Design of a Thermal Anemometer for a Titan Lander

Colin Wilson[1] , Nathan Donaldson[2], & Ralph Lorenz[3]

[1] Department of Physics, University of Oxford, UK; (colin.wilson@physics.ox.ac.uk); Department of Engineering Science, University of Oxford, U.K.; [3] Space Exploration Sector, JHU Applied Physics Laboratory, USA.

Introduction & requirements

Weather on Titan is of great interest: Titan has an active hydrological cycle just like Earth's (but different!) and its geomorphology reflects modification not only in the wind-mediated distribution of liquid methane on the surface, but also by the vast dunefields that girdle Titan's equator. Any landed mission to Titan is certain to demand wind measurement capability.

Wind measurements are required to:
(1) Resolve large-scale and mesoscale circulation patterns;
(2) Characterize the planetary boundary layer, which governs all surface-atmosphere exchanges of heat, momentum and volatiles;
(3) Provide context for other sensors, including seismometers.

Typical wind speeds on Titan are anticipated to be 0 – 2 m/s, although they may reach 5 m/s in storm conditions. Turbulence reconstructions suggest that fluctuations on the order of 0.1 - 0.2 m/s are expected over timescales of 1-3 seconds [1]. A Titan anemometer should be able to resolve these phenomena.
A Titan anemometer, therefore, must be able to measure a horizontal wind vector at typical windspeeds of 0 – 2 m/s, with an accuracy of 0.1 m/s or better.

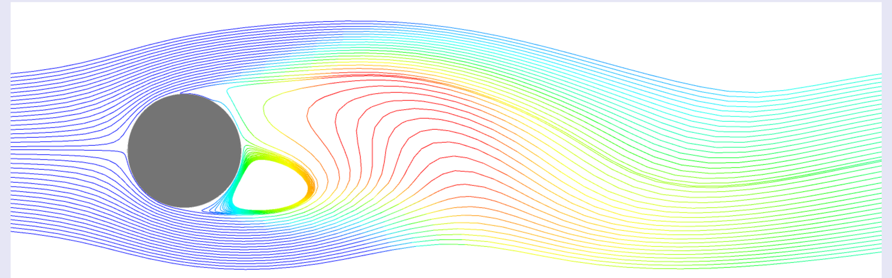
Thermal anemometry

Almost all planetary anemometers to date are those deployed on Mars, and most of these have been thermal anemometers due to their simplicity of construction and lack of moving parts. Calibration of thermal wind sensors on Mars is notoriously tricky: neither Pathfinder [2] and MSL [3] anemometers have met their performance goals, with much of their data still uncalibrated. However, the thermophysical characteristics of Titan's atmosphere [4] make it much better suited for thermal anemometry than that of Mars, in several ways: (1) its higher density leads to higher convective heat transfer coefficients, leading to better wind speed sensitivity; (2) Temperature fluctuations in Titan's near surface atmosphere are < 0.1 K [4] (unlike Mars where air temperatures can change by 10 K in 10 seconds in daytime turbulence); (3) thermal IR radiative fluxes are very low due to the low environmental temperature of only 93 K, leading to reduced uncertainties.
We therefore assess performance of a heritage thermal wind sensor for Titan, based on that flown on the Beagle 2 & Schiaparelli Mars landers [5-6].

Thermal anemometer flown on Beagle 2 (2003) and ExoMars 2016 (2016) Mars landers [refs. 5-6]

Acoustic time-of-flight anemometry offers more robust calibration and faster response times, which makes it ideal for turbulence measurement – but it is a much more complex instrument, requiring >>10 MHz timing accuracies and significant processing capabilities.

Flow regime

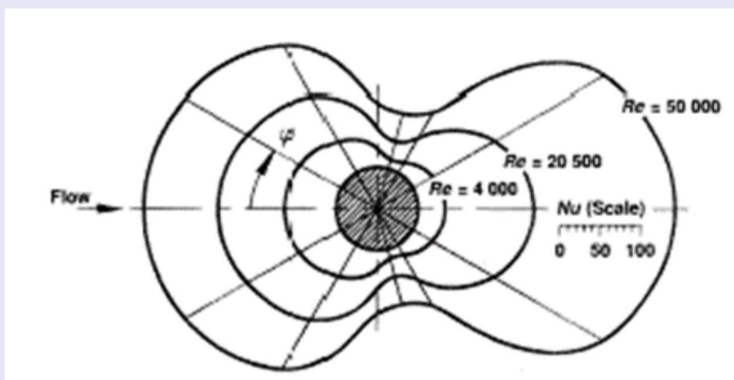


We consider first the heat transfer from a uniformly heated cylinder with the same dimensions as B2WS, 10 mm in diameter x 18 mm high, in typical flow conditions on Earth, Mars and Titan; these results are shown in Table 1. Table 1 includes calculations of Reynolds and Nusselt numbers, which are dimensionless representations of wind speed and convective heat transfer coefficient, respectively. Earth atmospheric conditions, at 20° C, are included to demonstrate the ease with which Titan wind conditions can be simulated in a standard 0 – 20 m/s wind tunnel on Earth, with 1:1 full scale models.

	EARTH (air)	MARS (CO2)	TITAN (N2)	units
T_air =	**300**	**250**	**94**	K
p =	**1000**	**6**	**1450**	mbar
molarmass	**0.0288**	**0.044**	**0.028**	kg mol-1
density=	1.17	0.013	5.25	kg m-3
viscosity	18.6	12.7	6.6	µ Pa s
conductivity k =	0.027	0.015	0.009	W m-1 K-1
specific heat c	1007	841	1099	J kg-1 K-1
gravity g =	**9.81**	**3.71**	**1.4**	m2 s-1
Prandtl #	*0.69*	*0.71*	*0.79*	
wind speed	**10**	**5**	**0.79**	m/s
diameter	**0.01**	**0.01**	**0.01**	m
height	**0.018**	**0.018**	**0.018**	m
Reynolds #	*6300*	*51*	*6300*	*to 2 sig.fig.*
mean Nu	*38*	*3.8*	*40*	*to 2 sig.fig.*
conv htc	104	6	37	W m-2 K-1

Criterion for sensor diameter

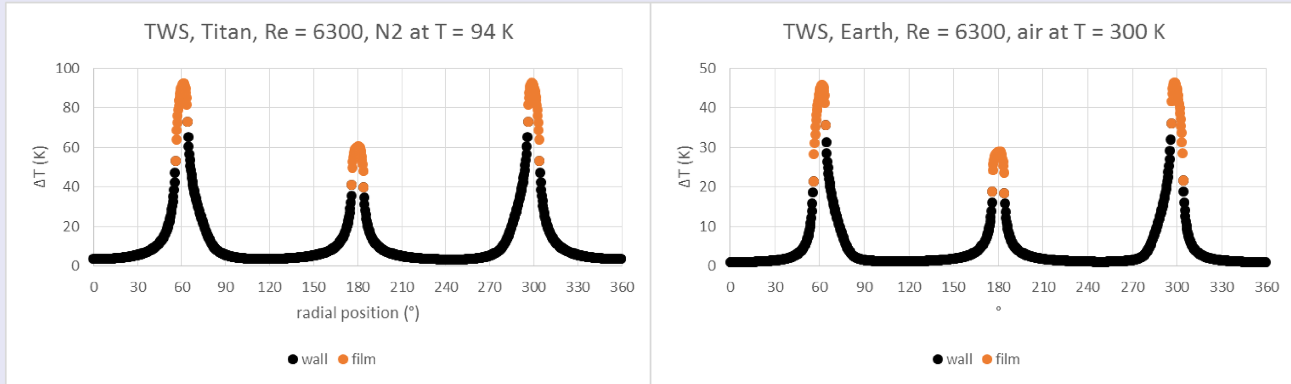
The Titan flow around the sensor differs importantly from Mars, due to the higher air density. The Reynolds numbers of 8000 – 16000 for wind speeds of 1 – 2 m/s on Titan correspond to a sub-critical flow regime: flow on the upwind side will be laminar, and on the downstream a turbulent wake will develop. For Reynolds numbers < 20,000, the convective heat transfer efficiency is markedly higher on the upstream face of the cylinder than on the downstream face. This is important, because this difference allows wind direction sensing. If the cylinder diameter were to be increased further, Reynolds numbers would increase proportionally, and the downwind side would experience increased wake turbulence and correspondingly higher convective heat transfer, as shown in the figure below; this would make wind direction sensing progressively more difficult (although wind speed sensing would be unaffected). This leads us to a preliminary conclusion that a cylindrical anemometer should be 1 cm or less in diameter for optimum wind direction sensitivity.



Distribution of local heat transfer coefficients (expressed as dimensionless Nusselt number Nu), for different Reynolds numbers Re. From Ref. [7].

Simulation of sensor performance.

We conducted 2D CFD simulations of the Beagle 2 / Schiaparelli Wind Sensor in Titan and Earth conditions (see plots below). Heat is dissipated in three isolated patches, each 0.7 mm wide x 5 mm tall, distributed evenly around the circumference of the cylinder.



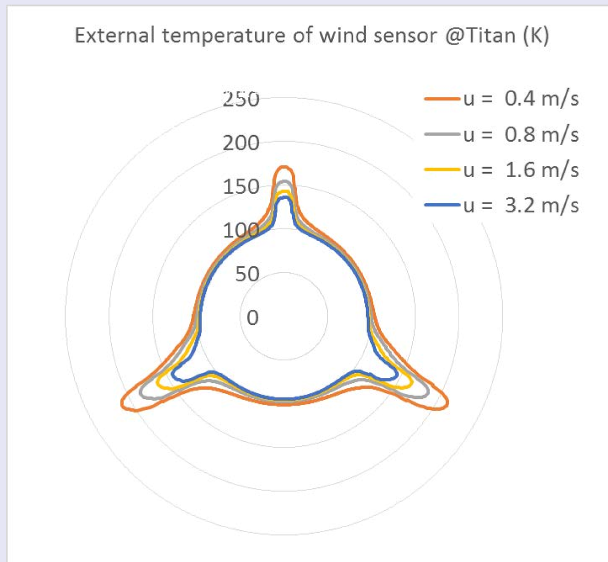
Two-dimensional CFD simulation of temperature distribution around the exterior of a B2WS sensor in (a) Titan and (b) Earth conditions.

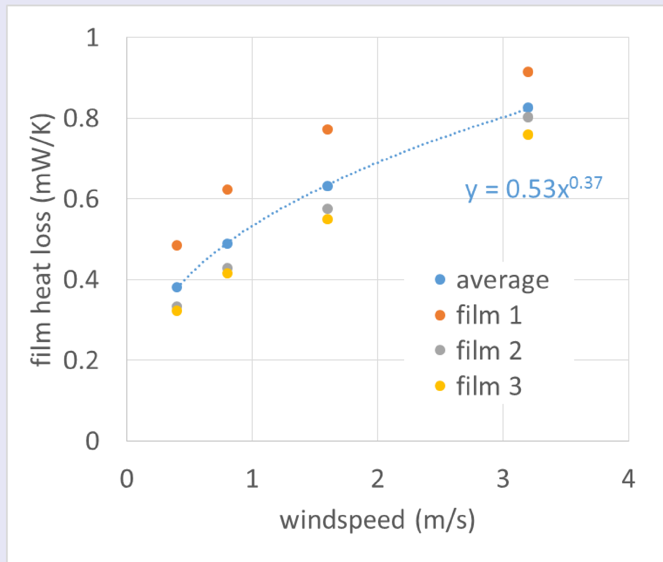
In the simulations above, the wind is coming from the 180° direction; it can be seen that the upwind film is cooler than the other two films, as expected.

One can also see here the good correspondence between behaviour in Titan and Earth cases at the same Reynolds number.

Wind speed measurement

The left plot below shows external temperatures of the wind sensor calculated using 2D CFD simulations, in Titan conditions, for different wind speeds as marked. Wind direction is from the top of the figure, which is why the film at the top of the figure is cooler than those on the downwind side of the sensor.

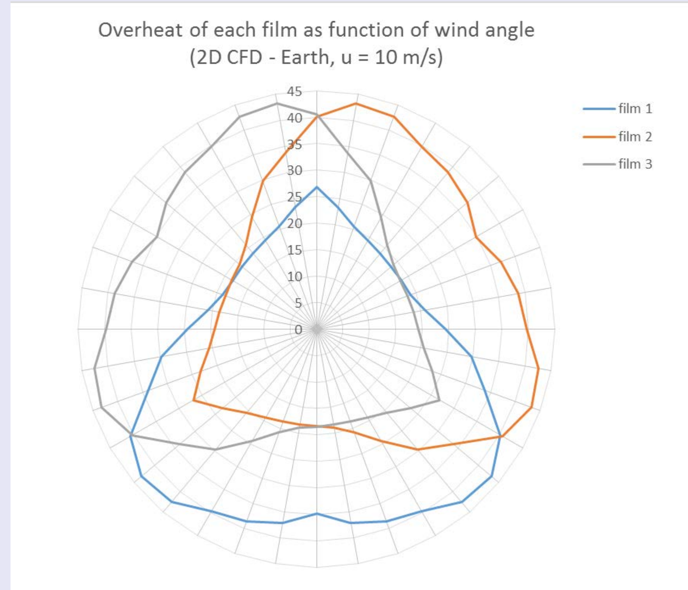




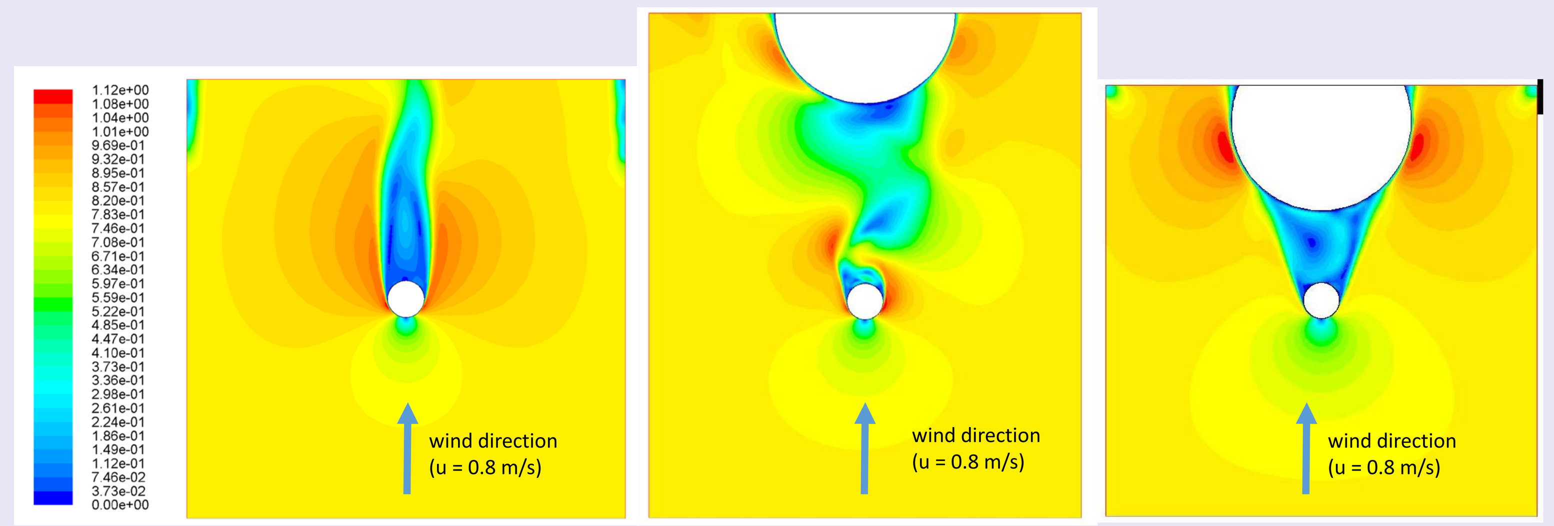
Plotting the convective heat transfer efficiency as a function of wind speed (right) we see a dependence of $u^{0.37}$. This exponent is somewhat less than the classical "King's law" exponent of 0.5 expected for convective heat transfer. This can be explained by looking at the extent of spreading laterally from the films; at light wind speeds there is considerable lateral spread of heat through the substrate from the films, so heat transfer is occurring from a large effective area. At higher wind speeds, more heat is directly lost to the air before spreading sideways so the effective area is smaller.

Wind direction measurement

The convective heat transfer efficiency from each film varies strongly as the wind direction changes. The following plot shows how the average temperature of each film (expressed as the overheat $T_{film} - T_{air}$), calculated using 2D CFD, changes as wind direction is altered in 10° azimuthal steps. This particular simulation is run in Earth conditions (1 bar, 293 K, 10 m/s wind velocity) – this has the same Reynolds number and therefore is the same flow regime as a wind speed of 0.8 m/s on Titan.



It can be seen that the film temperature does not vary monotonically with wind angle: maximum convective heat transfer occurs not when the film is directly facing the flow but rather when it is facing some 50° away from the flow, when the velocity shear near the surface is greatest.
For every combination of three film temperatures there is a unique solution to the wind speed and direction.



2D CFD simulations of wind velocities surrounding a cylindrical anemometer. Centre and right plots shows effect of a cylindrical structure 5 and 2 cm, respectively, from the anemometer. Significant flow interference is seen particularly in the 2 cm case.

Interference from mounting

Wind sensors are ideally located on tall masts away from other structures – this is unlikely to be achieved in practice. We consider here a case where a cylindrical wind sensor is mounted on the side of a vertical cylindrical structural element.
Clearly, the wind measurement is badly affected if the wind sensor is downwind of the structure; however, our CFD also indicates that the interference also occurs when the anemometer is directly upstream of the structure, because the sensor's wake is disrupted, affecting heat transfer on the sides of the anemometer. Our preliminary simulations show that suggests that a separations of > 5*D*, where *D* is the diameter of the wind sensor, yields adequate isolation for the wind sensor but further simulations with varying wind vectors and geometries will be carried out to verify this.

Conclusions

Titan's atmosphere is well-suited for thermal anemometry. We show here that a reflight of the Beagle 2 / ExoMars Schiaparelli wind sensor would largely meet the science requirements for Titan.
There may additionally be opportunities to perform anemometry by monitoring temperatures of heated parts of landers. Careful attention must be paid to calibration/validation plans and to sensor accommodation.

References

[1] R. Lorenz, under review, Icarus, 2017
[2] J.R. Murphy et al., DPS 2002.
[3] M. de la Torre Juarez et al., AGU 2015.
[4] Lorenz, R. D. AIAA J. Thermophys. Heat Transfer, 30, 257-265, 2016
[5] Towner et al., Planetary and Space Science 52, 1141-1156, 2004.
[6] F. Esposito et al., Space Sci Rev 2017 under re-view.
[7] Lohrisch, W.: V.D.I.-Forschungsheft Nr. 322 (1929).