HVAC Considerations for Small SSK Submarine Design

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SYNOPSIS

Heating, Ventilation and Air-Conditioning (HVAC) systems are essential to a submarine to fulfil several key roles: Atmosphere Renewal, Ventilation, Cooling, Heating and Moisture Control among others. They are critical systems that have changed little in the last 30-40 years and yet they contribute to some of the more difficult challenges in designing submarines by consuming large amounts of power, generating heat and noise and can pose significant spatial arrangement problems.

Submarine HVAC will begin to grow in importance in the future due to the proliferation of submarines with increasingly complex combat systems and an increased reliance on electrical equipment. These fairly recent developments involve equipment that generate large amounts of heat and require close humidity control to prevent short-circuit or static build-up, but at the same time the habitability performance of the platform cannot be compromised.

This paper investigates the challenges and considerations of future HVAC systems design from the perspective of a small conventional submarine. It will begin with an introduction to the HVAC design process to inform the reader on the impact of changing requirements. Further considerations are discussed including the external environment, operational modes, and noise and space, all of which place constraints on system arrangements and equipment specifications during the early design stages. It will conclude with a discussion on layout and technology options potentially available to ease such constraints whilst still meeting performance requirements.

The system design investigation has been carried out using the Vidar®-7 small SSK submarine concept as a case study with characteristics of the South Asian operating environment as a design basis before investigating the impacts of global regional operation. The Vidar®-7 design is for a small, conventional submarine offering an entry-level submarine capability to Navies.

BIOGRAPHY

Richard Hemsley is a Chartered Engineer at BMT Defence Services Ltd in Bath with 13 years experience in Naval Engineering, principally in HVAC systems design and submarine platform systems design and in-service support. Recent involvement in the UK MARS and Norwegian LSV auxiliary ships and a wealth of experience from supporting the UK submarine enterprise has provided him with a unique understanding of key HVAC design issues. His qualifications include Masters and Bachelor degrees in Engineering from the University of the West of England.

Currently, Richard is providing Independent Technical Assurance review of future submarine system designs for the UK MoD.

INTRODUCTION

HVAC is the common acronym for Heating, Ventilation and Air-Conditioning that encompasses several systems within a submarine to provide ventilation, cooling and control of a submarines environment. The current design aims of submarine HVAC systems have evolved into a complex matrix of challenging requirements.

Ventilation

Ventilation is moving air through a compartment at a specified rate to exchange the atmosphere. There are a number of reasons for doing this including distributing clean/refreshed air for crew respiration, supplying sufficient air to support diesel engine operation, evacuation of hazardous gases (e.g. Hydrogen in lead-acid...
battery compartments) or atmosphere exchange to ventilate unpleasant fumes/vapours (e.g. exhausts from the Galley or toilets).

Cooling

Often incorporating a Chilled or Tepid water cooling system under the overall banner of HVAC, a liquid cooling medium can cool the air circulating throughout the vessel or through heat exchangers attached to equipment to directly cool the equipment. This is particularly relevant to Combat Systems equipment which, being largely electronic in nature, generate large amounts of wild heat. In order for these pieces of equipment to continue to function efficiently this heat needs to be removed via integrated heat exchangers and transferred to the submarine exterior via Chilled/Tepid water and seawater circulation. This 'Direct' cooling is typically reserved for particularly sensitive pieces of equipment, such as electronic cabinets, or those that generate significant amounts of wild heat.

Environmental Control

The submarines’ environment has a critical role to play is supporting crew habitability and operational effectiveness. This is maintained by monitoring and controlling the humidity and temperature of the air circulating within compartments. While temperature control has obvious benefits of controlling heat build-up and ensuring heat exhaustion is avoided, humidity can play a much more significant role in the acceptability of the submarine environment.

Humidity is a general term used to describe the moisture content in air. Specific moisture content can be measured in kilograms of water per kilogram dry air but since the quantity of moisture that can be suspended in a volume of air is linked to the air temperature a more descriptive term used is 'Relative Humidity'. Relative Humidity (RH) is expressed as a percentage of the water that air at a specified temperature (and pressure) could support before condensation naturally occurs (at 100% relative humidity the dew point is reached).

The relationship between RH and dry bulb temperature is such that, at higher temperatures, air can support more moisture than at lower temperatures. Similarly, taking air at a lower temperature and increasing the dry bulb temperature without altering the moisture content will result in a lower RH at the new higher temperature. This relationship between dry bulb temperature, moisture content and RH is analysed in psychrometrics in graphical form as shown in Figure 1 below.

![Figure 1. Psychrometric Chart](image-url)
Why is it Important?

Without the HVAC systems performing their specified functions a submarine would not only become an unbearable hot (or cold) environment but vital equipment would be put at risk. Table 1 adds context to the general functions highlighting the risks associated with them.

<table>
<thead>
<tr>
<th>Function</th>
<th>Purpose/Justification</th>
<th>Associated Risks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ventilation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distribute Fresh/Refreshed Air for personnel</td>
<td>Crew have a minimum volumetric requirement for fresh air to survive and to operate effectively</td>
<td>Hypoxia (Oxygen deficiency)</td>
</tr>
<tr>
<td>Exhaust vitiated air</td>
<td>Carbon Dioxide from respiration needs to be circulated to absorbers to prevent build up inhibiting respiration</td>
<td>Asphyxia</td>
</tr>
<tr>
<td>Enable air to be drawn into the submarine</td>
<td>Support Diesel combustion to charge submarine batteries</td>
<td>Inefficient or inhibited combustion</td>
</tr>
<tr>
<td>Supply adequate air to Diesel Engines</td>
<td></td>
<td>Vacuum drawn on the submarine interior (crew health risk)</td>
</tr>
<tr>
<td>Ventilate compartments with hazardous gases</td>
<td>Compartments such as the battery compartment evolved hazardous gases such as Hydrogen which require dispersion or exhaust</td>
<td>Gas build-up leading to an explosion or other dangerous event (dependent on gases)</td>
</tr>
<tr>
<td>Ventilate compartment with unpleasant fumes/vapours</td>
<td>Compartments such as the Galley and Bathrooms/toilets evolve fumes and vapours that are unpleasant or unsanitary</td>
<td>Unpleasant or unsanitary compartments</td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Provide cooling directly to equipment</td>
<td>Certain equipment evolve high heat loads/are particularly sensitive to high temperatures and require heat removed directly</td>
<td>Overheating equipment</td>
</tr>
<tr>
<td>Provide cooling via the air-conditioning system</td>
<td>Equipment, personnel and external conditions generate heat to be removed to maintain optimal compartment conditions</td>
<td>Overheating equipment</td>
</tr>
<tr>
<td><strong>Environmental Control</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Provide temperature control of compartments</td>
<td>Personnel are not able to operate efficiently outside a tight temperature band</td>
<td>Compartment temperature too high or too low leading to heat stress, fatigue or possible hypothermia</td>
</tr>
<tr>
<td>Provide humidity control of compartments</td>
<td>Personnel are not able to combat health issues outside a set humidity range</td>
<td>Low RH results in lowered immunity</td>
</tr>
<tr>
<td></td>
<td>Equipment risks arise at very low and very high humidity levels</td>
<td>Static electricity, discharge and arcing at very low humidity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Risk of condensation and thereby short-circuit at high humidity</td>
</tr>
</tbody>
</table>

Table 1 – Functions, Purpose and Risk

From the table above it is clear that beyond being simply a control of submarine temperature, HVAC contributes to several key aspects of a submarine including operational capability, indiscretion ratio and health and safety and is therefore a key system for consideration during the design process.
This importance is likely to increase further in the future due to continuing trend for greater levels of automation and electronic equipment on board submarines and the ever-present desire to extend underwater endurance. This trend is a response to significant design pressure to reduce manpower, increase capability and reduce procurement cost. One consequence of employing more electrical equipment is that the levels of internal wild heat are raised and to counter this cooling must be increased.

It is also worth considering that, particularly for some European and North American navies, the platforms are being asked to deploy to new operational areas for which they were not designed. During the Cold War (1960s to 90s), the envisaged submarine battlefield or conflict zone was the icy waters of the North Atlantic, and to a lesser extent the Bering Sea. In these areas the highest atmospheric temperatures reached would be around 25°C and sea temperatures would not be expected to rise above 10°C. In the Northern extremes of this zone, and winter conditions further south, the temperature could drop as low as -29°C and sea temperature -2°C.

Fast forward to the end of the twentieth century and the areas of operation are much different. Submarines are now deployed to much warmer regions, almost unrecognisable from the cold war. The South Mediterranean, Persian Gulf and Somali coast have all been recent conflict zones where atmospheric temperature highs of up to 42°C (33°C seawater) are regularly encountered. This additional heat burden indicates some of the challenges a future submarine design must address, including specifying the correct external environment (e.g. air temperature, humidity, seawater temperature).

This paper outlines the highlighted considerations from a preliminary design exercise specifying an HVAC system for the BMT Vidar®-7 concept design. As part of the design process the environmental conditions representative of the Asia-Pacific region have been considered.

HVAC DESIGN

What are the Challenges?

As noted above, the HVAC system fulfils three main functions with various sub-functions and contributes to several key aspects of submarine operation. When designing an HVAC system it is important to consider the constraints transverse and general design requirements place on the system, the more pertinent requirements of which are as follows:

- Noise – Radiated noise means at best reduced submarine capability, but at worst the loss of the crew and the platform in a conflict environment. HVAC contributes to noise by use of rotating machinery such as fans and chilled water plants, which can be designed to emit less noise, and the noise of air running through ductwork;
- Platform Size – Reducing the size of the platform is dependent on reducing the size of the equipment within;
- Reduce electrical consumption – This is particularly important in conventional submarines (SSKs) as all power is drawn from the battery and the submerged endurance is determined by battery capacity and discharge rate.

These requirements, in parallel with the system functions lead to many design challenges, some of which are:

a) How is over-designing avoided?
b) How are all the simultaneous system demands met?
c) How can the equipment fit into the available space?
d) How can the system fulfil its role in all conceivable submarine scenarios?
e) How are design drivers managed?
f) What are the system options?

All of the above aspects should be addressed by careful system design; an iterative process which establishes the base design then reviews and revises it to address shortfalls in system functions and to conform to the design constraints.
Design Process

Early design of an HVAC system follows five main steps that are briefly described in the following sections and illustrated in Figure 2.

**Figure 2 – Simplified HVAC Design Process (One pass)**

**Establish System Parameters & Requirements**

This primary stage is to identify and understand the parameters of the system and submarine (compartment sizes, operational profile and environment, complement, equipment) and establish the requirements of the system.

**Establish a Heat Balance**

The heat balance is an equation relating the heat into and out of each of the submarine's compartments and includes external heat transfer, solar gain (when surfaced), equipment gain, lighting and gains from personnel which need to be controlled/addressed by cooling or heating until the desired internal conditions are achieved. This results in a determined air-conditioning airflow to each compartment to offset the heat load.

**Determine the Required Airflow**

The required air-conditioning airflow is compared to the minimum airflows to satisfy fresh air requirements and Air Change Rates and the maximum airflow of the three is selected as the design airflow requirement for each compartment.
Determine the Air-Conditioning Loads

The compiled design airflow requirements form the supply airflow from the centralised Air Handling Unit (AHU). Aligning with the volume of recirculated air, expected recirculating air conditions, external airflow and external air conditions, the cooling load of the AHU to cool the recirculating/external air mix down to supply conditions can be calculated. The process is illustrated in Figure 3 on a psychometric chart and allows the AHU, filters, cooling coils, ducting to be sized.

![Figure 3 - Air Conditioning Load](image)

Determine the Cooling Load

Compiling the air-conditioning cooling load, direct cooling and any local cooling loads undertaken by Fan Coil Units (FCUs), reveals the total vessel cooling load. This allows the Chilled Water Plant, piping and pumps to be sized, along with supporting fresh and seawater systems that enable the rejected heat to be transferred to external seawater.

The Design Cycle

It is important to note that the design process is iterative such that a viable design is unlikely after the first pass. Each pass is likely to uncover issues that need to be resolved and the solution may raise further issues. Several passes through the design process are likely to be needed before an optimised design is achieved.

At each stage the constraints, noted earlier, will present design challenges and there are considerations to be taken into account before making design decisions. These considerations are noted and discussed as follows.

Consideration 1: Layout and Modes

For a surface ship design, the design process calculations would only be carried out for the maximum (hot) and minimum (cold) conditions of the vessel. However, a submarine HVAC system has several modes that each have their own individual challenges that need to be considered:
A Surfaced running Diesels to charge batteries

Air is inducted via the snort mast and used to ventilate the submarine, being cooled as necessary. A portion of the incoming airflow, and/or a portion of the recirculated submarine air will be directed to the Engine Room to provide combustion air for the Diesel Engine which is exhaust from the submarine via the Diesel Exhaust mast. The heat balance should consider solar gain due to the exposed portions of the hull.

B Surfaced with hatches open (generally alongside)

Air is inducted via the snort mast and used to ventilate the submarine, being cooled as necessary. A portion of the airflow will be exhaust from the open hatch to ensure the submarine air is refreshed to allow atmosphere regeneration equipment to be turned off. The heat balance should consider solar gain due to the exposed portions of the hull.

C Submerged running Diesels to charge batteries

Air is inducted via the snort mast and used to ventilate the submarine, being cooled as necessary. A portion of the incoming airflow, and/or a portion of the recirculated submarine air will be directed to the Engine Room to provide combustion air for the Diesel Engine which is exhaust from the submarine via the Diesel Exhaust mast. The heat balance should not consider solar gain when the submarine is submerged.

D Submerged running the Low Pressure (LP) Blower

Similar to mode C, air is inducted in to the submarine but all air is directed around the submarine before a portion is directed to the Engine Room to be compressed in the LP Blower and exhaust from the submarine.

E Submerged normal running

The submarine is sealed up at depth (no inlet of external air) and all air is recirculated via the atmosphere regeneration equipment and the AHUs.

Table 2 – Ventilation Modes

Several compromises and innovative solutions will be required to ensure all requirements are met in all circumstances. For example, running the Diesels to charge the batteries has the potential to generate Hydrogen in the battery compartment and as a result a battery exhaust fan is required to ensure extraction from the compartment to keep Hydrogen levels below dangerous (explosive) levels. At the same time the Diesel Engine will be demanding combustion air from the Engine Room atmosphere. For the Vidar®-7 design, to ensure best possible use of air the battery compartment draws its air from the accommodation spaces and corridors and discharges into the Engine Room due to the larger volume available to decrease the Hydrogen concentration and allow some of it to be consumed by the Diesel combustion. This will of course, reduce recirculation to the AHU and demand more external air to compensate.

For the same setup under normal running, where the battery compartments do not require ventilating on such a scale, a set of low power Hydrogen clearing fans provide a lower air change and discharge the exhaust air to the main corridor. With a direct feed from the spaces to the battery compartments there would be an excess of air volume that would not be needed. To mitigate this a plenum taking supplies from the accommodation spaces and flexible space is provided, from which the battery compartment can draw what is needed and the remainder can be recirculated from the accommodation corridor back to the AHU or out an open hatch as necessary. During submerged periods where there is no access to surface air, the equipment in the engine room will require little access but there is still a requirement to keep the space ventilated to enable ships staff access for maintenance.

Design requirements of these types are noted in the following table for consideration. While these are important for the general layout of the system it is also important to consider what is driving the design in these modes, whether that is cooling, provision of fresh air or ventilation flow rate.
Table 3 – Mode Design Requirements

**Consideration 2: Establish Realistic External Conditions**

The pivotal step to identifying the requirements of an HVAC cooling system is to establish the submarine’s heat balance in all anticipated operations. This heat balance consists of the following contributors:

a) External heat gain/loss;
b) Solar heat gain/loss (when surfaced);
c) Equipment wild heat gain;
d) Lighting heat gain;
e) Personnel heat gain.

Since it should be the simplest to determine, right from the concept stage, the submarines’ operational area should lead to a definition of the maximum and minimum external conditions. External heat gain/loss (fabric gain) is determined by the temperature difference between the interior of the submarine and the external seawater/air and the heat resistant properties of the submarine hull, including any insulation measures. The external environment includes the external sea temperature which will be employed as the heat-sink for the air-conditioning systems, therefore an extremely high temperature will strongly influence and drive equipment size (i.e. Heat Exchangers would need to accommodate higher seawater flow rates).

As such it is critical that the external parameters for the submarine, which are derived from its envisaged area of operations or ‘reach’, are established realistically. These parameters are often taken from standards that include average values for typical regions of the world:

a) Tropical - Typically defined by high temperatures and high humidity (typically up to 40°C DB and 90% RH with an associated sea surface temperature of up to 35°C), this encompasses the equatorial region (approximately between 30° N and 30° S parallels) it includes countries such as Africa, Central America, Northern South America, India, Australia, Oceania and the Southern tip of the Middle East;
b) Temperate - Regions North and South of the Tropics defined by more moderate temperatures and humidity (typically up to 25°C and 70% RH), this encompasses North America, Europe, the southernmost regions of South America;
c) Arctic - The areas of the Arctic and Antarctic where temperatures can reach incredible lows and relative humidity can be high, but moisture incredibly low (-30°C and 100% RH, 0.00023kg/kg dry air).

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1 If including the sub-tropics.
It should be noted that although standards, and indeed some platform specification documents, state maximum air temperatures and humidity (e.g. 40°C and 90% RH) these values are, in reality, unlikely to occur simultaneously and therefore a system sized to incorporate these will be over-specified. The reason for this is that there is a general inverse relationship, at moderate to high temperatures, between dry bulb temperature and RH. Higher temperature air has the potential to support more water vapour and since RH is a measure of the amount of water that can be held at that temperature, unless a phenomenal amount of energy is expended to evaporate moisture into the atmosphere, as the temperature goes up the RH will come down. Therefore the lowest relative humidity will be experienced when the temperature is highest (frequently around midday) and the highest humidity will be when the temperature is around its lowest (early morning).

While standard values are often a useful base point, it is also important to consider the local conditions specific to the design platform, particularly with a submarine that is being designed not to venture too far from home base. This is because the standard values above cover large zones and do not allow much flexibility. For instance, the Tropical zone stretches from 30° N parallel to the 30° S parallel, and as such this zone includes locations such as:

- Muscat, Oman: maximum average temperature 40°C, corresponding humidity 25-65%;
- Panama City, Panama: with 34°C and 55-95%;
- Dubai, United Arab Emirates: 28°C and 30-87%;
- Antofagasta, Chile: 23°C and 57-87%.

Clearly, despite, Antofagasta being located within the perceived zone, specifying Tropical conditions for a platform operating in the locality could be considered over-designing.

Researching the Asia-Pacific region, the following figures (illustrative of the region) identified that the region was unlikely to reach the maximum temperature of 40°C but the humidity was reasonably high year-round. This indicated that upper conditions would be 34°C and 55-70% RH and therefore the majority of the cooling load for admitting external air would be to remove moisture from the atmosphere.

![Figure 4 - Langkawi, Malaysia Annual Temperature Variation](image1)

![Figure 5 - Langkawi, Malaysia Annual Humidity Variation](image2)
Over-specifying the upper limits of operation will not only result in over-sized equipment in a platform where space is at a premium, but since the majority of operations will be below the maximum condition, the efficiency and performance of HVAC equipment will be poor. Conversely under-specifying the maximum condition will result in a plant unable to maintain the desired internal conditions in hot conditions.

An example of the impact of varying the upper external environment limits is shown in Figure 6 below. As can be seen, specifying a tropical environment for a platform that will spend the majority of its operational life in the temperate zone will result in a penalty to the efficiency of the chilled water plant. It is also important to note that when specifying a design in the temperate zone, the majority of mode cooling loads are very similar and only begin to diverge when the specification ventures above 26°C outside air temperature. Within the temperate zone Mode C (Submerged running Diesel) tends to drive the design but as the outside temperature rises Mode A and B (Surfaced running Diesel and surfaced with hatches open) are dominant. Mode E (normal submerged running) is a fairly constant load across the temperature range, demonstrating how little sensitivity there is to outside conditions once external air has been precluded.

![Figure 6 – Air-Conditioning Load vs Outside Temperature](image.png)

Consideration 3: Establish Realistic Internal Conditions

**Crew Comfort**

It is important to control the temperature and humidity within a certain band to ensure crew comfort and optimum working conditions and recent trends have been noted in platform design that without the demands of active or cold war, and reflective of a professional navy, naval vessel designs have begun to favour improving accommodation standards which include more comfortable environmental control.

The simultaneous control of both temperature and humidity is important as higher humidity can influence a person to ‘feel’ a higher temperature than the Dry Bulb measurement indicates, for example:

- A temperature of 27°C (dry bulb) and 60% RH will 'feel' like 28°C;
- A temperature of 27°C (dry bulb) and 90% will 'feel' like 31°C.

Other factors that contribute to the temperature 'feel' are air velocity, adjacent hot equipment (wild heat output), clothing insulation and metabolic heat (dependent on the level of physical exertion). Of all these factors only
temperature, humidity and air velocity are within the direct control of the HVAC system. High temperatures can cause heat stroke and dehydration and while low temperatures have less severe symptoms they can cause drops in productivity as energy is re-directed to maintaining body temperature, and it can also interfere with sleep patterns. High humidity can lead to 'stifling' of breathing and perspiration leading to an energy-sapping effect but longer term it is known to promote mould and fungal growth which is hazardous to health. A low humidity can lead to the drying up of mucus in the nose and throat leaving the body more susceptible to viruses and bacteria.

Typically for spaces that are generally manned (i.e. crew accommodation, eating and operational spaces) the temperature should be maintained between 22°C and 26°C DB and humidity is controlled within the 45-65% RH range (zone illustrated in Figure 7). While higher temperatures and wider humidity ranges can be incorporated there is a risk-benefit assessment (with reference to Table 1) that needs to be considered carefully, weighing up the load on the system against the potential effects on personnel performance and health.

![Figure 7 – Crew Comfort Zone](image)

**Electronic Equipment**

Crew comfort is not the only factor to consider with respect to environment control, given the increasing level of automation and computerisation in modern submarines it has never been more important to control temperature and humidity. While it is widely understood that electronics can perform over a wider temperature range than people (roughly 5°C to 50°C) the effects of humidity are less widely publicised. At low humidity levels around electronic equipment there is an increased risk of static build-up and thereby arcing that can cause significant damage to equipment. Conversely, at humidity levels without localised air heaters there is a risk of condensation and consequently shorting of circuits. Even incorporating anti-condensation heaters, the high humidity poses a long term risk due to the humidity having an adverse effect on cable insulation which affects the dielectric strength and ageing resistance [1].

Spaces where there is a high electronic equipment density will have an associated high density of wild heat output. When this equipment is on, there will be an artificial increase in effect of raising the local temperature and consequently lowering of air humidity. Figure 8 illustrates the wild heat density (kW/m³) of the various spaces for the Vidar®-7 design.
Figure 8 – Compartment Heat Density (kW/m³)

It can be seen that the highest wild heat densities are in spaces that are not normally manned, namely the Auxiliary Machinery Space (AMS) and Engine Room. To avoid this wild heat density driving the air-conditioning calculation the designer should consider allowing the local temperature to rise higher than manned spaces but humidity should continue to be controlled, particularly low humidity which will necessitate humidifiers in certain circumstances.

Consideration 4: Determine the Driving Heat Loads

As noted in the general system design methodology, each compartment or sections relative airflow is driven by the maximum requirement to either: provide fresh air; ventilate to the desired level; or cool via air conditioning. This is worth some careful consideration as design decisions and trade-offs will need to be based on this information. For example, Figure 9 to Figure 11 below illustrate the various demands of the Vidar®-7 compartments graphically, highlighting the driving areas associated with each requirement.
As the figures illustrate, for the fresh air requirement the spaces where there is a greater concentration of crew are the drivers (accommodation and control/sonar rooms). In the case of air change rate and air-conditioning requirements, the compartments driving the demand are the Engine Room and Auxiliary Machinery Space, this is because they are likely to contain equipment evolving fumes or odours requiring higher air change and they also contain the majority of heat generating equipment.

Further consideration of the cooling requirements is advisable as the sources of heat may determine the design choices to be made. With reference to Figure 11, offsetting the entire heat load with air-conditioning will result in a very large amount of air moving through the vessel, driving equipment size and increasing radiated noise. Further, from Figure 12, it can be seen that the wild heat from equipment is by far the biggest driver for on-board cooling. It should be noted that this is completely at odds with the average surface ship design where solar gain and adjacent heat transfer are the more significant contributing factors.
It is also important to consider that, in line with Consideration 3, the various submarine modes will place varying loads of wild heat on the air-conditioning system. Figure 13 illustrates this variation for the submarine as a total.

As can be seen, the peak wild heat loads are experienced in modes A and C when the Diesel is running. For the majority of the other modes the load is reasonably consistent with a step up from Mode E between Periscope Depth (PD) and 50m due to the engagement of pumps and other depth-associated equipment.

This indicates the next complication in submarine HVAC design: that of varying electrical wild heat loads. The majority of varying loads are located in the Engine Room (Diesel and HP Air Compressors), Control & Sonar Rooms (Sonar equipment only fully engaged at depth and radar and optronic masts only engaged at or above periscope depth) and the Auxiliary Machinery Space (Atmosphere Regeneration equipment, Medium- and High-Pressure Pumps, Air Independent Propulsion among others). The wild heat load of other compartments such as
accommodation and Liquid Oxygen storage is reasonably stable across all modes. This contrast between heat loads requires careful consideration of the system design options.

**Consideration 5: Design Options**

Having ascertained the requirements for airflow to each compartment it is important the overall philosophy of the system reflects the general demands of the system under normal operation and can respond to the specific demands of each submarine mode.

Since a small submarine, such as the Vidar®-7 design does not have the space to allow a distributed air-conditioning system (i.e. multiple AHUs to handle the various section demands) a centralised AHU design is the only feasible option. However there are variations on the theme that can be considered to optimise the design, principally:

a. A ventilated submarine whereby air is propelled around the submarine in an unconditioned state and is cooled locally to offset large equipment loads. This is a system adopted by older platforms, particularly in northern Europe where external conditions are not so demanding and can provide a 'free cooling' effect through hull heat transfer. However a system of this type cannot effectively control temperature in more demanding conditions (i.e. higher temperature and high relative humidity) and therefore maintain an adequate working environment or prevent equipment failure/malfunction;

b. A fully air-conditioned submarine where the airflow is cooled to a set condition then distributed at the design flow rate to each compartment to balance the local heat transfer and generation and maintain the required environmental conditions. This is the most comprehensive system design, however it results in a larger system cooling load and much higher flowrates, leading to larger equipment and greater duct noise than are desirable in a submarine of this size;

c. A reduced air-conditioning system where the system is sized as a fully air-conditioned system except in cases where the heat density (refer to earlier section) is particularly high, in which case the central system airflow and cooling supplied to these compartments is sized on the basic heat load exclusive of particularly onerous equipment loads or those that vary dependent on operation or submarine depth. In these compartments direct cooling to equipment will be supplied where possible or local fan-coil (Chilled Water cooling) units will be fitted to adapt to the generated heat load.

For Vidar®-7, as has been discussed earlier, the principal heat dense compartments are the Engine Room, Auxiliary Machinery Space and Control Room (including the Sonar Space). As noted, these compartments have varying heat loads dependent on operation:

a. The Engine Room contains principally the Diesel Engine, Motor, HP Air Compressors and LP Blower. From these the Motor may be a constant load at sea, however the HP Air Compressors and LP Blower are infrequent operators and the Diesel Engine will not operate below periscope depth therefore Fan-Coil Units (FCUs) will operate infrequently. An added advantage of the FCU cooling of Engine heat is in the event of a need for a crash-dive/emergency go deep situation (running the Diesel Engine on the surface or at PD) while the main exit route of heat from the Engine Room (via Diesel Engine exhaust) is terminated the FCU can continue to operate dissipating the Diesel Engine heat that will continue to emanate as the submarine goes deep and for some time after shutdown;

b. The Auxiliary Machinery Space contains several pieces of equipment that operate only during certain manoeuvres, or at/below certain depths. For instance the HP Bilge/Ballast pump will not be expected to operate at shallow depths and there will not be a requirement to operate both hydraulic plants when on the surface since the number of planes operating is reduced. A fan-coil in this compartment can ensure adaptive cooling to match the equipment heat evolved from operating equipment;

c. The Control Room incorporates all command and controls, radar, sonar, weapons, communications and navigation equipment. Again not all of this equipment will be functioning at the same time, however the difference for this compartment is that equipment is unlikely to completely shut down during periods not in use therefore a 'keep alive' wild heat load still needs to be considered.
Consideration 6: Handling of External Air

When on the surface or snorting at PD outside air is key to ensuring adequate air for combustion of the Diesel Engines and allowing a steady replenishment of fresh air without the need to operate atmosphere regeneration equipment. However, this air has the potential to cause at best an imbalance in the submarines atmosphere (should outside conditions differ greatly from those being maintained internally) and at worst significant impacts on personnel and equipment arising from extremes of temperature and humidity as described in the earlier sections. To mitigate these risks it is key to regulate the amount of outside air and also to manage the way in which it is inducted into the submarine. The first point is simple: define what the maximum necessary air induction required is and that forms the baseline, in most cases this will be the combustion air requirement of the Diesel Engine, but other considerations are the required purge rate or LP Blower requirement in mode D.

Since all air will be inducted into the submarine via the snort mast the mast should be designed to accommodate this flow rate. The induction of air will be routed via a water separation system which may or may not incorporate a fan to overcome the air pressure loss of inducting air through the narrow, shaped entrance at the top of the mast. If this is incorporated then the fan may be required to be designed as a multi-speed fan to accommodate lower flow rates for other modes such as B and D. Older submarines routed the inducted air from the water separation system to the battery compartment to ensure that dispersion of generated Hydrogen was the first priority of inducting air. Since the Vidar®-7 design has battery exhaust fans, Hydrogen clearance fans and the use of the Diesel Engine to draw airflow from the battery compartment to other less critical areas, this method has not been adopted. Instead there are several options for air distribution:

a. Air can be directed to the Engine Room directly to provide for the Diesel Engine Combustion - This reduces any risk of the Diesel stalling due to restricted/insufficient air supply. However the trade-off will be that an additional air margin would need to be inducted through the snort mast to provide an oversupply to the engine room such that the remainder could be circulated around the submarine. This would require only the replenishment oversupply to be air-conditioned/heated before supply to compartments and would be tempered by recirculating air. Taking air from the Engine Room through the AHU would also require stringent filtration and monitoring to ensure fumes and other contaminants were not distributed around the submarine;

b. All air could be supplied to the AHU, circulated around the submarine and returned to the Engine Room for combustion and exhaust. This would require the large amount of incoming air to be air-conditioned/heated, and therefore greatly increase cooling and electrical load, but would offer a much higher rate of fresh air replenishment than the other methods;

c. The incoming air is split and delivered to the Engine Room and AHU simultaneously, with the larger proportion going to the Engine Room. The airflow directed to the AHU would be sized on the losses from the main submarine compartments to the Engine Room for Diesel combustion.

Since supplying direct to the Engine Room would require an over-sized snort mast and directing all air via the AHU will drive the air-conditioning system equipment sizes (Chilled Water coils, plants, pumps and the system fans), these are less than ideal. Therefore a split air arrangement is preferable and for Vidar®-7 this balance AHU air flow is delivered to the accommodation area, then is directed through the battery compartment to ventilate excess Hydrogen, and finally enters the Engine Room where it can be used in combustion.

Consideration 7: Cooling Arrangements

A modern submarine is a large vessel and, due to a large amount of electronic equipment and associated heat, requires a lot of cooling which utilises air-conditioning, direct cooling and FCUs. All of this equipment drives up the power requirements of the platform and requires space allocated for the equipment itself, but also for the supporting equipment that ensures the heat output is discharged overboard. These supporting systems can take many forms but a common example is illustrated below (Figure 14).
In the above diagram, heat is rejected from the air circulating the platform via a Chilled Water coil in the AHU, this operates to a relatively low set temperature differential which is inefficient in large systems due to the potential thermal transmittance into the pipework from adjacent hotter compartments. As a result a Fresh Water Cooling system (operating with larger temperature differential) receives the rejected heat from the Chilled Water system and transfers it to seawater in a Fresh Water/Sea Water heat exchanger and the seawater carries the heat out into the sea. This arrangement enables the Chilled Water system to operate at a relatively high level of efficiency, without the losses (heat gains) that a large ship-wide system would encounter, and the employment of a Fresh Water system reduces the need for ship-wide seawater systems. Such seawater systems would require deep diving depth pressure rating or suitable pressure-reducing and safety features that would increase the complexity of the system.

However, the employment of essentially four separate systems (air, chilled, fresh and sea water) is not suitable in a submarine as small as the Vidar®-7: the advantages are minimised and the space and power required for these systems simply isn’t available. As a result it is necessary to simplify the overall system design:

a. A Fresh Water cooling system has no advantage and therefore should be removed unless it is required for other uses;
b. The Chilled Water system continues to be of use and will replace some of the functionality of the Fresh Water cooling system since it is required to cool not only in the AHU but also the Fan Coil units and any directly cooled equipment (not illustrated);
c. While it is still important to minimise the amount of pressurised seawater pipework, a direct seawater-cooled Chilled Water Plant enables the removal of the FW cooling system.

An illustration of how this system might be arranged is shown in Figure 15.
Consideration 8: Special Compartments

While the HVAC system is generally designed to set rules, making certain assumptions about the spaces being served/cooled, there are of course exceptions that require particular attention.

A prime example of this type of special compartment, particularly prevalent in modern SSKs, is a Liquid Oxygen storage compartment. Oxygen is a pre-requisite component for several forms of Air Independent Propulsion (AIP) including: Fuel Cells, Closed Cycle Steam Cycles/Diesel Engines and Stirling Cycle Engines. These supplementary propulsion options allow conventional submarines to extend submerged durations and many modern SSKs have designed-in AIP or have been retrofit with AIP 'plug' hull sections.

In order to contain oxygen efficiently on-board a submarine it is pressurised and cooled until it becomes a liquid. As a liquid with a boiling point of -183°C, it is important that the fluid is stored properly to avoid boil-off, loss of Oxygen or an explosion hazard due to over-pressure. Rises in the temperature of the immediate environment will result in boil-off proportional to the temperature rise and the cooling/insulation factor of the vessel. As long as the rate of boil-off can be controlled it is neither wasteful nor dangerous, particularly as this boil-off of Oxygen can negate the need for other Oxygen generation equipment.

The HVAC system can play a role in controlling this boil-off rate by providing the cooling medium (Chilled Water) or cooling the surrounding environment and this should be considered a high priority requirement due to impacts on submarine and crew safety.

SUMMARY

This paper has sought to draw attention to the challenges of HVAC design for a small SSK and highlight the impact of changing requirements. This has brought about several topics that require careful consideration before and throughout the design spiral:

- The layout of major equipment and the demands of various modes of operation;
- Realistic external conditions;
- Realistic internal conditions;
- Design driving heat loads;
- System design options;
- Handling of external air;
- Cooling arrangements;
- Compartments with special requirements.
Furthermore the reasons behind the increasing importance of HVAC systems to the future design of submarines have been explained.

CONCLUSIONS

The increasing importance of HVAC systems design has emphasised now, more than ever, the importance of optimising HVAC systems design to ensure that the risks of over-, and under-specifying the system are minimised and all key safety and engineering requirements are captured. This paper concludes that while it is straightforward to design a HVAC system, to design a system that captures the requirements to support crew and equipment requires more than simple calculation.

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