
The DDG Flight IIa class represents the largest population of HES-C back-fit opportunities. Shown here is USS *Kidd* (DDG 100).

Chilled Water CHALLENGES

The evolution of systems used on naval surface combatants

BY MATTHEW FRANK AND KEVIN MARTIN

Similar to any large office building, naval surface combatants use air conditioning (AC) plants, commonly called chillers, to produce chilled water (CHW) that is circulated in a closed loop piping system connected to various fan coil units and heat exchangers to remove heat. Unlike an office building, the chiller onboard a naval surface combatant rejects heat absorbed by the CHW to seawater (SW) using a traditional single-stage, refrigerant vapor compression cycle.

Like commercial industry, naval surface combatant CHW systems have evolved and grown from small non-vital systems providing mostly habitability comfort cooling into large, robust, and mission-critical systems. Today, failure of a CHW system is no longer just a matter of comfort; failure of a commercial CHW can shut down Internet server centers, disrupting vital communications; shipboard failure can compromise vital command and control systems. However, naval combatants have unique mission requirements and space challenges that have forced pragmatic solutions and compromises when compared to commercial applications.

Naval surface combatant CHW systems are now vertically and horizontally segregated into multiple zones that support mission reliability and fight-through capability. Chillers are similarly distributed to improve survivability; completely contrary to commercial CHW designs that centrally locate equipment.

Naval surface combatant chillers were forced to trade equipment cost for space, mission performance, and reliability. Naval combatant chillers are customized, hardened designs suitable for extended operation in extreme environments such as heavy-weather vibration, and temperature fluctuations ranging from arctic to tropic. Mission tempo, the inherent corrosion challenges of seawater, limited maintenance space, and 40-year service life forced solutions such as heavy wall 70/30 copper-nickel condensing tubes to improve reliability and reduce overhauls. Standard marine chillers do not have all of these same concerns and can use thin wall 90/10 copper-nickel condensing tubes. The latest naval combatant chillers use lifetime, seal-welded titanium condensers to support even tighter ship packaging by essentially eliminating tube pull-space.

In comparison, some commercial ships forgo the issues of SW corrosion and fouling entirely by installing intermediary SW to freshwater heat exchangers, while other commercial ships with large central equipment spaces can easily support routine condenser re-tubing or wholesale AC plant replacement. That space luxury is not an option for a naval surface combatant.

For the last 50 years, naval surface combatants have relied on single-stage, fixed-speed centrifugal compressor chillers with fixed design criterion for evaporator and condenser differential temperature. The consequence has been a proportional increase in the CHW and SW systems as ship cooling load has grown. However, three very different objectives are positioning themselves to force change from this legacy chiller design: first, reducing ship acquisition cost; second, increasing cooling density to provide more cooling in less space; and third, improving life cycle cost. The United States Navy is now positioned to answer these three unique and opposing objectives.

In 2009, Naval Sea Systems Command, in a forward-thinking engineering investment strategy, began the High Efficiency Small-Capacity (HES-C) Chiller Program. The goal was simple—develop a chiller for the 21st century navy. The objectives were bold:

- increase the capacity of the 200-ton R134a chiller by more than 50% with no change to existing CHW/SW piping or pumps
- reduce the overall combined chiller, CHW, and SW acquisition cost by 25-30%
- improve reliability by more than 100%
- improve the overall life cycle cost by more than 50%
- design for both new construction and back-fit.

Delta-T and Delta-P

Increasing cooling capacity within the space and flow rate constraints of the 200-ton R134a AC plant meant only one thing—the evaporator and condenser water differential temperatures had to increase, leap-frogging accepted commercial chiller standards. For CHW, it meant colder water, as low as 40°F, which lowers evaporator pressure. For SW, it meant that the condenser pressure would increase well above legacy and commercial designs with stable operation up to 105°F—sufficient to meet any future demands. The solution demanded two-stage compression. But, a traditional oil-lubricated, two-stage, over-hung compressor design presented numerous obstacles. The additional bearings and supports required for shock and vibration resistance and consequential driveline length and weight makes the design impractical.

The solution was to use opposing (back-to-back) compressors, one on either end driven by a common high-speed motor. The execution became an engineering synergy: the collaboration of the navy with its most experienced chiller OEM and a few vendors with maturing innovative technologies, which together became Team HES-C. York Navy Systems (a Johnson Controls, Inc. company) would provide its 50 years of naval combatant and commercial chiller and compressor knowledge; and package commercial technology from Calnetix Technologies for the compressor-motor assembly.

Calnetix Technologies would provide commercial solutions for the magnetic bearings, a sensorless high-speed permanent magnet motor, and a variable speed drive (VSD) module.

Parker Hannifin would provide their commercial vaporizing dielectric fluid (VDF) cooling system for the VSD, and Fairlead Integrate Power and Controls would package and compact the Calnetix drive and Parker Hannifin VDF cooling system into a cabinet that would fit in the ship and complement the overall objectives.

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The outcome is the HES-C chiller. It is an economized, variable speed, two-stage centrifugal compressor using a semi-hermetic, refrigerant cooled, high-speed permanent magnet motor, suspended on three magnetic bearings (two-radial and one-thrust), direct driving two compressors, one at either end; mounted on an optimized mono-shell heat exchanger package; and all engineered for the operator and the maintainer. A mouthful, but the HES-C chiller benefits are impressive.

The opposed two-stage design yielded a compact compressor motor driveline module capable of three critical elements. First, it optimized installation of magnetic bearings significantly larger than commercial applications to handle ship vibration and ship heavy weather operation. Two, it optimized the location of the large catcher (back-up) bearings necessary to meet shock. And third, it enabled back-fit to the existing 200-ton R134a AC plant.

The two-stage compressor with an intercooler between stages improves overall efficiency beyond what is possible with the legacy single stage compressor. The two-stage compressor design, when coupled with the variable speed drive, proved so effective that the traditional pre-rotation vanes, hot gas bypass valve, and condenser water control valve (CWCV) were removed from the design. The absence of these valves, and especially the CWCV, has large acquisition and lifecycle benefits. The naval 200-ton R134a chiller uses lifetime, seal-welded titanium condensers. However,

TOP: A fouled seawater condenser. **BOTTOM**: The 200-ton HFC-134a AC plant (chiller) was the first navy unit designed to use ozone-friendly refrigerant HFC-134a, starting in the late 1990s.

a CWCV and the resultant low tube velocity in cool SW force the absolute need for chlorination to mitigate biological fouling. Not anymore, as the HES-C can run full condenser water flow all the time maintaining high tube velocity all the time, minimizing the need for chlorination.

The oil-free compressor design eliminates the oil lubrication system. This dramatically simplifies the chiller; eliminates the difficult marriage of refrigerant and oil; eliminates 80% of the valves and fittings that are sources of refrigerant leakage (maintenance and global warming); eliminates oil and filter changes (maintenance and hazardous waste disposal); and eliminates onboard oil stowage (space and fire hazard).

The VSD provides optimum energy efficiency at all conceivable operating conditions and reduces the starting in-rush current by at least 75%. This reduces energy usage, improves reliability, and reduces stress to the ship's electrical distribution system. Additionally, the lower starting current provides increased flexibility during emergency and casualty conditions when shipboard electrical power may be limited.

The motor, bearings, and VSD electronics are cooled by R134a refrigerant—all self-regulating with no need for active controls, no solenoids, no motor-actuated valves, no algorithms, and no software. Self-regulating refrigerant cooling provides maximum reliability at optimal electronic operating temperatures, increasing the life of the electronic components; and R134a as a dielectric and non-flammable fluid provides maximum safety. One gallon-per-minute (gpm) of water with 10°F ΔT can transfer 5,000 BTU/hour, but one gpm of R134a VDF cooling transfers more than 30,000 BTU/hour. The efficiency of refrigerant cooling allows the VSD and its electronics to be fully enclosed and densely packaged, resulting in a far more compact and cleaner operating cabinet than typical water-air cooled electronic equipment systems.

The chiller control system uses a "dashboard" with virtual gauges designed to enable assess to the basic chiller health in 15 seconds by anyone—trained or otherwise—arrows up in the green, and nothing flashing then all is OK. It has the ability to retain 10 years of once-per-minute data for trending and condition-based maintenance, and once-per-second data in a 24-hour buffer to assist troubleshooting; all in an open-architecture with appropriate cyber security provisions.

Lean 6 Sigma type analyses were used to invest heavily in improving manufacturability by modularizing the design with careful selection of weld repairable castings, and in militarizing known proprietary solutions, all in an effort to improve reliability more than five fold. Similarly, lower-cost commercial/industrial electronics have been carefully selected and packaged to support the reliability goals, including a reduction in the meantime to repair by a factor of six. The chiller maintenance strategy was part of the design, not an afterthought. It is an integrated solution using time-based replacement to ensure a high availability (A_0), conditioned-based maintenance to maximize use, and "fix when fail" for cost effectiveness when skill and time to repair are appropriate. The outcome is a major benefit to the ship and the operator: increased availability, less repair actions, less maintenance, less time to repair, less attention needed by the operator, and all at competitive cost.

Ship acquisition cost?

On a shipset cost per cooling ton, the HES-C chiller is proportional to legacy naval surface combatant AC plants, but the real savings come from the smaller footprint (high density cooling) and the smaller and less complex chilled water and seawater piping systems that constitute a significant portion of the total AC plant install cost. Large academic and commercial campuses are applying this same concept in what is often called low temperature, high delta-T chilled water systems. In these applications, like a large ship, smaller chilled water and condenser cooling water components (pumps, pipes, and valves) can be real savings.

Therefore, when the DDG51 Flight-III required a major increase in cooling load for the next generation radar, the HES-C chiller was the solution. The DDG51 Flight-III retains the existing CHW distribution system and replaces only the chillers, with HES-C providing a more than 50% increase in capacity. When the LPD28 presented the need for reduced ship acquisition cost, the HES-C chiller was the solution by using the same basic LPD17 class CHW system but reducing the number of chillers by 50%.

The legacy navy

Naval Sea System Command's forethought for the HES-C chiller program included the legacy navy. The HES-C compressor and controls are designed to back-fit to the existing navy 200-Ton R134a AC plant, more than 200 of which are in the fleet, and integrates with existing electrical switchboards with only minor modification. All of this leads to significantly reduced lifecycle cost. A single HES-C back-fit to a DDG51 Flight-IIA has a calculated return on investment (ROI) of less than five years. The greatest benefit of the HES-C in a simple, single chiller back-fit is that it does the heavy lifting. It operates 24/7 with the best-known, indisputable cost benefit: maintenance intensive legacy AC plants are turned off. The HES-C as a back-fit also is an enabling technology: it can significantly increase candidate, legacy ship cooling capacity to meet emerging mission needs, and it does so with an ROI. This is in stark contrast to the legacy solution of adding AC plants with its indisputable result, which is increased lifecycle cost.

Even the most basic equipment and systems are challenged by the mission, tempo, and dense packaging associated with a naval combatant, and its chilled water system and the associated chiller and seawater system are no different. Chilled water will be a cooling solution for many years. Fresh water remains the singular miracle fluid—a reasonable heat transfer fluid with the benefits of being non-toxic, non-flammable, and easy to produce at sea with little or no corrosion and fouling. For 50 years, the basic design elements—chilled water outlet temperature, chilled water delta-T, seawater delta-T, and the need for a CWCV—have remained mostly unchanged. The confluences of recent maturing technology, need, and the can-do spirit of a team have combined to yield the HES-C R134a chiller, a nearly seamless solution capable of going forward with new construction ships and backwards for legacy ships. The HES-C R134a chiller does not solve all the navy's chilled water challenges, but it is a major leap forward. **MT**

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