A Comparison of Thermal Management Design Tools S3D and ATTMO

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***Abstract*—Two software tools developed under Office of Naval Research auspices address design of thermal management solutions: Smart Ships System Design (S3D), and the Air Force Research Lab (AFRL) Transient Thermal Management Optimization (ATTMO). This paper describes the use of both tools in modeling small and large thermal systems to note the relevant use cases for the software tools and explore areas of synergy in their development and use.**

***Index Terms*—ship systems, thermal management, design tools**

I. Introduction

As Navy ships evolve technologically, they need an increasing amount of power, and these power systems generate heat. As a result, there is increased interest in development of tools for modeling shipboard thermal management systems.

The Office of Naval Research (ONR) has sponsored development of two thermal management system design and analysis tools: Air Force Research Laboratory (AFRL) Transient Thermal Management and Optimization (ATTMO) and Smart Ship System Design (S3D). This paper reports on a project that used both tools to model a simple system and a more complex system, with the goal of comparing capabilities of the tools and their applicability to different design problems.

The paper is organized as follows. Section II provides a short introduction to each tool. The modeling of the small experimental system is presented and discussed in Section III, and the large system is presented in Section IV. Conclusions and recommendations are presented in Section V.

II. Background

A. Introduction to ATTMO

ATTMO is a multi-domain, transient modeling toolset developed by PC Krause and Associates for integrated power and thermal systems. Integrated, component-based modeling began with a transient thermal management system (TMS) toolset for capturing heat transfer to and from fuel throughout an aircraft [3]. Building off the TMS toolset, a dynamic vapor cycle system (VCS) modeling package was developed to address controls and testing strategies throughout flight, with air cycle system (ACS) components added later in development [5]. This version of the toolset became the AFRL Transient Thermal Management and Optimization (ATTMO) toolset [2], [4]. While ATTMO's primary modeling focus is on dynamic fluid modeling, the addition of complex electrical components, generators, motors, and ACS components necessitated accurate modeling of additional, critical domains. As such, electrical, thermal, and rotational/mechanical domains were added to enable integrated multi-domain modeling.

ATTMO is an open-source, Matlab/Simulink toolbox and can be freely distributed and used for all department of defense (DOD) contractors. The underlying infrastructure of the toolset utilizes physical lines and ports for connecting components in any given domain. Core domain blocks handle all signal passing and critical calculations between components, while calculations within the components themselves allow for multiple domains to interact directly. As ATTMO has expanded to contain many components capable of modeling numerous system architectures, an emphasis has been placed on balancing simulation speed and model fidelity such that model components are capable of accurately capturing critical behavior while maintaining high simulation speed.

B. Introduction to S3D

S3D is a software environment developed by the Electric Ship Research and Development Consortium. It is used to define, analyze and understand power and energy flows in distributed systems and the physical implications in terms of weight, volume, and location of associated components [6]. S3D is fully integrated with the Leading Edge Architecture for Prototyping Systems (LEAPS) product model, which is the U.S. Navy's data repository for ship data. S3D adheres to the Formal Object Classification for Understanding Ships (FOCUS) metamodel, which is the product metamodel for surface ships and ship systems, thus ensuring ontological consistency with other Navy tools. The LEAPS-compatible ecosystem includes S3D.

S3D allows a user to define distributed power and energy systems by selecting system components from a catalog, parameterizing the components as necessary, arranging the

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components in a schematic view, and defining the logical and physical connectivity between the components. System schematics can capture connectivity within a single physical domain (e.g. electrical), across multiple domains (e.g. electrical, thermal), or linked between domain-specific subsystems.

Every component within S3D has a mathematical representation in each applicable discipline, with models available in electrical, piping and mechanical domains. Future development is expected in the HVAC and data domains. In addition to the mathematical representation, naval architecture properties such as dimensions, weight and location are populated, and it is possible to access CAD representations of the components in the LEAPS database.

Current capability includes power-flow-level simulation and analysis for quasi-steady-state systems; thus, full system-level analysis can provide data on each system regarding the across and through values such as voltage and current for electrical simulations, flow rate, pressure and temperature for piping simulations, and torque and rotational speed for mechanical simulations. Overall system data including such metrics as power usage, losses, weight, volume, component count, and more are available now from S3D.

A fully dynamic solver is available in the toolset; however, there are currently no component models using that solver available. This is an area of future expansion.

S3D can be used as a stand-alone tool, but is also being integrated into the Navy's Rapid Ship Design Environment (RSDE) with the goal of full integration into the broader design space exploration capability used in early-stage ship design. In order to achieve full integration into a design space exploration paradigm, one area that needs expansion is the development of scalable components, in which component models include sizing algorithms that generate the dimensions and weight of a component based on a small set of inputs. Examples of scalable components that have provided test cases for the concept include a scalable permanent magnet motor developed by Purdue University [7] and scalable cables developed by Mississippi State University [1].

III. Small System Modeling

In order to explore the capabilities of the tools, two systems were modeled. The first is a a small system for which experimental data is available to use as a comparison. The experimental system is designed to test thermal interface materials under various pressure profiles; the system is a scaled-down representation of a Power Electronics Building Block (PEBB) cooled by a water-chilled cold plate. The mock PEBB consists of an aluminum plate with four $600W$ power resistors attached to it, which represent the heated electronic components of the PEBB. Water is pumped from a reservoir to the cold plate, where it cools the mock PEBB and then flows back to the reservoir; this forms the system's hot loop. A water chiller, which takes a suction from and returns water to the reservoir, is used to cool the water in the reservoir to a temperature of $26°C$; this forms the system's cold loop. The reservoir acts as an open-loop heat exchanger, mixing the cold and hot streams. A diagram of the experimental setup is shown in Fig. 1.

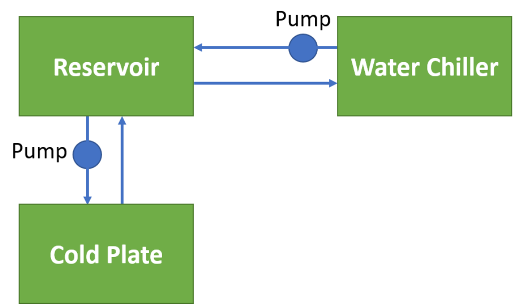

Fig. 1. Experimental system diagram.

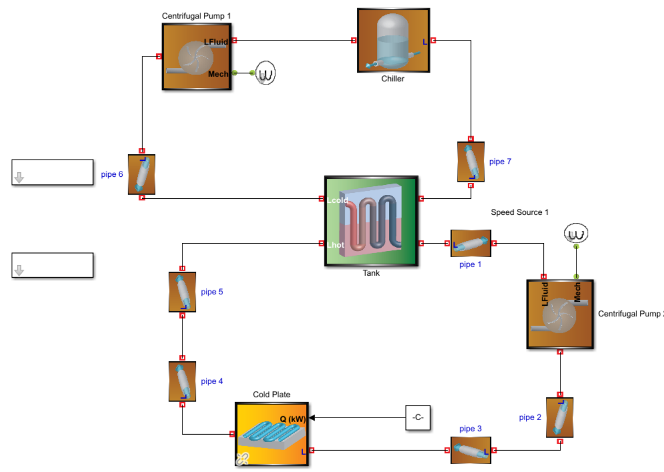

Fig. 2. Experimental system modeled in ATTMO.

A. *ATTMO Model*

The ATTMO model, shown in Fig. 2, utilizes the two-loop method shown in Fig. 1. The top section models the cold loop: the path of water between the water chiller and the reservoir. The bottom section represents the hot loop: the path of water between the reservoir and the cold plate.

In the cold loop, water is pumped from the chiller through a pipe to the reservoir, then returns via a second pipe.

The water chiller is modeled in ATTMO using a Tank Block, for which users can set variables such as volume and temperature. The tank is set to remain at a temperature of 26°C, mimicking the function of a chiller except for the power required to cool the water.

ATTMO provides the capability to model pumps in great detail. As seen in the Pump Sizing GUI in Fig. 3, a wide array of precise variables are required for input such as pressure, design head, flow rate, maximum speed, temperature, fluid type, and more. Proper selection of these properties will allow ATTMO to produce pump curves for a pump specifically designed for the application, including designation of an operating point on the curves. This can be seen in Fig. 3.

The pipe blocks in ATTMO include options to modify inner and outer diameter, relative roughness, temperature, and pressure. In addition, users can edit pipe structure by selecting from an array of piping components such as elbows of various angles, valves, and unions of various diameters. Using these components allows modeling of complex piping structures and calculating accurate pressure drop data.

The reservoir is modeled using a Heat Exchanger Block since, in the experimental system, the exchange of heat between the cool water from the chiller and the heated water from the cold plate occurs within the reservoir. The ATTMO heat exchanger model is of similar detail to the pump model; users can set parameters such as hot and cold fluid flow directions, various geometries within the heat exchanger, and material type.

In the hot loop, water is pumped from the reservoir through a pipe to the cold plate, then returns via a second pipe. The pump and piping are modeled similarly to the components in the cold loop.

The cold plate was designated a serpentine flow configuration with editable properties including dimensions, tube diameters, plate materials, and number of flow passes. The cold plate takes a constant heat input, set to 140.6W in this system.

The experimental system includes a flow rate sensor and temperature sensors in the hot loop. These are not specifically modeled in the ATTMO model, but a second pipe block is included upstream and downstream of the cold plate to account for pressure drop associated with these components.

B. *S3D model*

This experimental system was also modeled in S3D, shown in Fig. 4, with a cold loop (outlined in black) and hot loop (outlined in red). A third loop, outlined in blue, provides cooling water to the chiller; this is required by the component model in S3D since an air-cooled chiller model is not available.

As in the ATTMO model, the two loops are centered around a heat exchanger block. The pertinent properties in the S3D heat exchanger block are a heat transfer coefficient, set to 4,800W/m^2K, and a heat transfer contact area, set to 0.02m^2, based on model parameters. The component also includes a loss coefficient used in calculating pressure drop.

An electrical load placed in the hot loop acts as the PEBB. This load is parameterized to $281.2W$ with an electrical efficiency set to 50%, thus placing a load on both the electrical system and the cooling system.

The water chiller is parameterized with a design outlet temperature, a coefficient of performance to determine electrical demand, a heat transfer coefficient and contact area to determine heat transfer, and loss coefficients for the hot and cold loops for determining pressure drop.

The expansion tanks are S3D modeling constructs required for each closed loop; the tanks are used to declare a fluid type within the loop and provide loop pressure.

At present, there is no S3D component such as a reducer that changes the diameter of piping; a component providing this capability is still under development. Since S3D forces compliance such that diameters at connections must match, the diameter within a single contiguous loop cannot change. This meant that it was not possible to accurately model different pipe and port sizes.

Similar to the ATTMO model, the flow meter and temperature sensors were not specifically modeled in S3D.

C. *Results and Discussion*

The experimental data collected from the system includes cold plate inlet and outlet temperature, water flow rate, reservoir temperature, heat input, and ambient temperature. Water flow rate, heat input and reservoir temperature were used as inputs to the model. Ambient temperature was observed to ensure minimal impact on results, but was not modeled in either tool.

The ATTMO model was run with all components beginning at an ambient temperature of 26°C. After a period of 10,000 seconds, the cold plate inlet and outlet temperatures had reached steady state as shown in Fig. 5. In this plot, one can see that the inlet and outlet temperatures initially started at 26°C. After reaching steady state, the inlet and outlet temperatures reached approximately 29.74°C and 30.27°C, respectively.

TABLE I
ATTMO TEMPERATURE DATA COMPARED TO EXPERIMENTAL DATA

Component	ATTMO Model Steady-State Temperature (C)	Experimental Temperature (C)	Percent Error
Cold Plate Inlet	28.26	29.74	5.0
Cold Plate Outlet	28.68	30.27	5.3

Table I compares ATTMO steady-state temperature and experimental data temperature. The experimental data consists of over 18,000 measurements of the cold plate inlet and outlet temperatures. In order to find the steady state temperature for the experimental data, the last 100 data points were averaged for both the inlet and outlet. Compared to the ATTMO data, the percent error (assuming that all measurements are made in degrees Celsius) for the inlet and outlet were 5.0% and 5.3%, respectively.

TABLE II
S3D TEMPERATURE DATA COMPARED TO EXPERIMENTAL DATA

Component	S3D Model Steady-State Temperature (C)	Experimental Temperature (C)	Percent Error
Cold Plate Inlet	27.8	29.90	7.02
Cold Plate Outlet	28.8	31.70	9.12

Table II compares S3D steady state temperature and experimental data temperature. By nature of its solver, S3D tracks components' steady state temperature. The cold plate inlet and outlet temperatures were 27.8°C and 28.8°C, or an accuracy from 7 to 9%.

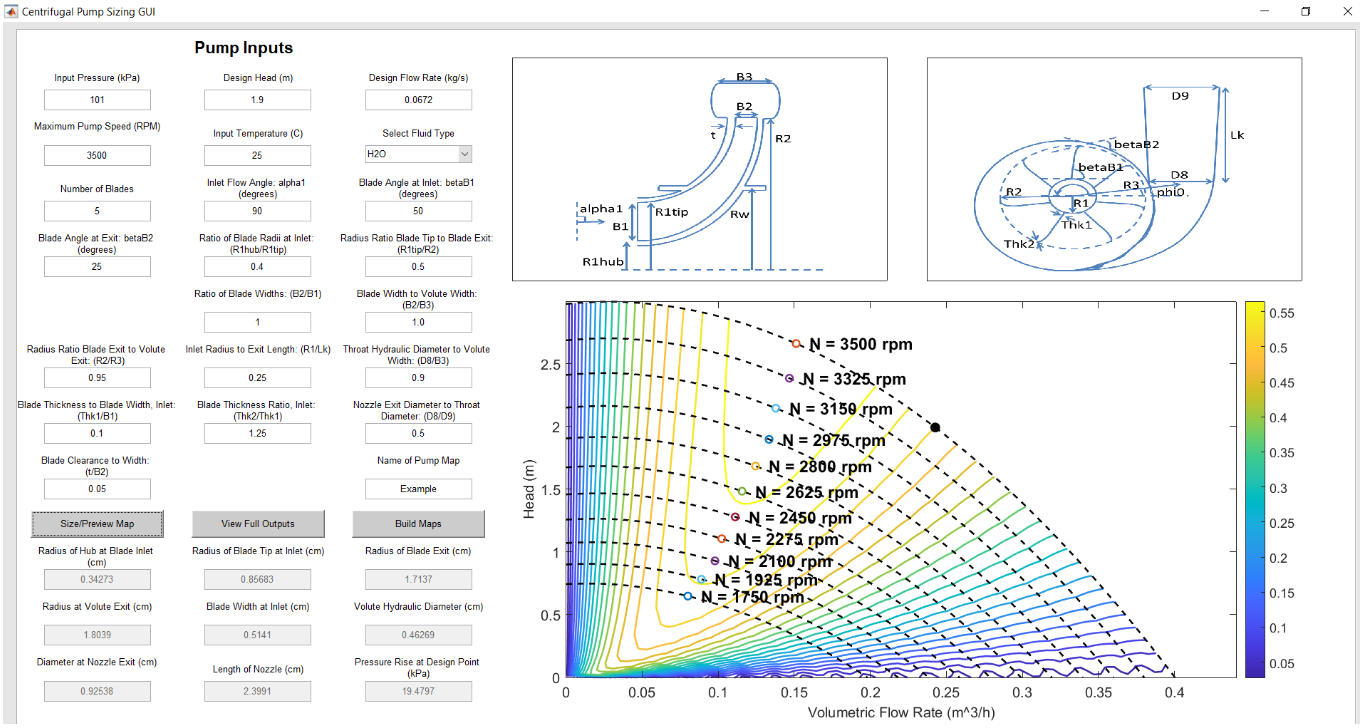

Fig. 3. ATTMO Pump Sizing GUI

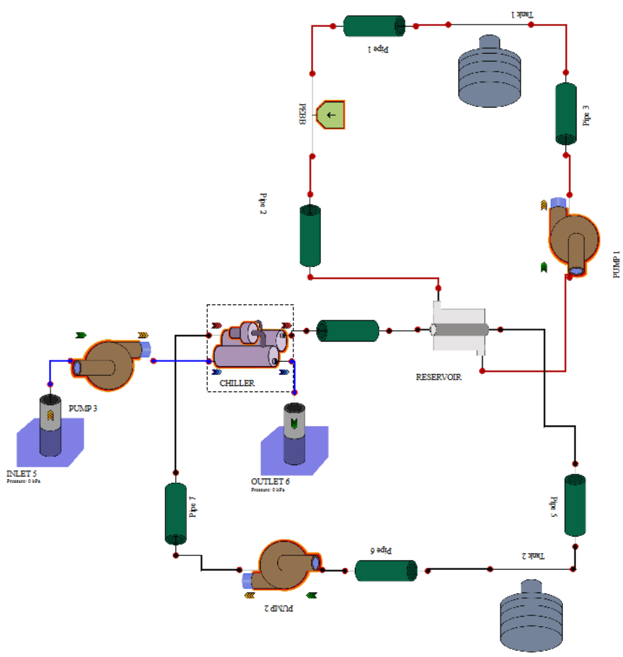

Fig. 4. Experimental system modeled in S3D.

It was possible to visualize pressure drop across all components in the system in both ATTMO and S3D. In order to correctly size the pumps in ATTMO, pump head needed to be calculated manually. To solve this problem, the system's design head was estimated, with each component and its respective pressure drop being considered. For both the cold and hot loops, minor and major losses were calculated, giving the design head for the respective loops.

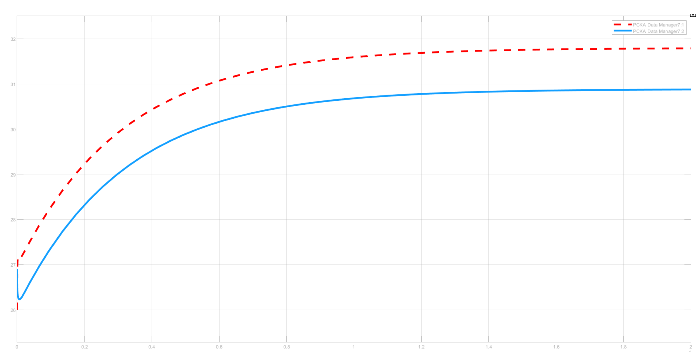

Fig. 5. Cold plate inlet and outlet temperatures (blue solid and red dashed lines, respectively) (NOTE: GENERATING NEW PLOT WITH MORE LEGIBLE AXES; IN THIS FIGURE, X IS TIME AND Y IS TEMPERATURE

Pressure drop results for each loop in each model are shown in Table III. Experimental values for pressure drop were not measured. While these values are in the ballpark with one another, the errors in modeling this particular system are evident; neither tool had a flexible hose as a piping choice, and the S3D system did not allow any variation in diameter.

IV. Large System Design

S3D is designed for modeling and simulating large systems and investigating the impact of design decisions on a full ship design. An example full-ship electrical system design was cre-

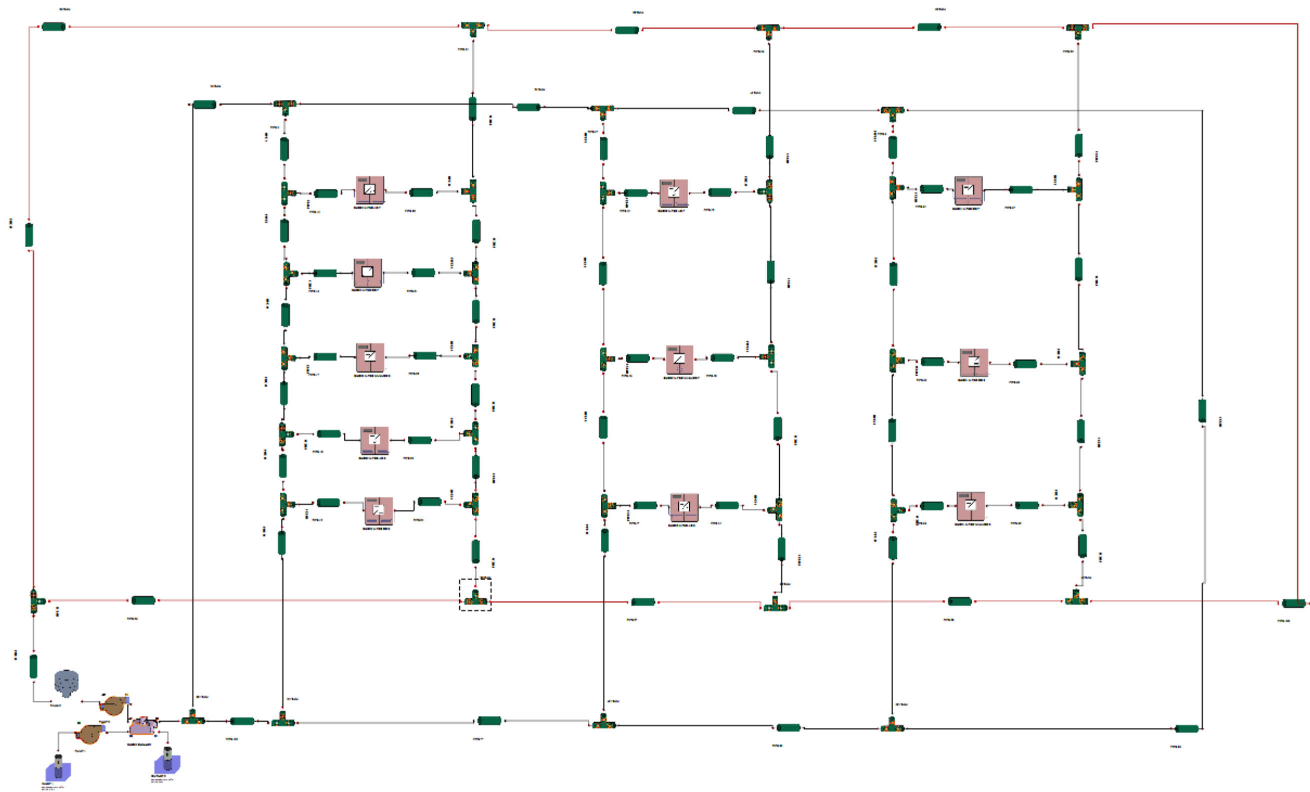

Fig. 6. Large system modeled in S3D; thermal domain displayed.

TABLE III
PRESSURE DROP DATA

	Cold Loop (kPa)	Hot Loop (kPa)
ATTMO	9.2	12.1
S3D	11.5	14.0

ated, and the thermal management system for the forward-most three watertight sections of the ship was modeled, as shown in Fig. 6. The electrical design contains approximately 400 individual components arrayed over fourteen watertight subdivisions, and the piping diagram contains over 120 components for just three watertight compartments. At this early stage of design, the detail required is fairly low, more consistent with the models inherent in S3D rather than ATTMO.

ATTMO is not intended for such large-scale system modeling; it does not contain pre-designed models of the wide array of electrical components required for a full electrical system design, and requires too much detail for each of the piping components in a thermal design. While it would be possible to create electrical models in Simulink for modeling a large system, this is really not the intended goal of the software.

V. SYNERGY, CONCLUSIONS AND RECOMMENDATIONS

The goal of this project was to compare the functionality of S3D and ATTMO and to seek areas of synergy where each tool can benefit the other. This was accomplished through modeling a small experimental system and creating a large early-stage design.

ATTMO is best used to solve a specific thermal management problem in detail. The precise level of parameterization offered by each component in ATTMO facilitates detailed modeling. In order to properly take advantage of the capabilities of ATTMO, the user must be technically skilled both in the area of interest and in the functionality of ATTMO. A non-expert may find it difficult to create a model due to lack of knowledge of engineering fundamentals or of ATTMO's functionality; however, an expert user can create detailed models of specific systems due to the component versatility in ATTMO.

Additionally, ATTMO is almost exclusively a thermal management tool. The electrical domain is somewhat sparsely populated. ATTMO is run on Simulink, so a user can create any component necessary for the electrical domain; however, these components are not part of the library packaged with ATTMO.

S3D is better suited for building large scale systems in early-stage design. Components have fewer modifiable variables and data collection is much quicker. This comes at a cost, however, since the S3D models, at their current level of development, will have greater uncertainty and are not appropriate for detailed design of specific cooling solutions. Component models automatically come with the appropriate mathematical model in each computational domain, as opposed to ATTMO in which the appropriate model for each domain must be selected and associated with the proper results in the other domain.

There is great opportunity for the two tools to work together in a synergistic manner, and for the tool development to proceed together as well.

S3D is in need of sizing algorithms for components based on functionality of real-world equipment. Many of the component models in ATTMO are built on experimental results quantifying the performance of various thermal technologies. The S3D sizing algorithms can take the form of behavior models developed from multiple designs of components within the ATTMO toolset, producing a Pareto-optimal front from multiple designs, similar to the models developed in [7]. This process would leverage the effort put into the development of the ATTMO toolset for the advancement of the Navy's early-stage design tools.

S3D can and should be used to develop broad system-wide design needs. Once a cooling paradigm is identified within an S3D design, the ATTMO toolset can be used to refine and detail the specific cooling solution, including such processes as heat exchanger or cold plate detailed design.

In conclusion, it was found that the two software tools serve different roles in thermal system design and that there is excellent opportunity for synergy between the development and use of the tools.

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