Thermal Modeling and Simulation of the Chilled Water System for Future All Electric Ship

Ruixian Fang[1], Wei Jiang[1], Jamil Khan[1], Roger Dougal[2]
Department of Mechanical Engineering[1] and Department of Electrical Engineering[2]
University of South Carolina, Columbia, SC, USA

Abstract— **A system-level model for a combatant ship's chilled water system is described and developed in this paper. Some major thermal components related to dynamic aspects are identified in detail. Given the vital heat load for each compartment and equipment, the steady state performances are evaluated for the normal two-loop alignment. Dynamic behaviors are also investigated at different operating conditions. Several extreme cases such as pipe rupture in the vital branch and time to overheat are also studied to evaluate the system survivability. The work presented in this paper continuous the efforts for using Virtual Test Bed as a potential system-level dynamic simulation platform for an all-electric ship thermal management.**

Keywords: *thermal modeling, chilled water system, thermal management, ship cooling system, Virtual Test Bed*

I. INTRODUCTION

For the Navy's future all-electric ships, thermal issues become more important due to the large amount of additional heat load generated [1-3]. The addition of advanced power electronics and weapons will result in heat loads eventually requiring a 700% increase over currently installed cooling capacity [4]. Advanced power electronics require a system approach to enable the high heat flux to be dissipated to the sea. To address thermal issues earlier in the design process, for example, loss of chilled water in the cooling system will result in overheating and eventually casualty of electronics, dynamic simulation tools for thermal management are essential for the development of the future all-electric ships.

Thermal management of a combatant ship consists of three main types of cooling approaches: freshwater cooling, seawater cooling and chilled water cooling. The fresh water cooling is mainly used for power converter module cooling or electronic device cooling. The seawater cooling is direct cooling with centralized seawater cooling system. The devices which use this approach include power generation module, power distribution module, air conditioning plants and steam condensers. The chilled water system is mainly used for compartment and equipment cooling. The chilled water comes from the ship's air conditioning (A/C) plants. These plants produce chilled water at 44 °F for circulation throughout the ship [5]. The rejected heat from the A/C plants is transferred to the centralized seawater cooling system. The following table summarizes the zonal heat loads on a combatant ship [6].

TABLE I.
A COMBATANT SHIP THERMAL MANAGEMENT LOAD SUMMARY

Cooling Schemes	**Heat Load (kW)**				
	Zone 1	***Zone 2***	***Zone 3***	***Zone 4***	***Zone 5***
Freshwater Cooling	110.3	368	205.7	203.6	145.6
Seawater Cooling	-------	3597	4241	3101	981
Chilled water Cooling	334.3	1108	148.7	100.6	652

Chilled water is also used as primary coolant for some combat cooling water systems, and for HVAC (Heating, Ventilating, and Air Conditioning) coils to vital spaces to provide ventilation for air cooled electronics. The chilled water system is required to support ship's heat load requirements over a wide range of operating environment.

The objective of this paper is to model and dynamically simulate the main loop and the vital branch of a combatant ship's chilled water system. The "Pilot Ship", Arleigh Burke class destroyer (DDG-51), was chosen as the basis for this thermal management simulation work. First, a baseline of the system is simulated based on available data. Then some system survivability concerns, such as time to overheat and pipe rupture in the vital branch, are investigated. The model would lay the ground work for simulating the entire ship thermal system.

The dynamic modeling tool, Virtual Test Bed (VTB), was chosen as the simulation platform. It provides an effective computational environment to simulate the dynamic performance of a ship's zonal fresh water cooling system [7], as well as thermo-electrical coupled co-simulation between a hybrid power generation system and a thermal plant [8].

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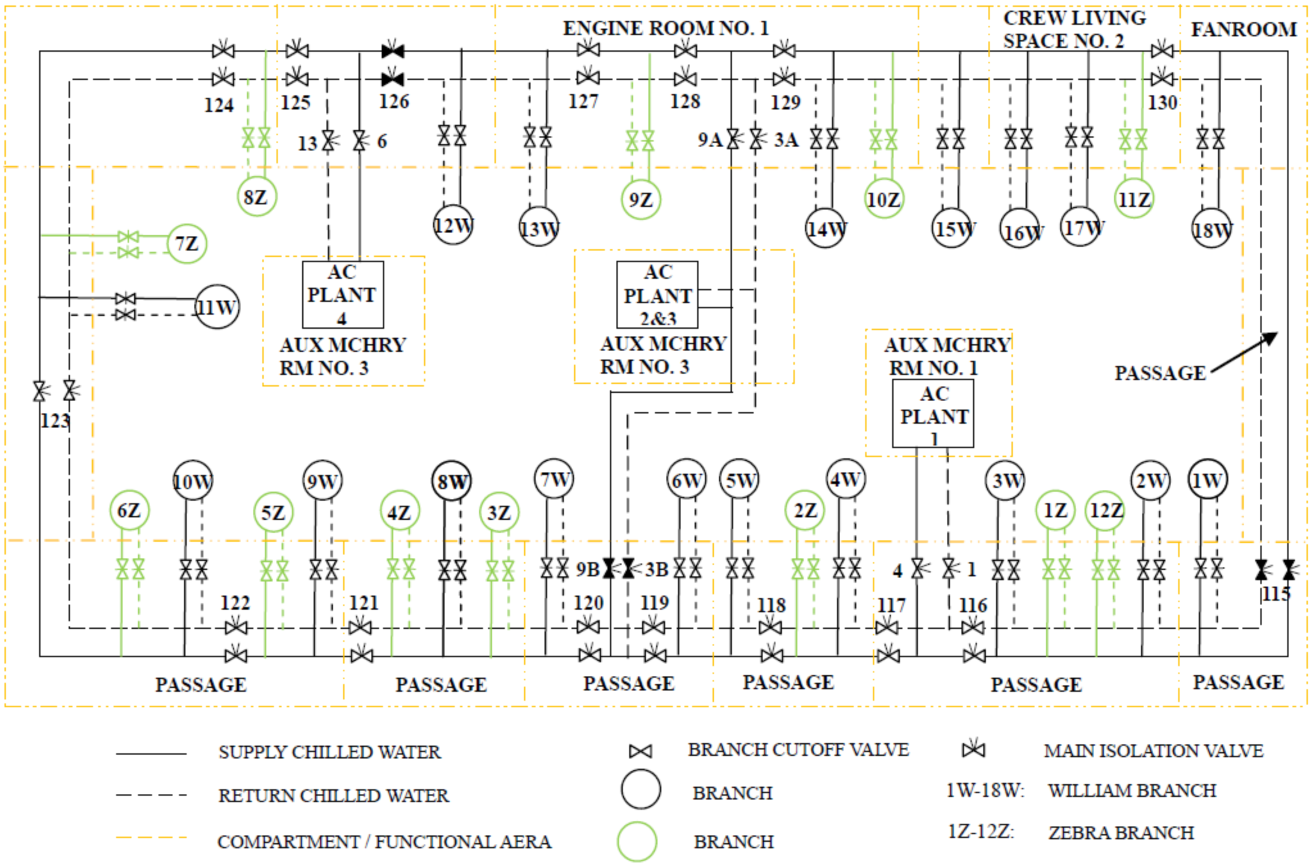

Figure 1. DDG-51 class chilled water system

II. SHIP'S CHILLED WATER SYSTEM

The layout of the chilled water system of the DDG-51 class combatant ship is shown in Figure 1 [9]. It has four 200-tons A/C plants on board and is designed to supply 44^0F chilled water throughout the chilled water system. A/C plants No. 1 and No. 4 work independently. A/C plants No. 2 and No. 3 have common supply and returning piping, they also share a common expansion tank. All the four A/C plants are connected with the chilled water supply and returning main pipes. The supply and return heads on both starboard and port sides of the ship are cross connected forward and aft. The main isolation valves, as denoted from 115 to 130 in Figure 1, segregate the system into portions and provide damages control if necessary.

The chilled water system has two types of branches, namely WILLIAM branch and ZEBRA branch respectively. As shown in Figure 1, the WILLIAM branch includes 18 zones, and the ZEBRA branch includes 12 zones. Each zone is connected with the chilled water supply and returning main pipes respectively. The branch cutoff valves can be used to isolate individual zone from the chilled water system.

Each zone of the branches includes several end users which need to use chilled water. Those end users can be compartment or equipment such as fan room, radar room, combat system equipment, sonar equipment, or crew living space, etc.

Based on the importance of the end users, the 18 zones in the WILLIAM branch are considered as vital zones in the chilled water system, while the ZEBRA branch contains those zones that have less important chilled water users comparatively.

Figure 2 below illustrates a typical zone piping distribution and end user configuration [9]. For Zone 1W in the WILLIAM branch as shown in the figure, four compartments and equipments, namely fan room and MAGAZINE room, sonar equipment No. 1 and No. 3 respectively, are cooled by the chilled water. Designed chilled water flow rate and vital heat loads for those components are listed in Table II below for illustration purpose [9].

In each zone of the WILLIAM branch, the number of compartments or equipments that need to be cooled ranges from 1-7 respectively. Vital heat loads from those components need to be dissipated by the chilled water system.

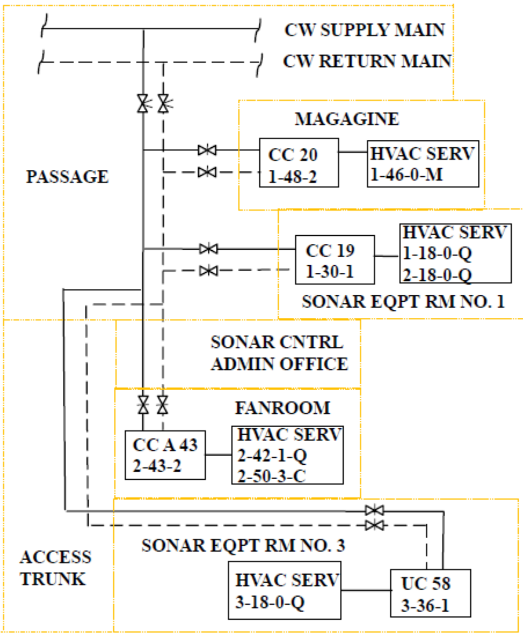

Figure 2. Zone 1W configuration

TABLE II.
ZONE 1W VITAL LOADS

Branch No.	Chilled Water User	Chilled water user Location	Designed Flow (gpm)	Heat Load (tons)
1W	CC 19	SONAR EQPT RM 1	13.7	3.80
1W	CC20	MAGAZINE RM	26.4	7.33
1W	CC A43	FAN ROOM	19.3	5.35
1W	UC 58	SONAR EQPT RM 3	36.0	10.0

III. THERMAL MODELING OF THE WILLIAM BRANCH

Thermal models for a zonal freshwater cooling subsystem and a chiller subsystem had been described and developed in detail in the authors' previous work in the effort of the ship cooling system modeling [7]. Those basic building blocks laid the ground work for simulating the entire ship cooling system. The present work integrated those components into the required configuration of the chilled water system.

A. *The zonal thermal subsystem model*

Using zone 1W as an example, the conceptual modeling layout is partially illustrated in Figure 3. Only those chilled water end users that generate heat are modeled. For system-level simulation, each compartment or equipment room is considered as a lumped cabinet. Inside each cabinet, the heat load is dissipated into the chilled water through forced convection heat transfer via a cooling coil or heat sink type of heat exchanger (HEX). The heated chilled water that comes out from each cabinet joint together and return to the main pipe.

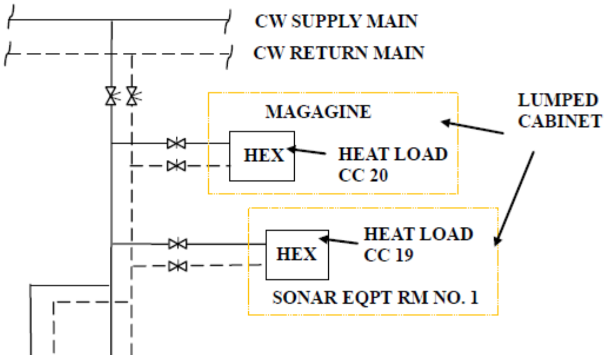

Figure 3. Zone 1W modeling conceptual layout

The modeling layout for zone 1W is fully implemented in the VTB simulation environment as shown in Figure 4 below.

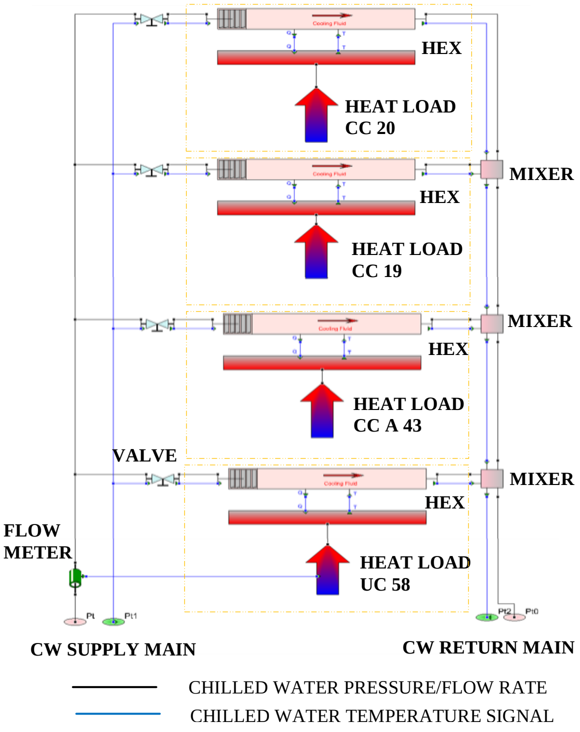

Figure 4. VTB schematic of chilled water cooling for zone 1W

The components in the above zonal modeling include heat source models, heat sink models, valves models, pipes models, and fluid mixer models. The heat sink model is a transient model. It includes two VTB thermal models as shown in Figure 4: one heat-sink model and one plate-fin heat exchanger model. These two models together represent a physical heat sink. It is assumed that the equipment temperature is the same as the heat sink temperature.

Detailed mathematic descriptions of the models were presented in [7]. The mixer model is used at the pipe joints where two streams with different temperatures and flow rates are meeting. Energy balance is applied to this model. The heat source model provides constant heat load from each chilled water user. VTB can distribute the mass flow rate into each of the four cabinets internally based on the fluid system characteristic. The valve models are used to control the flow rate of each end user by adjusting the valve openings respectively.

Same thermal modeling method is applied to all the 18 zones of the WILLIAM branch in the chilled water system. Totally 53 compartments and equipments are modeled in this simulation. Figure 5 shows the VTB schematic of the WILLIAM branch. Limited by the paper length requirement, only a portion of it is displayed here. The model has 18 sub layers. Those sub layers contain the detailed models for each zone.

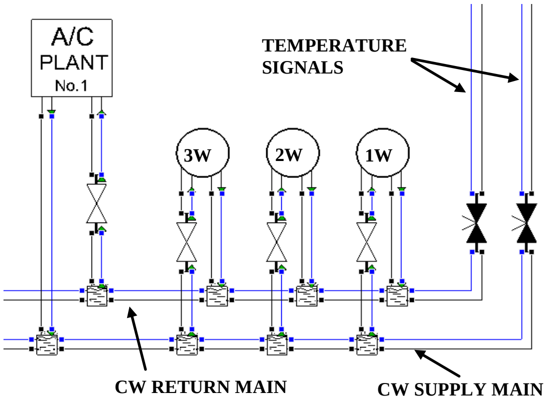

Figure 5. Portion of VTB schematic of the WILLIAM branch of chilled water system

B. *The A/C plants model*

For the A/C plants, it is still a big challenge to simulate more than two chillers in parallel because of the complexity of phase changing inside the chiller model. For the present simulation, each chiller is simplified as a heat exchanger with the cold side fluid entering it at a constant temperature of 44^0F, as shown in Figure 6. By this simplification, the dynamic details of the chiller is hided, and the chiller is idealized as a constant temperature sink. This assumption is applicable for system-level chilled water system simulations.

The transient plate and frame heat exchanger model is employed for modeling the chilled water to chiller water heat transfer. The heat transfer surface area of the heat exchanger is assigned to a large value so that the exit chilled water temperature is nearly 44°F. Detailed model mathematic descriptions and validation of the model were also presented in [7].

The chilled water pump is modeled based on the pressure versus flow rate characteristic. Each pump has a capacity of 900 GPM. The total head pressure is 75 psig. The pressure head drives the flow circulation through the chilled water system. The valve models are used to regulate the flow rate.

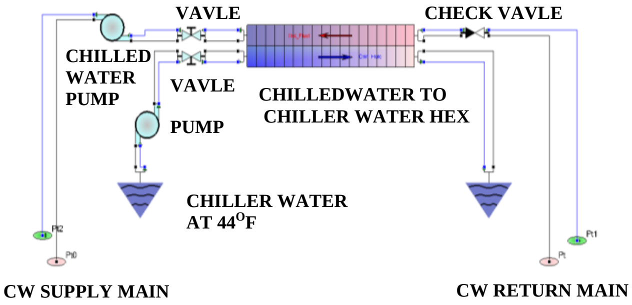

Figure 6. VTB schematic of the A/C plant No. 1 model

A/C plants No.2 and No.3 are modeled in a similar way as A/C plants No.1, except that they run in parallel and share a common pressure head as indicated in section II.

IV. CHILLED WATER SYSTEM ALIGNMENTS

The alignments of the chilled water system can be configured based on the load requirements. This is implemented by close corresponding valves on the main loop. Normally, the system is operated in two loops for full load [9], namely starboard loop and port loop as shown in Figure 7 below. The starboard loop fed from A/C plants No. 1 and No. 4, and the port loop fed from A/C plants No. 2 and No. 3. Valves 115, 126, 9B and 3B are closed in this alignment.

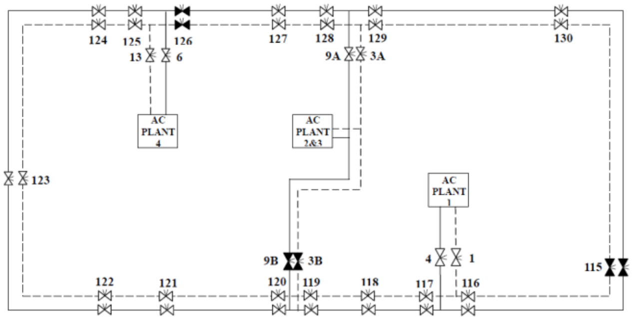

Figure 7. Normal two-loop alignment

During low operating loads normally experienced in cold weather or in port, only one A/C plant may be needed to satisfy load requirements. However, single chilled water pump operation cannot satisfy system head requirements. One or two chilled water pumps in other A/C plants need to be in operation to provide additional head to the loop. Figure 8 illustrate one configuration for low load alignment with A/C plant 1 and chilled water pump 4. Other low load alignments may also applicable such as A/C plants 2 and 3 operating with chilled water pump 4.

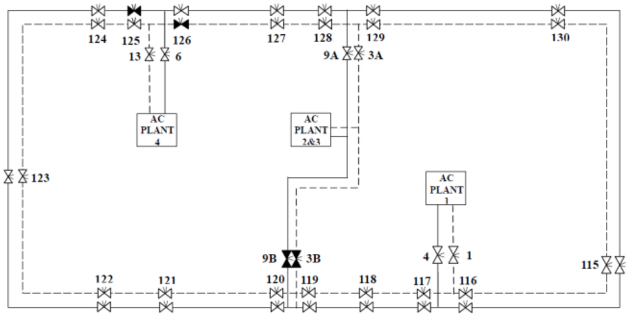

Figure 8. Low load alignment with A/C plant 1 and chilled water pump 4

V. EXAMPLE SIMULATION AND RESULTS

In present simulation, the normal two-loop alignment with vital loads for WILLIAM branch is simulated for both steady state and dynamic sate.

A. Steady state analysis

For steady state analysis, vital heat loads for each chilled water user [9] are assigned to the corresponding heat source models respectively. The chilled water flow rate for each end user is regulated by their corresponding valves. Same parameters are set for A/C plants 1 and 4 in the starboard loop. Also same parameters are set for A/C plants 2 and 3 in the port loop. VTB can distribute flow rate into branches based on their flow resistance. The mass conservation and the pressure drop versus flow resistances relation are always satisfied at each time step during simulation. Table III below summarizes the heat loads, flow rate and the resulting temperature from simulation for each compartment or equipment.

TABLE III.
CHILLED WATER VITAL LAODS AND SIMULATION RESULTS

Branch No.	Chilled Water User	Flow Rate (gpm)	Heat Load (tons)	Temperature (^{o}C)
1W	CC 19	13.7	3.80	32.36
1W	CC20	26.4	7.33	34.04
1W	CC A 43	19.3	5.35	36.42
1W	UC 58	36.0	10.0	43.22
2W	CC23	36.0	10.0	22.18
3W	CC82	54.9	15.24	32.41
3W	FCA11	13.7	3.8	20.41
3W	FCA8	18.5	5.14	24.65
3W	CC5	86.0	23.9	82.55
3W	SLQ-32	20.0	12.09	48.49
4W	C&D STBD	140.0	39.25	71.00
4W	CC A 61	31.0	8.60	36.64
5W	CC D 13	34.3	9.53	41.40
5W	CC B 14	49.0	13.6	53.96
6W	FCA 30	7.10	1.97	37.47
7W	CC A7	13.4	3.73	20.21
7W	FCA 17	14.9	4.15	21.50
7W	FCA 36	23.6	6.56	24.43
7W	CC A37	18.4	5.10	28.91
8W	CC 42	28.2	7.84	33.00
9W	CC 54	22.1	6.14	27.74
10W	CC 55	5.3	1.47	13.45
10W	CC 51	38.0	10.55	41.38
10W	FCA 53	13.1	3.63	19.99
11W	UC 57	5.0	1.39	19.53
11W	CC 69	15.5	4.3	30.92
11W	CC 41	25.9	7.19	40.53
11W	GC 95	3.0	0.83	17.37
11W	TACTAS	10.0	2.59	24.63
12W	LAPC 2	4.0	2.21	27.85
12W	LAPC 3	4.0	2.21	27.85
12W	CC 87	13.4	3.73	25.21
13W	CC 85	27.6	7.70	32.56
13W	CC C13	34.3	9.53	38.21
13W	CC C14	32.4	9.0	36.57
13W	CC A14	49.0	13.6	50.81
13W	CC 83	45.7	12.68	47.96
13W	AN/SPY 3	25.0	7.57	32.34
13W	AN/SPY 4	25.0	7.57	32.34
14W	LAPC 1	4.0	1.11	20.21
15W	CC 60A	68.0	18.87	67.17
15W	CC B61	31.0	8.60	26.50
16W	AN/SPY 1	25	7.57	32.36
16W	AN/SPY 2	25	7.57	32.36
16W	CC 2	20.3	5.55	25.90
16W	CC 4	86.0	23.9	54.99
16W	CC 18	13.4	3.72	20.28
16W	CC 21	15.7	4.36	22.25
16W	CC 24	16.6	4.61	23.03
17W	CC 71	16.9	4.69	23.25
17W	C&D PORT	140.0	39.25	69.52
18W	CC B43	19.3	5.36	25.32
18W	AN/SQS-53	36.0	14.62	54.94

The total chilled water flow rate is around 1580 GPM (100 kg/s) for all 18 zones. And totally around 455 tons of heat load (1600 kW) is dissipated through the chilled water system. In which, A/C plants 1 and 4 dissipated 118.3 tons and 111.1 tons respectively, while A/C plants 2 and 3 dissipated the same amount of 111.5 tons each. The loads difference between A/C plants 1 and 4 is caused by the position where they are located in the starboard loop. Comparatively, zones near A/C plant 1 generate more heat load than zones near A/C plant 4.

The resulting temperatures for each compartment or equipment are listed in the above table for illustration. They are calculated based on the heat transfer coefficient and surface area of the cooling coils or heat exchangers. For this example simulation, same type of the cooling coils is assigned for each end user, whereas the size is adjusted based on the corresponding heat load. In real case, the type and size of the cooling coils may differ from equipment to equipment. Temperatures can be accurately simulated by detailed modeling of each individual cooling coil.

From the steady state simulation with vital load, the hot equipments can be readily identified. The temperature distribution can also be mapped out for the system.

B. *Dynamic simulation*

By using this chilled water system model, the system's dynamic behavior can be investigated. It will permit system-level analysis of technology options and design tradeoffs in the thermal management area. In this section, the dynamic behaviors of the chilled water system are investigated for the following two cases:

Case (a) Isolate 5 zones from the chilled water cooling system

Case (b) Pipe rupture in vital branch

Both cases are simulated with the normal two-loop alignment (Figure 7).

1) *Case (a) Isolate 5 zones from the chilled water cooling system*

In this case, the system dynamics of isolating zones from the main loop are investigated. This is achieved by close the branch cut-off valves for the zones that need to be isolated. In this investigation, zone 3W, 5W and 10W in the starboard loop, and zones 13W and 15W in the port loop will be detached at the same time. The variation of total heat load dissipated by the system and the responses of equipment temperatures at other zones are discussed in the following.

First, startup the chilled water system simulation with all the 18 zones connected and operating in full loads, and with an initial temperature of 10 ℃, after the system reaches its steady state, pause the simulation and detach those 5 zones from the main loop. While the zones are detached, the heat loads associated with the heat sources insides those zones need also to be removed. Then continue to run the simulation till it reaches the next steady state.

In Figure 9, the variation of heat dissipated by the chilled water system is plotted. By detaching zones from the system, the total heat load is reduced. As it can be seen from the figure, heat dissipation from each A/C plant is reduced correspondingly. The load distribution between A/C plants 1 and 4 is determined by the system. Again, they are slightly different at new steady state. Heat loads for A/C plants 2 and 3 are always the same since they share common supply and returning piping and have common head all the time.

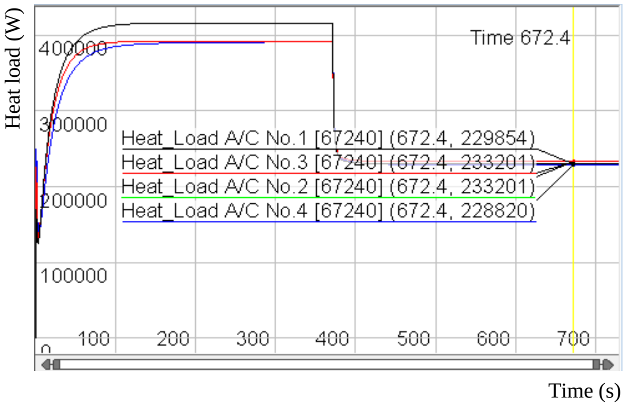

Figure 9. Variations of heat dissipated from the chilled water system

Figure 10 below shows the typical variations of temperature in neighborhood zones. Using zone 1W as an example, the temperature for each compartment or equipment is lowered by 1 ℃ ~ 2 ℃ as a response to this system-level load change. This temperature lowing phenomena is caused by the redistribution of chilled water flow rate. As the result of removing several branches, the flow rates through the remaining branches are increased.

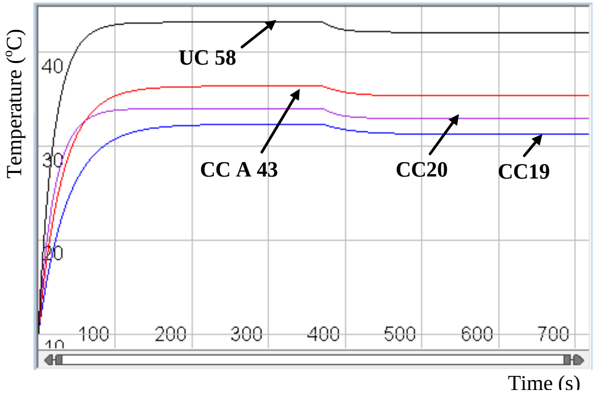

Figure 10. Temperature variations of the end users in zone 1W

2) *Case (b) Pipe rupture in vital branch*

For survivability concerns, water loss may affect entire loop if there is rupture in the main supply or returning pipe. If the pipe rupture happens in the vital branch, it may cause equipment overheating in a short time. In those cases the dynamic simulation may help to estimate the time to overheat or evaluate the damage effects on other zones in the system.

Figure 11 illustrate a damage example simulation for a total loss of chilled water for zone 1W. It takes around 60 seconds for UC 58, which is the equipment in the sonar equipment room, to overheat. Other than that, the flooding may over 95 gallons per minute at zone 1W. In real case, the overheating can be prevented by damage controls within the limited reaction time.

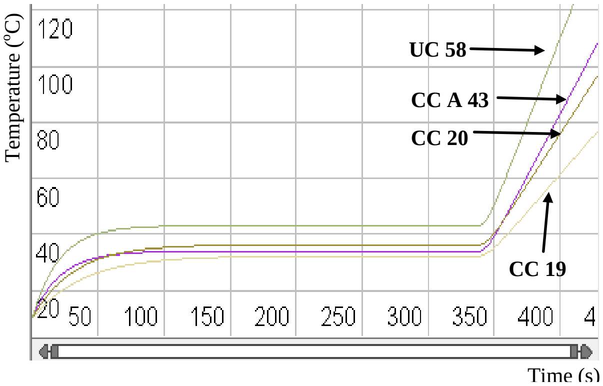

Figure 11. Temperature variations for loss of chilled water of zone 1W

Similarly, many other dynamic cases can also be studied by using this simulation, such as pipe ruptures in the main loop, low load system alignments, adding non-vital branches into the system, etc.

VI. CONCLUSION

This paper presented a system-level dynamic simulation model for the chilled water system of a combatant ship. The chilled water system on board of DDG-51 class vessel is employed as the base line for the modeling. Modeling method for the vital branch is described in detail. Steady state performance is evaluated for the system with vital heat load. Dynamic behaviors of the system response to isolating zones from the main loop are analyzed. Also, a damage example simulation for pipe rupture in a vital branch is performed to evaluate the time to overheat. Though it is simplified, the results from these simulations clearly demonstrate the ability of the model to capture the major dynamics of the overall system. This model also outlined a typical portion of such a configuration for the whole ship cooling systems. More work need to done on detailed thermal modeling of each compartment or equipment, integrating A/C models into the system, and coupling the system with dynamic heat loads before we can eventually perform system-level simulation and get fidelity results.

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