Utilization of Variable Emissivity Electrochromic Devices for Space Suit Thermal Control

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Abstract

Motivation
Evaluate the full suit, variable emissivity radiator architecture’s potential for reducing the consumable burden associated to current EVA thermal control mechanisms.

Purpose
Present an overview of work completed to address these needs, and collect feedback where appropriate.

Results
Provide first-order environmental and operational guidelines for future consideration.

Future Work
Complete remaining thermal vacuum assessment and compile work into dissertation.
Introduction - Fundamental Premise

• The space suit must provide the ability to “support human life and enable functionality [within working environment]” [Klaus et al., 2006]

• In terms of thermal – system must maintain the astronaut’s core temperature to the appropriate level to avoid impaired physical and mental performance [Buckey, 2006]
Sublimator Drawbacks

• Impacts to transport and logistics [Eckart, 1996]
  – ~3.6 kg of water lost per EVA [Nabity et al., 2007; Bue et al., 2013]

• Environment contamination concerns
  – Sensitive hardware – Hubble [Hedgeland et al., 1994]
  – Forward contamination of solar system bodies [Race et al., 2003; Conley and Rummel, 2008; Conley and Rummel, 2010]

• Performance degradation over time [Birur & Westheimer, 2007; Leimkuehler & Stephan, 2008; Sheth et al., 2012]

• Potential alternative thermal control method
  – Use the majority of a space suit’s surface area as a radiator
    • Proposed as early as 1965 for LEO [Richardson, 1965]
    • Elaborated upon in the Chameleon Suit [Hodgson, 2001; Hodgson et al., 2004]
    • Consideration of electrochromic devices to modulate dissipation potential [Metts, 2010; Metts et al., 2011]
Research Objectives Overview

• Investigate a potential space suit thermal control technology for closed-loop (non-venting) operations

• Proposed architecture: full suit flexible radiator with variable infrared electrochromic surfaces
  – Environment Characterization
  – Integration Architecture
  – Control Approach

• Results provide expanded operational and integration requirements (guidelines) from previous investigations
INDIVIDUAL ASSESSMENTS
Emissivity Impact on Performance Potential

- In otherwise static environment determine how sink temperature varies with changes in emissivity when radiator has a non-zero solar absorptivity
  - Evaluation of variable heat dissipation capacity variation at lunar pole with variations in radiator emissivity.
  - Established that an emissivity range of 0.3-0.8 is capable of providing ~275-1100 W of heat dissipation.

Citation:
Lunar Environment Suit Interaction

- **Static** suit surface properties
- Suit approximated as a flat plate
  - **Equal area** division where one side shades the other from the direct solar component
  - Assume **infinite plane** lunar surface in local EVA environment (e.g. featureless)
    - **View Factor** (VF) for either radiator area is 0.5 to both the lunar surface and space environment
- **Equation set for evaluations:**
  - Incident solar flux ($S$) of 1368 $W/m^2$ [Gilmore, 2002]
  - Lunar surface solar absorptivity ($\alpha_{Lunar}$) of 0.92
  - Angle from subsolar ($\theta$)
    \[
    q_{IR}'' = \cos\theta \times VF \times S \alpha_{Lunar}
    \]
    \[
    q_{sun}'' = VF \times S \text{ or } 0
    \]
    \[
    q_{Alb}'' = \cos\theta \times VF \times S (1 - \alpha_{Lunar})
    \]
    \[
    q_{rad}'' = \epsilon (\sigma T_{surf}^4 - q_{IR}'') - \alpha (q_{sun}'' + q_{Alb}'')
    \]
    \[
    q_{rad} = \sum \frac{A}{2} q_{rad}'' = \frac{A}{2} (2\epsilon (\sigma T_{surf}^4 - q_{IR}'') - \alpha (q_{sun}'' + 2q_{Alb}''))
    \]

Define $q_{rad}$ and solve for $T_{surf}$

Temperature requirements for 300W dissipation with gas pressure suit area

TFAWS 2015 – August 3-7, 2015 – Silver Spring, MD
Define radiator surface temperature guidelines for desired amount of heat dissipation on the lunar surface for radiator with static surface properties

- Characterize baseline radiator temperature to dissipate 300 W and 700 W of heat on lunar surface using the full suit flexible radiator concept
  - Black Body: $\alpha = 0, \epsilon = 1$; EMU: $\alpha = 0.18, \epsilon = 0.84$; Degraded: $\alpha = 0.5, \epsilon = 0.9$
- Identify threshold latitudes for long duration mission sites
- Can be used to characterize allowable thermal resistance

Threshold angles from subsolar point for 310 K and 290 K mean radiator surface temperatures.

<table>
<thead>
<tr>
<th></th>
<th>Blackbody 310 K</th>
<th>Blackbody 290 K</th>
<th>EMU 310 K</th>
<th>EMU 290 K</th>
<th>Degraded 310 K</th>
<th>Degraded 290 K</th>
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<tr>
<td>EMU Area 300 W Rejection</td>
<td>46°</td>
<td>60°</td>
<td>58°</td>
<td>70°</td>
<td>69°</td>
<td>80°</td>
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<tr>
<td>EMU Area 700 W Rejection</td>
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<td>72°</td>
<td>83°</td>
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<td>DNE</td>
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<td>69°</td>
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<tr>
<td>MCP-Suit Area 700 W Rejection</td>
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</tbody>
</table>

Citation:
Pixel Integration Concept & Considerations

- Need to define pixel area and corresponding number of pixels
- Electrochromic control modes: *continuously variable* vs. *high-low state mixing*
- Radiator integration modes: *constant temperature* (dual-loop) vs. *constant flux* (uniform heat leak)

Jade Suit Integration, Image Credit: www.theguardian.com

Individual Electrochromic Activation
First-Order Pixel Area Determination

• Used a cylindrical space suit approximation in a lunar pole environment

• Key Results
  – Constant Temperature
    • Either 1 or ~48 individual pixels depending on control mode
    • Required emissivity variation of 0.169 to 0.495
  – Constant Flux
    • ~400 individual pixels in continuously variable emissivity control
      – No transverse conduction within suit walls considered
    • Required emissivity variation of 0.122 to 0.967
  – Should consider these values to be a minimum baseline as more complex geometries will generally require additional pixelation

Citation:
Dynamic System Model

- Constructed simplified 7-node human metabolic model based on previous work [Crawford et al., 2000; Campbell et al., 2000; Montgomery, 1974; Stolwijk and Hardy, 1966]
- Model allows for asymmetric external environment exposure to a two-sided radiator approximation
Example Environment Variation

Profile

- Bulk variations in incident IR flux
  - Step increase of 100 W/m\(^2\) at 10 min.
  - Additional step increase of 125 W/m\(^2\) at 25 min.
  - Return to nominal condition at 31 min

This variation is consistent with bulk flux changes that may be experienced when entering a surface region with complex geometries (boulder, etc.)
4 test scenarios were completed: 2 metabolic variations and 2 environment variations

Emissivity saturation shown to have a negative impact on the simulated human’s thermal condition
- Short excursions can be compensated for by the system
- Prolonged exposure can cause the model to diverge (instabilities)

Nature of current model dictated that little or no variation in BHS is experienced before the system diverges
- Current output does not map one-to-one with NASA HIDH
- No excursion into potential dangerous regimes

Citation:
Martian Surface EVA Extension

- Examined diurnal variations in external environment for 4 seasons at 27.5 °S latitude
- Considered variations in wind speed, absorptivity, and area
- Seasonal supplemental thermal control guidelines identified
  - Limit heater capacity: 631 W
  - Limit additional dissipation capacity: 1423 W

Citation:

TFAWS 2015 – August 3-7, 2015 – Silver Spring, MD
ONGOING & FUTURE WORK
Mixed Emissivity Verification in Thermal Vac

• **Assess feasibility** and assumption quality for constant temperature and uniform flux integration

• **Demonstrate impacts of high-low emissivity state mixing** on thermal performance
  - Thermal vacuum, at CU
  - Test article is under construction and testing is to occur Fall 2015

![JSC Electrochromic Test Article]
Key Points for Further Elaboration

- Dynamic model expansion in fidelity and test scenarios
  - Use or expansion of 41-node metabolic man or Wissler models for asymmetric environments
  - Use more realistic working environment fluxes [Hager et al., 2015]
- Further definition of external environment restrictions for using the architecture
- Parametric definition of heat removal layer properties for maintaining thermal equilibrium
- Construction of an integrated test article for further testing and concept verification
CONCLUSIONS
Summary

• **Analytically and empirically** evaluated the potential to achieve closed-loop EVA thermal control by integrating variable IR emissivity electrochromics into a full suit flexible radiator thermal control architecture

• **Provided a robust mechanism for assessing integration feasibility**

• **Defined heat transport properties and requirements for supplemental heat rejection systems**

• **The scope of this work is very much inline with NASA’s EVA systems technology development goals**
Conclusions

• The full suit radiator with variable emissivity surfaces architecture has proven to be **feasible** for several environments, at the level of the investigations

• Outputs could be used to for operations planning and determination of integration requirements

• Results suggest that a hybrid thermal control system is required to expand EVA operational regimes

• Suggest that additional work be completed in physical device development so further integrated testing can be completed
Acknowledgements

• This work was supported by a NASA Office of the Chief Technologist’s Space Technology Fellowship (Grant No. NNX12AN17H)

• NASA Mentors
  – Rubik Sheth (primary)
  – Scott Hansen
  – Grant Bue
  – Craig Dinsmore
  – Keith Novak

• Remaining Committee Members
  – Louis Stodieck, CU Aerospace
  – Se-Hee Lee, CU Mechanical
  – Jonathan Metts, Bigelow Aerospace
  – Eugene Ungar, NASA JSC
References


QUESTIONS