Related Commercial Resources

CHAPTER 14. SHIPS

THIS chapter covers air conditioning for oceangoing surface vessels, including naval ships, commercial vessels, fishing boats, luxury liners, pleasure craft, and inland and coastal boats, as well as oil rigs. Although the general principles of air conditioning for land installations also apply to marine applications, factors such as weight, size, fire protection, smoke control, and corrosion resistance take on greater importance, and new factors (e.g., tolerance for pitch and roll, shipboard vibration, watertightness) come into play.

The importance of shipboard air conditioning depends on a ship's mission. On passenger vessels that focus completely on passenger comfort, such as cruise ships and casino vessels, air conditioning is vital and a significant energy consumer. Aboard commercial vessels (tankers, bulkers, container ships, etc.), air conditioning provides an environment in which personnel can live and work without heat stress. Shipboard air conditioning also improves reliability of electronic and other critical equipment, as well as weapons systems aboard naval ships. Air conditioning on oil rigs serves the same purpose as with commercial vessels (i.e., providing a suitable environment for workers), and for larger rigs with significant accommodation areas, the amount of cooling can be substantial, similar to passenger vessels. Oil rig applications also introduce the additional consideration of operating within areas classified as hazardous.

This chapter discusses merchant ships, which includes passenger and commercial vessels, and naval surface ships. In general, the details of merchant ship air conditioning also apply to warships. However, all ships are governed by their specific ship specifications, and warships are often also governed by military specifications, which ensure air-conditioning system and equipment performance in the extreme environment of warship duty.

1. MERCHANT SHIPS

Load Calculations

The cooling load estimate considers the following factors (discussed in Chapter 18 of the 2021 *ASHRAE Handbook—Fundamentals*):

- Solar radiation
- Heat transmission through hull, decks, and bulkheads
- Heat (latent and sensible) dissipation from occupants
- Heat gain from lights
- Heat (latent and sensible) gain from ventilation air
- Heat gain from motors or other electrical equipment
- Heat gain from piping, machinery, and equipment

The heating load estimate should include the following:

- Heat losses through decks and bulkheads
- Ventilation air
- Infiltration (when specified)

In addition, the construction and transient nature of ships present some complications, as addressed in the following:

SNAME. The Society of Naval Architects and Marine Engineers (SNAME 2015) *Technical and Research Bulletin* 4-16 can be used as a guide for shipboard load calculations.

ISO. The International Organization for Standardization's (ISO) *Standard* 7547 discusses design conditions and calculations for marine HVAC systems.

Outdoor Ambient Temperature and Humidity. The service and type of vessel determine the proper outdoor design temperature, which should be based on temperatures prevalent in a ship's area of operation. Use Chapter 14 of the 2021 *ASHRAE Handbook—Fundamentals* to select ambient conditions, with special attention paid to high-wet-bulb data; a ship's load is often driven by the latent load associated with the outdoor air. It is also common for different locations to be used for cooling and heating criteria. In general, for cooling, outdoor design conditions are 35°C db and 25.5°C wb; for semitropical runs, 35°C db and 26.5°C wb; and for tropical runs, 35°C db and 28°C wb. For heating, –18°C is usually the design temperature, unless the vessel will always operate in warmer climates. Design temperatures for seawater are 32°C in summer and –2°C in winter.

Solar Gain. Ships require special consideration for solar gain because (1) they do not constantly face in one direction and (2) the reflective properties of water increase solar load on outer boundaries not directly exposed to sunlight. For compartments with only one exterior boundary, the temperature difference (outdoor dry-bulb temperature – indoor dry-bulb temperature) across horizontal surfaces should be increased by 28 K and vertical surfaces by 17 K. For compartments with more than one exterior boundary, the temperature difference should be increased by 19 K for horizontal surfaces and 11 K for vertical surfaces. For glass surfaces, the solar cooling load (SCL) is taken to be 500 W/m^2 for spaces with one exterior boundary and 380 W/m^2 for spaces with more than one exterior boundary. A more modern approach is to use appropriate building energy simulation software (a full list of which is maintained by the U.S. Department of Energy) to model the ship's accommodation spaces. These programs generally allow building exposure to be changed globally, making it easy to examine the change in ship loads as the route direction changes.

Infiltration. Infiltration through weather doors is generally disregarded. However, specifications for merchant ships occasionally require an assumed infiltration load for heating steering gear rooms and the pilothouse.

Transmission Between Spaces. For heating loads, heat transmission through boundaries of machinery spaces in either direction is not of consequence. Allowances are not made for heat gain from warmer adjacent spaces. For cooling loads, the cooling effect of adjacent spaces is not considered unless temperatures are maintained with refrigeration or air-conditioning equipment.

Ventilation Requirements. Ventilation is a very important consideration, because it is frequently the main contributor to overall energy usage of the system. Rules and guidance are provided by conflicting standards, including ISO *Standard* 7547, SNAME *Technical and Research Bulletin* 4-16, and ASHRAE *Standard* 62.1-2022. Ultimately, that stated in the ship's specification and what is acceptable to the authority having jurisdiction (AHJ) govern ventilation requirements. However, given the opportunity to reduce energy (fuel) consumption and the need to ensure passenger health and safety, it behooves the system designer to apply modern tools, such as building energy simulation and demand-controlled ventilation to optimize the quantity of fresh air introduced under all conditions. There is a unique opportunity for fresh-air optimization aboard ships because the number of passengers is fixed and each person can only be in one location at a time. Significant overventilation that can occur by catering to the maximum fresh-air requirement in each space simultaneously.

Heat Transmission Coefficients. The overall heat transmission coefficients U for the composite structures common to shipboard construction do not lend themselves to theoretical derivation; they are usually obtained from full-scale panel tests. SNAME *Bulletin* 4-7 gives a method to determine these coefficients when tested data are unavailable. ISO *Standard* 7547 also gives some guidance in this area, as well as default values if better information is not available.

Indoor Air Temperature and Humidity. Thermal environmental conditions for human occupancy are given in ASHRAE *Standard* 55-2020.

People. Ships normally carry a fixed number of people. The engineer must select the location where the ship's fixed complement of people creates the greatest heat load, and then not apply the people load elsewhere. Note that occupants are only counted once when determining the chiller or condensing-unit load; however, air coils in each zone must be capable of removing the heat load associated with the maximum number of people in the zone.

Ventilation in the zone can also be reduced when occupants are not present. For the ventilation load, occupants are counted once, in the location where they create the greatest ventilation requirement. The practical way to apply this concept is by measuring CO_2 levels in a space and adjusting outdoor air accordingly. Although using this principle can reduce required chiller or condensing-unit capacity on all ships, it is most significant for passenger ships.

Equipment

In general, equipment used for ships is much more rugged than that used on land. Sections 6 through 10 of ASHRAE *Standard* 26 list HVAC equipment requirements for marine applications. When selecting marine duty air-conditioning equipment, consider the following:

- It should function properly under dynamic roll and pitch and static trim and heel conditions. This is especially important for compressor oil sumps, oil separators, refrigerant drainage from a condenser and receiver, accumulators, and condensate drainage from drain pans.
- Construction materials should withstand the corrosive effects of salt air and seawater. Materials such as stainless steel, nickel-copper, copper-nickel, bronze alloys, and hot-dipped galvanized steel are used extensively.
- It should be designed for uninterrupted operation during the voyage and continuous year-round operation. Because ships en route cannot be easily serviced, some standby capacity, spare parts for all essential items, and extra oil and refrigerant charge should be carried.

- It should have no objectionable noise or vibration, and must meet noise criteria required by the ship's specification.
- It should occupy minimum space, commensurate with its cost and reliability. Mass should also be minimized.
- A ship may pass through one or more complete cycles of seasons on a single voyage and may experience a change from winter to summer operation in a matter of hours. Systems should be flexible enough to compensate for climatic changes with minimal attention from the ship's crew.

The following general items should be considered when selecting specific air conditioning components:

Fans. Fans must be selected for stable performance over their full range of operation and should have adequate isolation to prevent transmitting vibration to the deck. Because fan rooms are often adjacent to or near living quarters, effective sound treatment is essential.

Cooling Coils. If more than 30% outdoor air is brought across a cooling coil, consider using copper tube, copper fin, epoxy-coated coils, or other special treatment. To account for the ship's movement, drain pans should have two drain connections, and should ideally be dual sloping, with extra depth. Because of size constraints, care must be taken to prevent moisture carryover. Face velocity limits (in m/s) for different coil materials and different fin spacing are as follows:

Fin Spacing, mm	Aluminum Fins	Copper or Coated Fins
3.2	2.8	2.6
2.3	2.8	2.1
1.8	2.8	1.9

Off-coil temperatures are another concern. Ships typically have low ceiling heights and cannot tolerate low air-introduction temperatures. Typically 12.8°C db and 12.2°C wb are used as limiting off-coil temperatures.

Electric Heaters. U.S. Coast Guard (USCG) approved sheathed-element heaters are typically required. The only exception is when the electric heaters, approved by a regulatory body such as UL, are incorporated in a packaged unit.

Air Diffusers. Care must be taken with selection of air diffusers because of the low ceilings typical of shipboard applications.

Air-Conditioning Compressors. Compressors of all types are used for marine applications. Care must be taken when using a centrifugal compressor because low-load, high-condensing temperature is a common off-load condition.

When high discharge temperatures are a concern, seawater-cooled heads are not normally an option; other methods such as fan cooling or liquid injection must be considered for maintaining acceptable discharge temperatures.

Typical Systems

All types of systems may be considered for each marine application. The systems are the same as in land applications; the difference is the relative weighting of their advantages and disadvantages for marine use. This section does not review all the systems used aboard ships, but rather some of the more common ones.

Direct refrigerant cooling systems are often used for small, single-zone applications. Aboard ships, places like control rooms and pilot houses lend themselves to a direct refrigerant system. For larger spaces, air distribution is of more concern; direct refrigerant cooling is thus less likely to be the optimum solution.

Two-pipe and **four-pipe fan coil systems** are often used for large systems. The water piping used in these systems takes up only a fraction of the space used by an all-air ducted system. Fan noise in the space being cooled is the disadvantage. In addition, limited humidity control and fresh-air requirements often need to be addressed separately.

Many types of **all-air systems** are used aboard ships. Space, cost, noise, and complexity are among the leading parameters when comparing different all-air systems. Using high-velocity air distribution for an all-air system offers many advantages; unitary (factory-assembled) central air-handling equipment and prefabricated piping, clamps, and fittings facilitate installation for both new construction and conversions. Substantial space-saving is possible compared to conventional low-velocity sheet metal ducts. Maintenance is also reduced. Noise is the one major drawback of a high-velocity system, which often leads to selection of a low-velocity system.

Terminal reheat air conditioning (described in Chapter 4 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*) is commonly used because of its simplicity and good zone control characteristics. However, as systems become larger, this system's energy inefficiency becomes a significant drawback. For large passenger ships, where energy efficiency is absolutely essential, the designer should consider more modern approaches. One method is delivering tempered ventilation air from a central-station air handler to the passenger staterooms, each of which is outfitted with a dedicated cabin fan-coil unit, including a chilled-water-cooling and hot-water-heating coil. The individual cabin is then either heated or cooled from a neutral temperature, using central loops, depending on specific needs. The efficiency of this approach is further improved by having reclaimed heat sources (e.g., from the central chillers or the main engine cooling system) to maintain the hot-water loop temperature.

Dual-duct systems (also described in Chapter 4 of the 2020 *ASHRAE Handbook—HVAC Systems and Equipment*) have the following advantages:

- All conditioning equipment is centrally located, simplifying maintenance and operation
- Can heat and cool adjacent spaces simultaneously without cycle changeover and with minimum automatic controls
- Because only air is distributed from fan rooms, no water or steam piping, electrical equipment, or wiring are in conditioned spaces

The major drawback is the inability to finely control temperature and humidity. This disadvantage is enough to preclude the use of these systems in many passenger vessel applications.

Aboard ships, **constant-volume systems** are most common. Their advantages include simplicity (for maintenance, operation, and repair) and low cost. However, for large passenger vessels, the energy efficiency and the tight control of zone temperature make **variable-volume/temperature systems** very attractive.

Air Distribution Methods

Good air distribution in staterooms and public spaces is difficult to achieve because of low ceiling heights and compact space arrangements. Design should consider room dimensions, ceiling height, volume of air handled, air temperature difference between supply and room air, location of berths, and allowable noise. For major installations, mock-up tests are often used to establish exacting performance criteria.

Air usually returns from individual small spaces either by a sight-tight louver mounted in the door or by an undercut in the door leading to the passageway. An undercut door can only be used with air quantities of 35 L/s or less. Louvers are usually sized for face velocity of 2 m/s based on free area.

Ductwork on merchant ships is generally constructed of steel. Ducts, other than those requiring heavier construction because of susceptibility to damage or corrosion, are usually made with riveted seams sealed with hot solder or fire-resistant duct sealer, welded seams, or hooked seams and laps. They are made of hot-dipped, galvanized, copper-bearing sheet steel, suitably stiffened externally. The minimum thickness of material is determined by the diameter of round ducts or by the largest dimension of rectangular ducts, as listed in Table 1.

The increased use of high-velocity, high-pressure systems has resulted in greater use of prefabricated round pipe and fittings, including spiral-formed sheet metal ducts. It is important that field-fabricated ducts and fittings be airtight. Using factory-fabricated fittings, clamps, and joints effectively minimizes air leakage for these high-pressure ducts.

In addition to the space advantage, small ductwork saves mass, another important consideration for this application.

Control

The conditioning load, even on a single voyage, varies over a wide range within short periods. Not only must the refrigeration plant meet these load variations, but the controls must readily adjust the system to sudden climatic changes. Accordingly, it is general practice to equip the plant with automatic controls. Increasingly, fully communicating network controls are being applied to optimize operation of the entire system under transient conditions. Moreover, such controls now can collect large amounts of operational data and offer proactive diagnostics based on these data, helping the ship operator maximize efficiency and reliability throughout the life cycle.

Table 1 Minimum Thickness of Steel Ducts

All vertical exposed ducts	16 USSG	1.52 mm
Horizontal or concealed vertical ducts		
less than 150 mm	24 USSG	0.62 mm
160 to 300 mm	22 USSG	0.76 mm
310 to 460 mm	20 USSG	0.91 mm
470 to 760 mm	18 USSG	1.21 mm
over 760 mm	16 USSG	1.52 mm

Regulatory Agencies

Merchant vessels that operate under the U.S. flag come under the jurisdiction of the U.S. Coast Guard. Accordingly, the installation and components must conform to the Marine Engineering Rules and Marine Standards of the Coast Guard covered under the *Guide to Structural Fire Protection* (USCG 2010).

Certified pressure vessels and electric components approved by independent agencies (e.g., ASME, UL) must be used. Wherever possible, equipment used should comply with ABS rules and regulations. This is especially important when vessels are equipped for carrying cargo refrigeration, because air-conditioning compressors may serve as standby units in the event of a cargo compressor failure. This compliance eliminates the need for a separate, spare cargo compressor.

The International Convention for the Safety of Life at Sea (SOLAS) (IMO 2014) governs the use of fire-dampers and duct wall thickness when passageways or fire boundaries are crossed.

2. NAVAL SURFACE SHIPS

Design Criteria

Outdoor Ambient Temperature. Design conditions for naval vessels have been established as a compromise, considering the large cooling plants required for internal heat loads generated by machinery, weapons, electronics, and personnel. Temperatures of 32°C db and 27°C wb are used for worldwide applications, with 29.5°C seawater temperatures. Heating-season temperatures are –12°C for outdoor air and –2°C for seawater.

Indoor Temperature. Naval ships are generally designed for space temperatures of 26.5°C db with a maximum of 55% rh for most areas requiring air conditioning. USN (1969) gives design conditions established for specific areas, and USMA (1965) lists temperatures for ventilated spaces.

Ventilation Requirements. As for merchant ships, there is conflicting guidance regarding ventilation requirements; see ISO *Standard* 7547, SNAME *Technical and Research Bulletin* 4-16, and ASHRAE *Standard* 62.1-2022.Ventilation must meet the requirements of the ship's specification and the U.S. government, but as with merchant ships, the system designer should apply modern tools, such as building energy simulation and demand controlled ventilation, to optimize the quantity of fresh air introduced under all conditions, ensuring safe operation and technical justification.

Air-Conditioned Spaces. Naval ship design requires that air-conditioning systems serving living and berthing areas on surface ships replenish air in accordance with damage control classifications, as specified in USN (1969):

- Class Z systems: 2.4 L/s per person
- Class W systems for troop berthing areas: 2.4 L/s per person
- All other Class W systems: 4.7 L/s per person. The flow rate is increased only to meet either a 35 L/s minimum branch requirement or to balance exhaust requirements. Outdoor air should be kept at a minimum to limit the size of the air-conditioning plant.

Load Determination

The cooling load estimate consists of coefficients from USN's *Design Data Sheet* DDS511-2, *General Specifications for Building Naval Ships*, or *Document* 0938-018-0010 (USN 1969) and has allowances for the following:

- Solar radiation
- Heat transmission through hull, decks, and bulkheads
- Heat (latent and sensible) gain of occupants
- Heat gain from lights
- Heat (latent and sensible) gain from ventilation air
- Heat gain from motors or other electrical equipment
- Heat gain from piping, machinery, and equipment

Loads should be derived from requirements indicated in USN (1969). The heating load estimate should include the following:

- Heat losses through hull, decks, and bulkheads
- Ventilation air
- Infiltration (when specified)

Some electronic spaces listed in USN (1969) require adding 15% to the calculated cooling load for future growth and using one-third of the cooling-season equipment heat dissipation (less the 15% added for growth) as heat gain in the heating season.

Heat Transmission Coefficients. The overall heat transmission coefficient *U* between the conditioned space and the adjacent boundary should be estimated from USN's *Design Data Sheet* DDS511-2. Where new materials or constructions are used, new coefficients may be used from SNAME (2015) or calculated using methods found in DDS511-2 and SNAME.

Heat Gain from People. USN (1969) gives heat gain values for people in various activities and room conditions.

Heat Gain from Sources in the Space. USN (1969) gives heat gain from lights and motors driving ventilation equipment. Heat gain and use factors for other motors and electrical and electronic equipment may be obtained from the manufacturer or from Chapter 18 of the 2021 *ASHRAE Handbook—Fundamentals*.

Equipment Selection

The equipment described for merchant ships also applies to U.S. naval vessels, except as follows:

Fans. A family of standard fans is used by the navy, including vaneaxial, tubeaxial, and centrifugal fans. Selection curves used for system design are found on USN's NAVSEA *Standard Drawings* 810-921984, 810-925368, and 803-5001058. Manufacturers are required to furnish fans that are dimensionally identical to the standard plan and within 5% of the delivery. No belt-driven fans are included.

Cooling Coils. The U.S. Navy uses eight standard sizes of direct-expansion and chilled-water cooling coils. All coils have eight rows in the direction of airflow, with a face area range of 0.06 to 0.93 m^2.

Coils are selected for a face velocity of 2.5 m/s maximum; however, sizes 54 DW to 58 DW may have face velocity up to 3.2 m/s if the bottom of the duct on the discharge is sloped up at 15° for a distance equal to the height of the coil. Construction and materials are specified in MIL-PRF-2939G.

Chilled-water coils are most common and are selected based on 7.2°C inlet water with approximately a 3.7 K rise in water temperature through the coil. This is equivalent to 65 mL/s per kilowatt of cooling.

Heating Coils. The standard naval steam and electric duct heaters have specifications as follows:

Steam Duct Heaters

- Maximum face velocity is 9.1 m/s.
- Preheater leaving air temperature is 5.5 to 10°C.
- Steam heaters are served from a 350 kPa (gage) steam system.

Electric Duct Heaters

- Maximum face velocity is 7.1 m/s.
- Temperature rise through the heater is per MIL-PRF-22594C, but is in no case more than 27 K.
- Power supply for the smallest heaters is 120 V, three-phase, 60 Hz. All remaining power supplies are 440 V, three-phase, 60 Hz.
- Pressure drop through the heater must not exceed 85 Pa at 5 m/s. Use manufacturers' tested data in system design.

Filters. Characteristics of the seven standard filter sizes used by the U.S. Navy are as follows:

- Filters are available in steel or aluminum.
- Filter face velocity is between 1.9 and 4.6 m/s.
- A filter-cleaning station on board ship includes facilities to wash, oil, and drain filters.

Air Diffusers. Although the U.S. Navy also uses standard diffusers for air conditioning, they are generally a commercial type similar to those used for merchant ships.

Air-Conditioning Compressors. In the past, the U.S. Navy primarily used reciprocating compressors up to approximately 530 kW; for larger capacities, open, direct-drive centrifugal compressors are used. On new designs, the U.S. Navy primarily uses rotary compressors (e.g., screw and centrifugal), frequently semihermetic. R-134a is the U.S. Navy's primary refrigerant. Seawater is used for condenser cooling at 90 mL/s per kilowatt for reciprocal compressors and 72 mL/s per kilowatt for centrifugal compressors, but in all cases, the maximum seawater velocity of 1.8 m/s must be deferred to in order to prevent tube erosion.

Typical Air Systems

On naval ships, zone reheat is used for most applications. Some ships with sufficient electric power use low-velocity terminal reheat systems with electric heaters in the space. Some newer ships use a fan-coil unit with fan, chilled-water cooling coil, and electric heating coil in spaces with low to medium sensible heat per unit area of space requirements. The unit is supplemented by conventional systems serving spaces with high sensible or latent loads.

Air Distribution Methods

Methods used on naval ships are similar to those discussed in the section on Merchant Ships. The minimum thickness of materials for ducts is listed in Table 2.

Control

The navy's principal air-conditioning control uses a two-position dual thermostat that controls a cooling coil and an electric or steam reheater. This thermostat can be set for summer operation and does not require resetting for winter operation.

Steam preheaters use a regulating valve with (1) a weather bulb controlling approximately 25% of the valve's capacity to prevent freeze-up, and (2) a line bulb in the duct downstream of the heater to control the temperature between 5.5 and 10°C.

Table 2 Minimum Thickness of Materials for Ducts

Sheet for Fabricated Ductwork				
	Non-Watertight		Watertight	
Diameter or Longer Side	Galvanized Steel	Aluminum	Galvanized Steel	Aluminum
Up to 150	0.46	0.64	1.90	2.69
160 to 300	0.76	1.02	2.54	3.56
310 to 460	0.91	1.27	3.00	4.06
470 to 760	1.22	1.52	3.00	4.06
Above 760	1.52	2.24	3.00	4.06

Welded or Seamless Aluminum Tubing		
Tubing Size	Non-Watertight	Watertight
50 to 150	0.89	2.69
160 to 300	1.27	3.56

Spirally Wound Duct (Non-Watertight)		
Diameter	Steel	Aluminum
Up to 200	0.46	0.64
Over 200	0.76	0.81

Note: All dimensions in millimetres.

Other controls are used to suit special needs. Pneumatic/electric controls can be used when close tolerances in temperature and humidity control are required, as in operating rooms. Thyristor controls are sometimes used on electric reheaters in ventilation systems.

Modern ship designs use fully communicating networked controls that optimize system operation and provide useful data and feedback to the operator. The Navy is increasingly implementing energy-saving measures aboard all of its ships.

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The preparation of this chapter is assigned to TC 9.3, Transportation Air Conditioning.