would specifically be the case in tropical climates, which is currently where the major asymmetrical and conventional threats present themselves. The recent suicide drone attack on the MV Mercer Street, Ref x, is one of an increasing number of attacks by drones and small missiles on commercial shipping in the Persian Gulf region.

The cooling system defined above was modified by the addition of a set of PCM modules containing PCM from Croda designed to melt at a nominal temperature of 19°C. In practice the body of PCM will partially melt either side of this as the plot of specific heat capacity in Figure 3 shows.

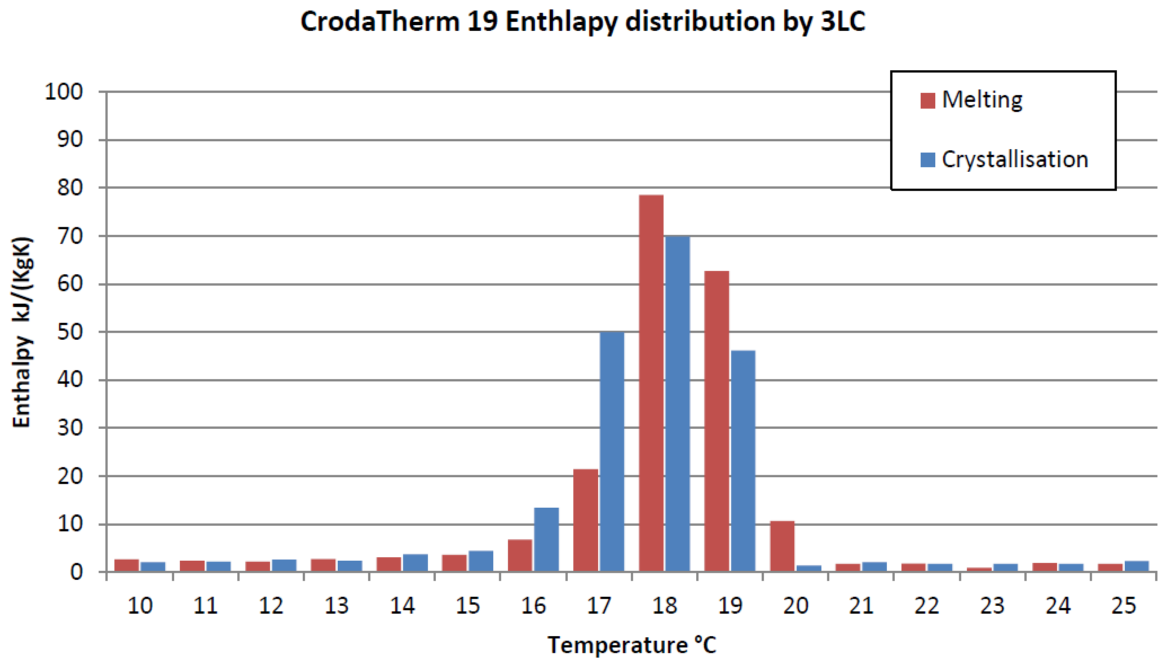

Figure 3. CrodaTherm19 Enthalpy v Temperature

Figure 3 shows that there is a broad range of latent heat capacity across the transition range. When PCM modules are added to the tank in an arrangement as shown in Figure 4, the energy storage capacity for the key temperature transition region is more than doubled.

The individual modules are located halfway across the tank and are piled up to near the surface. Narrow passages between each module allow water to pass at a velocity that facilitates a high heat transfer coefficient. BMT's own studies have shown that the heat transfer in and out of individual modules is key to the overall success of the increased heat storage capability. There is a trade-off between the latent heat of the PCM versus its thermal conductivity.

Return lines from the two principal heat exchangers return to one side where they mix before the water passes through the modules to allow excess heat to be captured by the PCM. A recirculation line also continually passes water from one side to the other to ensure the PCM absorbs all excess heat in the water when the LCS is not on load.

Diffuser meshes ensure water flows evenly across all modules so that heat absorption is even.

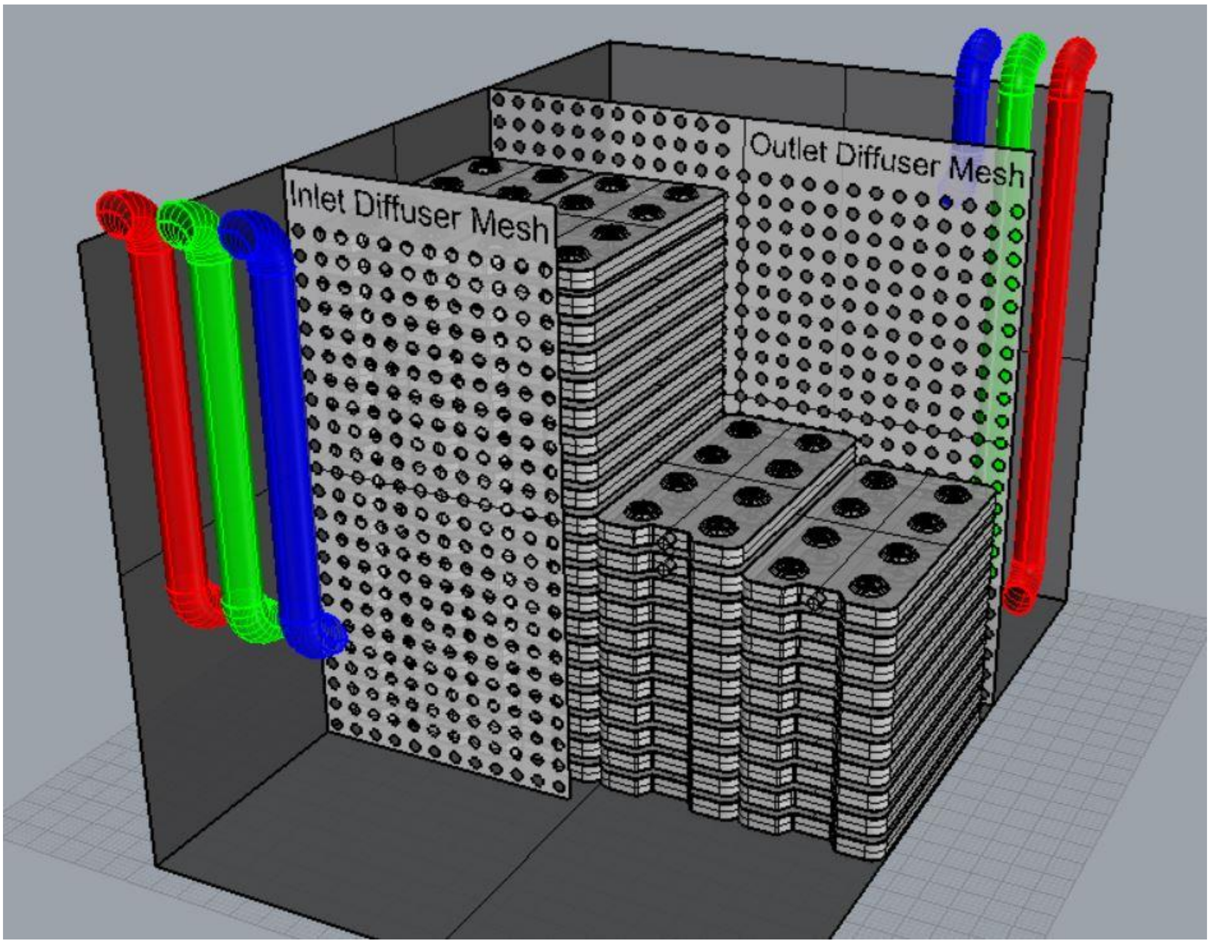

Figure 4. Case 2. PCM Tank Arrangement

6. PCM Solution Analysis

With the Case 2 PCM-based design, the system performance is such that it operates for 183s before the LCS supply temperature (#5.2) reaches its permissible limit of 25°C.

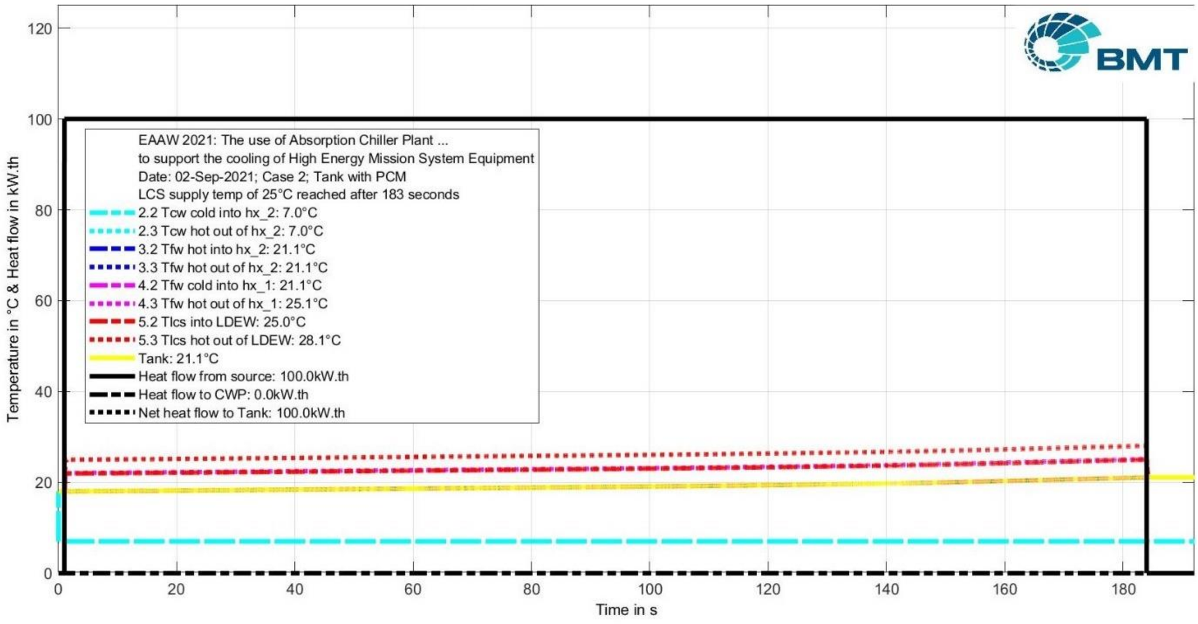

Figure 5. Case 2. Temperature & Heat Flows v Time

Figure 5 shows that line 5.2 takes 183s to reach the LCS supply temperature of 25°C, this is almost twice the duration of Case 1.

When retrofitting LDEW to in-service warships, it is likely that the power and thermal capacity of the vessel would require upgrading to accommodate the critical supplies the LDEW requires. Whilst there can be power upgrades as there has been for the Type 23 frigates, Ref xi and the Type 45 destroyers, Ref xii, the retrofit of increased CWP capacity is seldom an option, often due to space, weight and may be power supply considerations. However, to date there is limited knowledge and understanding of the future thermal loads, partly due to the classified nature of the LDEW products but also due to the challenge of understanding the way they may be used in future engagements.

Assuming that a new CWP would require not just space and weight but also more power, the power and energy challenge of a LDEW retrofit is then compounded by the demands of the weapon and its CW cooling system. Assuming a coefficient of performance of 3.0 for a 100kW.thermal capacity CWP, will add 33kWe to the ship's electrical load when one LDEW may be demanding 125kWe. Clearly, during an LDEW engagement, air conditioning CW demands can be bypassed for a limited period but a future swarm attack of suicide UAV drones would require a considerable period of time to dispense with and so this approach may be feasible but clearly additional installed CW capacity is preferrable.

7. Absorption Chiller Plant

An Absorption Chiller Plant (ACP) uses waste heat to pressurise a refrigerant and absorber mixture so that the refrigerant is pressurised and evaporates away from the absorber. The refrigerant is cooled by a heat sink (sea water) then allowed to expand through an expansion valve where it cools due to adiabatic expansion. The much cooler refrigerant at a low pressure is then used to cool the CW from 14°C to 7°C before it enters the tank where it recombines with the absorber. The diluted absorber is pumped to the generator tank where the refrigerant is evaporated off to re-start the cycle. This process is shown in Figure 7 which shows how the ACP is configured. The ability to use water as the refrigerant requires a low-pressure side so that the water is vapour at low temperatures. The absorber is lithium bromide.

Although there are currently few ACP at sea, it is known that Johnson Controls experimented with a 120kW.thermal unit on a commercial ship in 2008 and now has 1,250kW.th unit operating with smaller marine-based units under development.

Since then other companies such as Heinen & Hopman, Ref xiii, have offered them for marine use but the uptake has been slow. There may have been performance issues with ship motions and how they affect the absorber and refrigerant mixing and decoupling, and the need for sustained low pressure to allow the water to act as a refrigerant may also be an issue.

However, it is understood that these issues are being addressed and a range of products are in the pipeline for future consideration. In the absence of firm in-service technical information on marine ACP, this study has used published and other data from suppliers of ACP such as Heinen & Hopman, Johnson Controls, Klima and Thermax.

The approach was to make best use of waste heat from a diesel engine generating set (DG set) which is sized to supply a single 125kWe LDEW. Many ACP use a steam supply to achieve higher Coefficients of Performance (COP) than a hot water driven unit, providing a 1.2 versus 0.72 for hot water. However there is no appetite for the re-introduction of steam to modern warships so a hot water solution is adopted here.

Figure 6 shows how the ACP is coupled to a single DG set whereby the working Hot Water (HW) circuit is firstly heated by the DG set engine's FW cooling High Temperature (HT) line and then the engine's exhaust gas.

This study has taken a simplistic assumption that the wild heat from these two heat sources varies linearly with engine load. In practice, there will be a disproportionate supply of wild heat at lower loads where the engine is operating less efficiently. The Coefficient of Performance of the ACP varies with load. It is assumed to operate on or near its maximum COP of 0.72 between 50% and 100% load with a 10% COP reduction at 25% load. Below 25% load the COP ramps up from 10% to 90%.

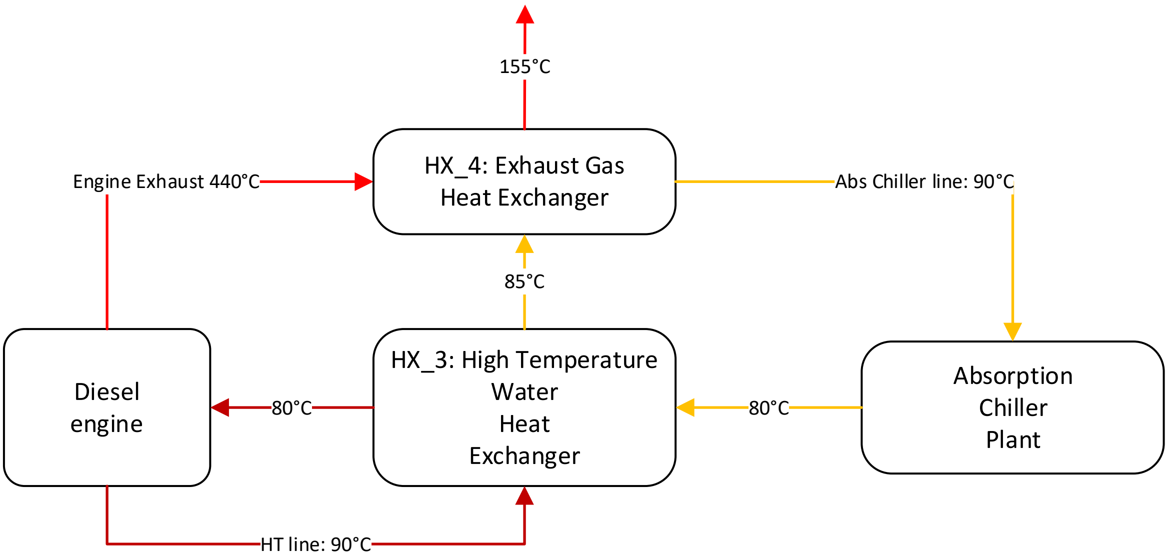

Figure 6. ACP Heat Collection Arrangements

Figure 7 shows how an arrangement of the flows within an ACP. The ACP takes a waste heat source (Qgen) to evaporate the refrigerant so that it is disassociated from the absorber. This together with the cooling stream (Qc & Qa out), (sea water for a ship) then allows a chilled fluid stream (negative Qe) to be generated which can be used as a supplement to the supply from the ship's CWP.

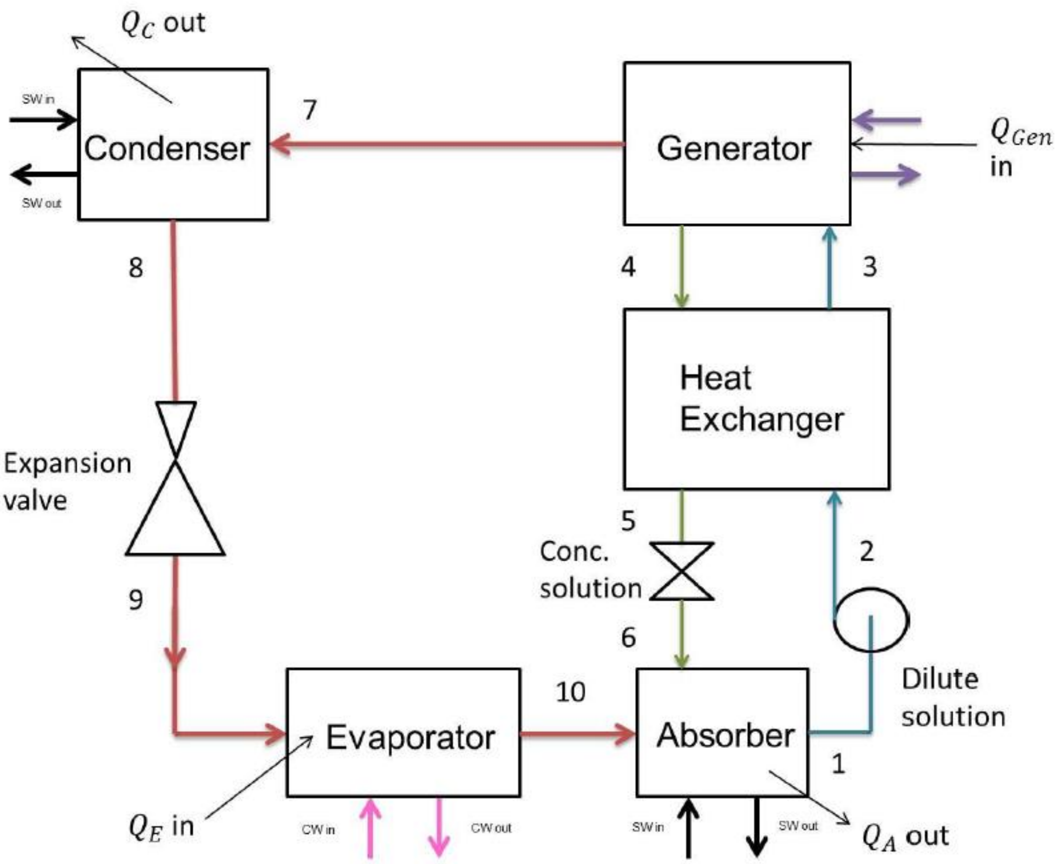

Figure 7. Schematic of an Absorption Chiller Plant Cycle

8. ACP Case Study

We considered above how an ACP might be used in conjunction with the existing ship's CWP and how non-essential loads may be selectively by-passed for short periods of time. We now consider how an ACP and a dedicated DG set may support one LDEW and its cooling supply arrangements.

With a DG set rated at 143kWe 100% MCR, when the engine is 88% loaded, it can supply the 125kWe for the LDEW. At this load, it is estimated that up to198kW.th of heat can be supplied to the ACP at its inlet design temperature of 90°C. Heat loads from DG sets will vary so these figures are indicative.

Using an indicative ACP from one of many industry candidate products, this provides COP of 0.72 to yield a CW supply rated at up to 142kW.th. This is in excess of the 100kW.th required to cool the LDEW.

This simple assessment shows that the operation of an ACP with an LDEW cooling system may:

a. Make better use of the engine's HT and exhaust gas waste heat;
b. Reduce the ship's infra-red signature;
c. Avoid the need to add an additional CWP with an additional electrical load of ~30kWe for a 100kW.th load;
d. Allow for a smaller water buffer tank;
e. Allow for a longer salvo period before the supply temperature to the LDEW exceeds its specification.

9. Transient Considerations

However, the foregoing has considered the steady state situation. Turning on the 143kWe DG set to a load of 80% could take 40s assuming a conservative 2%/s ramp rate and although the power supply issue is addressed by energy storage solutions, the heat supply from the engine would ramp-up with a lag with an assumed first-order time constant of 30s.

There would also be a performance lag at the ACP due to its thermal inertia within the internal working cycle. Consultation with a leading supplier of ACP, Ref xiv indicated that an ACP would reach 100% load in about 15-20 minutes. Assuming a first order response, a time constant of 200s is used to reflect this thermal lag behaviour.

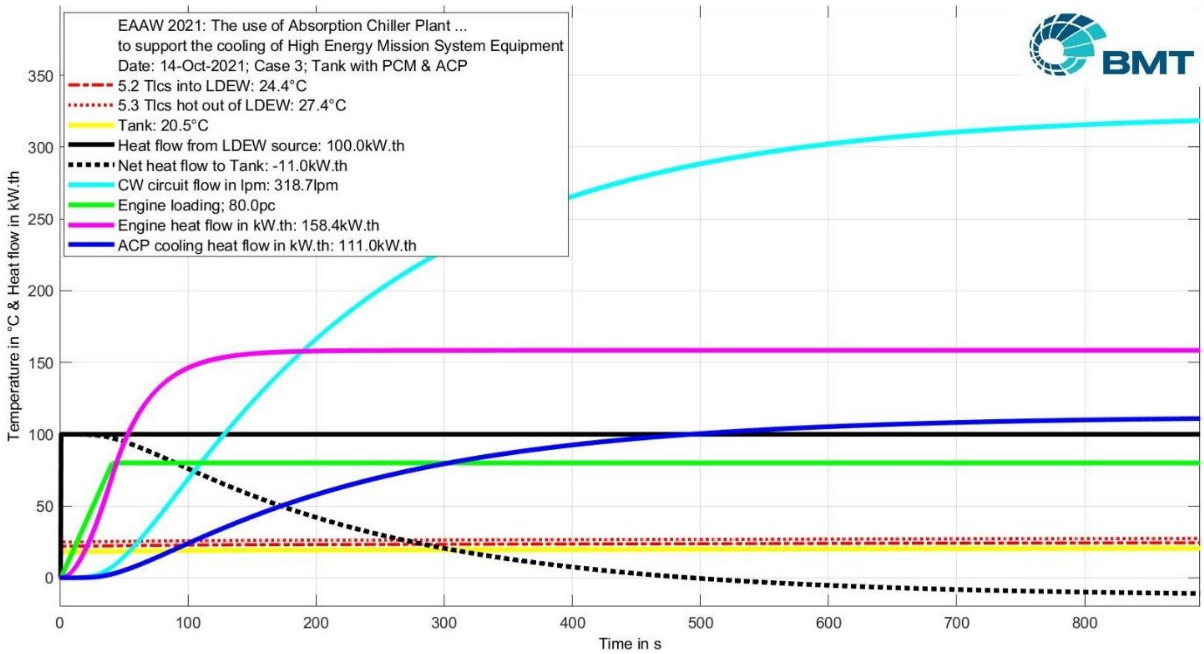

Figure 8. Case 3. Temperature & Heat Flows v Time

Figure 8 shows the time-variations of the individual line temperature and the principal heat flows. The gradual increase of the heat from the engine to the ACP (purple) is shown together with the ACP CW cooling capacity (dark blue) and the ACP CW supply flow (cyan) in response to the heat input. The legend shows that the temperature of the supply to the LCS (5.2) stays below 25°C and is 24.4°C after 900s (#5.2). The tank temperature after 900s is 20.5°C.

10. Other Considerations

As the lag due to the ACP is much longer than that for the diesel cooling systems, this, together with its reduced COP at lower loads, is the key consideration. The operation of the overall system design could assume that with the LDEW off, the ship's CWP and the diesel-driven ACP work together supplying the ship's CW needs. Excess CW capacity from the ACP could also pull down the tank temperature to below 18°C so it is primed as a useful over-cooled heat sink.

Once the LDEW is turned on, all CW output from a running ACP is diverted to the WBT, the CWP operate as normal but maybe the CW supply to non-essential equipment is temporarily by-passed to give more CW margin. The non-essential equipment could be the CW supplies to ATUs in accommodation and storage spaces, areas that would not be affected with a loss of cool supply air for 8 to 10 minutes in a high threat situation.

Alternatively, as with the case study #3, the whole LDEW-DG-ACP package could be self-contained with a CWP back-up. When the LDEW starts, the ACP CW supply ramps up to a steady-state output with the ACP supplying just the WBT.

There are therefore numerous different control and operation strategies that could be developed for each ship case. There is also scope for the consideration of a CW buffer tank to help manage such transients with a reduced need for fine sensors and controls.

11. Ship Impact

One standard commercial ACP to supply 105kW.th of CW would weigh 3 tonnes onboard and be 3m long by 2m wide and 2m tall, Ref xv. This could be located inside a standard shipping container. It would supply 18.1m^3/h CW with a HW supply of 8.4m^3/h . There would be a SW cooling flow demand of 39.6m^3/h .

Other units could supply higher cooling capabilities as required.

12. Conclusions

This study has sought to explore the potential for an ACP to support the use of an LDEW whose cooling is provided by a dedicated water buffer tank with PCM to enhance its storage heat capacity. The ACP makes best use of the waste heat from a nominally dedicated 143kWe DG set that supplies the LDEW.

The study has considered the additional waste heat emitted when a 150kWs/143kWe DG set is loaded up with the LDEW load of 125kWe i.e. at 88% MCR. The waste heat from the HT and the exhaust gas is sufficient to provide an additional 113kW.th of CW cooling from the ACP when the LDEW is emitting 100kW.th of heat.

Even when allowing for the time for the engine's exhaust and HT line to reach steady state temperature and also for the delay in the ACP achieving its steady state operations, the arrangement allows the LDEW to conduct operations without the LCS supply reaching the limit of 25°C.

Additionally, the ACP will allow collected waste heat to be used to heat the tank water if required and it will reduce engine exhaust temperatures for reduced IR signature just when LDEW is in use as a CIWS.

The thermal system considered here requires an integrated approach both for its sizing and its control when in operation to ensure the LDEW operates reliably with an assured supply of cooling water.

The complex interaction between the tank size and its arrangement, and its pumps and controls as well as the source of CW cooling indicates these to be a ship-based resource as the thermal system and its management will be tailored to each platform's LDEW and CW installation, usage, and layout.

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