Independent Verification and Validation of the *Orion* Multi-Purpose Crew Vehicle Active Thermal Control System Performance

Xiao-Yen J. Wang[1]
NASA Glenn Research Center, Cleveland, Ohio, 44135

This paper presents the efforts at the NASA Glenn Research Center (GRC) to validate dynamic models of the active thermal control system (ATCS) for the *Orion* Multi-Purpose Crew Vehicle. An independent ATCS model was built at GRC using Simulink/MATLAB (MathWorks) to validate the Orion ATCS performance models created by Lockheed Martin (LM) and Hamilton Sundstrand (HS) for both International Space Station (ISS) and lunar design reference missions (DRM). One measure of the ATCS performance is the amount of water needed for sublimation to supplement the radiative heat rejection system. For the ISS mission, the performance of the 606F ATCS configuration was modeled using SINDA/FLUINT (C&R Technologies) by HS and the results were validated in the current work using the Simulink model. The Simulink model was also used to validate the 606H ATCS SINDA/FLUINT model created by LM using the Thermal Desktop FloCAD modeling tool (C&R Technologies). The amount of water that would be sublimated during the mission timeline for different flight attitudes such as tail nadir, tail forward, tail to Sun, and nose forward were computed and compared for the two DRMs. Hot and cold biased parameters for the environment and optical properties were also considered. Seven mission timeline phases for the lunar mission were analyzed with the Simulink model for different heat loads in the 606H ATCS configuration. Finally, the current model results for the trade study of the 606F ATCS architecture with an LM eight-panel, an LM seven-panel, and a reduced-curvature (RC) seven-panel radiator configuration are reported, confirming the conclusions drawn in a previous study.

I. Introduction

The *Orion* Multi-Purpose Crew Vehicle (MPCV) project is managed under NASA's Human Exploration & Operations Mission Directorate (HEOMD). HEOMD is responsible for providing the management of NASA space operations related to human exploration in and beyond low Earth orbit including the elements that will transport humans and cargo to both the International Space Station (ISS) and the Moon. These elements include the *Orion* crewed vehicle and the Space Launch System (SLS). *Orion*, with a crew of up to four astronauts, will launch on SLS and then use its main engine to insert itself into a safe orbit to dock with the ISS or remain coupled to the upper stage of the SLS for a trans-lunar insertion (TLI) burn. For all missions, *Orion* will be responsible for separation, entry, descent, and landing. For lunar missions, *Orion* also will have to maintain itself in low lunar orbit and perform a trans-Earth injection maneuver to return from lunar orbit. *Orion* consists of the launch abort system (LAS), crew module (CM), service module (SM), and spacecraft adapter (SA). The CM is a capsule design that will provide the primary structure for crew support, incorporate the bulk of the avionics systems, and provide the capability for entry and parachute water landing. The LAS will safely extract the CM from the launch configuration in the event of an early launch abort. The SM contains the main *Orion* propulsive system, the solar array power generation system, the radiative active thermal control system, avionics, crew life support consumables and

[1]Aerospace Engineer, Thermal Systems Branch, 21000 Brookpark Rd./MS 86–12, AIAA member.

the structure that will interface with the CM and SA. The SA integrates the SM to the SLS upper stage segment.

This study focuses on *Orion*'s ATCS which is redundant cooling system comprised of a two CM ATCS cooling loops and two SM ATCS cooling loops. The purpose of the ATCS is to control the crew environment inside the CM while maintaining the temperature of all avionics within their temperature limits. As shown in Fig. 1, two CM fluid loops will pass through the CM, take heat generated inside the CM and from all electronics, then pass the heat to the SM fluid loops through two interface heat exchangers (IFHXs). The SM fluid loops will carry the heat to the radiator panels and radiate the heat to space. On the CM loop, there will be a water sublimator heat exchanger and for lunar missions a phase-change material (PCM) heat exchanger (HX) for thermal topping. The control loop will have several set points, such as the fluid temperature entering the pressurized volume of the CM and the maximum temperature at the cold plates associated with the batteries. There will be a bypass flow path on the CM side and a bypass flow path upstream of the regenerative heat exchanger (Regen HX) on the SM side.

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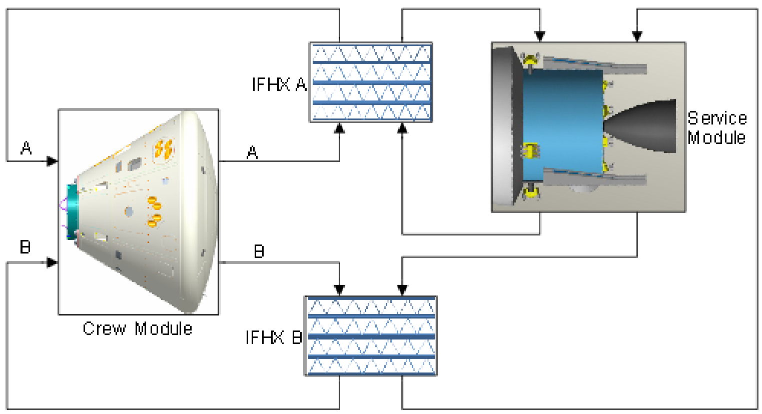

Figure 1. *Orion* ATCS.

The current modeling effort is part of independent validation and verification of the ATCS performance predicted by the analysis results from LM and HS. Simulink and MATLAB (MathWorks) were used to build a dynamic model independently to simulate the *Orion* ATCS performance. The model includes all major components in the ATCS, such as the cabin HX and cold plates on both the CM and SM sides, Regen HX and the radiator with fluid loops on the SM side, and the IFHX. The control system also was modeled to meet the thermal requirements for the ATCS. The user needs to define the initial conditions and provide the ambient radiation sink temperature for the radiator and heat loads for both CM and SM sides. The details of the mathematical models of heat exchangers and radiator are described in [1].

The following sections provide an overview of the *Orion* ATCS dynamic models for the 606F and 606H configuration, followed by the validation of the ATCS model for both the ISS and lunar missions. The numerical results are compared with the corresponding results from independent resources. Then, current model results are reported for a trade study of the ATCS with an LM eight-panel, LM seven-panel, and RC seven-panel radiator configuration. Finally, conclusions are drawn.

II. Dynamic Modeling for *Orion* ATCS

During the *Orion* ATCS design analysis cycle (DAC), the baseline *Orion* ATCS evolved quite a few times. The dynamic modeling efforts described here are focused on the last two configurations—606F and 606H. The 606H configuration was considered in DAC3, and the 606H configuration, an improved design based on 606F, was considered as the final design of the *Orion* ATCS in DAC3. The major differences between 606F and 606H are (1) the PCM and sublimator were switched in the flow direction, and (2) the three-way valve was moved from upstream to downstream of the SM cold plates.

Five dynamic models of the *Orion* ATCS were built for different purposes and applications: (1) GRC's current Simulink model [2], (2) HS's independent Simulink model, (3) HS's SINDA/FLUINT (S/F) model [3], (4) LM's FloCAD (C&R Technologies) model [4], and (5) NASA Johnson Space Center's

Thermal Desktop (C&R Technologies) (TD) model [5]. Each model has a specific focus and application. The models correlation and validation have been presented in [6-7]. The current Simulink model uses the same heat transfer characteristic for all the HXs in the ATCS as those used in other four models. The SINDA/FLUINT model has a full three-dimensional radiator model. All models use a similar mathematical approach. Simulink is a commercial tool for modeling, simulating, and analyzing multidomain dynamic systems. SINDA/FLUINT is a comprehensive finite-difference, lumped parameter (circuit or network analogy) tool for heat transfer design analysis and fluid flow analysis in complex systems. FloCAD is a TD module that allows a user to develop and integrate both fluid and thermal systems within a computer-aided design environment. Like TD, FloCAD is a graphical user interface for SINDA/FLUINT. The Simulink model focuses more on control algorithms and runs faster. The SINDA/FLUINT model focuses more on detailed thermal and fluid modeling, and takes longer to run.

In the current Simulink/MATLAB model, 20 mesh points are used in the flow direction for the IFHX, 30 mesh points are used in the flow direction for the Regen HX, and two mesh points are used in the flow direction for the sublimator and the PCM HX. The heat transfer rate for the IFHX, Regen HX, sublimator, and PCM HX are provided in [8]. For the cabin HX and the cold plate for the CM and SM sides, a constant heat load based on the power load was imposed. For the radiator, two mesh points were used for each panel, and all panels were modeled. The solver used in the Simulink model was ODE45 (Dormand-Prince) with a variable time step. The maximum time tsep, Δt, was 0.5 s; otherwise, the result would have diverged. The model took approximately 20 min to simulate a three-orbit (4.5-hr) run.

III. Model Validation for ISS Mission

From the ISS mission timeline, three major orbits—low Earth orbit (LEO) tail to Sun (TtS), LEO tail nadir (TN), and LEO nose forward (NF)—were used to run the model under different heat loads. The sink temperature is referred to [9]. Table I shows the water usage for each case. The ATCS 606F and 606H configurations were both studied here using the current Simulink model. However, the results from LM and HS are only available for the 606F configuration. Figure 2 compares water usage for the HS and GRC results for three different orbits at different heat loads. Excellent agreement is observed for all three orbits. From this curve, the total water usage for the entire mission timeline is 171 lbm without safe haven, as predicted by LM.

Table I. Model results and comparisons for ISS mission
[Environment, hot; orbit duration, 1.48417 hr.]

Attitude	Heat, Q, W	HS S/F(606F)	GRC Simulink (606F)		GRC Simulink (606H)	
		Total water usage, lbm/ loop-orbit	Heat, Q, W	Total water usage, lbm/ loop-orbit	Heat, Q, W	Total water usage, lbm/ loop-orbit
TtS	3060.84	0.00	2583	0	2583	0
TtS	3618.05	.96	3061	0	3061	0
TtS	3627.42	.96	3254	.480	3254	0
TtS	3818.00	1.37	3618	1.075	3618	.494
TtS	3875.99	1.42	3627	1.083	3627	.501
TtS	3912.34	1.45	3818	1.354	3818	.796
TtS	3973.45	1.67	3973	1.562	3973	1.016
TtS	4093.25	1.86	4031	1.667	4031	1.129
TtS	4152.49	1.94	4152	1.905	4152	1.335
TtS	4341.12	2.28	4341	2.222	4341	1.643
TtS	4446.37	2.46	4446	2.390	4446	NA
TtS	4680.52	2.86	4681	2.763	4681	2.164
TN	----------	NA	2697	0	2697	0
TN	4578.06	1.97	3466	.245	3466	0
TN	4715.10	2.19	4578	1.970	4578	1.369

TN	-----------	NA	4715	2.186	4715	1.604
NF	3627.42	1.13	3627.4	1.123	3627	.696
NF	3713.18	1.35	3713.2	1.350	3713	.873
NF	3815.14	1.57	3815.2	1.546	3815	1.021
NF	3878.08	1.62	3878.1	1.646	3878	1.122
NF	3982.83	1.84	3982.8	1.816	3983	1.298
NF	4261.71	2.35	4261.7	2.290	4262	1.750
NF	4341.12	2.49	4341.1	2.430	4341	1.870
NF	4438.59	2.66	4438.6	2.588	4439	2.024
NF	4716.72	3.10	4716.7	3.045	4717	2.420

Figure 3 compares water usage for the 606F and 606H configurations. It can be seen that the water usage is much less for the 606H configuration. For LEO TtS with the 606F configuration, the sublimator stayed off until the heat load reached 3100 W, whereas for the 606H configuration, the sublimator stayed off until the heat load reached 3250 W. At the same heat load, the 606H configuration used 0.5- to 0.6-lbm less water per loop per orbit than did the 606F configuration in both the TtS and NF orbits, and it used 0.2- to 0.6-lbm less water per loop per orbit for the TN orbit. However, the sublimator was turned on and off much more frequently, which might make it more costly to control the sublimator.

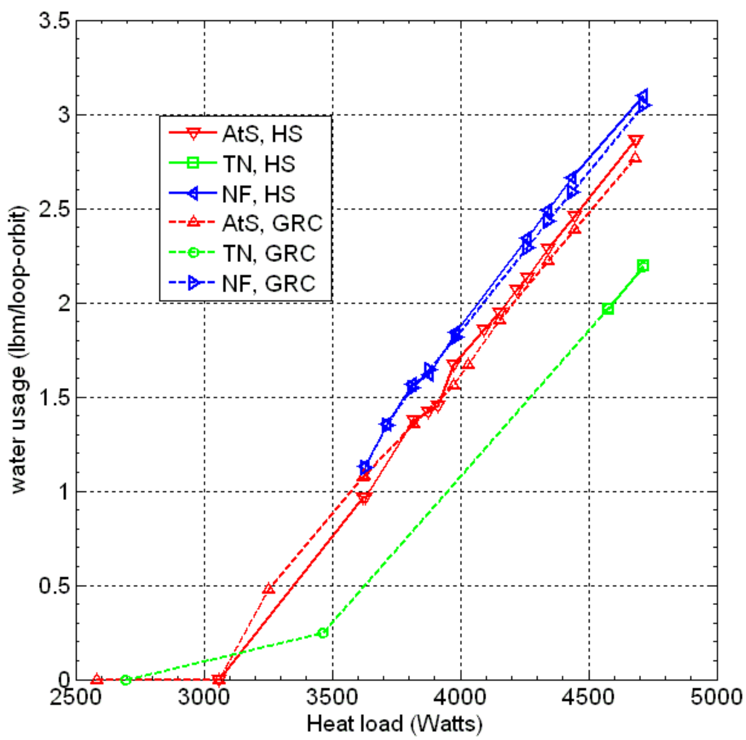

Figure 2. Comparison of water usage from HS data and GRC data for the ISS mission with the ATCS 606F configuration (LEO AtS (=TtS), TN, and NF).

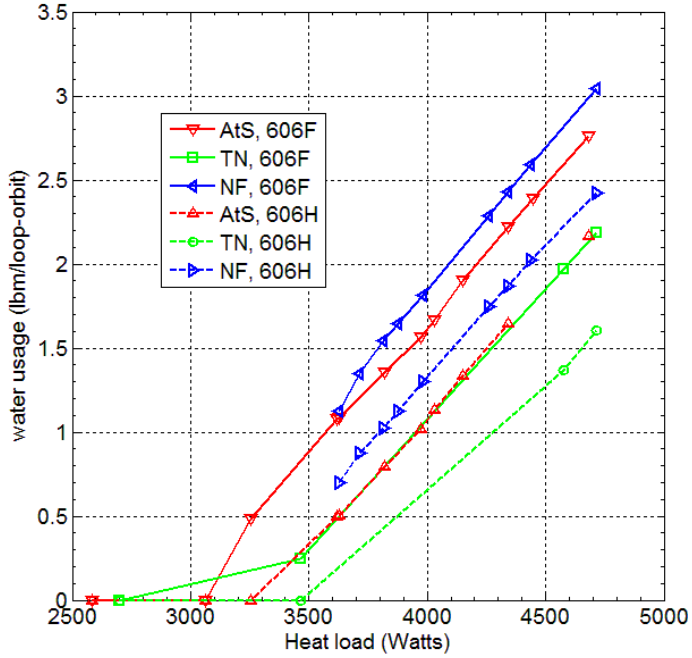

Figure 3. Comparison of water usage for the 606F and 606H configurations (GRC data).

IV. Model Validation for Lunar Mission

For the lunar mission, two orbits—(1) low lunar orbit (LLO) nose nadir (NN) hot and (2) LLO TtS cold—were used to validate the Simulink model for the 606F configuration in [1], showing very good agreement. Here, another LLO TtS hot case is used to validate the model for the 606H configuration. The heat load is 3518 W, and the sink temperature provided by LM is referred to [9].

Figures 4(a) and (c) compare the non-dimensional CM fluid temperature at the outlet of the sublimator and the PCM. Figures 4(b) and (d) compare the non-dimensional IFHX inlet and outlet temperatures for both the CM and SM fluids. The LM and GRC results show reasonable agreement with some minor discrepancies due to the use of different control algorithms.

Further, seven orbits from the lunar mission timeline were computed under different heat loads: (1) LEO local vertical/local horizontal (LVLH) node velocity vector (VV), (2) LEO LVLH tail VV, (3) LEO broadside to Sun (BtS), (4) transit TtS, (5) LEO TtS, (6) lunar NN, and (7) lunar LVLH nose VV. The sink temperature for each orbit provided by GRC is referred to [9], and the Simulink model results are shown in Table II. Validation of the results will be performed in the future.

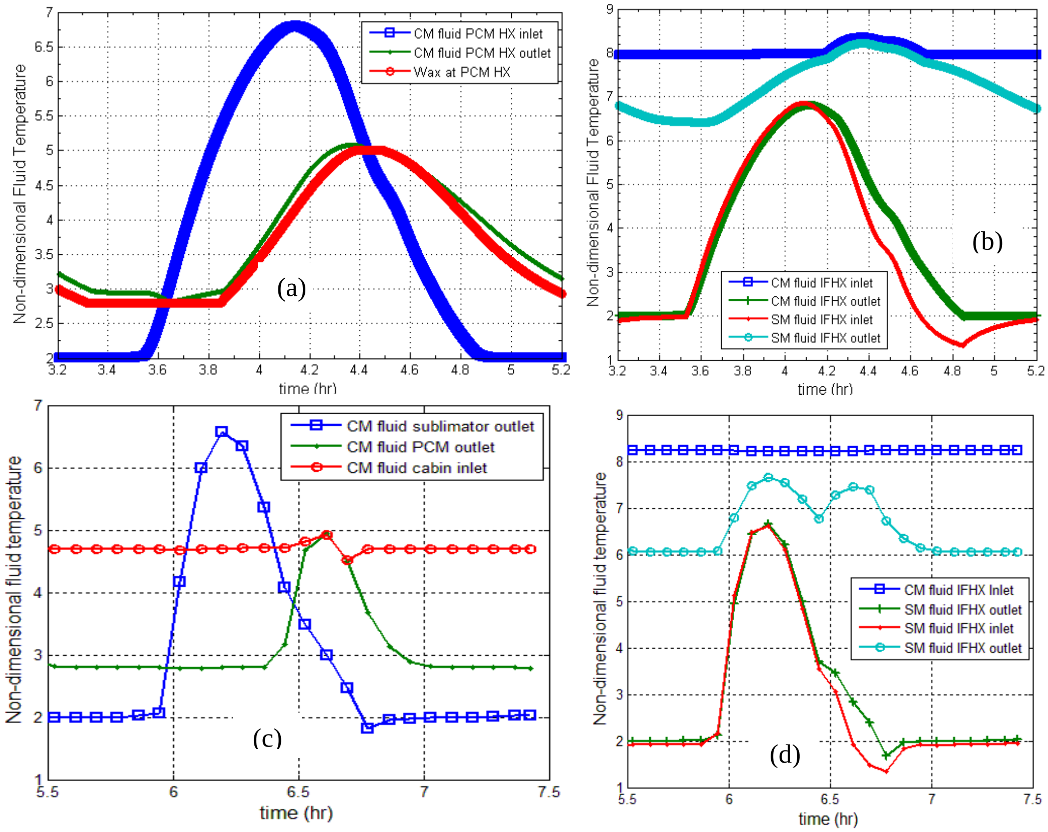

Figure 4. Comparison of results for LLO TtS hot. (a) CM fluid temperature at outlet of sublimator and at PCM (GRC data). (b)IFHX inlet and outlet temperatures for both CM and SM fluids (GRC data). (c) CM fluid temperature at outlet of sublimator and at PCM (LM data). (d) IFHX inlet and outlet temperatures for both CM and SM fluids (LM data).

V. Trade Study for LM Baseline Radiator and RC Radiator

In [10], the *Orion* ATCS 606F configuration with an LM eight-panel radiator (LM baseline), LM seven-panel radiator, and RC seven-panel radiator were considered for a trade study. The RC seven-panel radiator has the same total radiator area as the LM eight-panel radiator. Each RC radiator panel has 15-percent more area than each LM baseline radiator panel. Some orbits—LEO TtS, NF, TN hot cases, LEO NF, and TtS cold cases—were computed for the ISS mission. The conclusion is that, for the ISS mission, the ATCS with the RC seven-panel radiator performs better than LM baseline radiator and would use less water for sublimation. For the lunar mission, the ATCS with the RC seven-panel radiator would have performance similar to that of the LM baseline radiator.

Here, four orbits—LEO NF, TF, NN, and TtS—were studied under different heat loads for an ISS mission with the 606F configuration. Table III lists the water usage for the ATCS with the LM eight-panel baseline, LM seven-panel, and RC seven-panel radiator for the four orbits under two Beta angle (the angle between Sun vector and the orbital plane) of 60 and 75 degree. Figure 5 compares the water usage. It shows again that the RC seven-panel radiator uses a similar amount of water or less water than the LM eight-panel radiator. The LM seven-panel radiator would use significantly more water than the LM eight-panel radiator.

Table II. Model results for lunar mission

Orbit	Attitude	Environ-ment	Set	Heat, Q, W	Orbit duration, hr	GRC Simulink ATCS model (606H)	
						Total water usage, lbm/ loop-orbit	Notes
LEO	LVLH nose VV	Hot	1	2600	1.8	0	--------------------------
LEO	LVLH nose VV	Hot	1	3600	1.8	2.382	--------------------------
LEO	LVLH nose VV	Hot	1	4300	1.8	3.696	--------------------------
LEO	LVLH nose VV	Hot	1	5000	1.8	5.263	Exceeds T_{max}
LEO	LVLH tail VV	Hot	2	3600	1.75	1.51	--------------------------
LEO	BtS	Hot	3	2600	1.75	0	--------------------------
LEO	BtS	Hot	3	3600	1.75	0	--------------------------
LEO	BtS	Hot	3	4100	1.75	1.631	--------------------------
LEO	BtS	Hot	3	4400	1.75	2.192	--------------------------
LEO	BtS	Hot	3	5000	1.75	3.367	Exceeds T_{max}
Transit	TtS	Hot	4	3300	2	0	Wax crystalizes; Regen HX flow 0%
Transit	TtS	Hot	4	3800	2	0	Wax crystalizes; Regen HX flow 0%.
Transit	TtS	Hot	4	4000	2	0	No wax crystalizes; Regen HX flow 0%
Transit	TtS	Hot	4	4500	2	0	No wax crystalizes; Regen HX flow 0%
LEO	TtS	Hot	5	3100	1.75	0	---
LEO	TtS	Hot	5	3600	1.75	0	PCM melts; never freezes; sublimator off
LEO	TtS	Hot	5	3800	1.75	0	PCM melts, never freezes; sublimator off
LEO	TtS	Hot	5	4000	1.75	0	PCM melts, never freezes; sublimator off
LEO	TtS	Hot	5	4100	1.75	0	PCM melts, never freezes; sublimator off
LEO	TtS	Hot	5	4800	1.75	2.6	Sublimator on
LLO	NN	Hot	6	2600	5.21	0	Wax crystalizes; Regen HX flow reaches 80%
LLO	NN	Hot	6	3700	5.21	0	Wax crystalizes; Regen HX flow reaches 48%
LLO	NN	Hot	6	4300	5.21	0	Wax crystalizes; Regen HX flow reaches 25%
LLO	LVLH nose VV	Hot	7	2600	5.21	0	Wax crystalizes; Regen HX flow reaches 64%
LLO	LVLH nose VV	Hot	7	3300	5.21	0	Wax crystalizes; Regen HX flow reaches 50%
LLO	LVLH nose VV	Hot	7	3700	5.21	0	Wax crystalizes; Regen HX flow reaches 36%
LLO	LVLH nose VV	Hot	7	4300	5.21	1.25	Wax crystalizes; sublimator on; Regen HX flow reaches 15%

Table III. The GRC model results for the trade study (LM 8-panel, LM 7-panel, RC 7-panel)
[Orbit, *Orion* alone; environment, hot; configuration, *Orion* alone.]

Attitude	Altitude km	Beta angle, deg	Thermal load, W	Total water usage, lbm/loop-orbit		
				LM eight-panel	LM seven-panel	RC seven-panel
NF	230	60	1693.36	0.00	0.00	0
NF	230	60	2905.0	0.00	0.00	0
NF	230	60	3618.0	.55	1.78	0
NF	230	60	4717.0	3.40	4.96	1.03
NF	230	75	1693.4	0.00	0.00	0
NF	230	75	2905.0	.03	0.00	0
NF	230	75	3618.0	.94	2.40	0
NF	230	75	4717.0	4.30	6.11	1.95
TF	278	60	1421.0	0.00	0.00	0
TF	278	60	2697.0	0.00	0.00	0
TF	278	60	3466.0	0.25	2.20	0
TF	278	60	4717.0	2.73	5.83	2.04
TF	278	75	1421.0	0.00	0.00	0
TF	278	75	2697.0	0.00	.48	0
TF	278	75	3466.0	.08	2.75	0
TF	278	75	4717.0	3.27	6.83	3.44
NN	230	60	1948.1	0.00	0.00	0
NN	230	60	3014.0	0.00	.10	0
NN	230	60	3618.0	.06	0.93	0
NN	230	60	4717.0	1.51	3.70	0
NN	230	75	1948.1	0.00	0.00	0
NN	230	75	3014.0	0.00	0.00	0
NN	230	75	3618.0	0.00	.49	0
NN	230	75	4717.0	1.06	4.03	.46
TtS	230	60	1837.6	0.00	0.00	0
TtS	230	60	2583.0	0.00	0.00	0
TtS	230	60	3254.0	0.00	0.00	0
TtS	230	60	3618.0	0.00	1.31	0
TtS	230	60	4030.7	.09	2.30	.015
TtS	230	60	4681.0	2.29	4.26	1
TtS	230	75	1837.6	0.00	0.00	0
TtS	230	75	2583.0	0.00	0.00	0
TtS	230	75	3254.0	0.00	1.74	0
TtS	230	75	3618.0	.46	2.90	0
TtS	230	75	4030.7	2.07	4.18	.06
TtS	230	75	4681.0	4.05	6.25	2.47

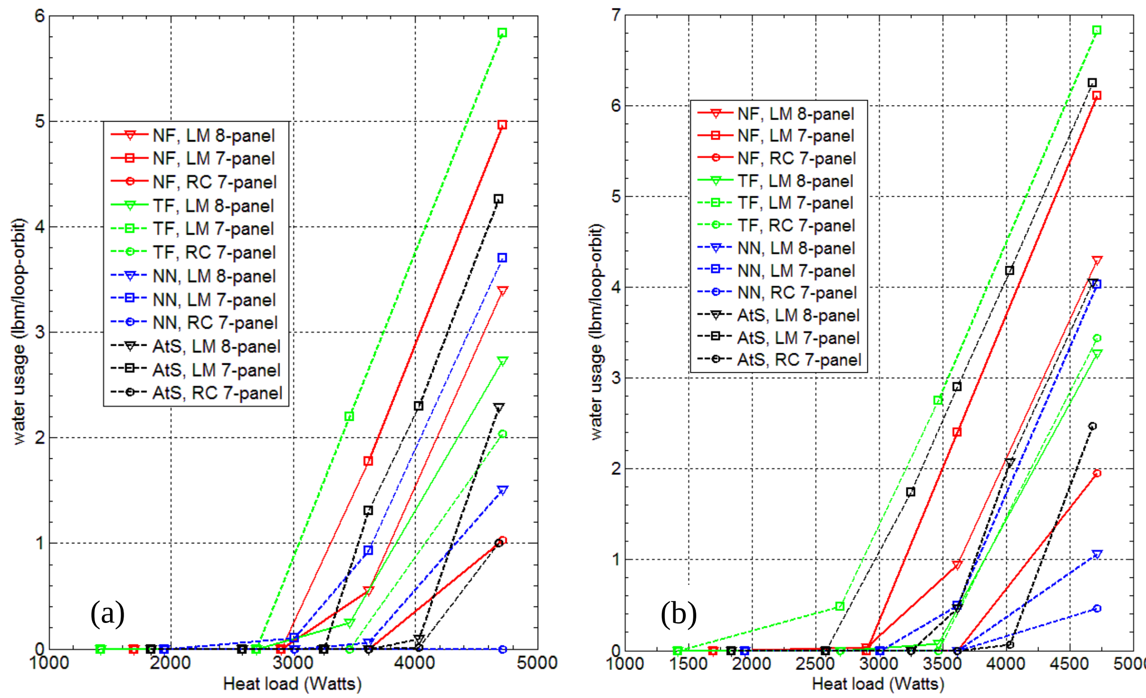

Figure 5. Water usage for LEO NF, TF, NN, and AtS (=TtS) for the ATCS with LM eight-panel, LM seven-panel, and RC seven-panel radiator. (a) Beta angle = 60°. (b) Beta angle = 75°.

VI. Conclusions

The independent verification and validation efforts at the NASA Glenn Research Center for dynamic modeling of the *Orion* ATCS were presented. An independent ATCS model using Simulink was built and used to validate the ATCS performance predicted by using LM and HS models for both the ISS and lunar missions. For the ISS mission, Simulink model results agree very well with the HS SINDA/FLUINT model results for all cases defined for the ATCS 606F configuration. For the lunar mission, Simulink model results agree reasonably well with the LM Thermal Desktop model results for the low lunar orbit tail to Sun hot case.

GRC Simulink results for the ATCS 606F and 606H configurations show that the 606H configuration needs much less water for sublimation but that the sublimator are turned on and off much more frequently. The validated Simulink model for the 606H configuration was used to run seven cases defined in the lunar mission timeline under different heat loads. The results are reported here.

In addition, the current model results for the trade study of an ATCS 606F configuration with an LM eight-panel, an LM seven-panel, and an RC seven-panel radiator are reported, showing the same conclusions as those obtained in a previous study [10].

Acknowledgments

The author thanks Thomas Haregot at Lockheed Martin for providing critical data for the modeling effort, Susan Marret at GRC for providing the case definitions and the sink temperature for the lunar mission, and James Yuko at GRC for leading this task under the *Orion* project.

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