

Integrated Computational Fluid Dynamics and Thermal Desktop Thermal Modeling for Assessment of the EMU in Support of ISS EVA 80

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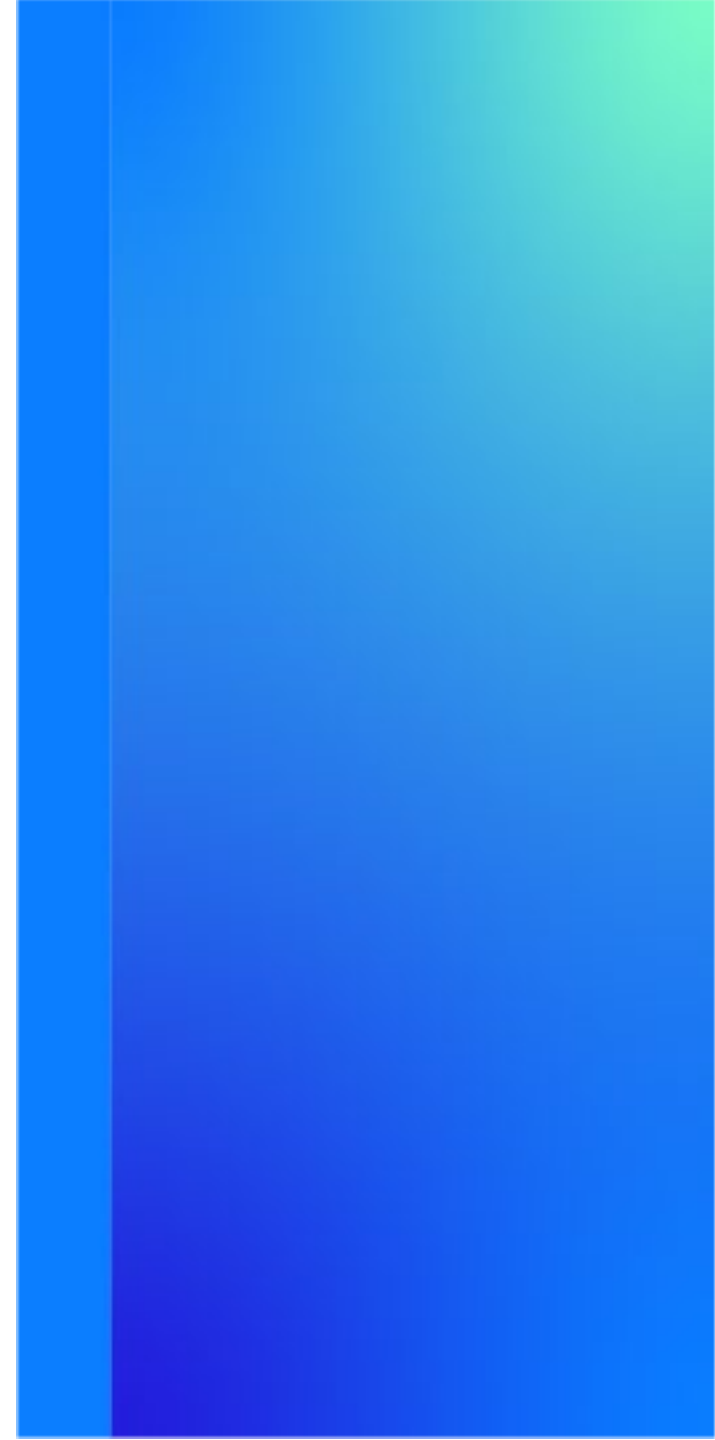
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Nomenclature

- CAD = Computer Aided Design
- CFD = Computational Fluid Dynamics
- EMU = Extravehicular Mobility Unit
- FPS = Fan-Pump-Separator
- LCVG= Liquid Cooling and Ventilation Garment
- OEM = Original Equipment Manufacturer
- PLSS = Portable Life Support System
- TCV = Thermal Control Valve

Introduction



Objective

Following the reports of water accumulation in the Extravehicular Mobility Unit (EMU) helmet during the ISS US EVA-80, various efforts for mitigation and further understanding of this phenomenon have been undertaken with the goal of prevention and to ensure crew safety in future EVAs.

- The primary objective of this modeling was to support the Water in the Helmet mitigation effort with a combination of Thermal Desktop and Computational Fluid Dynamics models to characterize various EMU components, specifically within the ventilation and cooling water loops
- This effort aims to assess the overall thermal-fluid performance in comparison with existing models and design points, with the potential to evaluate worst case scenarios and historical EVA conditions.

EMU PLSS Modeling Overview

- Two thermal/ fluid modelling efforts used to analytically predict pressure drops, temperatures, condensation production, and water removal performance of the Extravehicular Mobility Unit (EMU) Portable Life Support System (PLSS) ventilation and cooling water loops
 - Thermal Desktop/ SINDA Fluint two-phase flow and pressure drop correlation models
 - Computational Fluid Dynamics pressure drop and sublimator flow distribution
- The sublimating heat exchanger (Sublimator), condensate removal paths (Slurper) and the Valve Module were focuses of these models

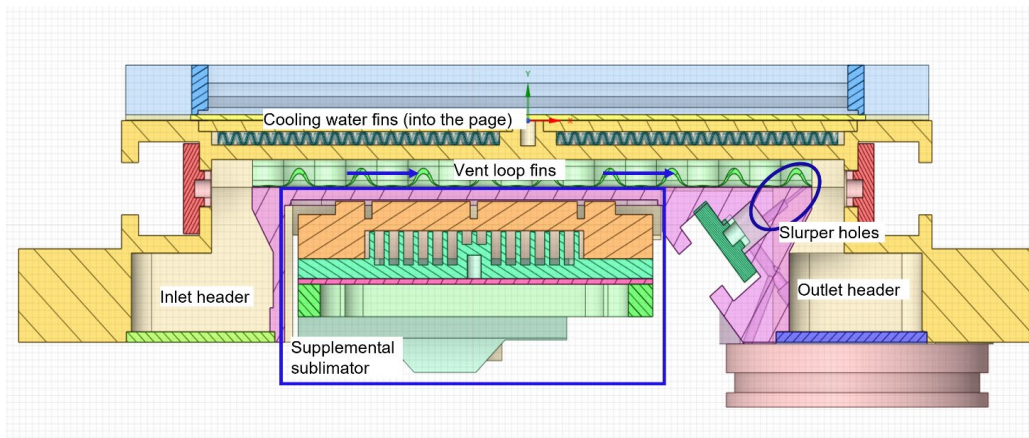


Figure 2: Sublimator Cross-Section

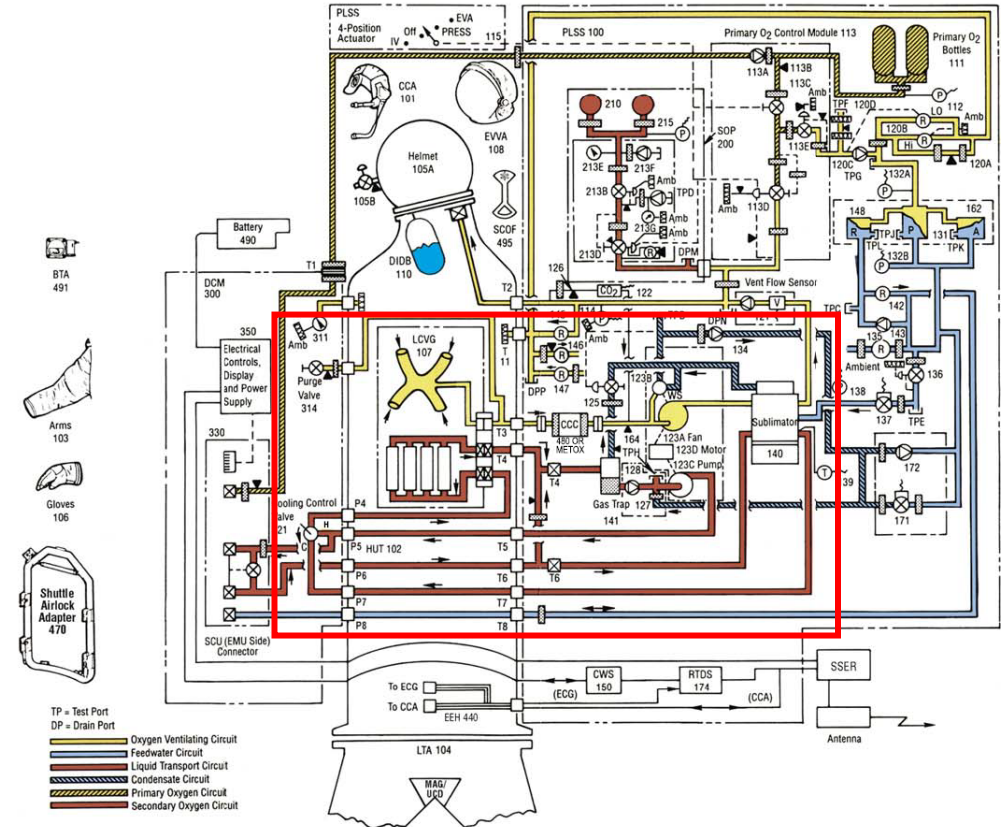
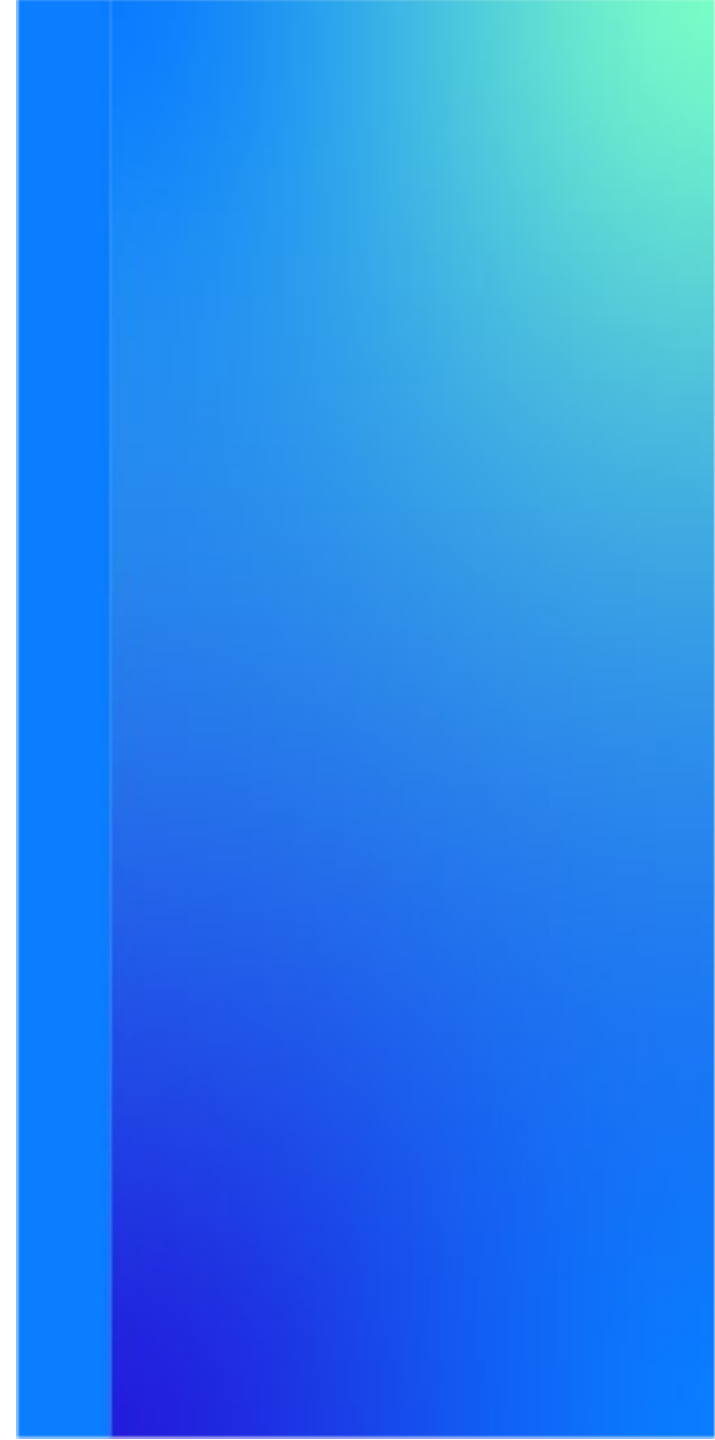


Figure 1 : EMU Schematic [1]

Thermal Desktop Modeling



Standalone Sublimating Heat Exchanger Model

- A Thermal Desktop/FloCAD model was created to evaluate heat transfer, condensation production and two-phase flow behavior within the sublimator
 - The thermal model is created from simplified CAD geometry, and primitives within Thermal Desktop
 - The fluid model is created with FloCAD lumps and paths that are tied to the flow paths within this thermal model

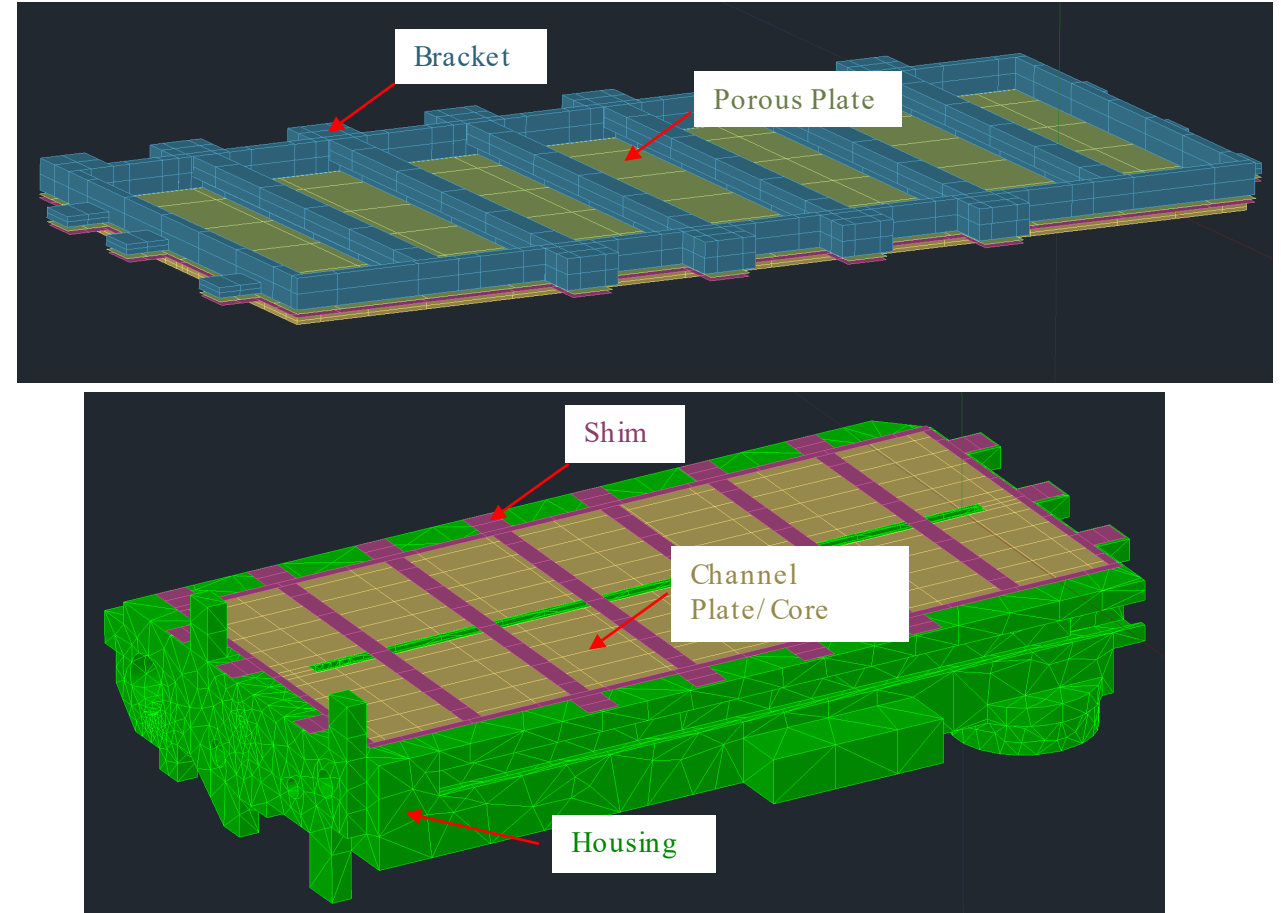


Figure 3: Sublimator Thermal Model

Approach – Geometric Simplification and Meshing

- Geometric Simplifications in CAD for Thermal Desktop
- Some primitive geometry created in Thermal Desktop used for simple components
 - 13,723 Nodes

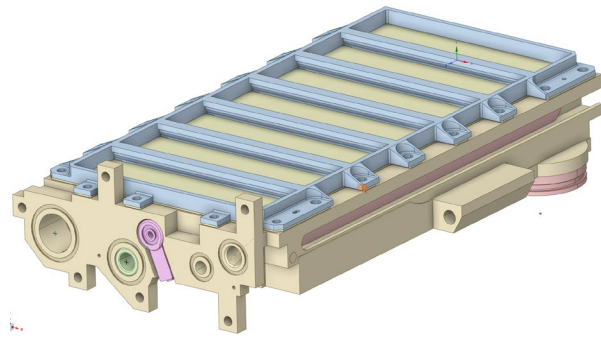
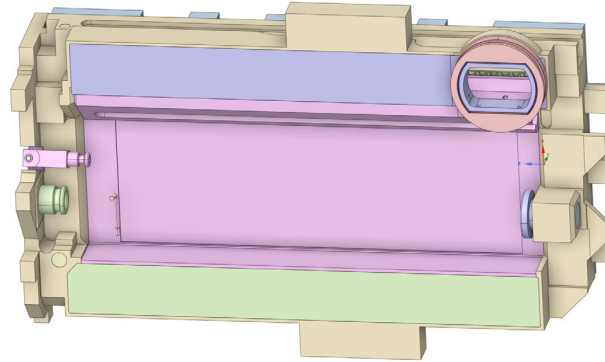
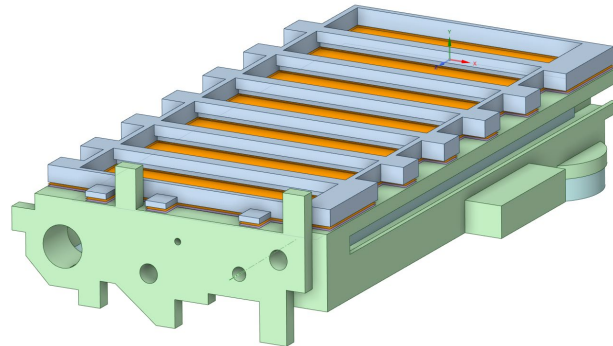
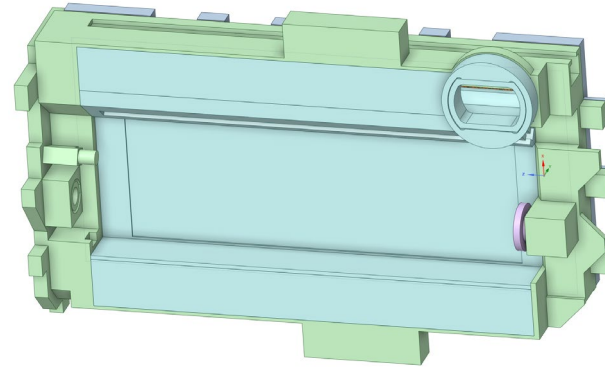
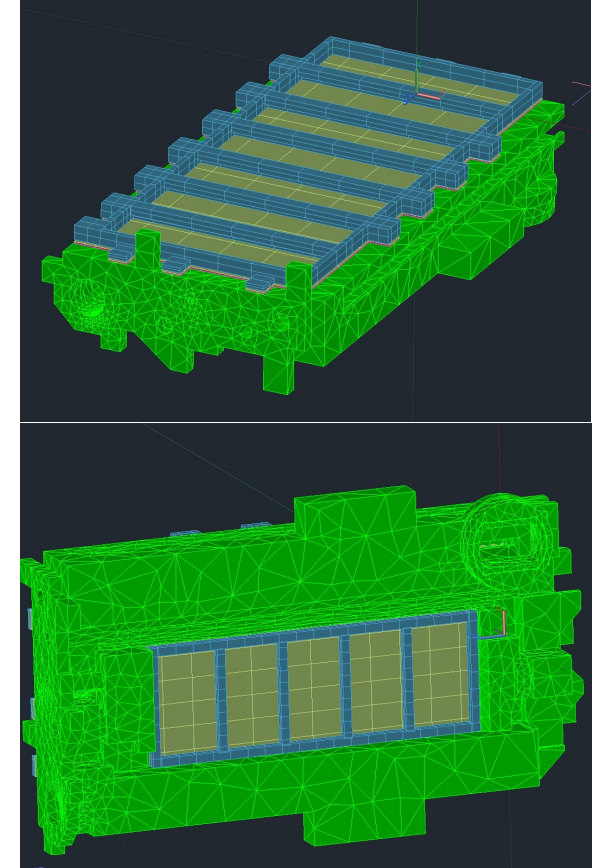


Figure 4: Sublimator Geometric Simplification and Mesh

Assumptions

- The porous plate will be set as a 32 °F boundary condition
 - Since heat is lost due to sublimation, and an ice layer forms, this simplifies the modeling
- Feedwater flow is not modeled. Instead, a Thermal Conductor is used that represents conduction from the porous plate through a thin layer of water (properties defined at 33 °F)
- Simplifications are made to certain portions of the sublimator by creating “primitives” in thermal desktop rather than meshing to reduce node count. (Bracket, porous plates, feedwater shims, fins)
- Contactors taken from Spacecraft Thermal Control Handbook [3]

Approach – Fin Simplification

- To reduce node count and complexity, the sublimator internal fins were simplified into straight channels having a similar surface area per channel
 - Surface area of wavy fins computed by Spaceclaim, and the required perimeter for straight fins was calculated
 - Fin profile created with straight lines adjusted until the perimeter was correct
- The fins are then created as thermal desktop primitives, rather than meshing

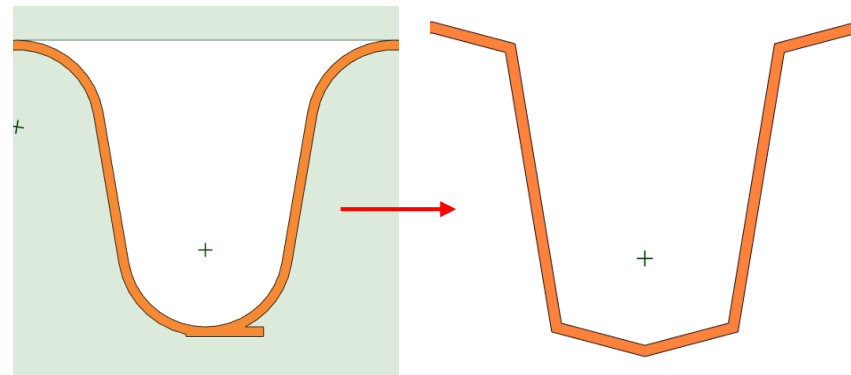


Figure 5: Sublimator Internal Fin Simplification

- Similar method done for the LCVG water fins
- To make the thermal mass equivalent, the density is adjusted

Approach – Tie to Fins

- 11 pipes are used to represent vent fins
 - 7 channels per pipe, 9 channels for center pipe
 - Each pipe has the flow area and hydraulic diameter of a single channel.
 - Path Duplication factors are used upstream and downstream to account for amount of flow through the total channels that each pipe represents
- Each pipe is heat transfer tied to the surfaces of their corresponding channels.
 - Tie Duplication factors are used to represent a multiplier to the area that the fluid lumps and fin nodes should “see” respectively.
- An additional heat transfer coefficient multiplier is used to modify the heat transfer rate for correlation to test data
- 2 pipes are used for the two flow paths with LCVG water fins in a similar manner

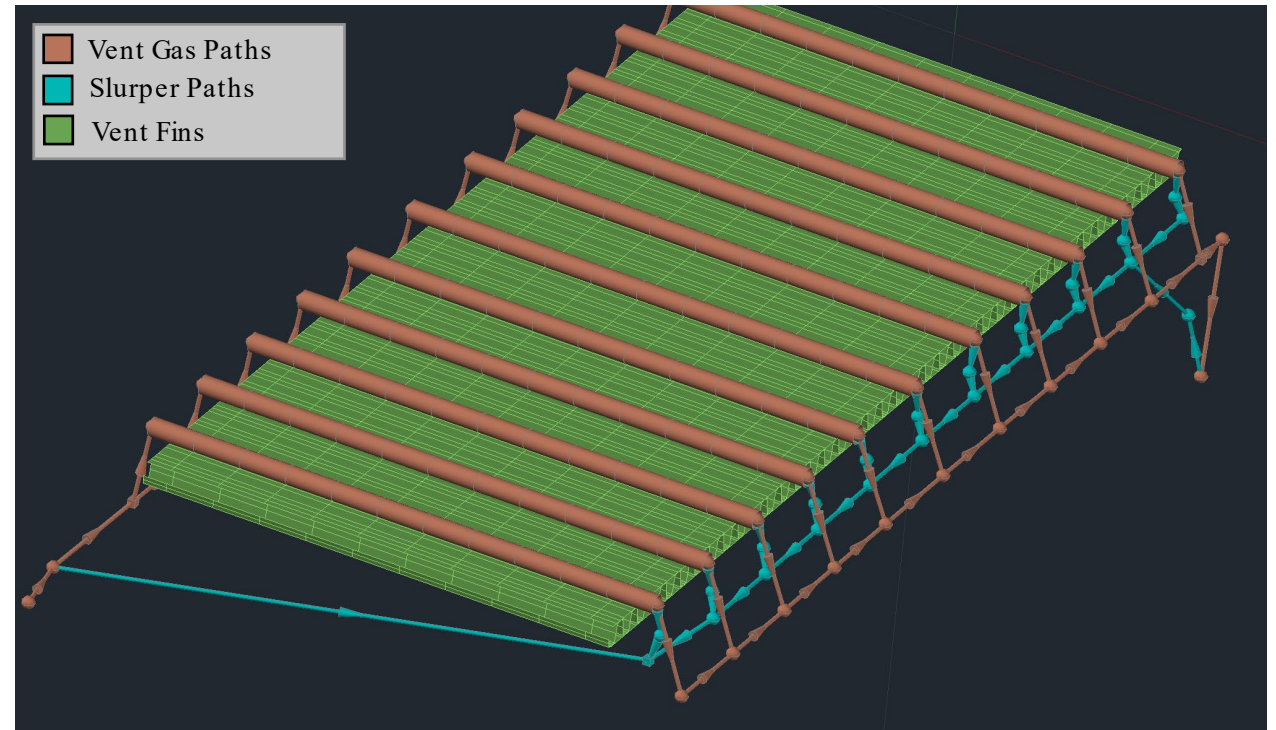


Figure 6: Sublimator Ventilation Internal FloCAD Layout

Model Correlation - Comparison with OEM Blackbox Model

- The model was compared to an OEM MATLAB Black Box model and test data (appendix).
 - 4 cases with varying sublimator inlet conditions
- Correlated at 1 G, with annular flow regime within vent fins,
- UA multipliers were applied to the heat transfer ties within the fins to correlate the model
 - Vent Multiplier: 2.0
 - Water Multiplier: 0.8
- Vent and Water loop outlet conditions were compared from the TD model and Blackbox OEM model
 - Condensation rates were within a 13% difference

Table 1: Sublimator TD Model Comparison to Blackbox Results

Model Inputs: 4.3 psi gas, 19.1 psi water						Model Outputs Comparison: [OEM Expected, Thermal Desktop]			
Case	Vent Flow	Vent Inlet T	Water Flowrate	Water Inlet T	Inlet DEWPT	Vent Outlet T	Water Outlet T	Outlet DEWPT	Condensation Rate
	ACFM	F	lb/hr	F	F	F	F	F	lb/hr
1	6.56	79.3	70.4	47.1	49.3	[39.63, 37.41]	[34.73, 34.41]	[39.63, 37.41]	[0.0645, 0.0719]
2	6.77	95.2	19.3	62.1	51.7	[39.07, 37.44]	[33.61, 32.96]	[39.07, 37.44]	[0.0873, 0.0913]
3	6.85	104.5	196.9	44.7	55.1	[41.08, 41.03]	[37.64, 38.19]	[41.08, 41.03]	[0.108, 0.1042]
4	7.87	135.5	11.1	75.4	84.0	[38.58, 46.38]	[37.28, 34.17]	[38.58, 46.38]	[0.633, 0.549]

Table 2: Sublimator TD Model Comparison to Blackbox: Summary of Deltas

Case	Lower than Blackbox		Higher than Blackbox		
	Vent ΔT [°F]	Water ΔT [°F]	DEWPT ΔT [°F]	Condensation Rate Δ, [lb/hr]	
1	-2.22	-0.32	-2.22	0.0074	11.42
2	-1.63	-0.65	-1.63	0.0040	4.64
3	-0.05	0.55	-0.05	-0.0038	-3.54
4	7.80	-3.11	7.80	-0.0831	-13.13

Integrated Thermal -Fluid Model

The integrated model consists of the Sublimator model combined with 2 separately created models

- Valve Module
 - This component interfaces with the sublimator and link various ventilation and water loop flow paths with the rest of the EMU (Fan/ Pump/ Water Separator, METOX, LCVG, Helmet, etc.)
- Aluminum Horn
 - Outlet gas from the sublimator flows through this component, mixing with oxygen from the O2 tanks, and flows into the valve module before entering the helmet
 - Determination of condensation production in this region is of interest for possible sources of water in the helmet

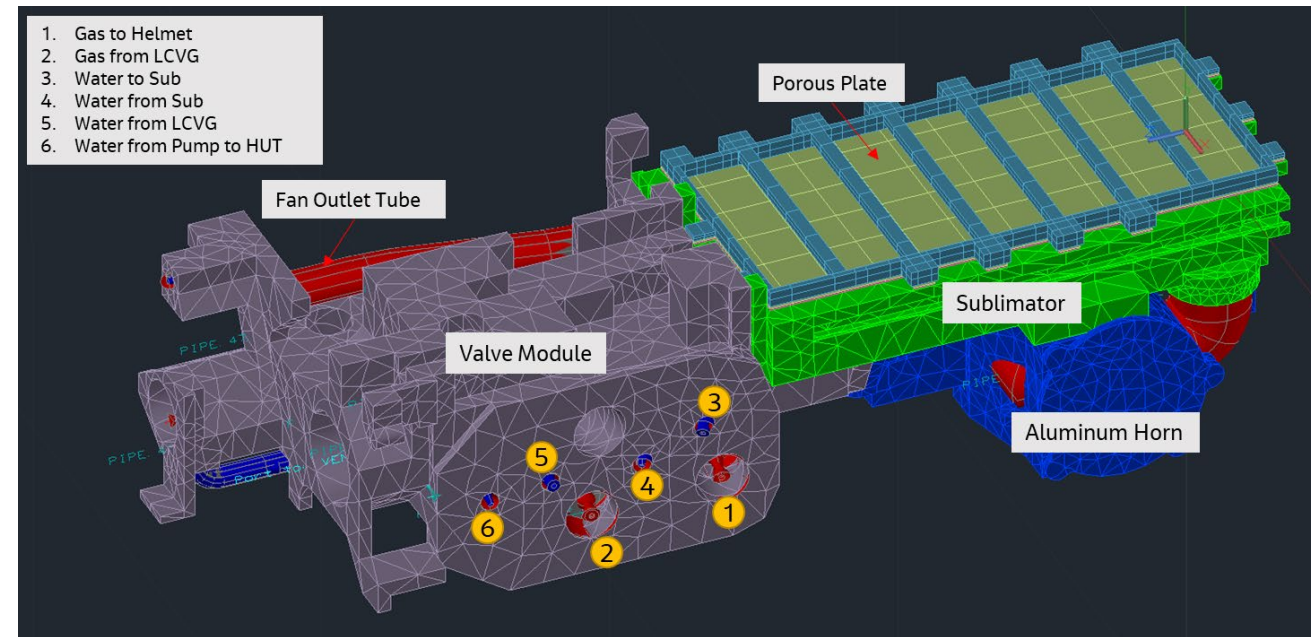


Figure 7: Integrated Thermal Desktop Model

Pressure Drop Models

- This thermal desktop model only represents the ventilation loop in a schematic portion, and does not tie to any geometry
- Uses metabolic rate correlations for breathing species production and consumption
- Provides heat addition from METOX into vent loop
- Sublimator is modeled as a pipe with duplication factors tied to a constant temperature node

The key difference of this model is that it places more focus on the slurper holes and downstream path to the water separator to evaluate and correlate pressure drop

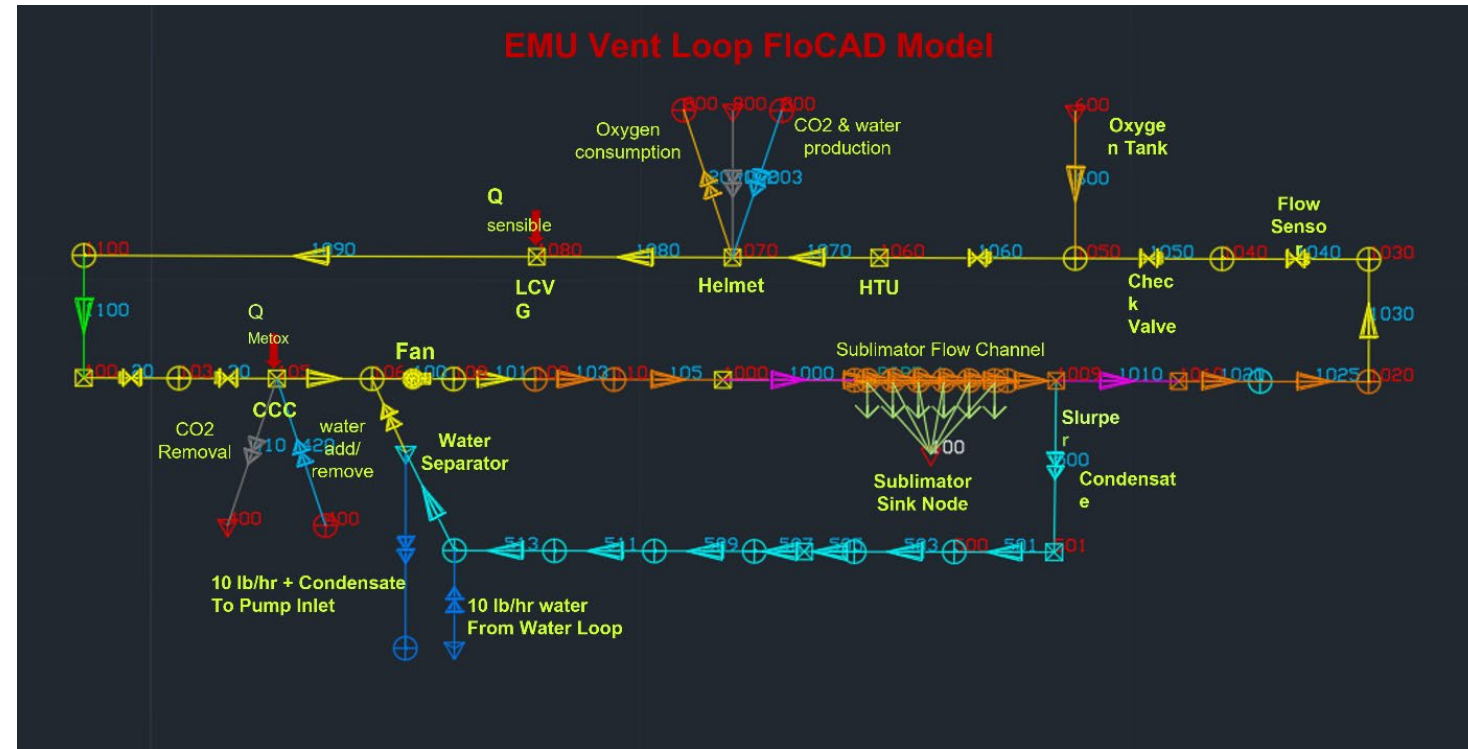


Figure 9: Schematic of FloCAD for EMU vent loop pressure drop analysis and correlation development

Pressure Drop Models (continued)

Using the Thermal Desktop model, the slurper pressure drop was found for different flowrates, and correlated to the CFD model (more details in the next sections).

- Thermal Desktop uses pipe correlations to determine pressure drop, while CFD evaluates Navier-Stokes with a fine mesh of the actual geometry, therefore the CFD model is considered the “trusted” model for pressure drop
- The correlation used in this model is carried over into the previously mentioned sublimator and integrated models

The slurper hole flowrates were seen to be higher in the TD model than in CFD at different operating pressures, so a loss coefficient (FK factor in Thermal Desktop) was applied so that the slurper flowrates matched (Eqn. 1)

$$FK = 3.16 * \left(\frac{P}{4.3} \right)^{0.19433} \quad (1)$$

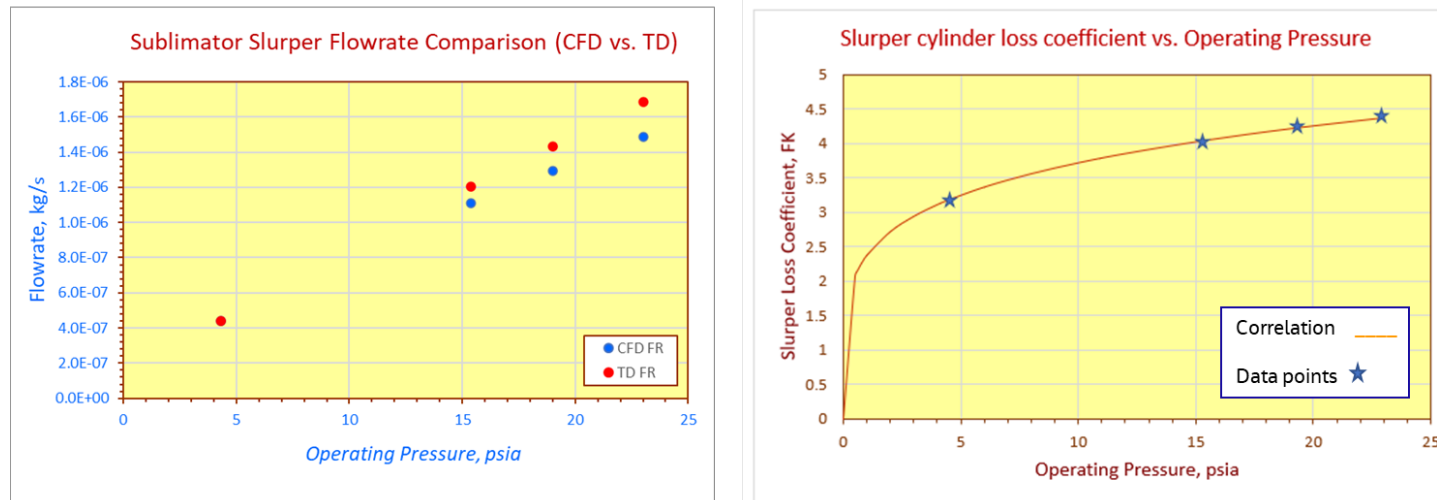


Figure 10: Thermal Desktop and CFD slurper flowrate comparison and FK factor correlation

Future Work of Thermal Desktop Modeling

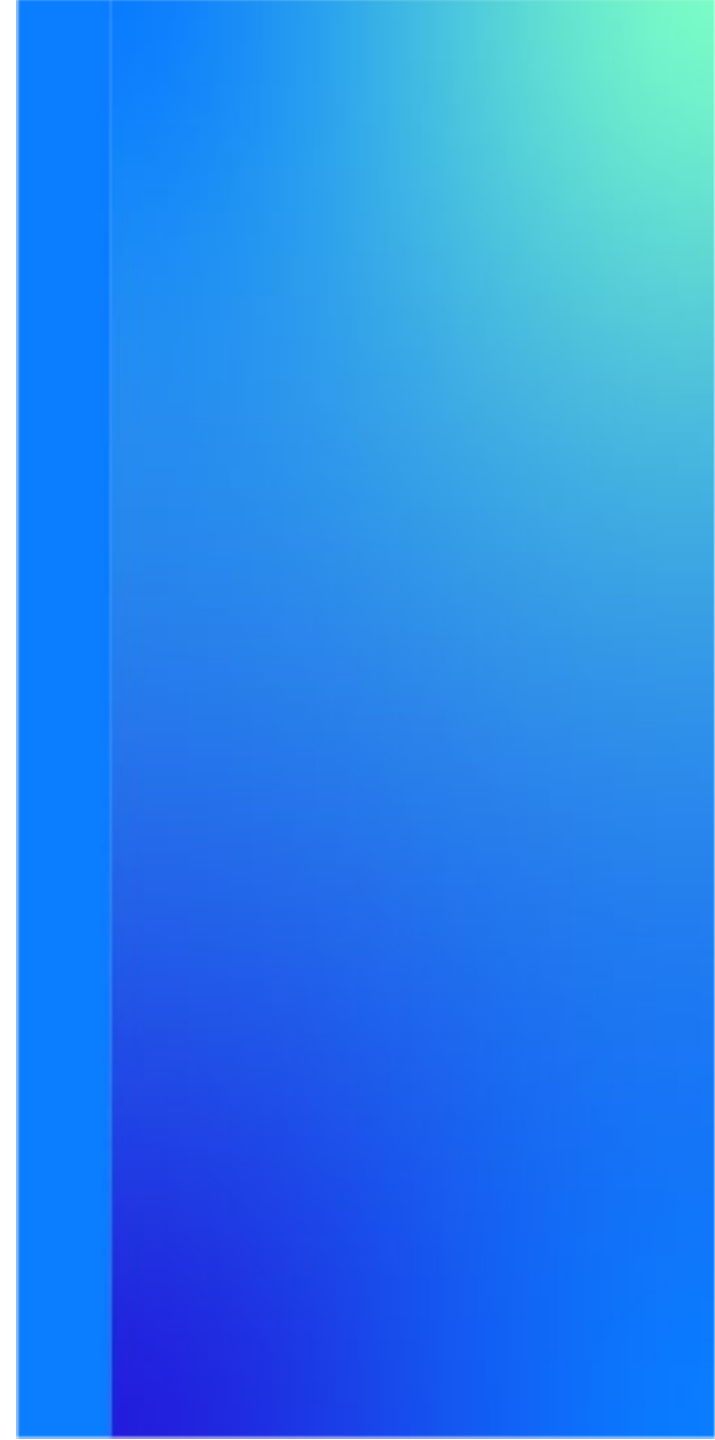
- Further development of the integrated model
 - Needs more realistic flow through the slurper and into the water separator for more accuracy in the downstream condensation/carryover assessment
 - Once complete, assessments for worst case transients with rapid TCV and metabolic rate changes are planned, as well as the actual EVA-80 conditions
- Further use of the pressure drop models to correlate the pressure drop throughout more system components based on new CFD models

The future work of the Thermal Desktop modeling aims to provide further support to understanding the complex behavior of the sublimator and vent loop components

Improvements on these models will help determine sources of water in the helmet, and provide a better evaluation of the slurper water removal performance which may correlate to water carryover

- Much of the above future work has since been completed in the time following the writing of this paper.

CFD Modeling



Sublimator Flow Distribution and Pressure Drop Models

- ANSYS Fluent was used to further characterize flow behavior and pressure drops within the sublimator ventilation and slurper paths
- Internal volumes were extracted from CAD and simplified for meshing
- The overall goal is to map the pressure drop of the sublimator and slurper and provide means to correlate the Thermal Desktop models, as well as determine the distribution of gas through the sublimator fins

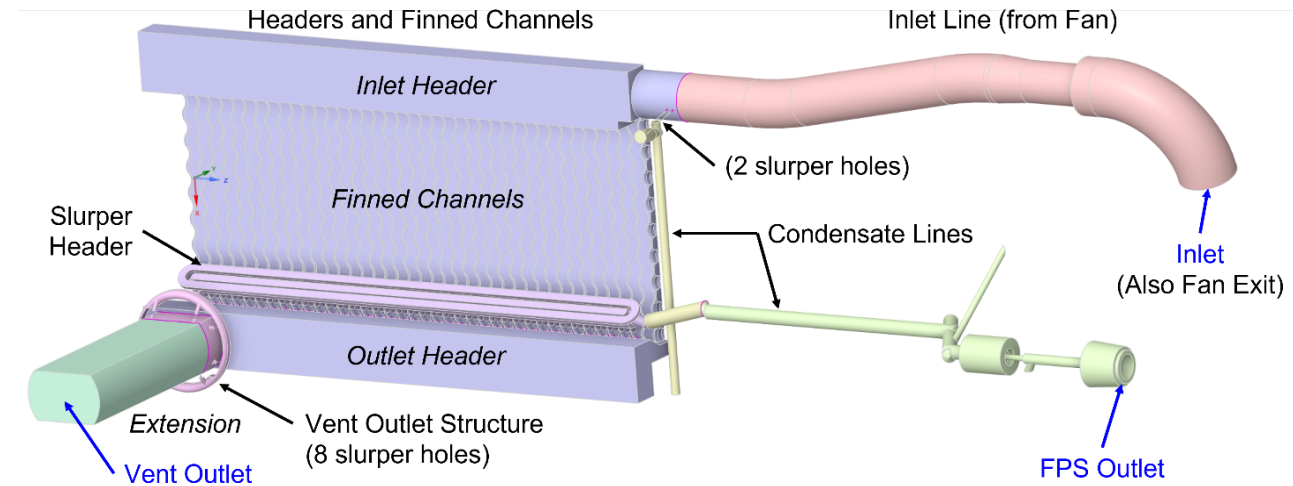


Figure 11: Sublimator/ Slurper Labeled Flow Paths and Internal Volume (Including upstream inlet from Fan, and downstream slurper to water separator)

Sublimator Flow Distribution CFD

- A model using the sublimator internal volume was used to determine the distribution of gas flow from the inlet header into the fins
- The gas velocity at the entrance to different fins along the header is mapped
- The dry gas flowrate increases further along the header as it enters each vent fin passage
 - The flow into the thermal desktop vent fins could be compared against these values to see if a similar trend is observed
- The vent gas pressure drop was also evaluated with this model and was seen to vary from 0.60 to 0.95 in-H₂O from flowrates of 6.00 ACFM to 7.50 ACFM respectively

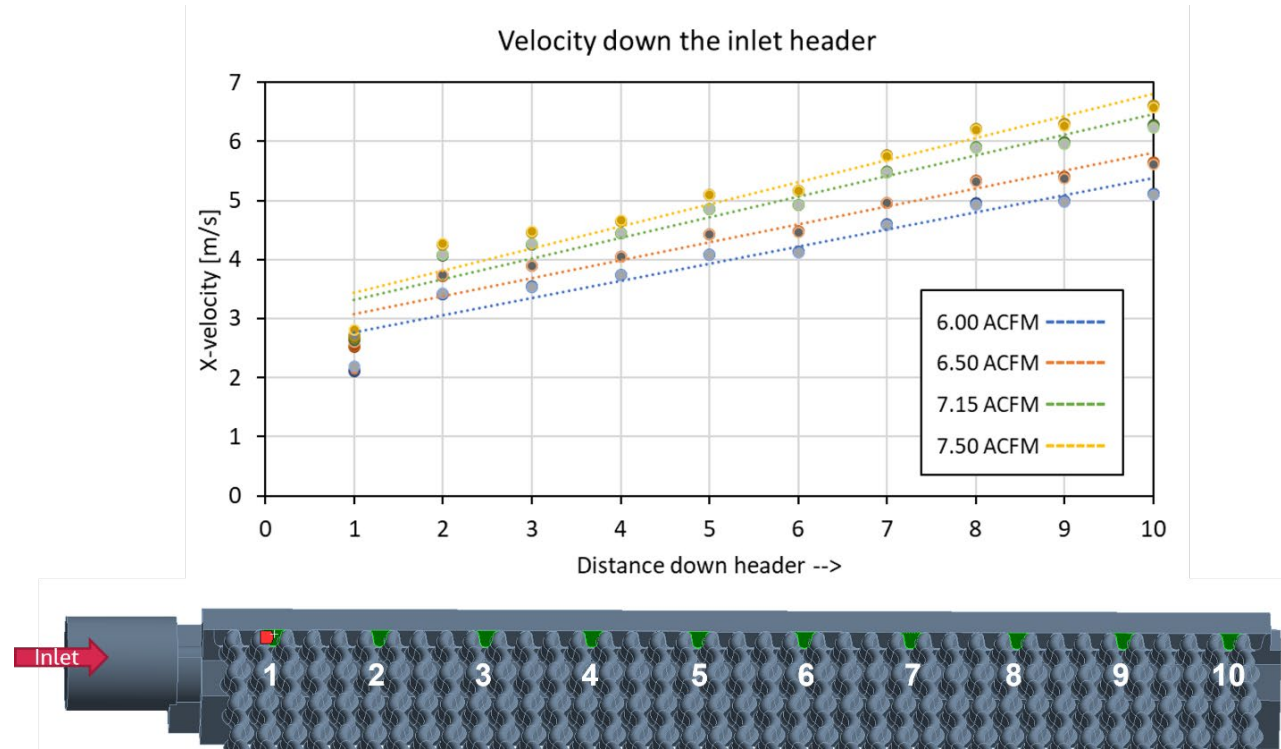


Figure 12: Flow distribution into 10 sampled vent fins from inlet header

Slurper Pressure Drop CFD

- The fluid volume from Figure 11 including slurper and downstream to the water separator is used in this CFD analysis
- Boundary conditions include:
 - Fan outlet velocity based on desired CFM
 - Vent outlet set to constant pressure based on suit pressure
 - Water separator (downstream of slurper) set to various pressures to achieve a desired volumetric slurper flow
- This model evaluates dry gas flow, not two-phase with condensation
- Results were seen to be unaffected by inlet temperature or gravity
- These CFD results serve as a reference for improvement of the other thermal-fluid models

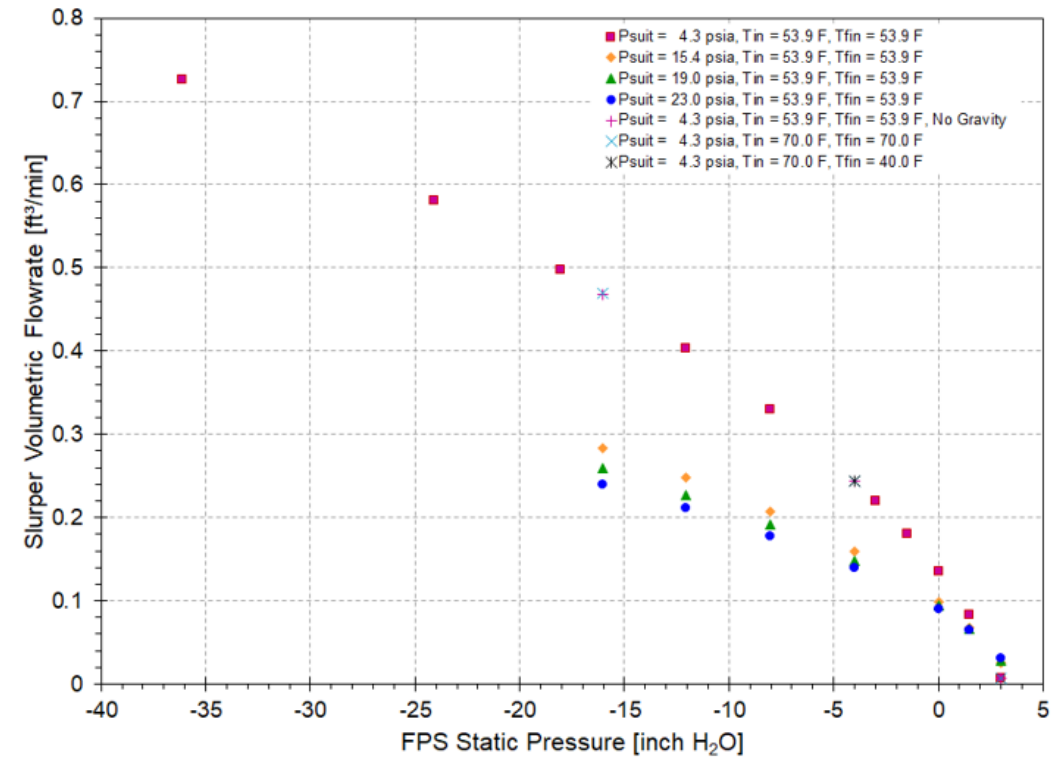


Figure 13: Slurper flowrate vs Water Separator boundary condition pressure for various operating conditions

Future Work of CFD Modeling

- Creation of more CFD models for the whole vent loop system to provide correlations for other models
 - This has been done in the time since writing this paper
- Since the current work involves a characterization of the slurper pressure drop and flow rates, use of these results to further characterize the water removal performance would assist in understanding the capabilities and limitations of the system
- Possible implementation of two-phase flow in CFD could further support understanding of the condensation and removal behavior

Overall, the CFD models add more physical understanding of the system and provide support for adding realism to existing models. Continual improvement and additional CFD models will provide more in depth knowledge of the “how” and “why” of sublimator and slurper characteristics

Conclusions

- Multiple computational models have been created in the form of CFD and Thermal Desktop to support specific objectives involving the EVA-80 water in the helmet mitigation investigation
- This combination of models has provided further understanding of the intricacies of sublimator and ventilation loop behavior in a variety of scenarios
 - Enhanced insight of slurper humidity/condensate removal and potential to provide predictions of liquid condensate transfer to the helmet
- Correlation to other models and test data allows for future improvements and assessments to be made more quickly than before, and to evaluate scenarios before they happen in reality, and predict worst case outcomes
 - Potential to determine other failure modes (what causes condensation downstream of sublimator) and establish prevention methods
 - Potential becomes even more valuable with the integrated EMU PLSS model

Acknowledgments

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References

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Appendix

Test Point	Case 1	Case 2	Omitted due to similarity with case 1	Case 3	Case 4
	11/14/2018 93°F Dew Pt. 240 pph T.F. 4.3 psia	11/15/2018 94°F Dew Pt. 30 pph T.F. 4.3 psia		04/23/1991 76°F Dew Pt. 250 pph T.F. 4.3 psia	04/22/1991 78°F Dew Pt. 161 pph T.F. 4.3 psia
Vent Fluid	Oxygen	Oxygen		Oxygen	Oxygen
Vent Fluid Volumetric Flow (acfm @Inlet)	7.20	7.29		7.18	7.22
Vent Fluid Inlet Pressure (psia)	4.28	4.29		4.26	4.27
Vent Fluid Inlet Temperature (°F)	105.1	105.4		104.4	116.8
Vent Fluid Inlet Dew Point (°F)	92.7	93.5		75.9	77.8
Vent Fluid Mass Flow - Oxygen (lbm/hr)	8.03	8.10		8.69	8.51
Vent Fluid Inlet Mass Flow - Water Vapor (lbm/hr)	0.98	1.01		0.57	0.59
Vent Fluid Mass Flow - Total (lbm/hr)	9.00	9.11		9.26	9.10
Vent Fluid Outlet Temperature (°F) - DATA	55.7	45.3		52.3	54.7
Vent Fluid Outlet Dew Point (°F) - DATA	54.2	42.2		51.1	53.3
Vent Fluid Outlet Condensate (lbm/hr) - DATA	0.67	0.78		0.34	0.35
Transport Fluid	Water	Water		Water	Water
Transport Fluid Flow (lbm/hr)	240.0	30.2		249.6	160.6
Transport Fluid Inlet Pressure (psia)	19.4	19.1		19.1	18.5
Transport Fluid Inlet Temperature (°F)	62.8	75.4		60.7	70.3
Transport Fluid Outlet Temperature (°F) - DATA	49.9	35.0		48.7	48.3

Lower than Data

Higher than Data

Case	Vent ΔT [°F]	Water ΔT [°F]	DEWPT ΔT [°F]	Condensation Rate Δ, [lb/hr]	Condensation Rate Percent Difference [%]
1	-0.95	-0.73	0.55	0.0333	4.9648
2	4.23	0.63	7.33	-0.0031	-0.4008
3	-1.23	-0.91	-0.03	-0.0138	-4.0499
4	-1.97	-0.96	-0.57	-0.0103	-2.9479

Figure A1 : Correlation of sublimator model to test data