System-level ship thermal management tool for dynamic thermal and piping network analyses in early-design stages

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***Abstract*—We present herein the coupling of two system-level ship thermal management tools, namely, Cooling System Design Tool (CSDT) and vemESRDC developed at MIT and FSU, respectively, for dynamic thermal and piping network analyses in early-design stages. Each tool exhibits unique features that allow naval architects to investigate and visualize distinct ship thermal responses. vemESRDC, for instance, provides dynamic equipment and shipboard space temperature and relative humidity, while CSDT arranges realistic piping network layouts and provides pressure distributions in the network. In this work, we elaborate the integration strategy and conduct a simple case study using the integrated tool to verify the coupling. We then present the results to demonstrate the capability of the integrated tool.**

***Keywords*—CSDT; Early-design stage; ESRDC; Ship cooling; Ship piping network; Ship thermal management; vemESRDC**

I. INTRODUCTION

The growing complexity and power requirements of naval shipboard combat systems have dramatically increased the overall cooling demand over the last few decades. High-power pulsed loads such as radar and railgun as well as advanced electronic devices in all-electric ships, for instance, dissipate excess heat that must be constantly removed from the vessels to prevent system breakdown. Failure to comply with the cooling requirement can be detrimental during combat, in particular, when most ship equipment is operating at its maximum capacity. Consequently, preliminary design assessment of all-electric ship cooling systems have become imperative to cope with the high cooling demand—to ensure proper operation of every ship equipment in all operating modes. According to [1], ship design within the US Navy begins with the identification of a desired capability and ends with the production of the data required to construct a specific vessel. Such a design practice implies the need to conceive and analyze cooling systems capable of mitigating the adverse effects of increased thermal loads during early-design stages.

Several tools of different fidelity and suitability are available to the naval architect to design and evaluate cooling systems at various design stages [2]–[5]. Early-stage design tools are typically employed at the start to a new (or modified) ship design, and they provide the naval architect with the basic idea of a ship based on relatively few input parameters. Mid-stage design tools are equipped with more capabilities for detailed analyses of ship cooling system designs including piping structures, weight, and flow network. Late-stage design tools are based on more sophisticated and complex mathematical models for accurate sizing and integration of onboard HVAC systems, and they are employed at the final design stage or during construction.

The Electric Ship Research and Development Consortium (ESRDC) has developed several reliable and validated thermal management simulation tools that can be used in the initial design stages to propose and evaluate appropriate ship cooling systems [1]. The basis of the present work lies in the development of two complementary tools: Cooling System Design Tool (CSDT) [6]–[8] developed by MIT, and vemESRDC [9], [10] developed by FSU. Whereas CSDT arranges and analyzes realistic ship piping networks, vemESRDC provides the thermal response of ship equipment and shipboard spaces. As part of the joint effort between FSU and MIT, these tools have been merged previously as a comprehensive tool [11], allowing the users to design ship cooling systems and assess the impact of design decisions at early-design stages with the flexibility to evaluate new equipment or technologies.

The work presented herein proceeds with our previous effort to integrate CSDT and vemESRDC for enhanced ship thermal management. The previous integrated tool [11] solved the conservation of mass, momentum, and energy for flow and temperature distributions in the pipes and shipboard spaces, respectively. The tool, however, exhibited numerical deficiencies owing to the fundamental discrepancy in the mathematical formulation of the two complementary tools. The governing equations in CSDT were represented by a system of intricate partial differential equations (PDEs) whereas vemESRDC was based on a system of ordinary differential equations (ODEs). As a result, different numerical methods had to be implemented for each tool, affecting the overall numerical complexity and

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This work was sponsored by the US Office of Naval Research under contract N00014-14-1-0198 (FSU), N00014-16-1-2956 (FSU and MIT), N00014-14-1-0166 (MIT), N00014-16-1-2945 (MIT), and NOAA Grant Number NA14OAR4170077 (MIT). Any opinions, findings, and conclusions or recommendations are those of the authors and do not necessarily reflect the views of the Office of Naval Research.

efficiency. In general, PDEs describe physical phenomena more accurately than ODEs but in exchange for remarkably higher computational cost. Hence ODEs are oftentimes preferred over PDEs to model physical systems with sufficient accuracy, especially in early-design stages wherein numerous parametric analyses and what-if simulations are conducted.

As an initial step to mitigate the aforementioned numerical issues that emerged in our previous coupling of the two complementary tools, we present the integration of the steady-state model of CSDT with vemESRDC. In particular, the objectives of this work are to (1) translate CSDT from MATLAB to Fortran for the integration; (2) identify variables that need to be shared between the two complementary tools; and (3) conduct a simple case study with the integrated tool to verify the coupling.

II. CSDT AND VEMESRDC

We briefly introduce the Cooling System Design Tool (CSDT) and vemESRDC in this section for congruity of our paper. However, we suggest readers to reference [7], [8] for the detailed mathematical formulation of CSDT and [10], [12] for that of vemESRDC.

A. Cooling System Design Tool (CSDT)

The key purposes of CSDT are to provide rapid visualization and analysis of the chilled water and seawater cooling systems to test their overall feasibility and performance [7]. The tool has been developed based on the thermodynamic and hydrodynamic principles that govern fluid flow, and incorporates flow network analysis (FNA) for accurate computation of pressure distribution. For example, the losses that affect fluid velocities and pressure in the piping network are given by [13]

$$h_L = h_{L,major} + h_{L,minor} = f\frac{Lv^2}{2gD} + K_L\frac{v^2}{2g}, \tag{1}$$

where h_L is the head loss, L the pipe length, v the mean fluid velocity, g is the gravity constant (i.e., $9.8\ \mathrm{m/s^2}$), D is the hydraulic diameter, and K_L is the loss coefficient. CSDT considers head losses due to friction, entrance effect, valves, and bends in converging, diverging, series, and parallel flows. In addition, the tool solves the energy balance to evaluate the temperature rise along the pipe due to fluid work.

An expansion of CSDT, referred to as System-level design of Marine Cooling Systems (SMCS) and previously integrated with vemESRDC [11], solves the quasi-1D flow model in elastic pipes derived by reducing the dimensionality of the full Navier-Stokes equations under the assumptions listed in [8]. The model is therefore described by the three conservation equations (mass, momentum, and energy) as follows:

$$\frac{\partial A}{\partial t} + \frac{\partial uA}{\partial x} = 0, \tag{2}$$

$$\frac{\partial u}{\partial t} + \frac{\partial u^2/2}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x} - \frac{fu^2}{2D} - g\sin\theta, \tag{3}$$

and

$$\rho c_p\left(\frac{\partial T}{\partial t} + \frac{\partial\,(uT)}{\partial x}\right) = 0, \tag{4}$$

where A is the cross sectional area $A(x,t)$, u is the axial velocity component, T and ρ are fluid temperature and density, respectively, p is the pressure, θ is the angle between the pipe axis and the horizon, and c_p is the specific heat of the fluid at constant pressure [8].

CSDT features a simple MATLAB user interface which enables its users to quickly visualize and analyze cooling networks aboard naval ships. Another remarkable asset of CSDT is the flexibility that allows the users to easily add and/or modify piping network components such as heat exchangers, chillers, and thermal loads as needed. Such an attribute facilitates the coupling and promotes the adaptability of the integrated tool.

B. vemESRDC

vemESRDC is a system-level ship thermal simulation tool developed in Fortran based on the volume element model [12]. The tool employs a novel mesh generation strategy that discretizes the computational domain using hexahedral elements with sufficiently accurate representation of an actual ship geometry [14]. The first law of thermodynamics is then applied to each element to derive an ODE of the following form:

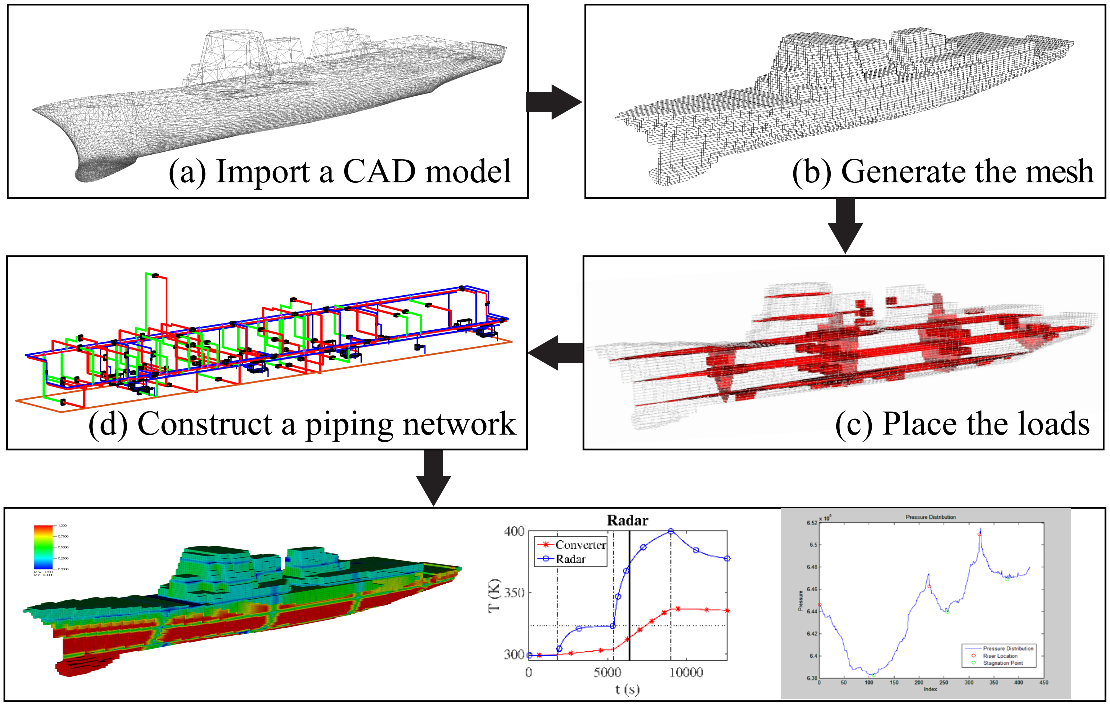
$$\frac{dT_i}{dt} = \frac{1}{(\rho Vc)_i}\left[\sum_{j=e,w,t,b,n,s}\dot{Q}^j + \dot{Q}_{gen} + \dot{Q}_{conv}\right]_i, \tag{5}$$

where $1 \le i \le N$, with N being the total number of elements in the mesh; T_i is the temperature of element i; ρ and c are density and specific heat of the material inside the element (fluid and/or solid); V is the total element volume; $\dot{Q}^j$ is the heat transfer rate across east, west, top, bottom, north, south faces of element i by conduction, natural or forced convection, and radiation; $\dot{Q}_{gen}$ is the heat sink or source inside the element; and $\dot{Q}_{conv}$ is the net heat transfer rate collected/rejected through convection by one or more fluid streams (e.g., chilled water, air or seawater) that flow across the element i. Note that heat transfer interactions with adjacent elements through the six faces are quantified by employing fundamental laws of heat transfer as well as appropriate empirical correlations.

vemESRDC is a unique tool that allows for the calculation of ship equipment and shipboard space temperature and relative humidity within permissible time owing to its simple mathematical formulation. In addition, the tool captures the intricate dynamic thermal interactions between ship components as well as with their respective surroundings and cooling systems—by assuming a virtual piping network with negligible pressure drop. Therefore, CSDT complements vemESRDC by providing a realistic piping network with pressure distribution.

III. INTEGRATION PROCESS

The first step in the integration was to translate CSDT from MATLAB to Fortran to rebuild it as a standalone tool, independent of MATLAB and its built-in functions that require the users to purchase the software. Furthermore, not only this transition facilitates its coupling with vemESRDC written in Fortran, but also its integration with S3D [15] that is in its transition to C++. Once the translation to Fortran was



(e) Export results including indoor temperature and relative humidity fields, temperature variations of ship loads, pressure distribution in the piping network, etc.

Fig. 1: A simplified flowchart of the integrated tool.

completed, we defined the key roles of CSDT and vemESRDC in the integrated tool as follows:

1) vemESRDC imports and extracts all necessary data such as ship geometry, cooling strategies, and thermal loads for simulation, minimizing the need for the users to interact with both tools. The variables passed from vemESRDC to CSDT include length overall (LOA), beam, number of thermal zones, and locations of bulkheads, decks, chillers, and thermal loads as well as the cooling parameters, e.g., cooling fluid type, mass flow rates, heat generation rate, etc.
2) CSDT constructs a double main piping network based on the ship geometry and thermal load data provided by vemESRDC, and computes steady-state velocity and pressure distributions in the piping network before vemESRDC is initialized to solve for dynamic or steady-state thermal responses of equipment and shipboard spaces.

According to the results presented by Babaee et al. [8], the transient period in the ship piping network is short; that is, chilled water mass flow rates are high enough that its transient effects can be neglected. This supports the validity of employing the steady-state model of CSDT.

We retained the unique features of each tool in the integration by minimizing the modification of original variables and the number of interactions (e.g., function calls) between them. For instance, chiller locations in CSDT are defined starting from the forward-most port side chiller towards starboard, then aft—all with respect to the global origin which in CSDT is defined at the amidships, centerline, and baseline of a ship. In vemESRDC, chiller locations are solely defined by the user-input coordinates with respect to the global origin defined by the imported CAD model, typically located near the bow, centerline, and baseline of a ship. Locations of other ship components such as bulkheads and equipment are defined likewise. As a result, we created a separate Fortran module containing shared coordinate variables that are rescaled or transformed accordingly, without affecting any existing variable. In this manner, we also facilitate the integration and allow the users to easily modify a tool in isolation. A simplified flowchart of the integrated tool is depicted in Fig. 1.

A. *Assumptions*

We highlight the following assumptions imposed to simplify the integration:

1) Negligible temperature variations along the pipe as shown in [7].
2) Chilled water supplied from the chillers at 6.67 °C.
3) Chilled water temperature at the equipment outlet is equal to that of the equipment; hence we neglect heat exchangers in all thermal loads and the resulting head loss.
4) The default main piping height is 5.2 m on the port side and 10.2 m on the starboard side. The extents of the rectangular double main piping system is 3 m from the bow, 3 m from the stern, and half the beam minus 0.9 m from the centerline.
5) The piping offset distance between the supply and return header is 0.5 m. Similarly, the offset distance

for the branch piping is 0.1 m.

In addition, there are assumptions related to the location of valves, pumps, seawater piping, and thermal characterization of loads and cooling methods which are described in [7], [10].

B. Determination of chilled water mass flow rates

The integration of CSDT and vemESRDC requires a careful assessment and coupling of cooling variables on which both tools are heavily dependent. For example, chilled water mass flow rates directly affect ship thermal response modeled by vemESRDC as well as velocity and pressure distributions in the piping network modeled by CSDT. The three primary cooling methods employed by the US Navy for its future electric ships are chilled fresh water, seawater, and chilled air. Large thermal loads such as radar, generator, and railgun are typically cooled by fresh water, whereas smaller thermal loads are cooled by chilled air which is, in turn, cooled by chilled fresh water. Since CSDT does not model the air-conditioning systems beyond the load they place on the chilled water systems, only freshwater-cooled loads are considered for the arrangement of piping networks.

As standalone tools, both vemESRDC and CSDT compute the fraction of the total zonal chilled water mass flow rate supplied to each thermal load differently. In case of vemESRDC, the mass flow rate fraction, denoted as ϕ henceforth, is determined by first computing the minimum allowed zonal mass flow rate ($\dot{m}_{fw,z}$) required to maintain all equipment under their ceiling temperatures from a simple energy balance as

$$\dot{m}_{fw,z} = \frac{\dot{Q}_{tot,z}}{c_{fw}\left(T_{design,z} - T_{fw,s}\right)}, \tag{6}$$

where z and $T_{design,z}$ stand for zone and equipment ceiling temperature, respectively, c_{fw} is the specific heat of chilled water, and $T_{fw,s}$ is the temperature of chilled water supplied to each load in the respective zone (e.g., $6.67°\mathrm{C}$). Noteworthy is that $\dot{Q}_{tot,z}$ is the sum of zonal chilled water and air-cooled thermal loads, owing to the fact that air conditioning units are also cooled by chilled water. Zonal mass flow rates of chilled air are determined in the same manner as for the freshwater, by replacing $\dot{Q}_{tot,z}$ in Eq. (6) with the zonal air-conditioned thermal load [10]. Subsequently, the corresponding ϕ supplied to equipment i was determined according to the ratio of the component's heat generation rate ($\dot{Q}_{gen,i}$) to $\dot{Q}_{tot,z}$ in the respective zone. The conservation of mass is respected in all cases, i.e., the sum of ϕ in each zone is unity.

The piping network generated by CSDT comprises supply and return headers connected to chillers and loads through risers and branches, respectively. CSDT computes the chilled water mass flow rate in branches by assuming an initial fluid velocity and estimating piping diameters based on the thermal load. The tool then refines branch and header velocities and mass flow rates using FNA that accounts for head losses given by Eq. (1). The total zonal mass flow rate in the supply and return header is determined by adding up the mass flow rates in branches corresponding to the zone.

We reversed the order in which CSDT computes the mass flow rates in the integrated tool. First, vemESRDC computes the total zonal mass flow rate and ϕ as described earlier and passes them to CSDT. Subsequently, CSDT takes these values to compute branch velocities by estimating a reasonable branch piping diameter according to [7]

$$D = \left(\frac{4K\dot{Q}_{gen}}{\pi C}\right)^{2/5}, \tag{7}$$

where $K = 4.5\ \mathrm{gpm/ton}$, $C = 4\ \mathrm{ft/s/in}^{0.5}$, and $\dot{Q}_{gen}$ is given in ton. The estimated diameters are then rounded up to the nearest diameter found in the database or set to 0.015 m as the minimum branch piping diameter.

The estimated velocities are then refined using FNA as described earlier, in which overall loss coefficients for the branches and header segments are used to set up a resistance network. Consequently, these velocities are refined by solving the resistance network and the conservation of mass. After each iteration, the solved velocities are compared against the previous velocities and this process is repeated until their difference is within a prescribed tolerance, e.g., $\Delta v < 10^{-8}\ \mathrm{m/s}$.

IV. INTEGRATION RESULTS

We present the results of a simple case study conducted to verify the integration; since this initial step of the project is the conversion of the code to Fortran and subsequent integration, we present only an overview of the simulation conditions and results to demonstrate the successful integration, but leave detailed analysis to external papers. Imposed simulation and ship operating conditions, such as weather and cooling parameters, can be found in [10] under battle mode. We included 58 notional thermal loads in our simulation excerpted from [10]; of those, 25 are freshwater-cooled loads that were included in the piping network. Fig. 2 shows the volume element mesh of the notional all-electric ship with 8 bulkheads and 10 decks, visualized in ParaView [16].

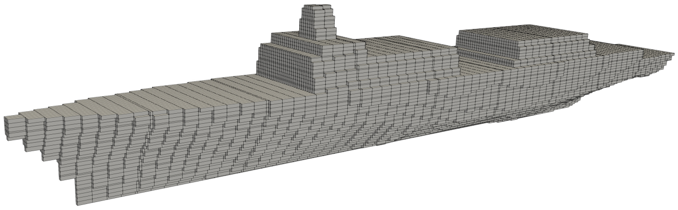
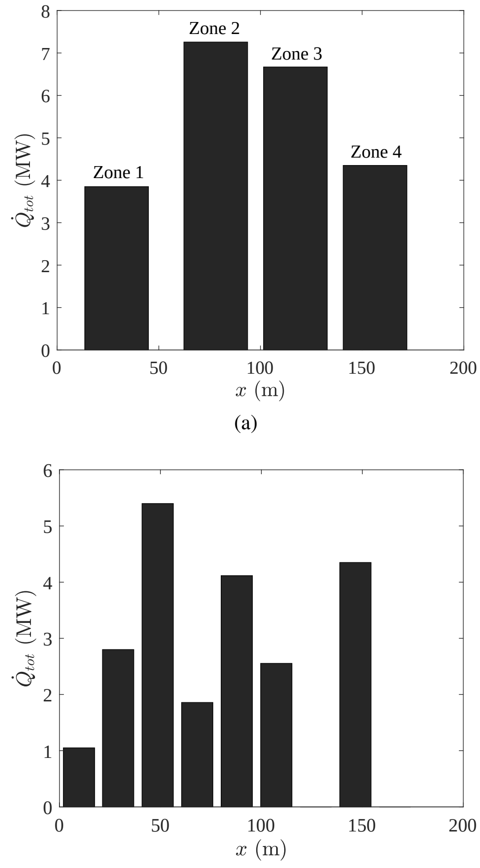


Fig. 2: Volume element mesh of the notional all-electric ship under analysis.

The total thermal load per zone and per compartment are illustrated in Fig. 3, wherein the compartments are separated by user-defined number of bulkheads and their coordinates are given in the x-direction, i.e., longitudinal axis. Fig. 3 can be used to determine appropriate number of zones and bulkheads for uniform distribution of thermal loads in a ship.

Fig. 4 shows the evolution of chilled water velocities in the header and branches as they are refined using finite element analysis (FNA) i.e., intermediate and final. Note that the results in Fig. 4 pertain to a case where only the forward-most port side chiller and its pump are in operation. The branch index corresponds to the order of the branch junctions along the supply header. For example, branch index 1 is the



(a)

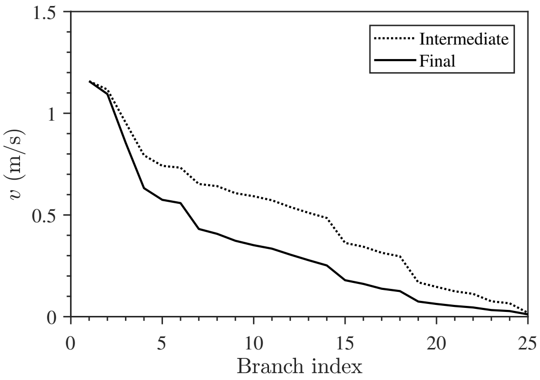
(b)

Fig. 3: Total thermal load (a) per zone and (b) per compartment separated by bulkheads; x represents the distance along the longitudinal axis.

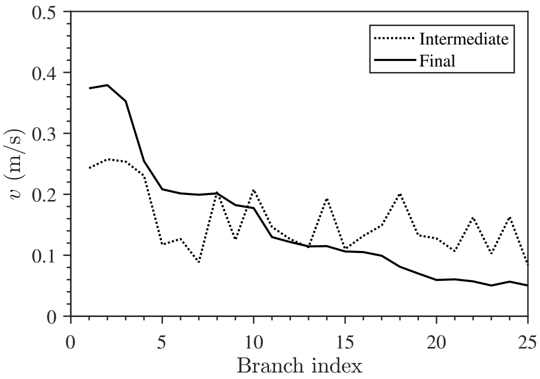
first branch junction after the riser junction, assuming flow in the clockwise direction through the supply header while the isolation valve between the last branch junction and the riser is closed. According to Fig. 4a, the chilled water velocity decreases along the length of the supply header, and a similar trend is observed with branch velocities in Fig. 4b as the distance from the branch junction to the riser increases.

The pressure along the supply header is depicted in Fig. 5 with respect to the distance from the riser junction. The chosen reference point in Fig. 5 (i.e., $x = 0$) corresponds to the forward-most port side riser junction (the first chiller in Zone 1 as in Fig. 4), and the clockwise flow along the supply header is extended in the $+x$ direction. The asymmetry of the curves in Fig. 5 can be attributed to pressure drops computed as functions of velocities that vary with the flow direction due to different head losses.

In addition to velocity and pressure distributions, variations in the required cooling capacity, the chilled water temperature at the return riser of each zone, and the radar temperature are displayed as functions of time in Fig. 6. The instantaneous cooling demand per zone plotted in Fig. 6a implies the amount of heat that must be removed by the chiller. Note that two chillers in each zone have been merged as one to simplify the analysis; since the flow through the pipe is assumed to be adiabatic, the piping network does not affect the chilled water temperature beyond providing connectivity to heat sources and sinks. Fig. 6b shows the return temperature of the chilled water over time. The imposed zonal mass flow rates and ϕ ensured that all equipment remained within their design temperatures; see, e.g., the radar in Fig. 6c.



(a) Supply header



(b) Branch

Fig. 4: Refined header and branch velocities with only the forward-most port side chiller in operation.

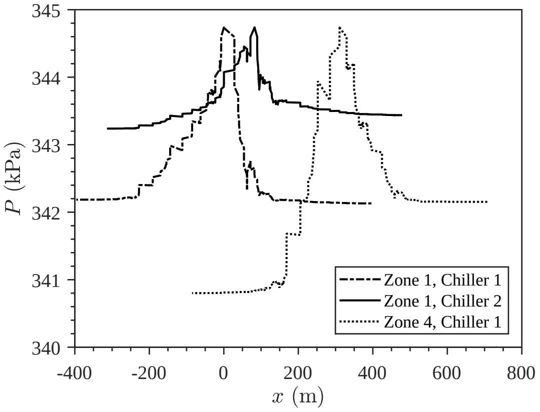
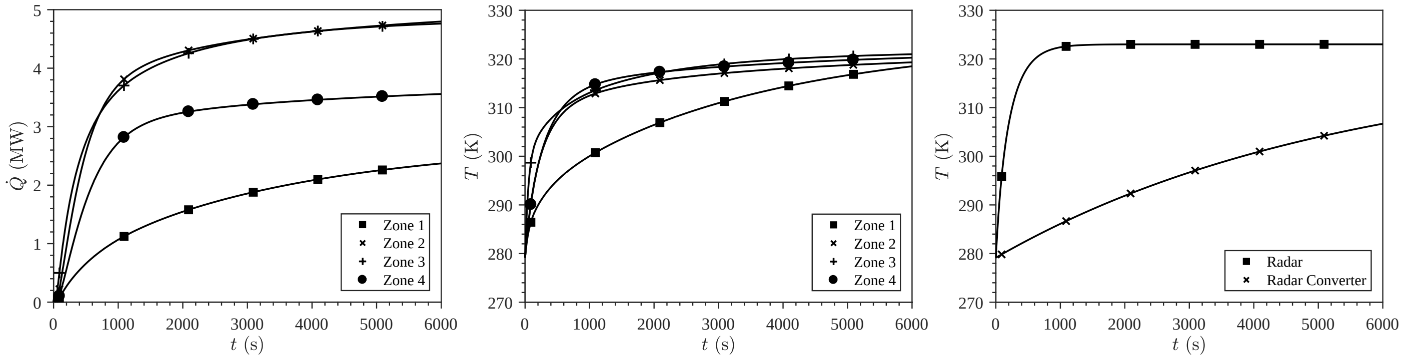


Fig. 5: Pressure along the supply header.

Fig. 7 shows the ship temperature field in 3D with the piping network, in which the ship has been partially sliced along the centerline to display both interior and exterior temperatures. This feature can be used to investigate the indoor



(a) Cooling demand (b) Chilled water (c) Radar / Converter

Fig. 6: Cooling demand and temperature of chilled water, and radar as functions of time.

thermal environment, such as the temperature variation of air surrounding a load or the effects of exterior conditions (e.g., weather) on indoor thermal responses. Further analysis of the interaction between an equipment and its surroundings can be performed to determine optimal equipment distribution across the ship for enhanced heat dissipation. In Fig. 7, for example, the shipboard spaces below waterline exhibit relatively low indoor temperatures owing to the absence of direct solar irradiance and lower surrounding seawater temperature than that of air. Therefore, placement of large thermal loads below the waterline may enhance heat dissipation and reduce the cooling load imposed on chillers.

We extended the visualization feature for the integrated tool to export the piping network as .vtk file, enabling the users to display it within the simulated ship as shown in Fig. 7. We can verify in the figure that the branches are appropriately connected to the loads placed in the volume element mesh. However, the piping network generated in this work does not fit within the considered notional all-electric ship; part of the risers extending from the chillers as well as few branches and auxiliary seawater network cross the ship boundary. Further enhancement in the network construction algorithm, such as the use of parametric equations that define the ship boundary, is necessary.

V. CONCLUSION AND FUTURE WORK

The objectives of the present work were to (1) translate CSDT from MATLAB to Fortran; (2) identify variables to be shared between the two complementary tools and integrate; and (3) verify the coupling via a simple case study. As an initial step, we coupled the steady-state model of CSDT with vemESRDC for pressure and temperature analysis in the piping network generated using the data from vemESRDC. Future work may include the addition of a chilled air network as well as the implementation of chiller and heat exchanger models for more sophisticated cooling system analyses. Furthermore, the piping network can be discretized in space using volume

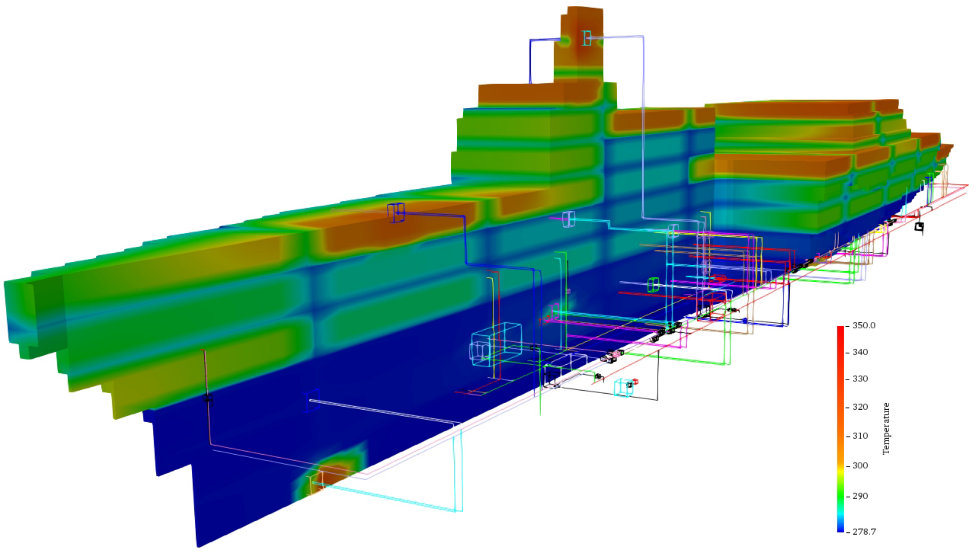


Fig. 7: Combined visualization of the notional all-electric ship under analysis obtained with the integrated tool. Note that the ship has been partially sliced along the centerline.

elements as in vemESRDC, and account for the transient effects in the piping network with a system of ODEs.

We anticipate the integrated tool to serve as a practical and reliable early-design stage ship thermal management tool in the near future, and allow naval architects to examine and visualize different aspects of ship thermal responses. Although further improvements are required, we demonstrated herein the unique capabilities and potential of the integrated tool to provide insights into appropriate cooling system designs that ensure proper operation of every ship equipment in all conceivable operating modes.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the contributions of Ethan Fiedel and Amiel Ben Sanfiorenzo who wrote the initial versions of the Cooling System Design Tool while graduate students at MIT, and the contributions of Dr. Hessam Babaee who created the System-level Marine Cooling System Design tool while a post-doctoral associate at MIT. CDR Fiedel and LCDR Sanfiorenzo returned to serve on active duty with the United States Navy upon leaving MIT, and Dr. Hessam Babaee is now a professor at the University of Pittsburgh.

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