Improving Energy Efficiency of HVAC Systems on Navy Ships

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Synopsis

The function of the heating, ventilation, and air conditioning (HVAC) system on a Navy ship is to provide the required ventilation, heating, and cooling to the occupants and equipment on board. HVAC systems for Navy ships are designed to operate in areas with diverse and extreme ambient environmental conditions, ranging from sub-Arctic winter conditions to humid, hot coastal deserts. The HVAC system is sized for these extreme conditions, resulting in oversized systems for the more moderate environments these ships mostly encounter throughout the year. This leads to low efficiency, high energy consumption, and increased CO2 emissions. This paper proposes options for improving the energy efficiency of HVAC systems by incorporating free cooling, energy recovery, direct and indirect evaporative cooling, and the use of absorption chillers that utilise waste heat for generating chilled water. Engine waste heat is harnessed to provide heat to the hot water system, resulting in significant power savings and increased system efficiency.

Keywords: Efficiency; Energy consumption; Waste heat recovery; HVAC.

1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems on board Navy ships are significant consumers of hotel load power. These systems are designed to operate in diverse and extreme ambient environmental conditions, ranging from sub-Arctic winters to humid, hot coastal deserts. Consequently, they are often oversized for the more moderate environments typically encountered throughout the year, leading to low efficiency, high energy consumption, and increased CO2 emissions.

The efficiency of HVAC systems on Navy ships can be enhanced by incorporating free cooling through economisers, energy recovery, direct and indirect evaporative cooling, and absorption chillers. Engine waste heat can be utilised to provide heat to the hot water system and as a power source for absorption chillers, resulting in significant power savings and increased system efficiency.

To evaluate these options for improving the HVAC system, an environmental model of the ship was created using IES VE software (IES, 2023). This model includes the ship's structure and insulation, heat loads from people and equipment, and a detailed representation of the HVAC system. The HVAC system is modelled using a schematic component-based interface, which allows for the accurate representation of cooling coils, heaters, fans, chilled water plants, and controllers. This interface also enables the linking of the HVAC system to the relevant compartments in the model using duct and room components.

The environmental model can predict the internal environmental conditions (temperature, humidity) of the ship under various weather conditions and operational scenarios. The options for improving the HVAC systems are simulated using a weather file that represents conditions encountered in Arctic areas in January and hot, humid areas such as the Arabian Gulf from February to December.

Author's Biography
Younus Abbas is a Principal Mechanical Engineer at Babcock International Group. He currently leads the HVAC functional group at Babcock UK ME. A Chartered Engineer, he has a background in HVAC, marine auxiliary systems, and noise and vibration. He has delivered several major projects, ranging from the delivery of an HVAC system for a Navy frigate to the design of the auxiliary cooling system for an amphibious transport dock vessel. His research work includes improving HVAC and auxiliary cooling systems for ships.

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2. Ship Environmental Model

The ship's environmental model was created using Dynamic Thermal Simulation software IES VE (IES, 2023), which incorporates the following features:

- Weather data based on ship location and time,
- Ship structure and insulation,
- Internal heat gains, including lighting, people (latent and sensible heat), and equipment heat emission,
- Profiles for simulating people's movement within the ship and equipment operating frequency,
- Modelling of the HVAC system, including chillers, cooling coils, heaters, controllers, etc.

A weather file simulating conditions encountered in Arctic areas in January and hot, humid areas such as the Arabian Gulf from February to December was created by combining weather data from Truro, Canada, for January and Kuwait for the period from February to December.

The ship and compartment geometries were modelled by importing DXF files for each deck. These files were then converted to 3D geometry, with insulation and construction materials applied to each compartment bulkhead, deck, and deckhead. All external surfaces below the waterline were set to a profile that allows for easy adjustment of seawater temperature to suit the ship's location. For winter conditions, a seawater temperature of 2°C was assumed, and for summer conditions, a seawater temperature of 32°C was assumed. Figure 1 presents an isometric view of the modelled ship geometry, highlighting the position of the waterline.

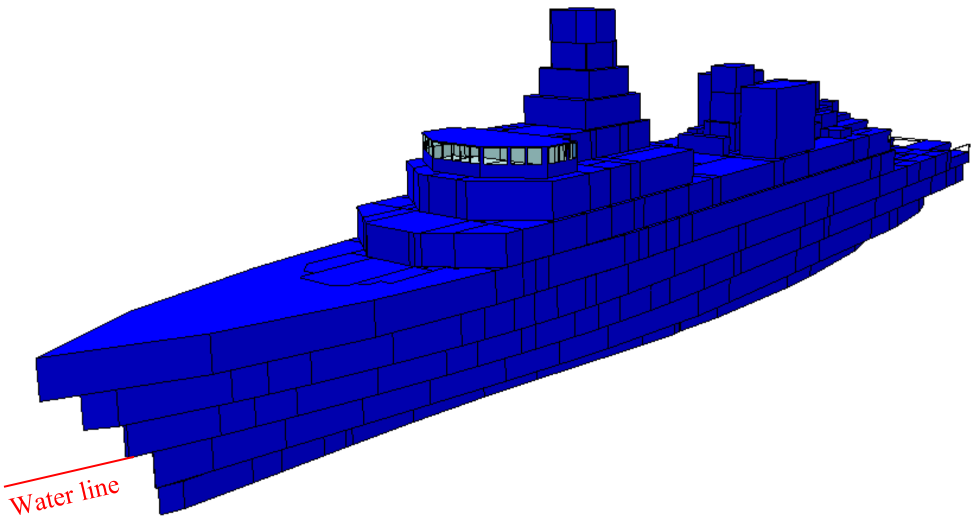

Figure 1: ISO view of the modelled ship geometry.

Internal heat gains for people, lighting, and equipment were assigned to each space with a profile, allowing for control of these heat gains at different times of day or year using daily, weekly, and yearly profiles.

Each compartment is assigned a relevant occupancy profile, enabling the simulation of people's movement within the ship. For this model, it is assumed that cabins are occupied from 19:00-07:00 and 16:00-18:00 hours, dining halls are occupied from 07:00-08:00, 12:30-13:30, and 18:00-19:00, and working areas are occupied between 08:00-12:30 and 13:30 -16:00.

Heat loads from personnel were input into the model as 70 W/person sensible heat and 50 W/person latent heat for all occupied compartments, except for the gym, which used values of 85 W/person sensible and 150 W/person latent heat. Lighting loads of 8 W/m² were applied to all lit compartments.

The HVAC system is modelled using a schematic component-based interface, which enables the accurate representation of cooling coils, heaters, fans, chilled water plants, and controllers. This interface also allows for the linking of the HVAC system to the relevant compartments in the model using duct and room components. Figure 2 illustrates part of the HVAC model.

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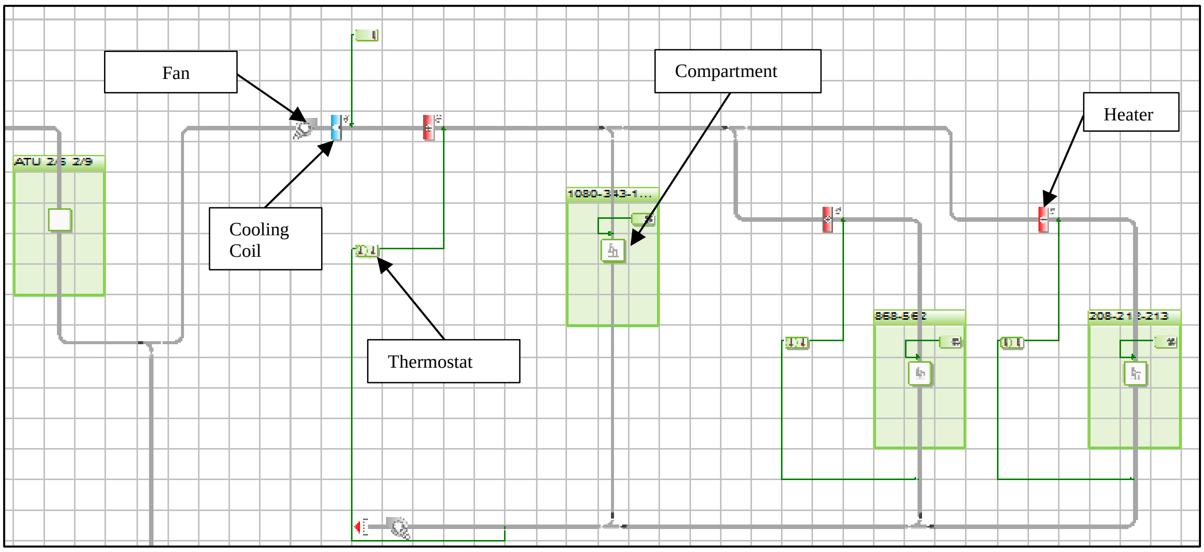

Figure 2: HVAC system components.

3. HVAC system energy recovery on current navy ships

The Heating, Ventilation, and Air Conditioning (HVAC) system on a naval ship is divided into two sub-systems:

1. Air-Conditioning (AC) system; and
2. Mechanical ventilation system.

The AC system provides conditioned air to accommodation areas, recreation spaces, the galley, messes, and other living spaces, as well as command and control areas, ship control spaces, and other working environments. This system is served by air-handling units (AHUs) installed in dedicated compartments.

Figure 3 illustrates a basic example of the air conditioning (AC) system on board a navy ship. Cooling and dehumidifying the air in this system is achieved using chilled water-cooled heat exchangers, while heating is provided by electrical heater elements or hot water heat exchangers supplied by an oil-fired boiler for preheating. Fresh air enters the Air Handling Unit (AHU) and mixes with the recirculated air within the AHU. The air mixture passes through the heat exchanger, reducing its temperature and humidity (W). Before being supplied to the compartment, the air passes through an electric heater. This heater regulates the compartment's temperature via feedback from a thermostat installed in the compartment or the recirculating duct. Dry, cool air is supplied to the compartment (S), removing heat and moisture until it reaches the desired condition. Part of the air is extracted as exhaust (E), while the remainder is recirculated back to the AHU to be mixed with fresh air (M).

In this AC system, limited exhaust energy recovery is achieved by recirculating the exhaust air from the HVAC system back to the AHU inlet. Typically, only 50% to 80% is recirculated and mixed with fresh air. This energy recovery method is widely used on naval ships but is limited in effectiveness, as the energy in the percentage of air exhausted to the atmosphere is not recovered.

Machinery spaces such as engine rooms, chilled water plant rooms, and steering gear rooms are served by mechanical ventilation systems, with no air conditioning or heat recovery methods typically used. These systems utilise a supply fan to provide fresh air to each space and an extraction fan to remove the exhaust air. Air is not recirculated in these systems. Chilled water-cooled Fan Coil Units are sometimes used for cooling in extremely hot climates to prevent compartment temperatures from exceeding equipment operational limits.

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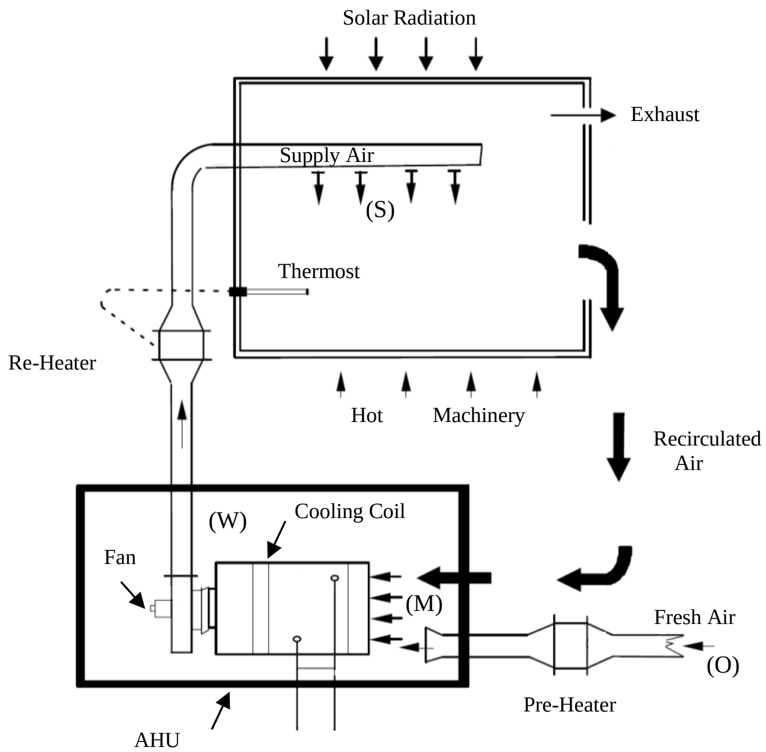

Figure 3: General AHU layout (MOD, 2005).

Naval vessels are typically equipped to survive in a Chemical, Biological, Radiological, and Nuclear (CBRN) environment. In such scenarios, a CBRN safe containment, commonly known as a Citadel, is formed by isolating all external intake and exhaust terminals. A relatively small amount of fresh air is supplied to the AHUs through Air Filtration Units (AFUs) to prevent CO2 concentration and maintain the minimum required overpressure of 5-8 mbar in the containment. Pressurisation of the Citadel ensures that no contaminated air from outside the ship enters. Overpressure dampers are used to bleed air from the Citadel through the cleansing station airlocks, which serve as entry and exit points. Under these conditions, the majority of the air is recirculated within the Citadel, making heat recovery impossible.

4. Use of Air Economisers

Air economisers can reduce HVAC energy costs and improve indoor air quality in cold and temperate climates by using cool outside air to cool the indoor space. When ambient conditions are hot and humid or very cold (Arctic conditions), economisers cannot be used, as outdoor air will increase the cooling or heating loads on the system. In these conditions, only the minimum required ambient air is supplied to the system.

An air-side economiser is a duct and damper arrangement with a control system that enables the HVAC system to use outdoor air to meet the cooling load when outdoor conditions are favourable, by closing the return air damper and fully opening the fresh air damper. Figure 4 shows a basic HVAC system with an economiser. Control of the economiser is achieved by comparing the return and outdoor air temperature or enthalpy. If the return air temperature or enthalpy is greater than the outdoor temperature or enthalpy, the economiser is activated (cooling). If the return air temperature or enthalpy is less than the outdoor, the economiser is isolated. Dry-bulb sensors work well in all but humid climates, where enthalpy sensors are more appropriate. For naval ships, it is recommended that enthalpy sensors are used due to the varied ambient conditions encountered and the potential for operating in hot, humid climates.

For naval ships that primarily operate in areas with cold and temperate climates, economisers can provide significant energy savings.

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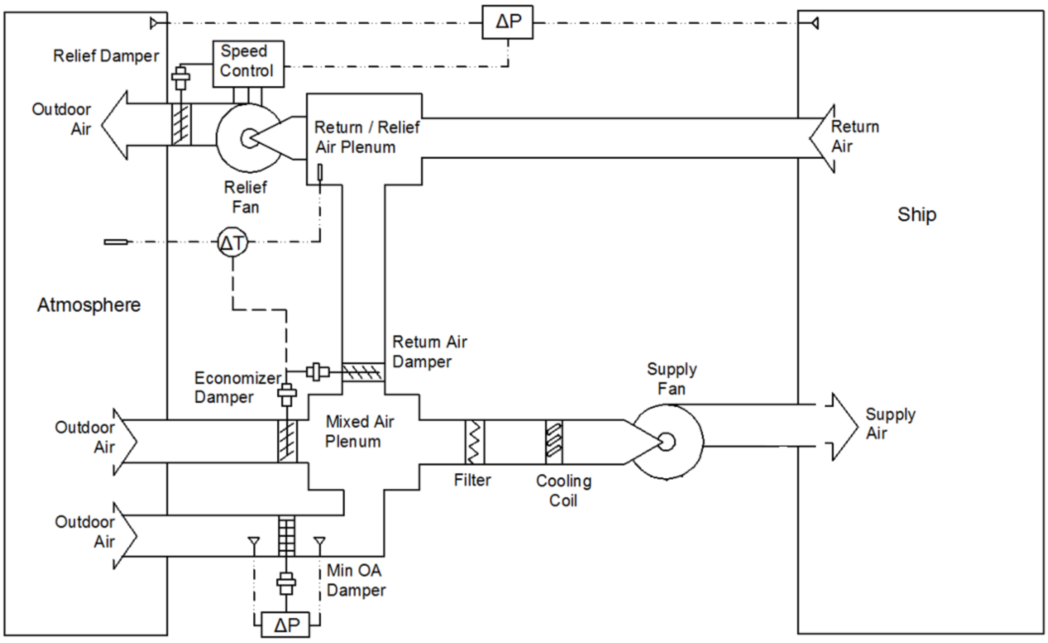

Figure 4: Basic schematic of an Economiser (EDR, 2009).

4.1. Economiser Case Study:

To assess the impact of introducing an economiser to the HVAC system on board a typical naval frigate, an economiser is added to the HVAC environmental model Air Handling Units (AHUs).

The model simulation results presented in Figure 5 show the monthly chilled water system load comparison between the HVAC baseline system and the HVAC system with economisers added to the AHUs. Figure 6 shows the simulation ambient annual mean temperature. Both figures show that the economisers are only active when the ambient mean temperature drops below 27°C and are inactive between May and September.

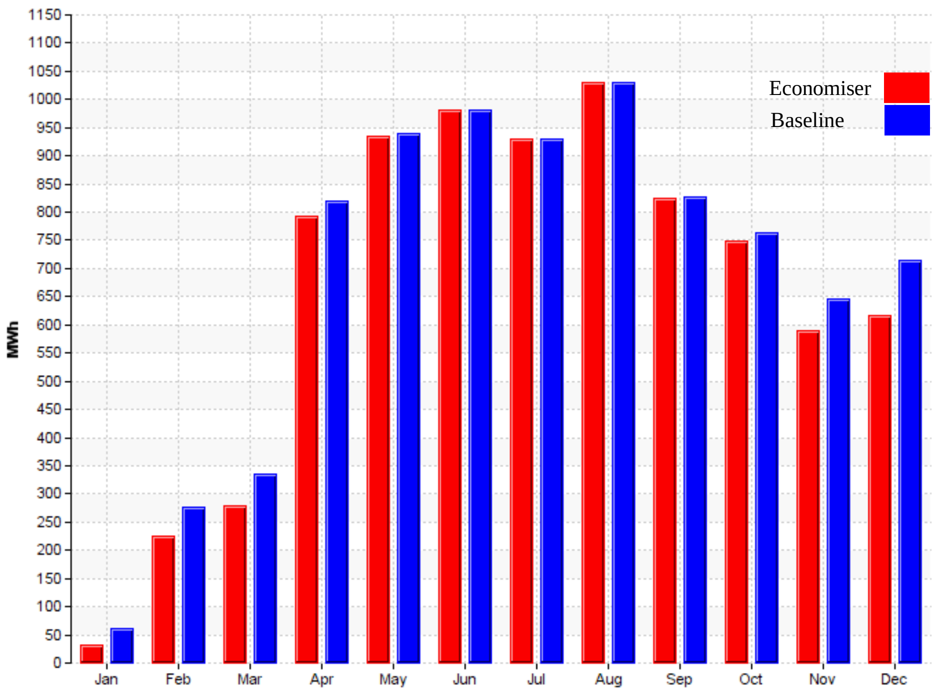

Figure 5: Monthly Chilled water load (kWh) simulation results, comparison between baseline and using Economisers.

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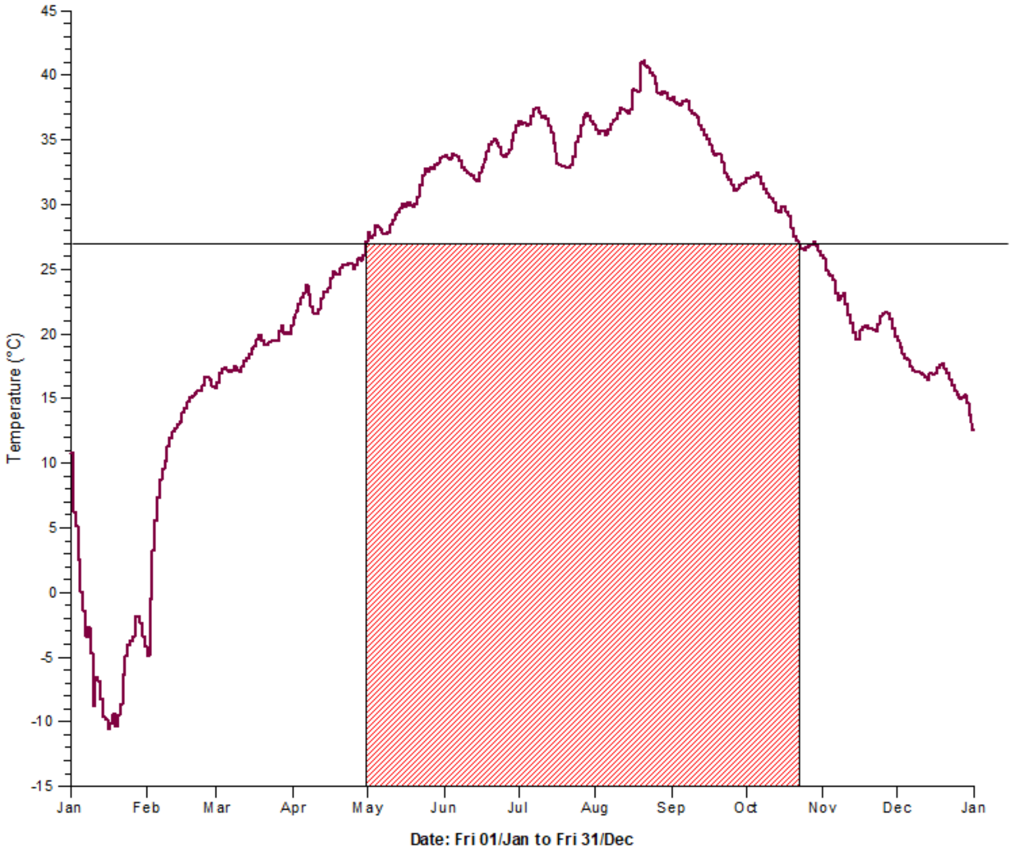

Figure 6: Simulation ambient mean temperature. Showing zone where economiser is not active.

Table 1: Reduction of Chilled water plant power consumption when using economisers

Month	Baseline CW Load (MWh)	Economiser CW Load (MWh)	Reduction (%)
Jan	15.0	7.8	48%
Feb	41.8	32.5	22%
Mar	51.7	41.4	20%
Apr	148.8	143.8	3%
May	191.7	191.2	0%
Jun	214.8	214.8	0%
Jul	196.2	196.2	0%
Aug	224.5	224.6	0%
Sep	172.2	172.0	0%
Oct	146.9	144.4	2%
Nov	113.6	103.4	9%
Dec	118.1	101.7	14%
Summed total	1635.3	1573.7	4% (61.7 MWh)

The model simulation results presented in Table 1 show that the total annual Chilled Water Plant (CWP) energy saving when using an economiser is 61.7 MWh. The use of an economiser is more effective in energy saving in more moderate climates.

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5. Air-to-Air Heat Recovery

Air-to-air heat recovery involves the transfer of heat between two airstreams at different temperatures. This process is crucial for maintaining acceptable indoor air quality (IAQ) while minimising energy costs, overall energy consumption, and carbon dioxide emissions. This section outlines various air-to-air energy recovery technologies that can be implemented on navy ships.

5.1. Fixed-Plate Heat Exchangers

Fixed-plate heat exchangers are available in numerous configurations, materials, sizes, and flow patterns. Many have modules that can be arranged to meet almost any airflow, effectiveness, and pressure drop requirement. The heat transfer resistance through the plates is minimal compared to the airstream boundary layer resistance on each side of the plates. Consequently, the heat transfer efficiency is not significantly affected by the heat transfer coefficient of the plates. Aluminium is the most popular construction material due to its non-flammability and durability. Polymer plate exchangers may enhance heat transfer by inducing some turbulence in the channel flow and are favoured for their corrosion resistance and cost-effectiveness.

Typically, plate exchangers conduct sensible heat only; however, water-vapour-permeable materials, such as treated paper and microporous polymeric membranes, can be used to transfer moisture, thus providing total (enthalpy) energy exchange. One advantage of the plate exchanger is that it is a static device with minimal or no leakage between airstreams.

The effectiveness of heat exchangers depends significantly on the airflow direction and pattern of the supply and exhaust airstreams. Parallel flow exchangers (Figure 7 A), where both airstreams move along heat exchange surfaces in the same direction, have a theoretical maximum effectiveness of 50%. Counterflow exchangers (Figure 7B), where airstreams move in opposite directions, can theoretically achieve effectiveness approaching 100%, though typical units have lower effectiveness. Cross-flow heat exchangers have somewhat lower theoretical effectiveness than counterflow exchangers, with typical units achieving 50 to 70% effectiveness (Figure 7C) and 60 to 85% for multiple-pass exchangers (Figure 7D).). In practice, construction limitations favour designs that use transverse flow (or cross-flow) over much of the heat exchange surface (Figures 5C and 5D) (ASHRAE, 2020).

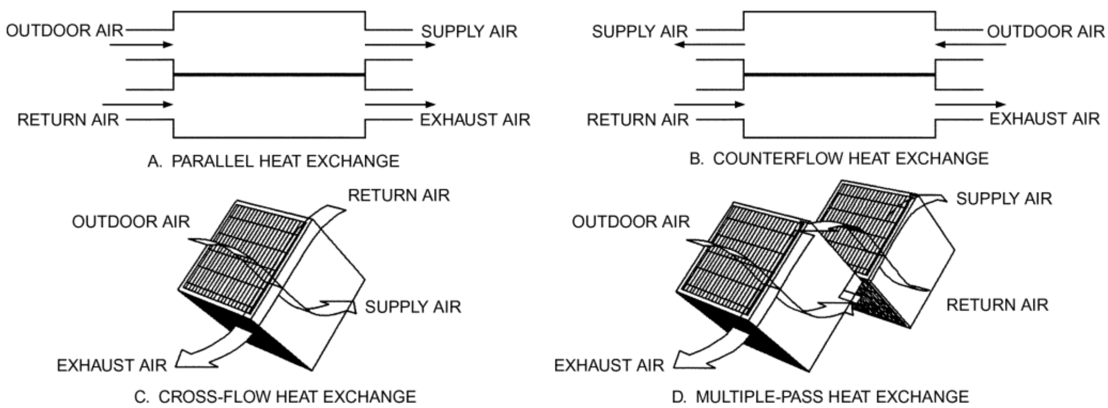

Figure 7: Plate Heat or Heat and Mass Exchanger Airflow Configurations (ASHRAE, 2020)

5.2. Coil Energy Recovery (Runaround) Loops

A typical coil energy recovery loop (Figure 8) places extended surface, finned-tube water coils in the supply and exhaust airstreams. These coils are connected in a closed loop by counterflow piping through which an intermediate heat transfer fluid (typically water or an antifreeze solution) is pumped.

A three-way temperature control valve prevents the supply coil from freezing. The valve is controlled to maintain the temperature of the solution entering the exhaust coil at 5°C or above. This condition is maintained by bypassing some of the warmer solution around the supply air coil. The valve can also ensure that a prescribed air temperature from the supply air coil is not exceeded. Coil energy recovery loops are highly flexible and well-suited to retrofitting. The loop accommodates remote supply and exhaust ducts and allows simultaneous transfer of energy between multiple sources and uses. An expansion tank must be included to allow fluid expansion and contraction. A closed expansion tank minimises oxidation when ethylene glycol is used. Typical effectiveness values range from 45 to 65% (ASHRAE, 2020).

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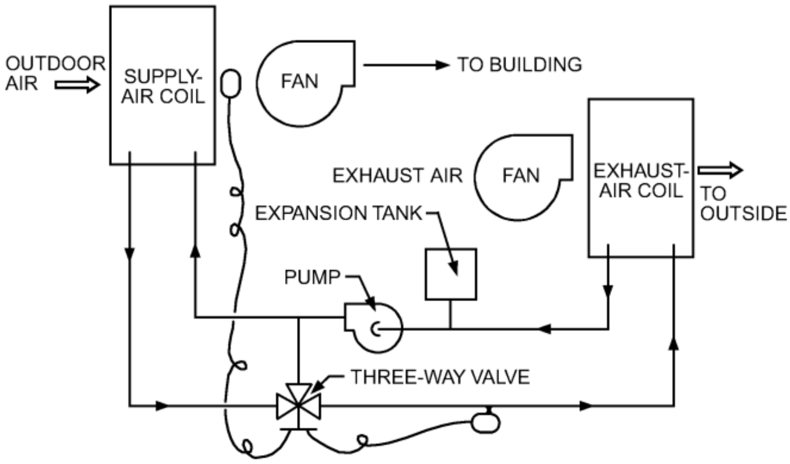

Figure 8: Coil Energy Recovery Loop (ASHRAE, 2020)

5.3. Thermosiphon Heat Exchangers

Two-phase thermosiphon heat exchangers are sealed systems comprising an evaporator, a condenser, interconnecting piping, and an intermediate working fluid present in both liquid and vapour phases. In coil-type thermosiphons, evaporator and condenser coils are installed independently in the ducts and interconnected by the working fluid piping, similar to a coil energy recovery loop. In thermosiphon systems, a temperature difference and gravity force are required for the working fluid to circulate between the evaporator and condenser (ASHRAE, 2020).

A small pump is introduced to assist in the circulation of the condensed refrigerant, enabling temperature control and an extended piping system.

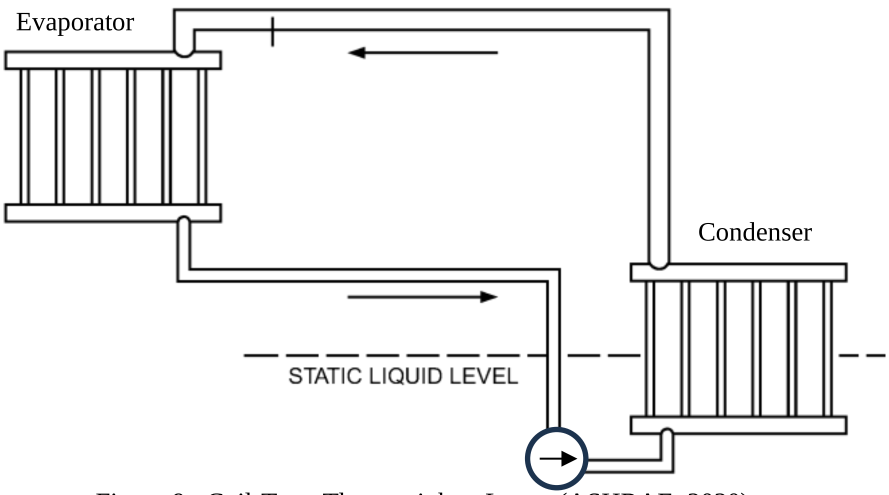

Figure 9: Coil-Type Thermosiphon Loops (ASHRAE, 2020).

5.4. Heat Recovery Unit Case Study

To evaluate the impact of integrating heat recovery units into the HVAC system of a typical naval frigate, units with an effectiveness of 60% were added to all fresh air supply and exhaust ducts for all AC systems in the HVAC model.

The simulation results, illustrated in Figure 10, display the monthly sensible heat recovery from the exhaust air of an AHU via a heat recovery unit. The bar chart indicates that the highest cooling heat recovery occurs in August, while the greatest heating heat recovery is observed in January. These months represent the peak ambient conditions for which the system is designed. Unlike economisers, heat recovery units reduce the peak load, leading to smaller equipment sizes.

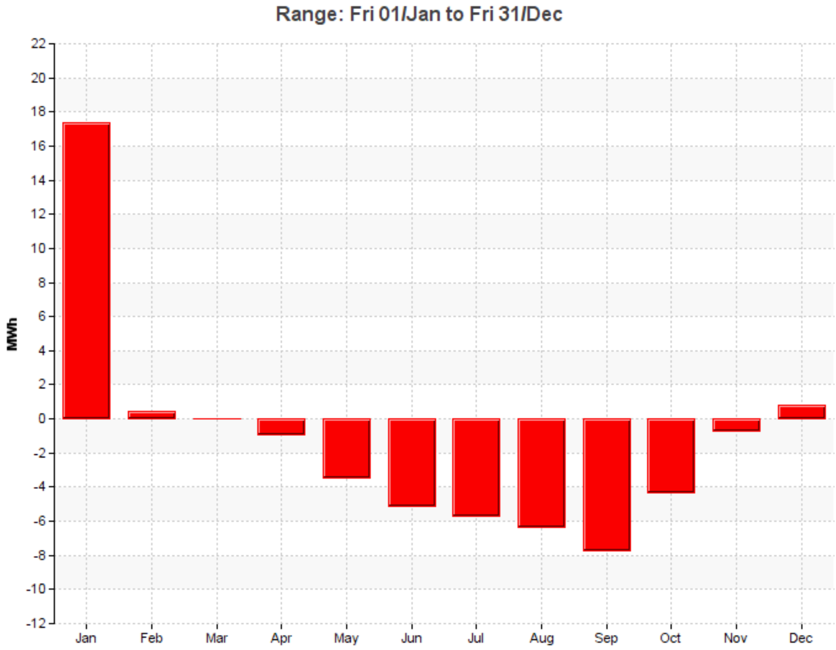

Figure 10: Monthly sensible heat recovery (MWh) from the exhaust air of an AHU heat recovery unit.

The model simulation results presented in Figure 11 show the monthly chilled water system load comparison between the HVAC baseline system and the HVAC system with heat recovery units added to the AHUs. The bar chart indicates that the chilled water loop peak heat load is reduced during summer peak ambient conditions.

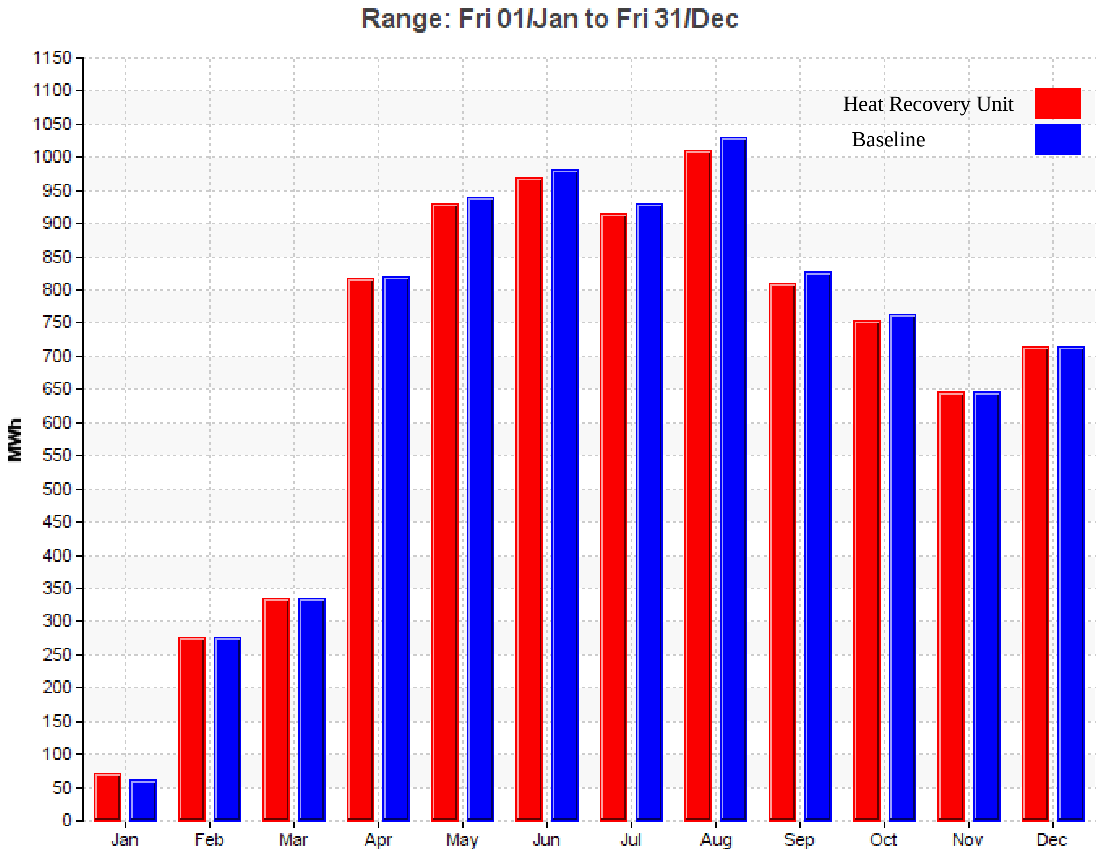

Figure 11: Monthly Chilled water load (kWh) simulation results, comparison between baseline and using heat recovery units on AHUs.

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Table 2: Reduction of chilled water plant power consumption when using heat recovery units on AHUs

Month	Baseline CWP Energy (MWh)	Heat Recovery Unit CWP Energy (MWh)	Reduction in CW Plant load (%)
Jan	15	15	0%
Feb	42	42	0%
Mar	52	52	0%
Apr	149	149	0%
May	192	190	1%
Jun	215	213	1%
Jul	197	194	2%
Aug	225	221	2%
Sep	173	169	2%
Oct	147	145	1%
Nov	114	114	0%
Dec	118	118	0%
Total	1638	1622	1% (17MWh)

The model simulation results presented in Table 2 demonstrate that the use of heat recovery units is more effective in saving energy at peak ambient conditions. However, it also shows that the total annual Chilled Water Plant (CWP) energy saving when using heat recovery units on AHUs is only 17 MWh, representing a reduction of just 1% from the baseline power consumption. This limited saving is due to the high percentage of air recirculation (80%) in the system. Therefore, the use of energy recovery units alone in this application would not be a cost-effective solution.

6. Indirect Evaporative Air Cooling

In indirect evaporative cooling, the exhaust air passes through a water spray and absorbs water vapour until it becomes nearly saturated. As the water evaporates, it absorbs sensible energy from the air, lowering its temperature. The evaporatively cooled exhaust air is then used to cool supply air through an air-to-air heat exchanger.

As the exhaust air is cooled by passing it through a water spray, wet filter, or other wetted media, a greater overall temperature difference between the supply and exhaust air is achieved, resulting in more heat transfer. Energy recovery is further enhanced by improved heat transfer coefficients due to the wetted exhaust-side heat transfer surfaces. No moisture is added to the supply airstream, and there are no auxiliary energy inputs other than fan and water pumping power. Because less mechanical cooling is required with evaporative cooling, both energy consumption and peak demand load are reduced. Overall mechanical refrigeration system requirements are reduced, allowing for the use of smaller mechanical refrigeration systems (ASHRAE, 2020). Water for the evaporative cooling process can be provided from the ship's existing water supply.

6.1. Indirect Evaporative Air-Cooling Case Study

To evaluate the impact of using indirect evaporative cooling in the HVAC system on board a typical naval frigate, heat recovery units with an effectiveness of 60% were added to all fresh air supply and exhaust ducts in the AC system and mechanically ventilated systems that serve machinery spaces, excluding the engine rooms. Evaporative coolers were also added to the exhaust duct upstream of all heat recovery units. Figure 12 shows the schematic arrangement of the indirect evaporative cooling implemented in the HVAC model.

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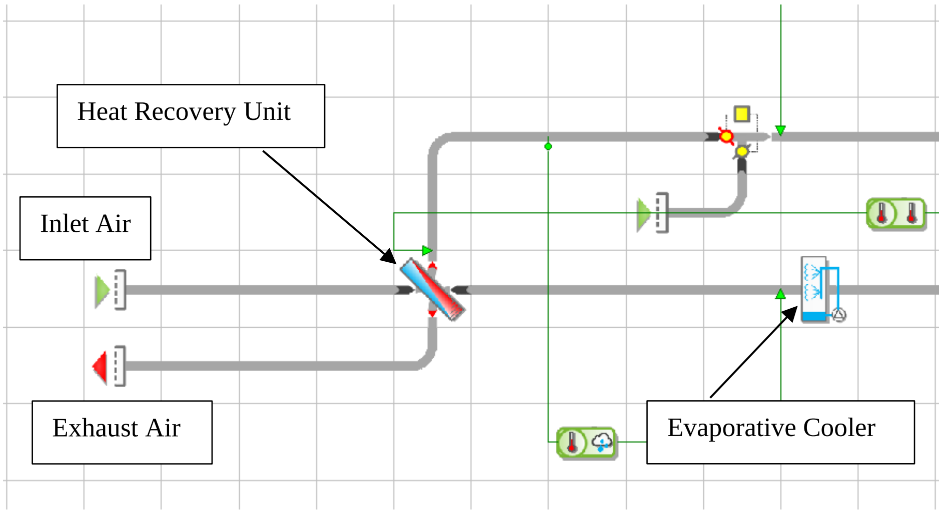
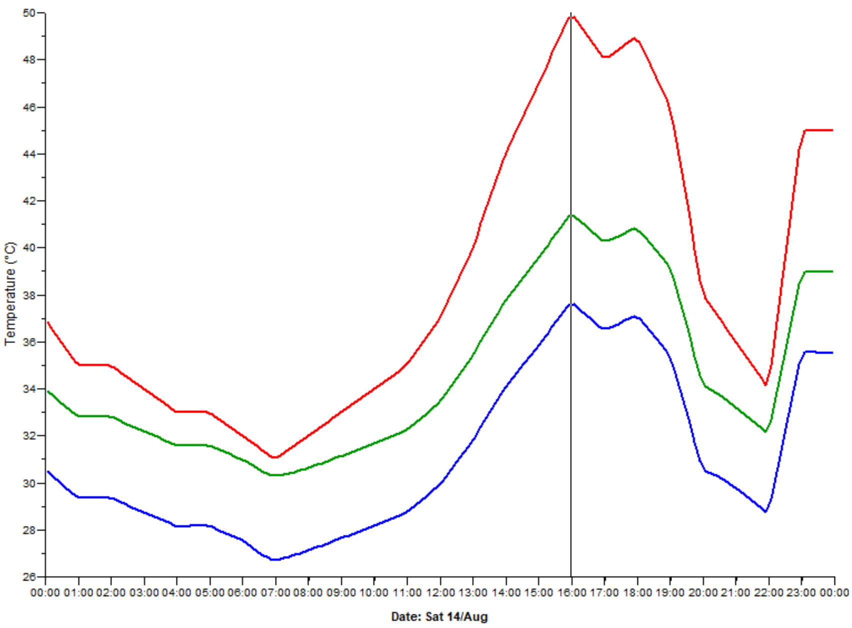


Figure 12: Indirect evaporative cooling schematic arrangement in the HVAC model.

Figure 13 presents the simulation results of the inlet air temperature to an AHU when using a heat recovery unit and indirect evaporative cooling, compared to no form of heat recovery. The results indicate a reduction in AHU inlet temperature from 50°C to 41°C when using a heat recovery unit, and a further reduction to 37°C when using indirect evaporative cooling.

Figure 14 shows the model simulation results for air entering a mechanically ventilated space. The graph indicates that the reduction in temperature when using a heat recovery unit alone is negligible. However, there is a significant reduction of 13°C in temperature when indirect evaporative cooling is used. This demonstrates that, due to the high exhaust temperature from mechanically ventilated spaces, the use of heat recovery units alone is not effective. The use of indirect evaporative cooling significantly impacts energy savings and improves indoor conditions.



Variable Name	Line Colour	Value
Base line air entering temperature (°C)		50
Heat recovery unit air entering temperature (°C)		41
Indirect evaporative cooling air temperature (°C)		37

Figure 13: Comparison between peak AHU air entering temperature using heat recovery unit and Indirect evaporative cooling.

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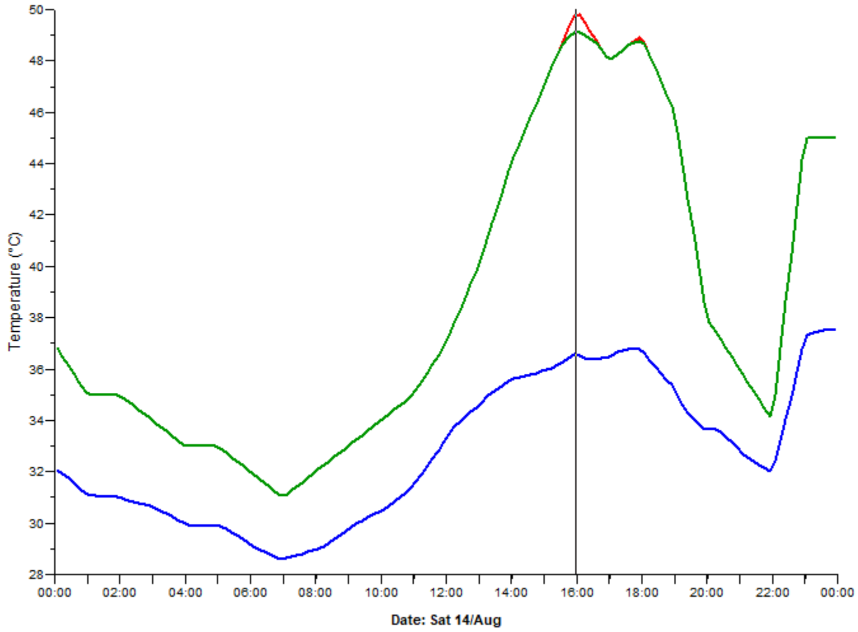

Variable Name	Line Colour	Value
Base line air entering temperature (°C)	(red)	50
Heat recovery unit air entering temperature (°C)	(green)	49
Indirect evaporative cooling air temperature (°C)	(blue)	37

Figure 14: Mechanically ventilated space- Comparison between peak air entering temperature using heat recovery unit and Indirect evaporative cooling.

The main and auxiliary engine rooms' supply and exhaust air ducts are very large and are typically part of the ship's structure, known as downtakes and uptakes, respectively. It would be impractical to fit heat recovery units in these ducts. However, by using direct evaporative cooling through the installation of water mist nozzles in the intakes, it is possible to significantly reduce the air inlet temperature, providing the required cooling in hot climates and eliminating the need for cooling through chilled water Fan Coil Units (FCUs).

One drawback of direct evaporative cooling is the increase in supply air humidity. However, due to the nature of the space and the high IP rating of an engine room, this should not be an issue in this case.

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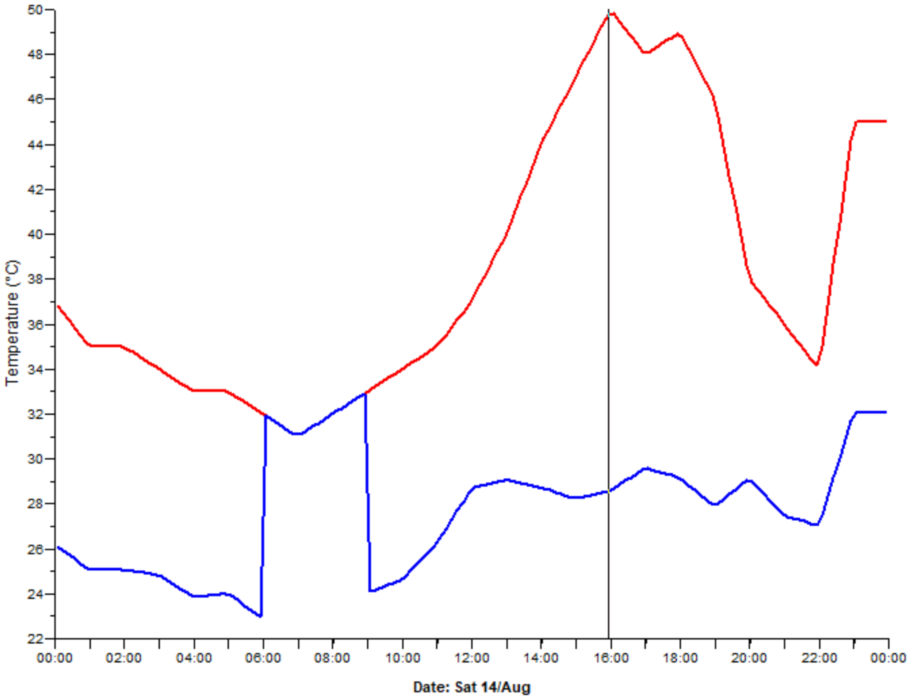

Variable Name	Line Colour	Value
Ambient air temperature and relative humidity		50°C-13%RH
Air entering the engine room temperature and relative humidity		29°C – 74%RH

Figure 15: Mechanically ventilated space peak air entering temperature using heat recovery unit and Indirect evaporative cooling.

Table 3: Reduction of Chilled Water Plant (CWP) energy consumption when combining indirect evaporative cooling, engine room direct evaporative cooling and economisers

Month	Baseline CWP Energy (MWh)	Combined Direct and Indirect Evaporative Cooling with Economisers - CWP Energy (MWh)	Reduction in CWP Energy (MWh)	Reduction in CWP Energy (%)
Jan	15.0	7.8	7.2	48%
Feb	41.9	19.3	22.6	54%
Mar	51.8	21.9	29.9	58%
Apr	149.1	59.8	89.3	60%
May	192.1	95.9	96.1	50%
Jun	215.2	121.3	94.0	44%
Jul	196.7	116.0	80.7	41%
Aug	225.0	135.9	89.1	40%
Sep	172.6	101.2	71.4	41%
Oct	147.2	78.8	68.4	46%
Nov	113.8	48.9	64.8	57%
Dec	118.2	30.6	87.7	74%
Total	1638.5	837.2	801.3	49%

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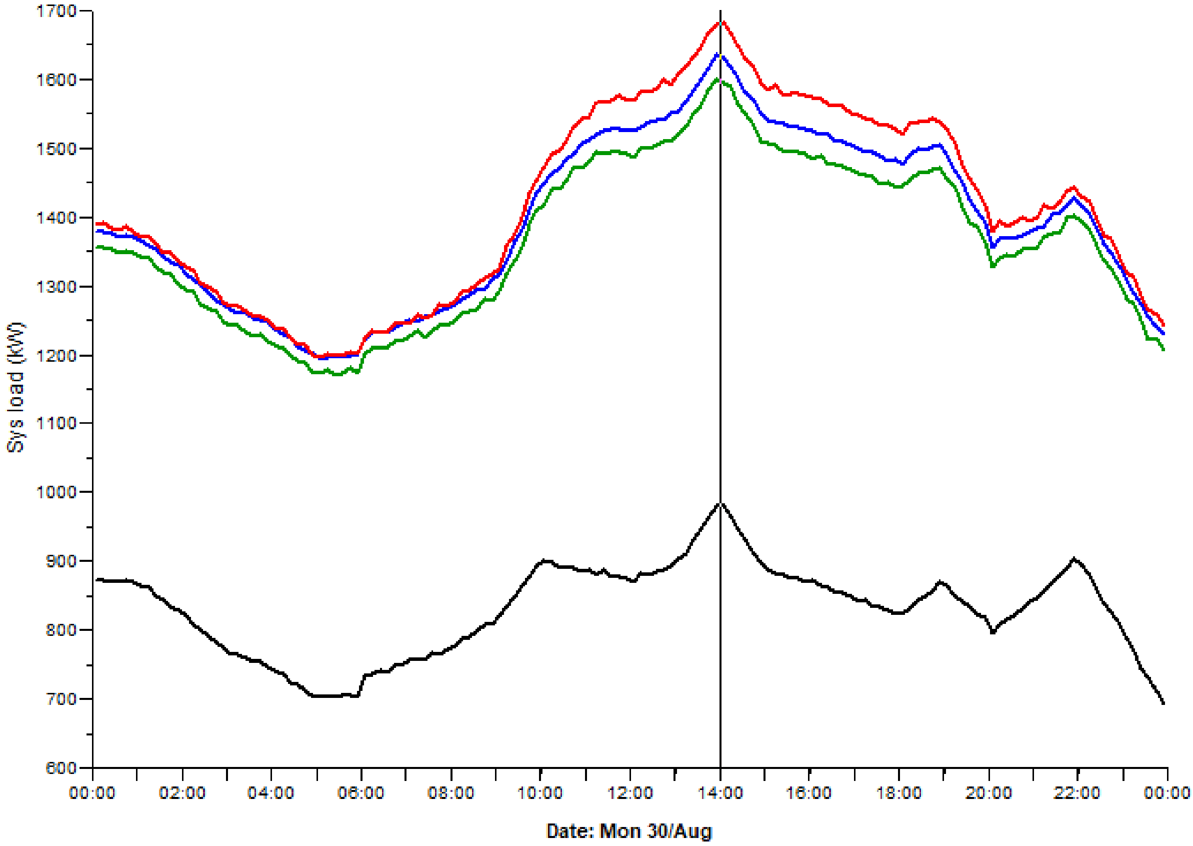
By combining indirect evaporative cooling, engine room direct evaporative cooling, and economisers, significant energy savings can be achieved at peak and moderate ambient conditions. The HVAC model simulation results presented in Table 3 show that the annual total reduction in energy consumption of the CWPs is 801.3 MWh. Assuming a diesel generator with a fuel consumption of 208 g/kWh, the total annual fuel consumption saving would be 166.7 tonnes for a typical navy frigate. This would lead to an increase in the frigate's range or a reduction in diesel tank capacity and weight.

Additionally, due to the significant reduction in the chilled water system peak load, the size of the chilled water plant required would be reduced. HVAC model simulation results for the chilled water system peak load presented in Figure 16 show a comparison between several options. The results from the simulations indicate that the chilled water peak load has reduced from 1681.4 kW to 980.1 kW, a 42% reduction.



Chill Water Peak Load (kW)	Line Colour	Chill Water Peak Load (kW)
Baseline		1681.4
Heat recovery units		1632.9
Indirect evaporative cooling		1597.1
Indirect evaporative cooling and engine room direct evaporative cooling		980.1 (42% reduction)

Figure 16: Chilled water system peak load comparison.

7. Absorption Chillers and Engine Waste Heat Recovery

Absorption chillers are refrigeration systems that use heat and a concentrated salt solution (lithium bromide) to produce chilled water. These chillers utilise waste heat from other processes to produce chilled water, which is then distributed for cooling needs. The system employs lithium bromide as the absorbent and water as the refrigerant, eliminating ozone-depleting refrigerants and using very little electricity compared to conventional chillers.

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Absorption chillers consist of an evaporator, absorber, condenser, generator, solution heat exchanger, absorber heat exchanger, refrigerant/solution pumps, and controls. Water is used as the refrigerant in vessels maintained under low absolute pressure (vacuum). The chiller operates on the principle that under vacuum, water boils at a low temperature. In this case, water boils at approximately 5.5℃, thereby cooling the chilled water circulating through the evaporator tubes. A refrigerant pump circulates the refrigerant water over the evaporator tubes to improve heat transfer.

To make the cooling process continuous, the refrigerant vapour must be removed as it is produced. For this, lithium bromide solution (which has a high affinity for water) is used to absorb the refrigerant vapour. As this process continues, the lithium bromide becomes diluted, reducing its absorption capacity. A solution pump then transfers this weak (diluted) solution to the generator, where it is concentrated by hot water. The refrigerant vapour released in the shell side of the generator enters the condenser to be cooled and returned to a liquid state. The refrigerant water then returns to the evaporator to begin a new cycle.

To remove heat from the machine, cooling seawater is first circulated through the tubes of the absorber to remove the heat of vaporisation. The seawater is then circulated through the tubes of the condenser. The strong solution from the generator flows back to the absorber to begin a new cycle. For efficiency reasons, the strong solution from the generator is passed through the heat exchanger to preheat the weak solution while pre-cooling the strong solution (Berg Group, 2023).

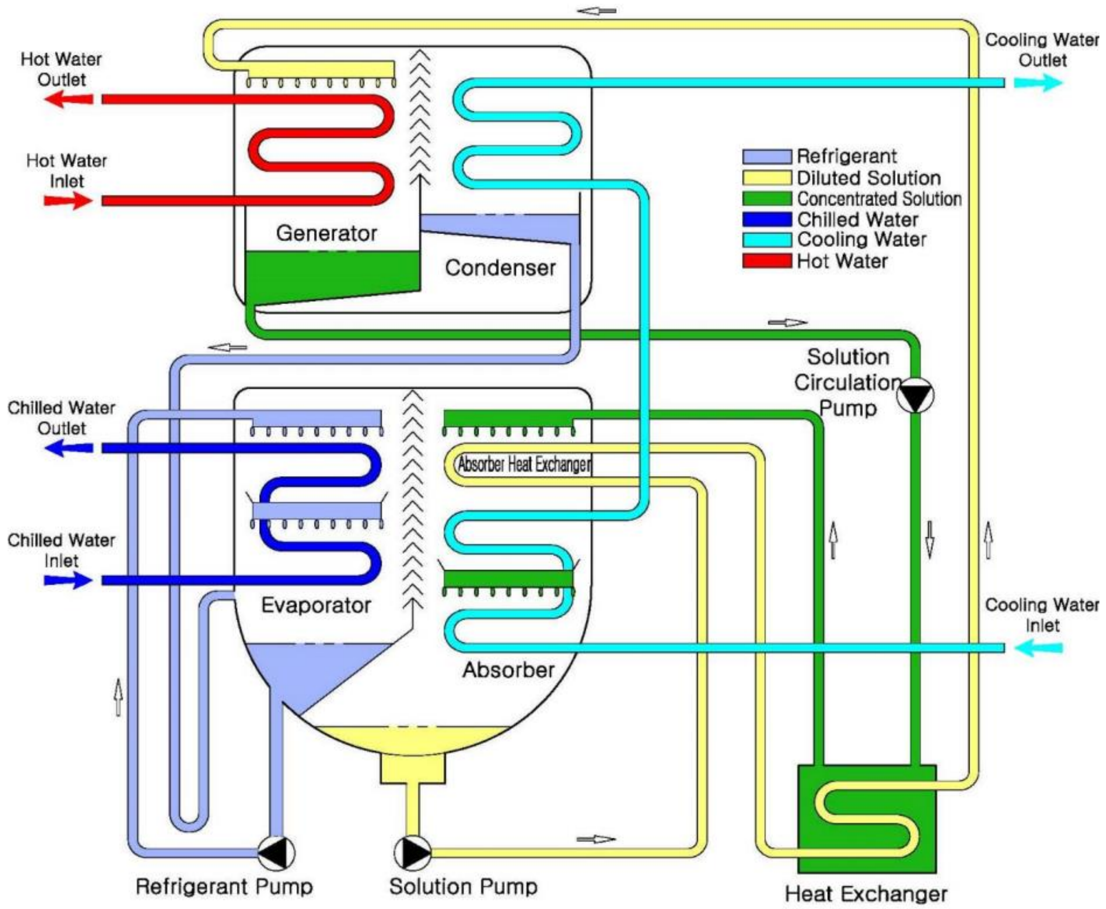

Figure 17: Absorption chiller refrigeration process (Berg Group, 2023)

Conventional chilled water plants rely on refrigerant compressors, which significantly increase the ship's electrical load. In this study, the baseline frigate is equipped with two chilled water plants, collectively consuming 528.3 kW of electricity. By replacing these with two equivalent absorption chillers, each with a cooling capacity of 1000 kW, the total electrical load would drop to 6.6 kW, achieving a 99% reduction. This change would decrease the overall electrical load by 521.7 kW, allowing for a smaller diesel generator due to the reduced peak electrical hotel load.

Annually, the absorption chillers would consume 58 MWh of power, compared to the 1638 MWh consumed by the conventional chillers (as shown in Table 3). This results in an electrical energy saving of 1580 MWh per year, which equates to a reduction of 328.6 tonnes of diesel fuel annually.

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Absorption chillers do not use F-gases as refrigerants, making them more environmentally friendly than conventional chillers. They are not subject to F-gas quota restrictions and phase-out regulations. Additionally, absorption chillers have fewer moving parts, making them more reliable and reducing noise and vibration.

7.1. Utilising Engine Waste Heat

Only a portion of the fuel energy consumed by a marine engine goes to propulsion or electrical power, with a large amount lost as heat in the engine exhaust. It is sensible to reclaim as much of this energy as possible. The diesel generator (DG) exhaust waste heat can be recovered to power the absorption chillers and hot water system using engine exhaust waste heat recovery systems currently available in the market. One example is the Alfa Laval Aalborg Micro Waste Heat Recovery Boiler for marine auxiliary engines (Alfa Laval, 2024). It is installed after the vessel’s DG. When the exhaust gas passes over its heating surface, the waste heat energy in the gas is absorbed to produce hot water or steam.

The heat recovery unit is used in conjunction with oil-fired boiler(s) or steam drum(s), which serve as the steam/water space. Forced circulation supplies the heat recovery unit with water at saturation temperature from the oil-fired boiler(s) or steam drum.

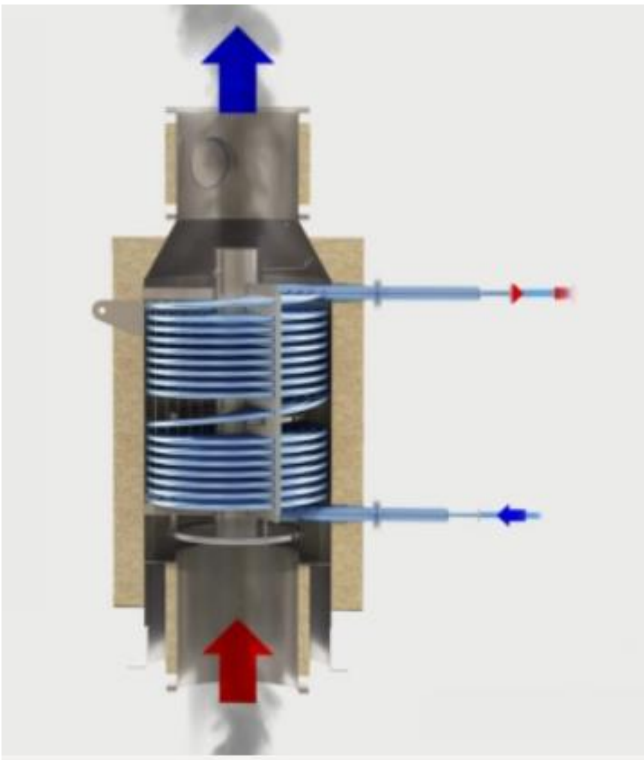

Figure 18: Engine exhaust waste heat recovery unit (Alfa Laval, 2024).

Figure 19 illustrates how exhaust heat recovery units can be integrated into a naval frigate’s hot water system to supply hot water to absorption CWPs. Each auxiliary engine exhaust is connected to the heat recovery unit, so if any one of the four engines is running, heat will be recovered to the system. On a naval frigate, there are typically two auxiliary engines running and two on standby. This arrangement also provides redundancy for the hot water heater. If the ship is docked and using shore power, where no auxiliary engine is running, hot water for the absorption CWPs can be provided by the HW heater.

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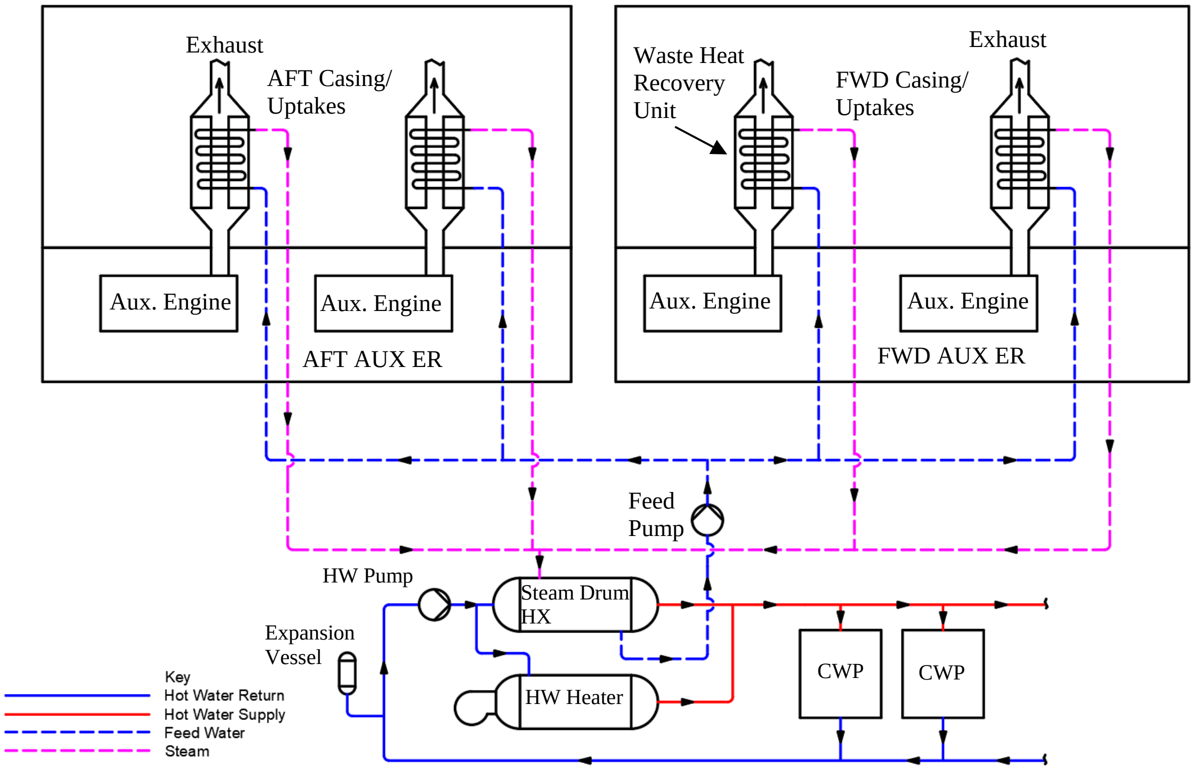

Figure 19: Integration of exhaust heat recovery units into a naval frigate's hot water system.

8. Conclusion

This study has explored various strategies to enhance the efficiency of HVAC systems on naval ships, with a focus on reducing energy consumption and CO2 emissions. By incorporating advanced technologies such as economisers, air-to-air heat recovery units, indirect evaporative cooling, and absorption chillers, significant improvements in system performance can be achieved.

Environmental model simulations demonstrated that the integration of these technologies leads to substantial reductions in peak loads and overall energy consumption. For instance, the use of economisers showed notable energy savings, particularly in moderate climates. Indirect evaporative cooling further enhanced energy efficiency by significantly lowering the inlet air temperature to AHUs and mechanically ventilated spaces. Additionally, by employing direct evaporative cooling in engine rooms, it is possible to significantly reduce the air inlet temperature, providing the required cooling in hot climates and eliminating the need for chilled water cooling.

The adoption of absorption chillers, powered by engine waste heat, presented a compelling case for reducing the electrical load on the ship. This approach not only decreases the reliance on conventional chillers but also leverages waste heat, contributing to a more sustainable and environmentally friendly solution. Additionally, absorption chillers do not use F-gases as refrigerants, making them more environmentally friendly than conventional chillers. They are not subject to F-gas quota restrictions and phase-out regulations. Furthermore, absorption chillers have fewer moving parts, making them more reliable and reducing noise and vibration.

Overall, the findings indicate that a combination of these advanced HVAC technologies can lead to a more efficient, reliable, and environmentally sustainable system for naval ships. Future work should focus on the practical implementation of these technologies and the evaluation of their long-term performance and cost-effectiveness in real-world naval operations.

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10. Glossary of terms

AC : *Air Conditioning*
AFU: *Air Filtration Unit*
AHU: *Air Handling Unit*
CBRN: *Chemical, Biological, Radiological, and Nuclear*
CW : *Chilled Water*
CWP: *Chilled Water Plant*
DG : *Diesel Generator*
DB : *Dry Bulb*
DXF : *Drawing Exchange Format*
FCU: *Fan Coil Unit*
HVAC: *Heating Ventilation and Air Conditioning*
HW: *Hot Water*
IAQ : *Indoor Air Quality*
WB : *Wet Bulb*