Dynamic modelling of thermal energy flows in ships

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Abstract

Despite significant developments in naval architecture, up until recently limited effort has been expended to improve energy performance in ships. The key reasons were relatively low operational costs and lack of stringent regulations concerning environmental impact. As a result, energy systems were designed to safeguard against worst case operational conditions and their design was based on past experience or steady state calculations, which resulted in oversized ship components and plants, operating away from their optimum efficiency. This paper introduces a novel way to improve the performance of onboard energy systems by modelling the dynamics of thermal energy flows in ships during the design, retrofitting and operational stages. The dynamic simulation of energy flows in HVAC and refrigeration systems under varying ambient conditions and operational profiles offers an estimation of the power requirements of these systems, early in the design. This allows for optimisation of these systems per se or as part of an integrated-ship-energy-systems model where the interaction between thermal systems and other ship systems is considered and the right balance achieved. The emphasis in this paper is on the generic modelling of ship accommodation blocks and systems from geometric, topological and numerical perspectives, leading to knowledge intensive models that will be key to design and optimisation studies. This work is part of the Targeted Advanced Research for Global Efficiency of Transportation Shipping project (TARGETS, www.targets-project.eu), which is jointly funded by the 7th Framework Programme and industry.

Keywords: Dynamic energy modelling; HVAC modelling; Energy efficiency;

1. Introduction

Despite remarkable advancements in naval architecture over the years, fuel efficiency has never been the key objective within the shipping community due to the low price of fuel oil and the absence of strict environmental regulations. However the newly adopted mandatory measures to reduce greenhouse gas emissions (MEPC, 2011) along with the increasing price of fuel oil have forced ship owners, operators and yards to explore different possibilities to reduce fuel consumption. It is clear that the room for improvement is vast if one considers the complexity of ships, the variety of the onboard power systems and the limited effort that has been expended to optimise them.

Up to now most attempts to improve energy efficiency have been based either on past experience or on trial and error approaches. By monitoring the effect of different operational conditions and system configurations on the power consumption of the ship, changes that led to reduction in fuel consumption would be applied to new builds. Although straightforward and easy to implement, such techniques are time and money consuming since they involve constant onboard monitoring of the power consumption of an operating vessel. Thus the need for alternative optimisation methods is more prominent than ever with systems modelling offering the best way forward.

The advance in numerical techniques and computational power has paved a new way for the design and assessment of power consumption of ships. By numerically modelling onboard energy systems, the power consumption of one or more systems can be assessed early in the design stage providing an estimation of power requirements among other useful information. With the current state of computational power, results can be quickly generated and several scenarios can be assessed once a good

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model has been developed. Following this methodology, this work started as a part of a bigger attempt to address all onboard energy systems and focuses on the modelling of the heating, ventilation and air conditioning system (HVAC) based on a first principles approach that will allow for the assessment of the power consumption of different configurations and scenarios in the design and operating stages and for retrofitting purposes.

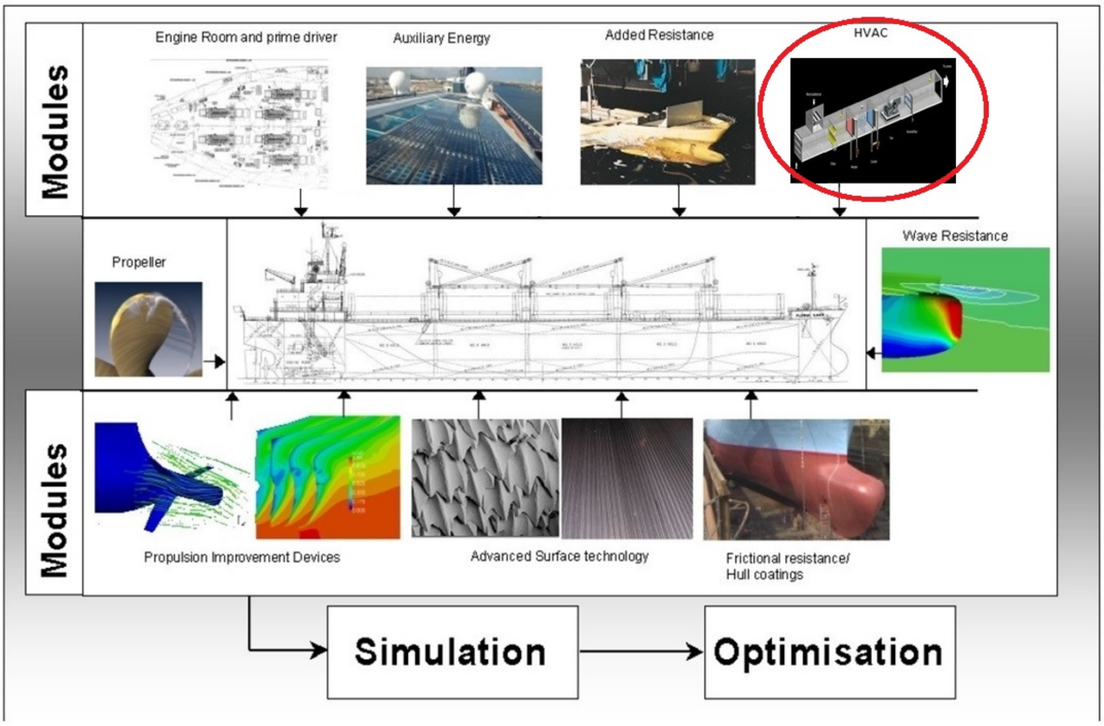

Figure 1. Ship energy model

2. HVAC in ships

2.1 Energy systems

Although some systems can be found onboard all ship types (propulsion, fresh water, fuel oil etc), there are some the presence and size of which is defined by the type and mission of the ship. Commercial ships are divided broadly in two main types: passenger ships and cargo ships. Although these two types share many commonalities in terms of systems onboard, the distribution of power consumption among those systems varies significantly between the two.

Cargo ships (tankers, containers, bulk carriers etc.) are responsible for 90% of the world's intercontinental trade. As a result they use the majority of the onboard generated power for propulsion, at a percentage of 80 to 85%. Roughly 10% is used for electricity generation that feeds several onboard systems (fresh water, HVAC etc.) and the rest 5 to 10% is used by the steam system, depending of course on the operational state and specific ship type. Although HVAC is barely one of the dominant power consumers, the fact that cargo ships account for 89% of the total gross tonnage of world fleet (IMO, 2009) and are responsible for 80% of the total greenhouse gas emissions of the shipping sector (Psaraftis and Kontovas, 2008) shows that even small reductions in fuel consumption are translated in large reduction in total greenhouse gas emissions.

On the other hand, passenger ships and, in particular, cruise liners have a different distribution of power consumption among their systems. With passenger comfort being the main objective and thousands of people onboard, HVAC is responsible for roughly 1/3 of the total power consumption, with propulsion being the other major power consumer, for roughly again 1/3 of the total. The rest 1/3 is designated to accommodation facilities (lighting, fresh water, electrical appliances, etc.) and other type specific systems (swimming pools, cinemas, etc.). The big percentage of the total power consumption occupied by the HVAC system, is enough to justify why effort has to be spent towards its optimisation.

All of the above combined with antiquated design methods that will be discussed later in this paper have triggered this work which focuses on optimising the power consumption of the HVAC system using time-domain simulation of the thermal flows onboard.

2.2 HVAC system configuration

Ships travel around the world and are subject to extreme weather conditions since natural phenomena are way more adverse at sea. In addition, due to the ships' total exposure to the environment, indoor conditions are greatly affected by external weather. Thus it is essential to ensure viable working conditions for the crew and comfortable living conditions for both passengers and crew. Since indoor comfort is not just a function of temperature but also humidity and purity of the air, the need arises for a closed system where the air is treated, circulated in living spaces and returned. This system is the HVAC and serves the following purposes:

- provision of thermal comfort in occupied spaces,
- provision of viable conditions in working spaces,
- prevention of the dispersion of contaminants to living spaces and
- exhaust of air from sanitary spaces.

Three main types of HVAC systems can be found onboard ships: single-duct, twin-duct and single-duct with reheat (Taylor, 1996). Although there are differences between the three types, they all share a very similar configuration, which is described below:

The HVAC system is comprised of 6 main plant components. 1) One or more fans to circulate the air, 2) a heater to add heat to the air, 3) a cooler to remove heat from the air, 4) a humidifier to add moisture, 5) a filter to remove small particles that might be imported from the ambient environment or the re-circulated air and 6) a network of ducts to circulate the air within the system. The fan generates positive pressure that draws fresh air from the outside and re-circulated air from the conditioned spaces. A minimum of 30-40% of fresh air is required in order to ensure the quality of the supplied air (ISO 7547, 2002). The air is then passed through a filter where small particles are removed and is therefore either heated in the heater or cooled in the cooler, depending on its temperature after returning from the conditioned spaces. Subsequently, humidity is added to the air if needed and the conditioned air is supplied to the spaces through a network of ducts. The air is then returned to the main air handling unit (AHU) where it undergoes the same process. Air from sanitary spaces and galleys is directly exhausted to the environment from a separate network, which ensures that the quality of the supplied air is not affected.

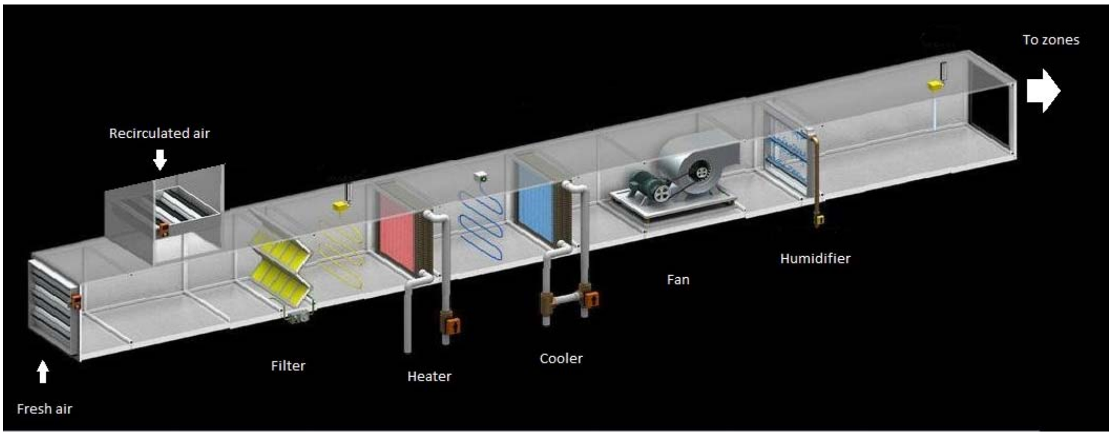

Figure 2. Typical configuration of an air handling unit

Although the system configuration is quite straightforward, the selection of the installed components is not a trivial task and should be dealt with caution since the sizing of the power consuming components (cooler, heater, fan and humidifier) has a major impact on the total power consumption of the vessel.

2.3 Current design methodology

Estimating the heat gain or loss of a space is the core process in the design of an HVAC system. A good indication of power demand early in the design stage allows the designer to select components that will operate efficiently. A good description of the current design methodology of marine HVAC systems can be found in Rawson (2001: 605). However, despite the need for accuracy, new builds follow rather antiquated regulations for the design of HVAC systems that are characterized by lack of transience, inaccuracy in heat transfer calculations and several simplifications.

The sizing of the plant components is currently based on steady state calculations. As demonstrated in Table 1, the system is designed in order to safeguard against extreme ambient conditions (ISO 7547, 2002) which might never be met during the ship's lifetime and as a result the system operates away from its maximum efficiency for long periods of time. The need for transience in the design process is obvious since with the calculation of the power demand over time, the average load of the system can be estimated, peaks in the load curve can be identified and components can be chosen that will operate close to their optimal point. Furthermore thermal modelling in indoor spaces is based on constant coefficients derived from past experience that do not account for fundamental heat transfer parameters (wind speed, wind direction, etc.) and many of the heat transfer processes occurring in reality are omitted with radiation exchange between surfaces and the external environment being the most indicative. Finally, many simplifications are observed in this heat load calculation methodology such as the fact that heat gains from occupants and lighting that are vaguely taken into consideration in spite of their effect in the heat balance.

Table 1. Design conditions for the HVAC system

	Summer		Winter	
	Temperature	Humidity	Temperature	Humidity
Outdoor air	+35ºC	70%	-20ºC	-
Indoor air	+27ºC	50%	+22ºC	-

All these are indicators that a new design methodology should be considered that will allow for a more educated design of the HVAC system. Accuracy and transience in the method need to be introduced as designing based on assumptions and single scenarios can only lead to a bad design.

3 Dynamic energy modelling

3.1 Esp-r

Dynamic modelling of thermal flows has been used in the building industry for over 30 years where it has allowed for the assessment of the energy performance of buildings. Several separate efforts have been made to develop integrated dynamic energy modelling software (Crawley et al, 2005) but only a few have succeeded in the development of an integrated tool due to the complexity and large number of the interacting thermal phenomena. The software adopted for this work is "Environmental Systems Performance – research edition" (Esp-r) (Clarke, 2001).

Esp-r is an open source dynamic energy modelling tool developed by the "Energy Systems Research Unit" (ESRU) in the University of Strathclyde. It is used to simulate the performance of buildings by modelling the actual physical systems in an in-depth manner and during its development it has always regarded buildings as:

- systemic (many parts make the whole),
- dynamic (the parts evolve at different rates),
- non-linear (the parameters depend on the thermodynamic state) and
- complex (there are myriad intra- and inter- interactions).

Esp-r follows a finite volume conservation approach, in which a problem is transformed into a set of conservation equations (for energy, mass and momentum) which are then integrated at successive time-steps in response to climate, occupant and control system influences. Therefore Esp-r can be used to assess the energy performance of systems during both early and detailed design stage, during retrofitting with selection of different configurations and during operation with varying operational scenarios in existing configurations.

3.2 Accommodation modelling with Esp-r

In order to create a model that can be simulated and produce useful results several steps need to be followed. Firstly, the dimensions of the spaces are required. Whether a new design is considered or an existing ship is modelled, information should be available for the topology and the geometry of the spaces. Once this information is available, the accommodation block is modelled and divided in several thermal zones. Usually, it is sufficient to represent one room as a single thermal zone; however, there are cases where some discretisation is required, especially for large spaces found in cruise liners (atria, dining halls, etc.). Secondly, a boundary condition should be applied to every surface in the model. Surfaces can be exterior, interior (in contact with another zone), adiabatic and a few other case specific types (ground, similar, etc.). Then the construction materials that comprise each surface are selected from an existing database or can be created anew by assigning the material thermal properties (conductivity, density, heat capacity, emissivity and absorptivity). Esp-r also allows for windows modelling, where glazing is treated as a transparent material that allows solar radiation to enter the zone. Similarly, casual gains from occupants, lighting and small devices can be assigned as a daily profile of heat gains to the thermal zone.

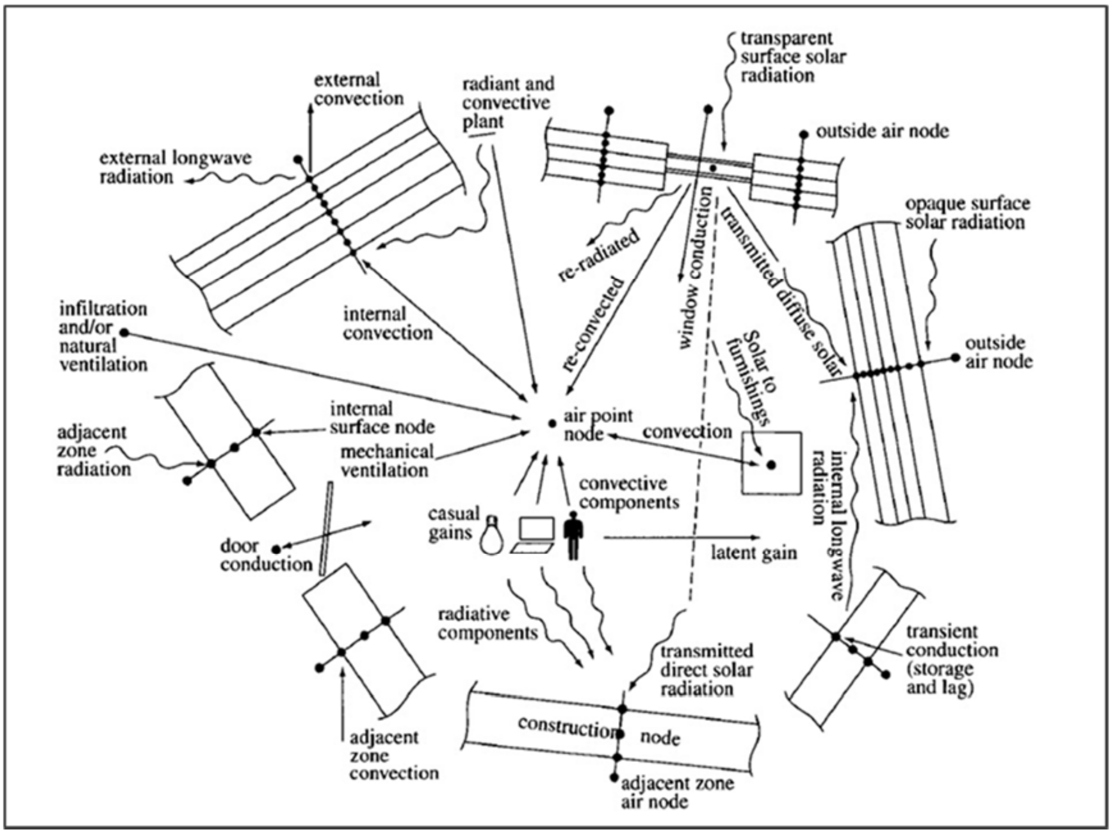

Figure 3. Building energy flow paths (Clarke, 2001).

In the case of air infiltration or mechanical exhaust/intake, the airflow modelling facility of Esp-r can be used where the user can specify cracks, openings, fans and several other airflow components to create a network, which accounts for heat added to the thermal zones from mass flow exchange between zones or infiltration from outside. Esp-r also allows for modelling of plant component HVAC systems where the heat and mass flow interactions between the plant components are modelled and coupled to the thermal zones. A control strategy can be imposed to all networks (thermal, airflow and plant) through the control module of Esp-r, which includes different control options (PID, on/off etc.).

Once the model is set the user can select a climate file, which includes hourly data for the ambient weather (solar radiation, temperature, wind speed, wind direction and relative humidity) and the simulation time-step can be selected according to the level of temporal accuracy required. Since thermal processes might occur faster in airflow and plant networks, finer temporal discretisation can be selected for those networks. When the model and the simulation parameters are set the simulation can commence and results can be either read from an in-built Esp-r module or can be printed in a separate file.

3.3 Application in the shipping sector

Although the modelling methodology remains the same, several differences exist between the building and the shipping sector that have to be accounted for during the application of dynamic thermal energy modelling in ships. To begin with, construction materials vary significantly, with ships using specific materials such as mild steel for structural support and insulation materials that are defined by fire safety regulations (SOLAS, 2009). Secondly, space configurations differ since ships are comprised of a variety of spaces ranging from engine rooms to large theatres. As a result care should be taken in space discretisation and definition of occupancy profiles.

Furthermore, the total exposure of ships to the weather along with the extreme weather conditions encountered at sea make ships more sensitive to ambient conditions, which calls for control strategies that cater for these extreme changes. Climate data used for the simulation can be obtained from online weather databases (Woodruff, 2005) and can be indicative of the ship’s route. In addition, since ships are moving objects that frequently change direction when “on sail”, the varying geographical location and orientation of spaces has to be accounted for since thermal behaviour is greatly affected by the two. All the above and other less significant differences have to be taken into consideration when applying energy modelling software designed for the building industry, to ships.

4. Accommodation modelling in ships

4.1 Accommodation modelling of a cargo ship

Esp-r is a powerful tool that can be used to tackle a variety of problems and can produce accurate and valuable results very fast, if used correctly. When it comes to HVAC optimisation during ship design the most obvious way forward is to start with a blank sheet and explicitly model all spaces, processes and interactions that can be found in the accommodation block. Following this approach the spaces are modelled, all the parameters of the model are set and simulations are run for different operational scenarios and environmental conditions. Then based on the results, decisions can be made about the sizing of the components, space configurations and operational scenarios that might reduce the power consumption of the system.

Within the framework of EU project TARGETS, data available for the accommodation block of bulk carrier ‘Star Aurora’ was used in order to develop a thermal model of her superstructure. In this paper, this model is going to be used to exhibit how alternative configurations influence the power demand of the HVAC system. The wireframe of the superstructure produced with the Esp-r software can be seen in figure 4.

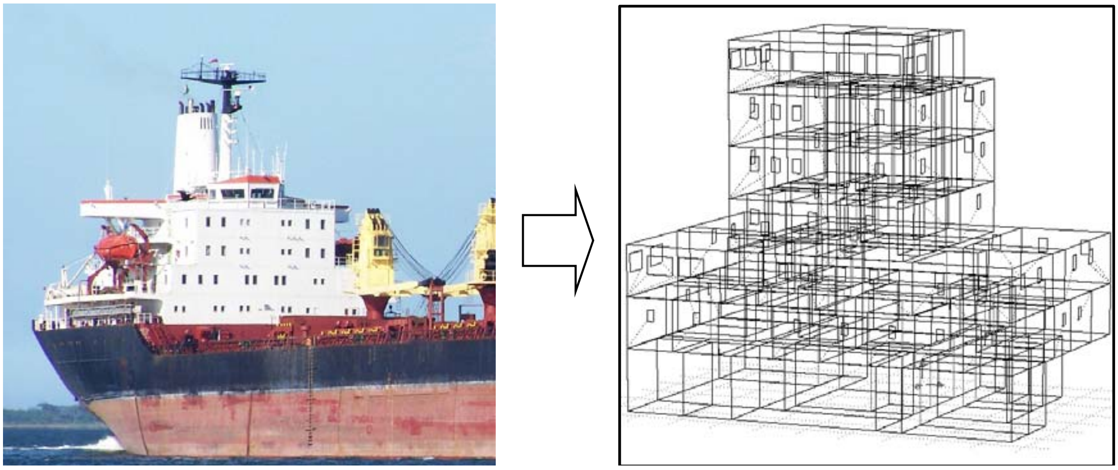

Figure 4. Designing the geometry of the superstructure in the Esp-r software.

A good approach early in the design, is to skip detailed plant component modelling and assess the power demand required to maintain each zone within a certain comfort range (20-24^{o}C and 40-60% relative humidity). Although this is not the actual power demand of the HVAC components, the effect of different configurations can be quantified (glazing, operational schedules, insulation, etc.), peaks in the power demand can be identified and the most efficient configurations can be selected for detailed component modelling.

In order to demonstrate the impact of different configurations on the power demand, two simulations are run for different insulation thickness of the external bulkhead. The duration of the simulation is one month with an hourly time-step, under typical cold climate conditions. As seen in Figure 5, with the use of enhanced insulation (100mm instead of 50mm) the power demand is reduced by up to 2kW, the peaks of the demand curve are significantly lowered and the curve becomes smoother. Following the same methodology the effect of different geometrical, topological and thermal configurations can be assessed. This paper does not intend in any way to assess every different configuration but to introduce the tools and methodology to achieve it.

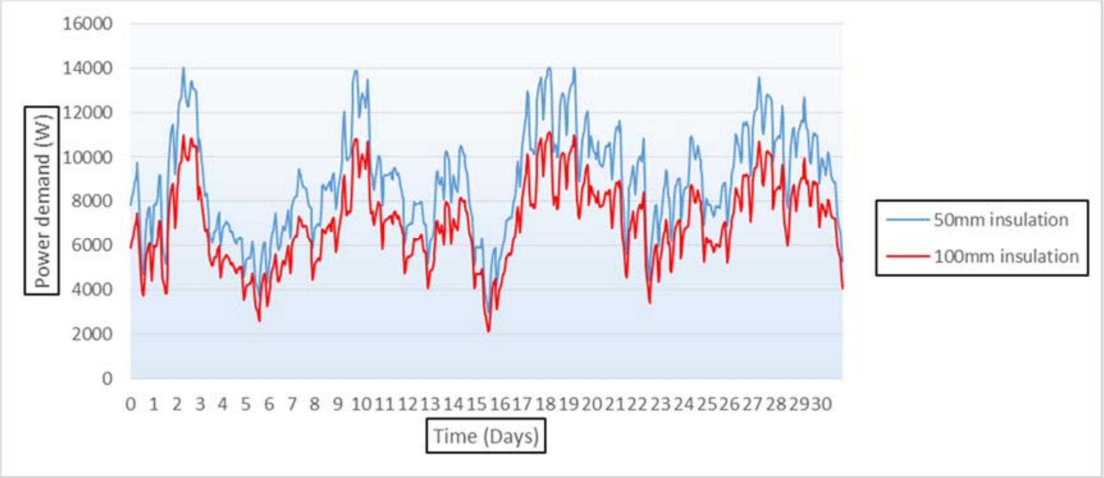

Figure 5. Ideal power demand of the accommodation block of a cargo ship for a cold month, for different thermal insulation (50mm and 100mm of rockwool).

Once the most efficient configuration is identified, detailed plant component modelling can be applied. All the plant components are modelled and a steady mass flow rate is maintained in order to provide adequate fresh air to spaces. A PID control strategy is applied on the heater, which has a 70kW heating capacity. In Figure 6 the actual power demand of the heater is shown. Following this methodology, different control strategies can be assessed and decisions can be made for the sizing and operation of the plant components.

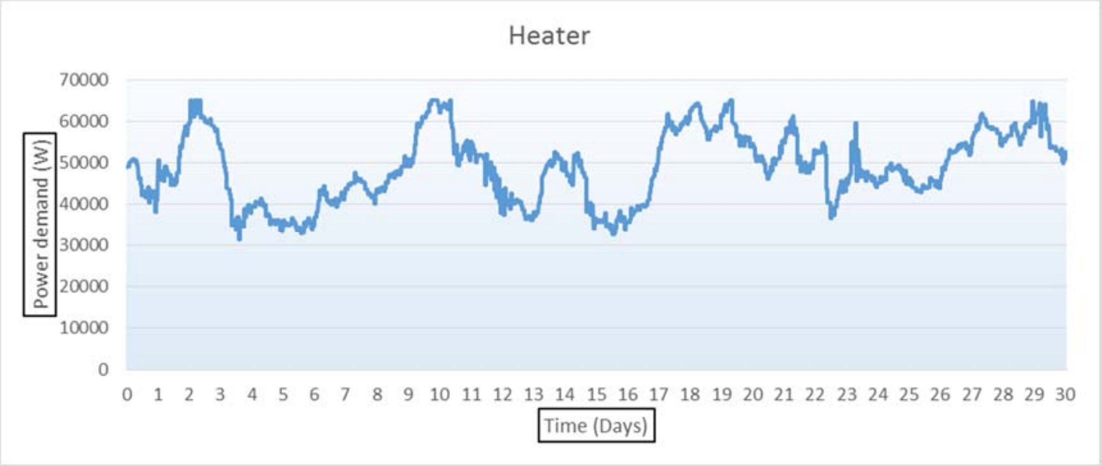

Figure 6. Power demand of the heater for a monthly simulation.

4.2 Need for modularity

Whole accommodation modelling is very appealing since it is quite straightforward to implement and produces results fast (a yearly simulation of a cargo ship accommodation block with 1-hour time-step takes around 5 minutes). However it does not come without disadvantages. Explicit topology modelling is the most time consuming step of the process. For example, in order to model each space of the superstructure of a cargo ship in a topologically correct model, a number of 80 to 90 thermal zones are necessary. This would take an experienced user about a week to develop and if a new configuration was to be assessed, reconfiguration of the model would require about a day or two in order to assign all parameters correctly. To add to the problem, if we consider passenger ships that are comprised of thousands of spaces, it becomes very obvious that explicit topology modelling becomes prohibitive and different approaches should be considered.

In order to address this problem, the concept of modularity is introduced in an attempt to topologically decouple the thermal zones and reduce the number of input parameters without sacrificing accuracy, by creating a library of parametric modules that can be used to form full models of accommodation blocks. Although the development of the modules is currently underway, this paper outlines the methodology followed to achieve that.

4.3 Knowledge intensive models

Commencing from a detailed model of an accommodation block, the development of knowledge intensive models involves reducing the number of input parameters by identifying the most dominant ones and excluding or keeping the rest constant, without sacrificing the accuracy of the result. A thermal model has three types of parameters: geometrical, topological and thermal.

Geometrical parameters of a thermal model are the dimensions of its zones. Since Esp-r is based on a finite volume conservation method, the definition of thermal zones is based on points in the three dimensional space that form surfaces and volumes. The area of a surface and size of a volume have a major impact on the thermal behaviour of zones, therefore the geometry of the modules cannot be kept constant. Spaces are grouped depending on their size since several spaces in ships appear to have commonalities in terms of geometry. By assessing the effect of geometry in spaces of similar size, modules can be introduced based on the size of their surfaces and volume. For example cabins can be divided in small and large, a bigger module can be used to describe dining and recreational spaces and even larger modules can account for large atria.

Topological parameters are the boundary conditions of thermal zones. Each surface must be assigned a boundary condition, which can be one of the following: “external” (exposed to the environment), “another” (in contact with another zone), “similar” (in contact with a hypothetical zone identical to the current) and “adiabatic” (no heat flux allowed). In a topologically correct model, adjacent zones are thermally connected to each other, which as described earlier, is a major setback in thermal modelling of large accommodation spaces. In an effort to decouple adjacent zones, the possibility of replacing boundary conditions of the “another” type, with a different type of boundary condition (similar, adiabatic, etc.) can be assessed through a set of simulations. By accomplishing this decoupling, modules can be selected from a library, regardless of their position in the ship, which allows for reduced modelling time, therefore assessment of a larger number of configurations.

Finally, thermal parameters are the properties of the construction materials, heat gains from people lights and electrical equipment and ambient conditions. Through a sensitivity study the most dominant parameters can be identified, their effect on the output can be assessed and the less dominant ones can be either discarded or kept constant. By reducing the number of input parameters, fewer simulations will suffice for the assessment of different configurations and scenarios on the power consumption of the HVAC system.

5. Conclusion

In light of the global need to reduce greenhouse gas emissions and fuel consumption, this paper introduces a novel methodology to design energy efficient HVAC systems in ships using dynamic modelling of thermal flows. The operation of the HVAC system onboard ships is described and the disadvantages of current design practices are discussed. The process of designing the accommodation block of bulk carrier Star Aurora using the dynamic energy modelling tool Esp-r is demonstrated and results of a monthly simulation are presented. Finally, the need for modularity in the design process is explained and considerations on how to address this in the future are outlined.

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