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Mathematical formulation and demonstration of a dynamic system-level ship thermal management tool

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ABSTRACT

This paper presents the mathematical formulation and unique capability of a system-level ship thermal management tool, vemESRDC, developed to provide quick ship thermal responses in early design stages. The physical model combines principles of classical thermodynamics and heat transfer, along with appropriate empirical correlations to simplify the model and expedite the computations. As a result, the tool is capable of simulating dynamic thermal response of an entire ship, characterized by intricate thermal interactions within a complex ship structure, within an acceptable time frame. In this work, vemESRDC is demonstrated through three case studies in which transient thermal responses of an all-electric ship to different ship operation modes, weather conditions, and partial loss of cooling are investigated. The analysis examines particularly the following: (1) the required cooling capacities to maintain each ship component within its design limit; (2) equipment temperature variations with respect to partial cooling loss in battle mode; and (3) the assets of installing seawater heat exchangers to pre-cool deionized freshwater before chillers. For the notional all-electric ship conceived and assessed in this work, the results verify the capability of vemESRDC to capture dynamic thermal interactions between shipboard equipment and their respective surroundings and cooling systems, e.g., the tool provides practical insights into pulse load cooling strategy, and different solutions are obtained for distinct weather conditions. In addition to the case studies performed in this work, vemESRDC can be employed to conduct diverse studies based on which concrete ship thermal management strategies can be formulated in early design stages.

1. Introduction

System-level thermal analysis of an all-electric ship is an essential procedure during its early design stages for devising effective thermal management strategies, to satisfy ship cooling requirements in all conceivable operation modes and scenarios. In an all-electric ship, devices integrated for control, power, propulsion, and weaponry are predicted to dissipate considerable amounts of heat [1–5]. In [3–5], the authors report the notional pulsed weapon system, radar, and vital loads (e.g. sensors, data processors, etc.) to generate heat at approximate rates of 2.8 MW, 3.5 MW, and 0.76 MW, respectively. Similarly, non-vital loads and personnel are also estimated to significantly contribute to the total heat generation. As a result, Zerby [2] anticipates 700% increase in the overall cooling capacity of the future all-electric ship to ensure proper operation of all equipment within the ship. These values, however, do not reflect the transient nature of each equipment in different ship operation modes and possible cooling losses, and therefore, the global performance of an actual all-electric ship is expected to depend more heavily on dynamic ship thermal responses.

In order to study ship thermal responses and its cooling network at the system level, reduced-order mathematical model and simulation tool, capable of addressing the transient nature of every ship component at a low computational cost, is required for reliable assessments. Such a tool can be employed to promote concrete thermal management strategies and improve ship survivability in all conceivable operation modes by satisfying its cooling requirements. In addition, the tool can be used to capture and predict ship thermal behaviors in cases such as system failures, e.g., partial cooling loss. In efforts to comply with these objectives, several studies on dynamic system-level thermal response of an all-electric ship have been conducted previously by means of simple mathematical models, and a few representative ones are discussed in this brief review.

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Nomenclature

A	heat transfer area (m^2)
C	heat capacity rate (W/K)
c	specific heat ($J/kg\ K$)
c_p	specific heat at constant pressure ($J/kg\ K$)
g	gravity (9.8 m/s^2)
H	total swept height (m)
h	convective heat transfer coefficient ($W/m^2\ K$)
I	global solar irradiance (W/m^2)
L	total swept length (m)
l	length or width (m)
$\dot{m}$	mass flow rate (kg/s)
n	total number
Pr	Prandtl number
$p_{v,\ i}$	partial vapor pressure (Pa)
p_{vs}	water vapor pressure (Pa)
$\dot{Q}$	heat transfer rate (W)
Ra_H	Rayleigh number
Re_L	Reynolds number
T	temperature (K)
T_{i0}	initial temperature (K)
T_∞	ambient air temperature (K)
$\mathbf{T}$	solution vector
t	time (s); thickness (m)
U	overall heat transfer coefficient ($W/m^2\ K$)
V	volume (m^3)
v	flow velocity (m/s)

Subscripts

adj	adjacent
b	bottom
c	solid volume element number
conv	convection
e	east
eq	equipment
ext	exterior
f	fluid
fc	forced convection
fw	freshwater
gen	generation
i	volume element number
in	inlet
int	interior
j	volume element face index
l	volume element side face index
m	direction index
max	maximum
mesh	mesh
min	minimum
n	north
nc	natural convection
out	outlet
r	ratio
rad	radiation
s	south
sw	seawater
t	top
w	west; wall
z	zone; z-direction

Greek letters

α	absorptivity
α_T	thermal diffusivity (m^2/s)
β	thermal volumetric expansion (K^{-1})
ε	relative error; emissivity
ε_{hx}	heat exchanger effectiveness
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant ($5.67 \times 10^{-8}\ W/m^2\ K^4$)
ϕ	relative humidity
ϕ_{i0}	initial relative humidity

Chiocchio et al. [6] conducted a preliminary analysis for future real-time, system-level hardware-in-the-loop (HIL) simulations. The primary objective of this study was to validate a mathematical model developed for a 5 MW rotating machinery test facility using the experimental data. Subsequently, the authors analyzed transient thermal behaviors of two 2.5 MW induction motors and their speed drives in conjunction with the cooling network. Factor screening and uncertainty propagation were employed to validate the model and determine which uncertain parameters had the largest effect on the simulation results.

Ruixian et al. [7,8] investigated an integrated approach for performing thermal-electrical coupled co-simulation of integrated power and cooling systems of future all-electric ship. The authors assessed the temperature variation of power conversion module (PCM) under a step change of the service load [7]. Furthermore, the study aimed to evaluate the transient interaction between power and thermal subsystems using a hybrid electrical power model and chilled water system developed on the virtual test bed (VTB) platform. Simulation results demonstrated the ability of the model to capture significant system dynamics while providing insights into the optimal system configurations and operating parameters. Similarly, Hewlett and Kiehne [9] elaborated and validated a dynamic thermal modeling and simulation (DTMS) framework for its potential use as a shipboard HVAC optimization tool. The authors implemented two non-traditional shipboard cooling concepts in DTMS and compared them to current chilling systems. These advanced cooling systems not only resulted in immediate power savings relative to baseline models, but they provided potential for simulation of dynamic reconfiguration for future all-electric ship.

Backlund et al. [10] developed total ship-zonal distribution models of electric power, chilled water, and refrigerant air systems. The authors presented a highly reconfigurable modeling approach that enabled users to configure shipboard electrical, chilled water, and refrigerated air distribution architecture. Furthermore, the paper advocated the use of metamodels and discrete variable classifiers as a mean to provide fast responses. Sanfiorenzo [11] devised a cooling system design tool (CSDT) to model the cooling network in the notional all-electric ship, and evaluated the overall ship cooling capacity, pressure drops in the pipe network, and temperature variation of each thermal load. CSDT was also capable of visualizing the pipe network (i.e., joints, bends, and valves) within the predefined ship geometry.

According to the literature review, mathematical models and simulation tools have already been developed to address system-level ship thermal behaviors in the trainset regime. Several of these works also exhibited component-level thermal analyses under dynamic heat loads and cooling capacities, and proposed novel approaches to optimize the cooling network. Previous studies, however, failed to fully address the intricate energy interactions between equipment and their surroundings within the ship, in which case the heat transfer between an equipment and its adjacent components (e.g. another equipment or ambient air) may have significant effect on the cooling network design. Furthermore, these tools were incapable of portraying complex ship geometry constituted of hull, superstructure, and multiple bulkheads and decks,