Convective Heat Transfer at the Martian Boundary Layer, Measurement and Model

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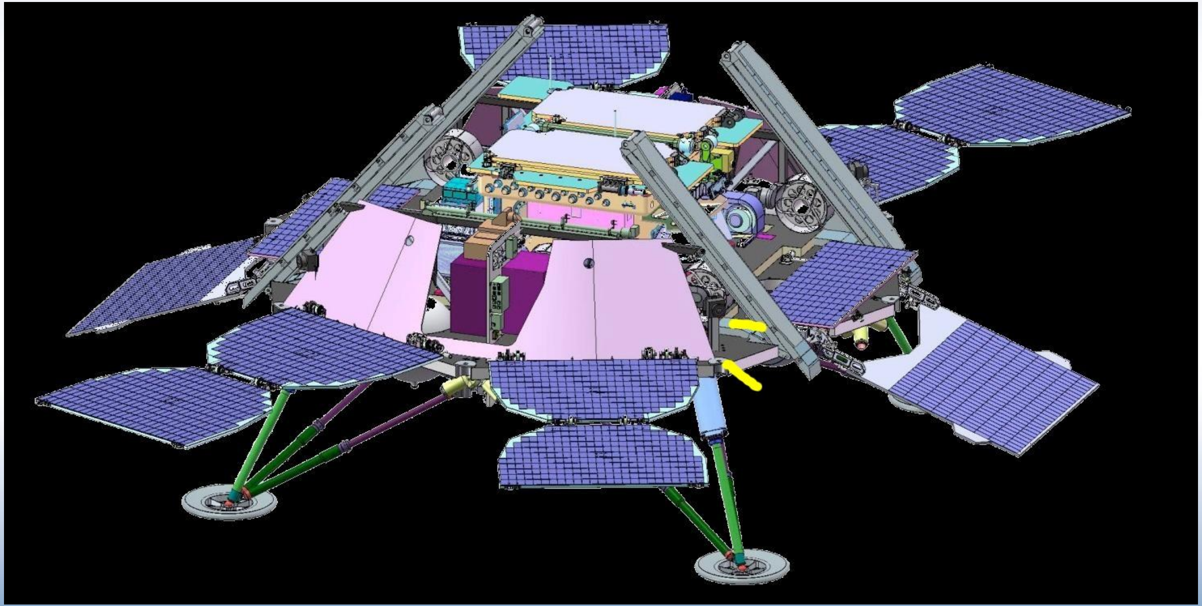
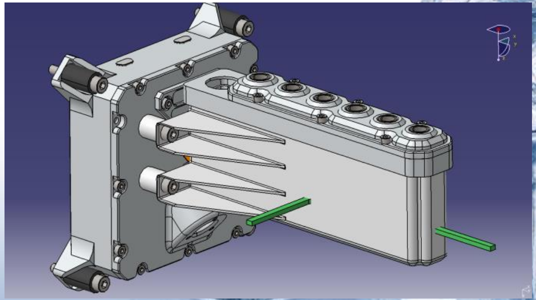
Context: ExoMars 2018 mission

- Context: HABIT (HabitAbility: Brines, Irradiation and Temperature), instrument included in ExoMars 2018 mission (http://www.esa.int/Our_Activities/Space_Science/European_payload_selected_for_ExoMars_2018_surface_platform). First Swedish instrument for the surface of Mars.



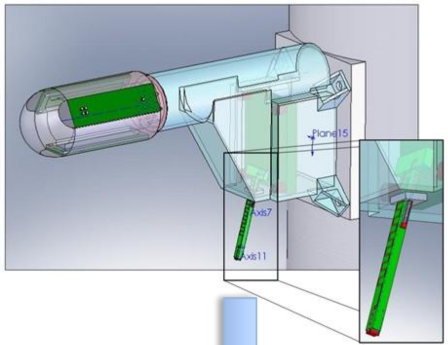
Components:

- 6 UV sensors
- 3 Air Temperature Sensors (ATS)
- 1 Ground Temperature Sensor (GTS)
- BOTTLE (Brine Observation Transition To Liquid Experiment)

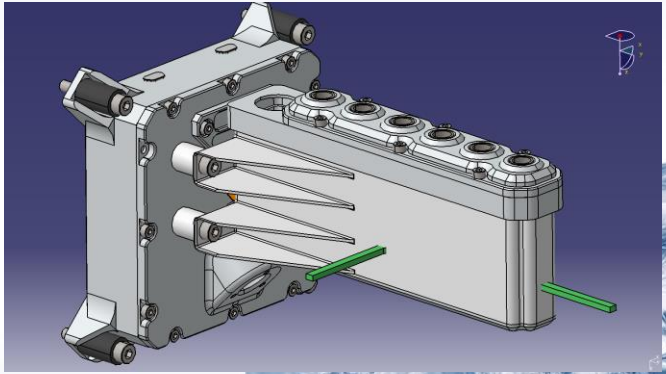


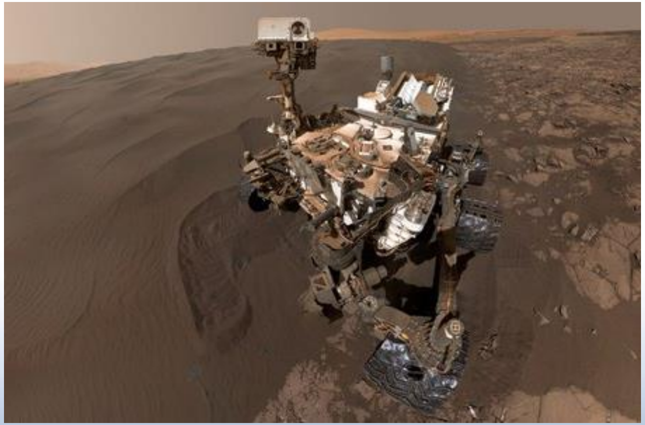
HABIT ATS sensors

- Objective: Use the HABIT ATS sensors to characterize the wind on Mars surface through the convective heat transfer coefficient.



HABIT (HabitAbility: Brines, Irradiation and Temperature) heritage. Operating from 2018.





REMS (Rover Environmental Monitoring Station) heritage. Operating from 2012.

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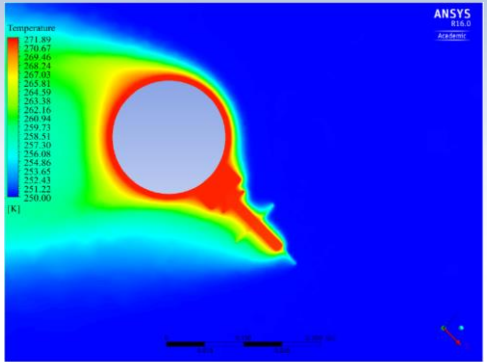
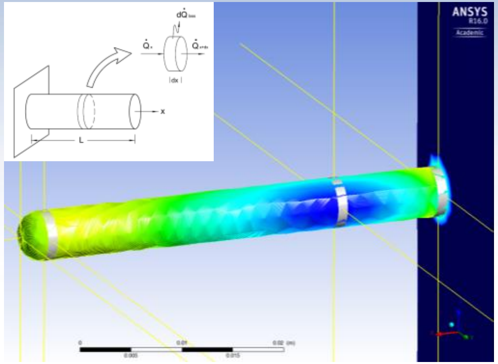
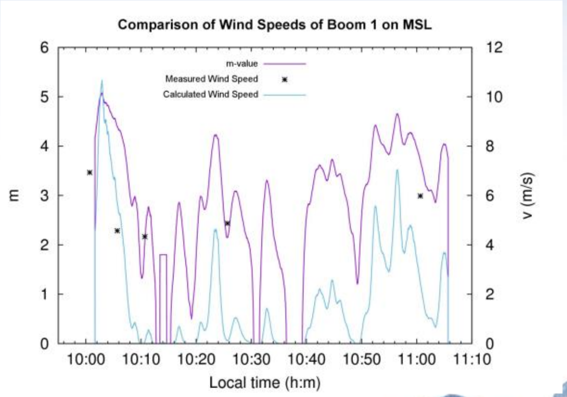
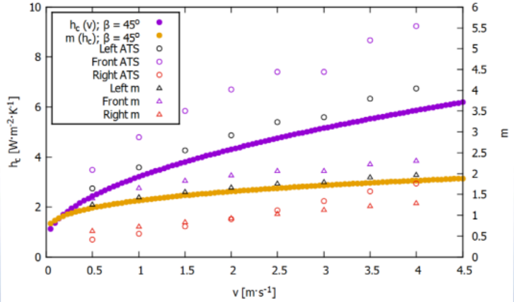
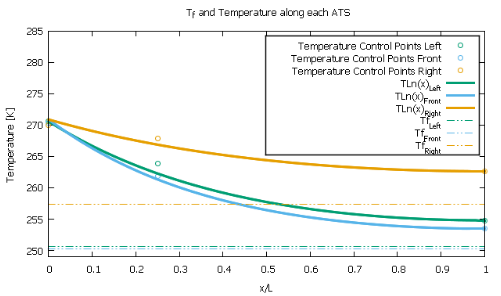
Wind Retrieval Model for the ATS











Method → Variation m → Variation h → Variation h_c → Retrieval forced convection each ATS → Wind characterization

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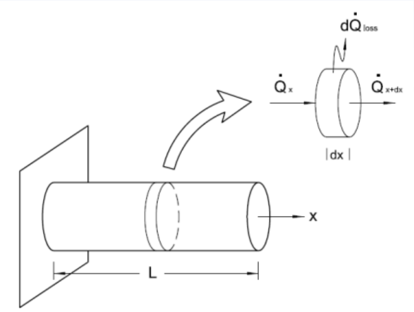
1. Theoretical Model

- Energy Balance:

$$\frac{d}{dx}\left(\kappa A_c \frac{dT}{dx}\right) = h_c \frac{dA_s}{dx}(T - T_\infty) + \varepsilon\sigma \frac{dA_s}{dx}\left(T^4 - {T_\infty}^4\right)$$

- Heat transfer coefficient:

$$h = h_c + h_r = h_c + \varepsilon\sigma(T^2 + {T_\infty}^2)(T + T_\infty)$$



- Organizing:

$$\frac{d^2\theta}{d\chi^2} - {m_\chi}^2\left(\chi, \theta, T_f, \beta\right)\theta = 0$$

$$\theta = T_x - T_f, \chi = x/L$$

- M-Parameter:

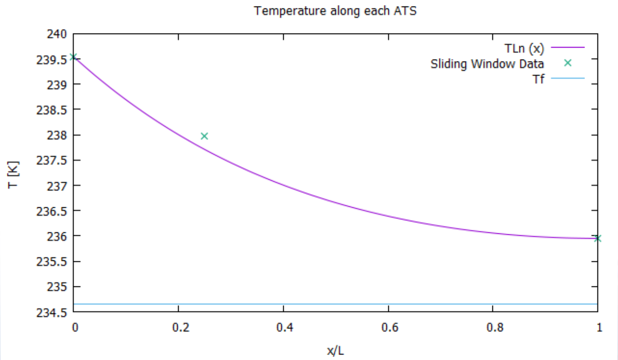
$$m_\chi = L\sqrt{\frac{\left[3(1+\cos(\beta)) - \sqrt{(3+\cos(\beta))(1+3\cos(\beta))}\right]h}{D\kappa}}$$

1. Theoretical Model

- Non-Linear Boundary-Value Problem along ATS sensors:

$$\begin{cases} \theta|_{\chi=0} = \theta_b \\ \left.\dfrac{d\theta}{d\chi}\right|_{\chi=1} = 0 \end{cases} \rightarrow \quad \theta_{(\chi)} = \theta_b \frac{\cosh(m(1-m))}{\cosh(m)} \quad \rightarrow \begin{cases} (T_a - T_f) = (T_b - T_f)\dfrac{1}{\cosh(m)} \\ (T_{Ln} - T_f) = (T_b - T_f)\dfrac{\cosh(m(1-\frac{1}{n}))}{\cosh(m)} \end{cases}$$

- Analytical solution: m averaged over length of the rod.
- Retrieval Method:
  - Three simultaneous measurements
    - T_b: Temperature at the base (Platform).
    - T_{Ln}: Temperature at $x = L/n$.
    - T_a: Temperature at the tip.
  - Unknowns: m, T_f
    - T_f: Fluid temperature
    - $m_\chi = L\sqrt{\dfrac{[3(1+\cos(\beta))-\sqrt{(3+\cos(\beta))(1+3\cos(\beta))}]h}{D\kappa}}$



Method → Variation m → Variation h → Variation h_c → Retrieval forced convection each ATS → Wind characterization

2. CFD Simulations: Governing Equations

$$\nabla \cdot \vec{v} = 0,$$

$$\rho \nabla \cdot (\vec{v}\vec{v}) = -\nabla\left(p\bar{\bar{I}}\right) + \nabla \cdot \tau + \rho \vec{g}_M,$$

$$\rho \left[\vec{v} \cdot \nabla \left(c_P \cdot T + \frac{1}{2} v^2\right)\right] = -\nabla \cdot (p\vec{v}) + \nabla \cdot (\tau \cdot \vec{v}) + \nabla \cdot (\kappa \nabla T) + \rho \vec{g}_M \cdot \vec{v} + Q,$$

$$\frac{dI(\vec{r},\vec{s})}{ds} + (a_b + \sigma_s) \cdot I(\vec{r},\vec{s}) = a_b n^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r},\vec{s}) \Phi\left(\vec{s} \cdot \overrightarrow{s'}\right) dw$$

$$\frac{p}{\rho} = R_g T$$

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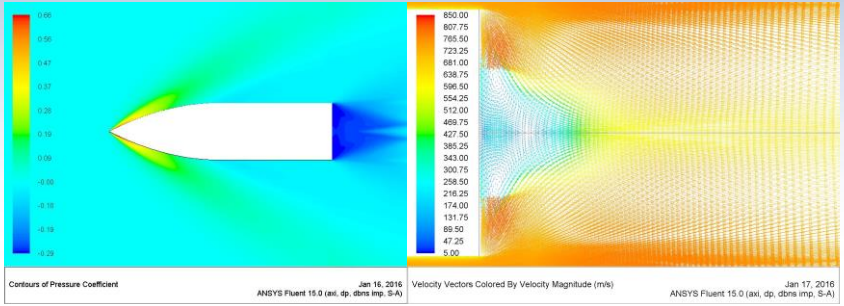
2. CFD Simulations: Assumptions

- Fluid Model:



$$\mathrm{Pr} = \frac{C_p(T)\mu}{\kappa_f(T)}, Re = \frac{\rho v_{wind} L_c}{\mu}, L_c = D/\cos(\beta)$$

$$Nu = \frac{h_c L_c}{\kappa_f(T)};\ Nu = 0.3 + \frac{0.62 Re^{1/2} Pr^{1/3}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}} \left[1 + \left(\frac{Re}{28200}\right)^{5/8}\right]^{4/5}$$

- Temperature dependent polynomial models for $C_p(T)$ and $\kappa_f(T)$ in low-pressure $[1, 10^4] mbar$ and low-temperature $[200{,}1000] K$ domains.
- Chapman-Enskog's Kinetic Theory for μ (constant).
- Incompressible ideal gas CO_2 laminar flow $(M < 10^{-3})$.

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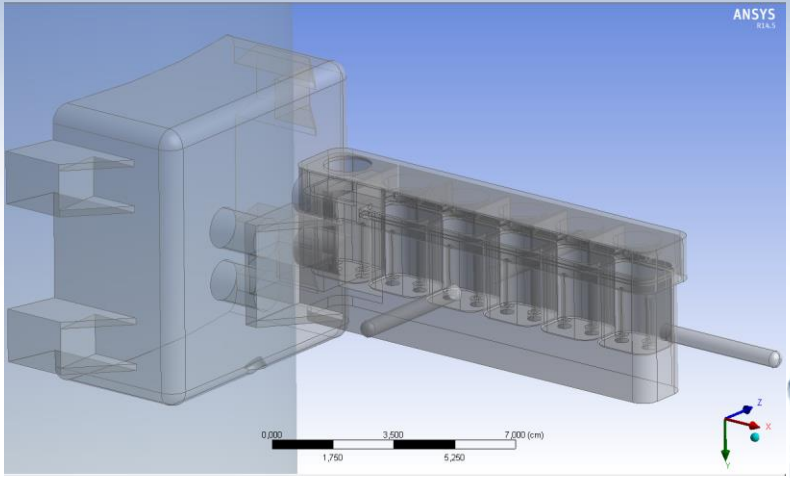
2. CFD Simulations: Assumptions

- Boundary conditions:
  - Vertical pole.
  - 2 Structures: HABIT (Al) + ATS sensors (FR4).
  - Carbonate properties for Mars surface fixed at 280 K.
  - Surface Platform temperature fixed at 272.177K.
  - Radiative heat transfer (IR band $[0.4{,}0.7]\ \mu m$)..
  - Solar load not included.
  - Emissivity and absorptivity (table).
  - Stationary
- Study cases:
  - Deviation angle $\beta = 45^o$.
  - Fluid temperature $T_\infty = 250\ K$ (sol 45).
  - Velocity inlet: Range $[0.5, 4]\ ms^{-1}$ each $0.5\ ms^{-1}$.
  - Each case with and without radiative heat transfer



Surface	Emissivity ε	Absortivity α_r
Space Paint	0.88	0.2
FR4	0.9	0.3
Dolomite	0.9	0.5

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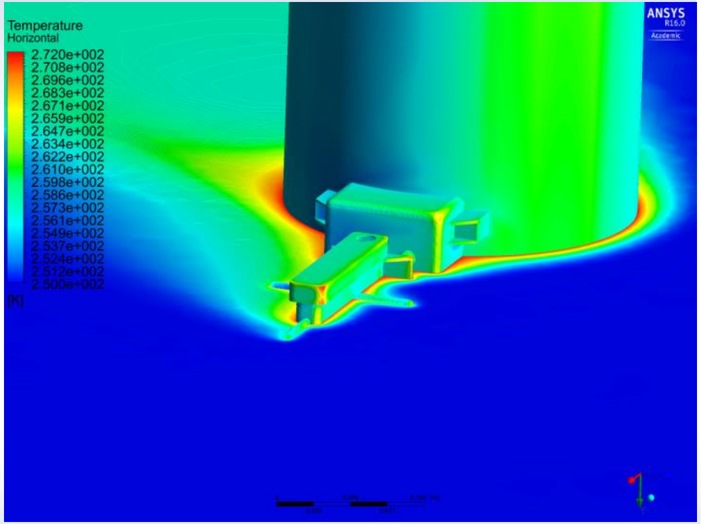
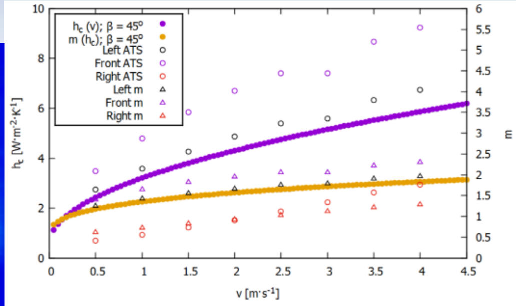
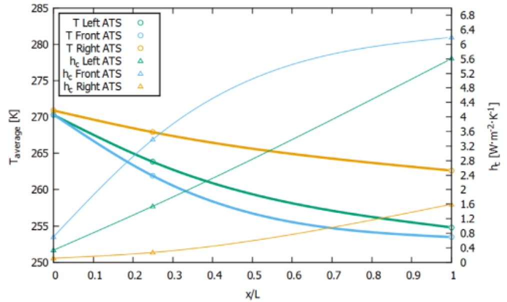
3. CFD Simulations: Results







Case	$v\ [ms^{-1}]$	ATS	$h_c\ [Wm^{-2}K^{-1}]$	m
1	0.5	Left	2.7375	1.2559
		Frontal	3.4820	1.4164
		Right	0.6860	0.6287
2	1.0	Left	3.5745	1.4351
		Frontal	4.7835	1.6602
		Right	0.9335	0.7334
3	1.5	Left	3.5745	1.4351
		Frontal	4.7835	1.6602
		Right	0.9335	0.7334
4	2.0	Left	3.5745	1.4351
		Frontal	4.7835	1.6602
		Right	0.9335	0.7334
5	2.5	Left	5.3980	1.7636
		Frontal	7.4055	2.0656
		Right	1.8675	1.0370
6	3.0	Left	5.5980	1.7959
		Frontal	7.4105	2.0663
		Right	2.2410	1.1363
7	3.5	Left	6.3345	1.9104
		Frontal	8.6765	2.2359
		Right	2.6205	1.2288
8	4.0	Left	6.7390	1.9705
		Frontal	9.2360	2.3068
		Right	2.9330	1.2999

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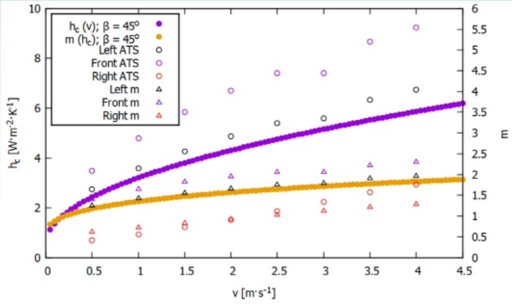
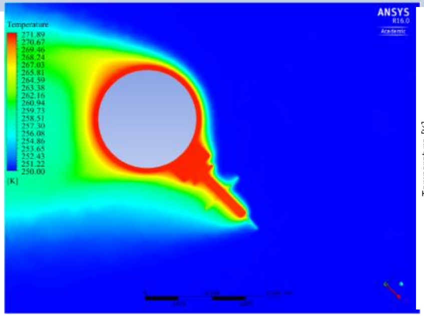
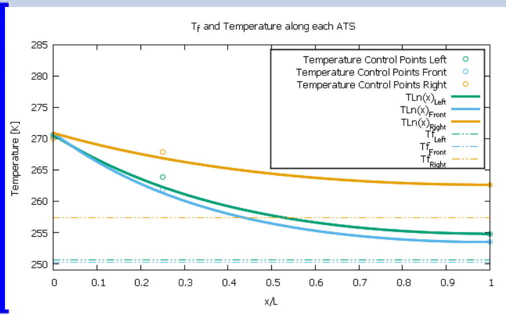
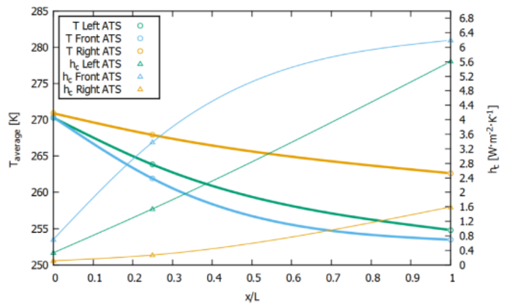
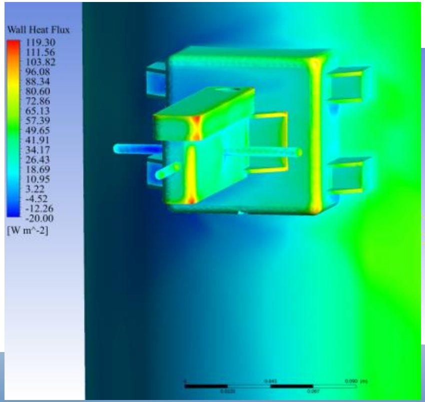
4. CFD Simulations vs. Theoretical model

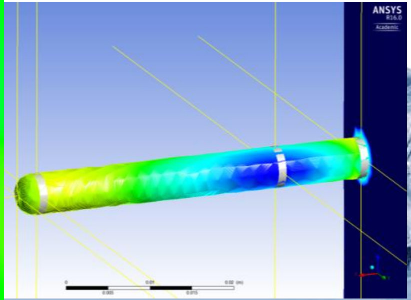












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5. Conclusions

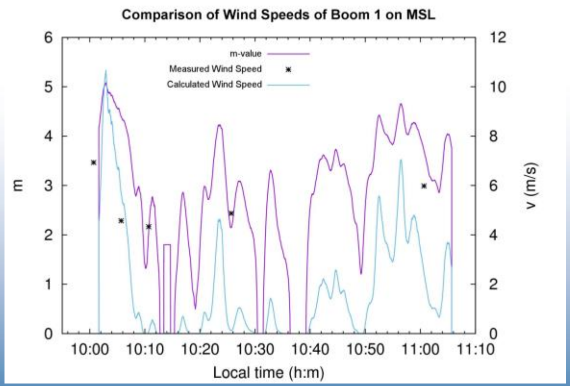
- Averaged heat transfer coefficient h and m parameter show a growth with the wind speed for the same near environmental conditions.
- The model presents a limitation in low velocity fluid flow conditions, when it can be assumed that there is not wind and thus not forced convection.
- The model does not describe the wind orientation over a single sensor, only through the variation of its value given this parameter is sensitive to it.
- Despite the limitations of retrieving the orientation of the wind through a single ATS sensor, their disposition over the HABIT allows a preliminary retrieval through the different temperature distributions and m parameter over them. This retrieval is conditioned to an horizontal wind.
- The ATS locations are different over the HABIT and the REMS instrument → Future comparative analysis with REMS ATS data from Planetary Data System (PDS) will be influenced by this fact.
- The CFD simulation is here used to obtain a plausible thermal profile of the ATS under exposure to Mars wind conditions. The temperatures at three control points are successfully used to retrieve the temperature of the air in the vicinity of the instrument.

5. Conclusions

- The model shows a better resolution than the REMS Wind Sensors (WS) currently operating on Mars on-board Curiosity rover,. It can be seen how changes in the incident wind speed are seen as real time changes of the m value within 60 seconds of time span, while WS provide wind velocity averaged each 5 minutes.
- In the near future the m, rod-long averaged, values will be retrieved from the heat flux, rod-long averaged, values at each ATS and compared with the m values that are retrieved from the three temperatures of the control points. This shall be done under different angles of incidence and wind speeds at stationary conditions, considering the limits of the assumptions of the retrievals.
- Heat fluxes under Martian conditions are very low, of the order of $100\ W/m^2$ and strongly changing in the vicinity of the spacecraft. The main limitations of this model are the problems to retrieve low wind speeds, given that heat losses due to forced convection are too small compared to radiative ones through the surface of the sensors.
- The model is applicable to stationary scenarios, while the wind characterization on Mars is foreseen to be in continuous change. It could be acceptable in case they can be considered as quasi-stationary changes.

6. Source of Errors

- Nusselt number formulation applicable to a cylinder perpendicularly exposed and without attack angle to an external fluid flow.
- One-dimensional model versus two-dimensional temperature and h_c distributions over the ATS sensors rod-shape.
- Local force convection over the sensors not described in the mathematical model.
- Temperature and hc values at control points from CFD studies averaged over a revolution surface of $A \approx 1.57 \cdot 10^{-5} m^2$.
- Convective heat transfer coefficients h_c for each ATS averaged from averaged h_c at the middle and tip control points.



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