V European Conference on Computational Fluid Dynamics
ECCOMAS CFD 2010
J. C. F. Pereira and A. Sequeira (Eds)
Lisbon, Portugal,14-17 June 2010

SIMULATION OF THE THERMAL HEAT EXCHANGE NEAR THE PHOENIX MARS LANDER

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Key words: Mars, Heat transfer

Abstract. *When attempting to simulate an extra-terrestrial atmosphere, a 1D numerical approach is traditionally chosen, in which the large scales of the full planetary boundary layer is modeled. The experimental data from lander or rover missions can then be used to compare and calibrate these models. The problem here, however, is that the models ignore the effects that the lander has on the meteorological data collected. The present study is concerned with the numerical simulations of the local 3D environment around a martian lander, in which the lander itself disturbs the temperature and velocity fields. In particular, the recent Phoenix Mars Lander [1] is modeled and the simulations used to help interpret the mission data [2]. Results show that the thermocouples can be affected by the lander's heat under certain wind directions and speeds. It is also found that the natural convection resulting from the lander will not affect the Telltale velocity sensor.*

1 INTRODUCTION

The Mars Phoenix lander (see Figure 1) successfully landed in the northern region of Mars on May 25, 2008 beginning its 150 sol mission [1]. One of the payloads on the lander was the meteorological station, which consists of a pressure sensor, three temperature sensors, mounted at different elevations along a mast [2], a Lidar [3], and a wind speed sensor (Telltale) mounted on top of the mast [4].

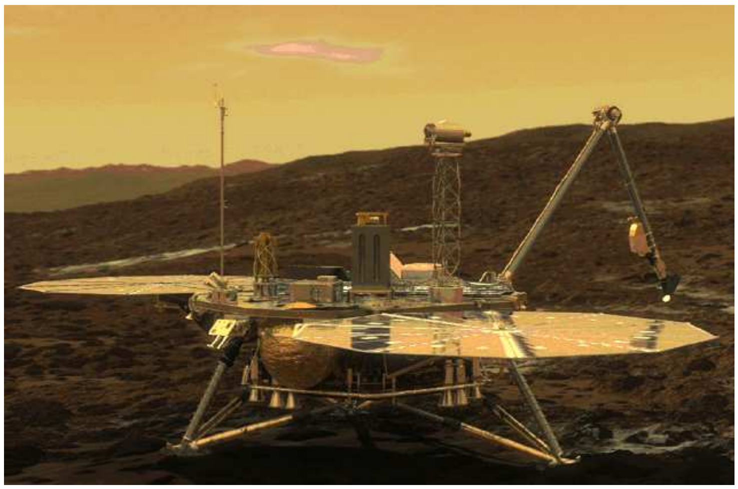

Figure 1: An artist's rendition of the Phoenix Mars Polar Lander (Credit: NASA/JPL).

The purpose of these sensors is to measure representative values of the nearby environment. The temperature, velocity, and pressure sensors used are intrusive instruments subject to measurement uncertainties. It is expected that, under certain conditions, the lander and instruments will affect the readings near the sensors. Quantification of these effects using experiments is difficult, due to the extreme martian environmental conditions (CO_2 gas at a temperature of 200 K and a pressure of 800 Pa in a gravitational field of 3.7 m/s^2). For this reason, CFD is the only viable tool for analysis.

This paper presents the study of momentum and heat transfer near the lander to determine potential uncertainties introduced into the measurements.

2 PROBLEM SETUP

2.1 Overview

When numerically solving for the heat and momentum transfer around a martian lander, a range of length scales is encountered, varying from $\sim 10^{-3}$ to $\sim 10^{1}$ m. Full numerical resolution of this problem in all scales would require an unfeasibly large amount of data storage. The present approach is to break the problem into two levels of detail (see Figure 2). In the first, the momentum and heat transfer is solved with the full lander, without the Telltale mounted on the mast, to reveal the large scale structures of the flow.

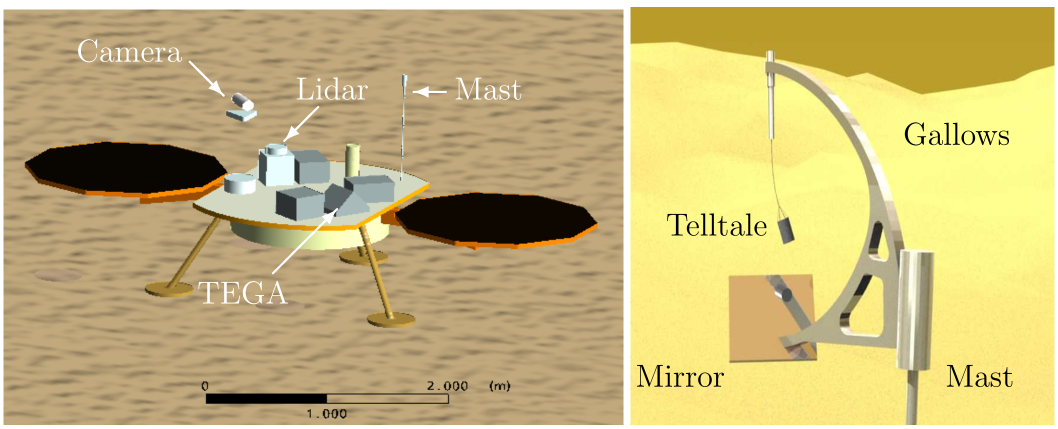

Figure 2: A sketch showing the model of the Mars Phoenix lander (Left) and of the Telltale (Right).

The second series of simulations focuses on the Telltale only, where the lander is ignored. The wind sensor works by correlating the displacement of the Telltale, hanging from the gallows and viewed by the camera through the mirror, with the wind speed and direction. Here, the simulations are taken as isothermal using only a vertical wind to mimic the effects of natural convection produced by the heating of the Lander.

The equations used to solve this problem are the standard conservation of mass, momentum and energy equations written respectively as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0 \tag{1}$$

$$\begin{aligned} \frac{\partial \rho \mathbf{U}}{\partial t} &+ \nabla \cdot (\rho \mathbf{U} \otimes \mathbf{U}) - \rho g = \\ &- \nabla \cdot \left(P\delta - \mu \left(\nabla \mathbf{U} + (\nabla \mathbf{U})^T \right) \right) \end{aligned} \tag{2}$$

$$\frac{\partial \rho c_p T}{\partial T} + \nabla \cdot (\rho \mathbf{u} c_p T) = \nabla \cdot (\nabla T) \tag{3}$$

where $\mathbf{U}$ and P, and T are the velocity, pressure, and temperature of the environment and ρ, μ, c_p, and λ are the density, dynamic viscosity, isobaric heat capacity, and thermal conductivity of the CO_2 gas under martian conditions.

The problem is solved on a 36 processor Linux cluster using ANSYS CFX-11.0 with a high resolution method for the advection terms and a second order backwards Euler method for the transient terms. A solution to these equations is deemed converged when the rms residuals of the solution to (1)- (3) are less than 10^{-4}.

2.2 Initial and boundary conditions

A sketch of the domains of the current problem is shown in Figure 3 and the setup of each simulation is explained in detail below.

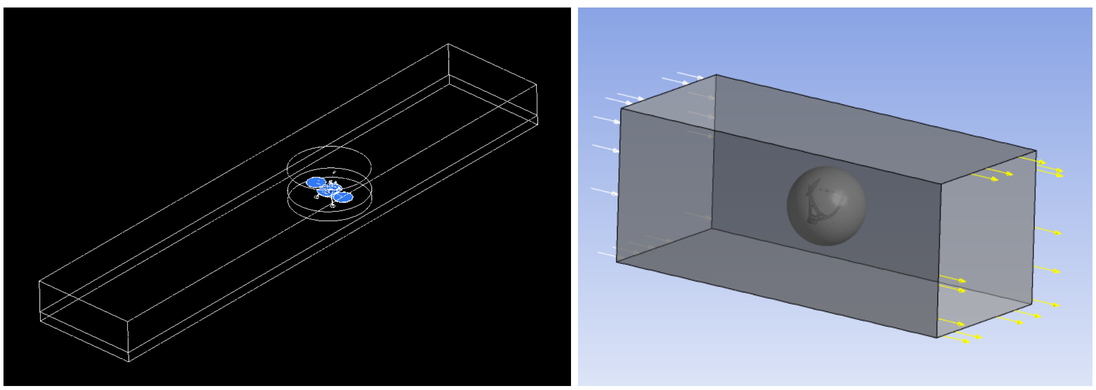

Figure 3: Sketch showing the full domain of the Lander (Left) and Telltale assembly (Right).

The Lander setup (Left) is centred within a 50x10x4 m rectangular domain. In order to study the effect of heat and mass transfer on the lander, a constant horizontal wind velocity at an environmental temperature, T_e and pressure P_e is set at the inlet of the domain. Different wind directions are obtained by rotating the cylindrical sub-domain containing the lander at an angle of α (clockwise starting from North). Around the top and sides free slip boundary conditions were used. The bottom of the domain representing the ground was set to no-slip. The lander itself was set to a no-slip wall with a possible constant temperature (T_h). Finally, the outlet of the domain was set to a prescribed velocity. Ideally, an average pressure should be used, however, problems with the software were noted with the average pressure boundary condition at the outlet. To attempt to circumvent this problem, the outlet was switched to a constant velocity profile, and the length of the domain was increased so that the effects of this boundary near the lander would be lessened. Here, a total of 1,492,012 mesh nodes were used for the simulations.

The parametric study for the lander simulations was broken into two sets. The first set looked at the general effect of the wind direction using $P_e = 787$ Pa, $T_e = 197.15$ K, $T_h = 233.15$ K, $U = 4.14$ m/s, and $\alpha \in \{5°, 15°, 25°, 35°, 45°, 55°, 355°\}$. The second set used data from the mission in attempt to explain temperature data from sol 52. Here the parameters were set using $P_e = 796$ Pa, $T_e = 226$ K, $T_h = 246$ K, $U = 4.14$ m/s, and $\alpha \in \{\ 355°, 5°,\ 15°, 25°,\ 35°, 45°,\ 55°, 60°,\ 70°, 80°,\ 90°, 100°\}$.

The Telltale wind sensor assembly, shown in Figure 3 (Right), was centred within a 300x300x750 mm rectangular domain. In order to study the effects that natural convection could have on the velocity measurements, a constant normal velocity is set at the inlet of the domain. Different wind directions are represented by rotating the spherical sub-domain, containing the Telltale and Gallows. An ideal CO_2 gas was used as the working fluid at a temperature and pressure of 200 K and 800 Pa, respectively, which represent the approximate atmospheric conditions on Mars, and results in $\rho = 0.021$ kg/m^3 and $\mu = 1.1 \times 10^{-5}$ Pa·s. A free slip wall was used for the remaining boundaries with the exception of the Telltale and Gallows, which were set to no-slip walls. A grid convergence study determined that a mesh of 947,302 nodes was suitable for the Telltale assembly. The parametric study used a vertical wind orientation with $U \in \{0.16,\ 0.38,\ 0.76,\ 1.52,\ 3.80\}$ m/s. In addition, a horizontal wind configuration was calculated using $U = 2.5$ m/s.

3 RESULTS

3.1 Telltale

Representative results of the flow over the Telltale assembly is shown in Figure 4.

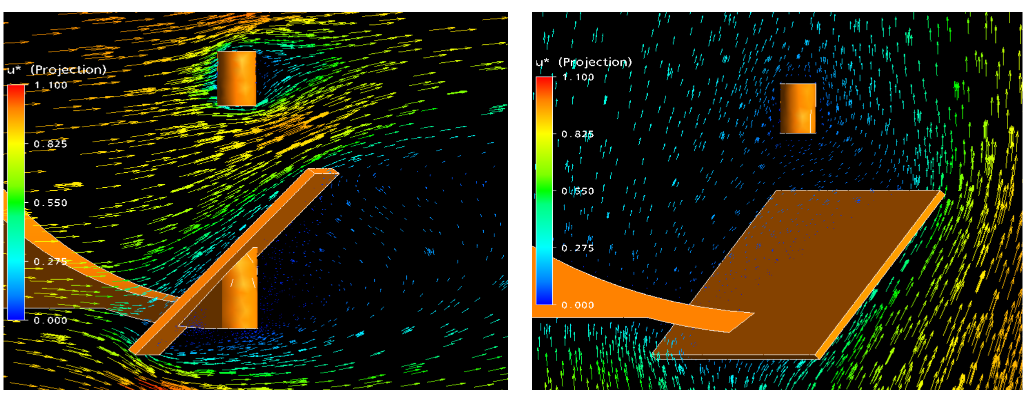

Figure 4: Vector plot showing results of the wind flow over the Telltale for a horizontal flow (left) and a vertical flow (Right). Here the velocity is normalized with U.

To begin, Figure 4 (Left) shows a vector plot for a typical horizontal flow case. Here, the mirror acts to divert the flow towards the Telltale, altering the drag force acting on the surface of it. The effect of the Gallows and the mirror on the horizontal wind is already taken into account in the wind measurements of the Phoenix mission through extensive wind tunnel characterization experiments. Effects of a vertical component of the wind, which could be due to natural convection plumes resulting from the heating of the lander, were not tested experimentally. The results of the present parameter study on vertical flows are well represented in Figure 4 (Right). Here, the mirror (similar to the horizontal case) acts as a blunt body, diverting the wind around it. The Telltale is found to be positioned in the wake of the mirror and a reduction of a vertical wind speed by 90% is found, which translates into a reduced force on telltale, effectively shielding it from a vertical wind perturation. Also, there is a general flow from left to right along the mirror, which results in a net normal force that acts on the Telltale.

3.2 Thermocouples

Representative results of the effect of the lander heating on the thermocouples are shown in Figure 5.

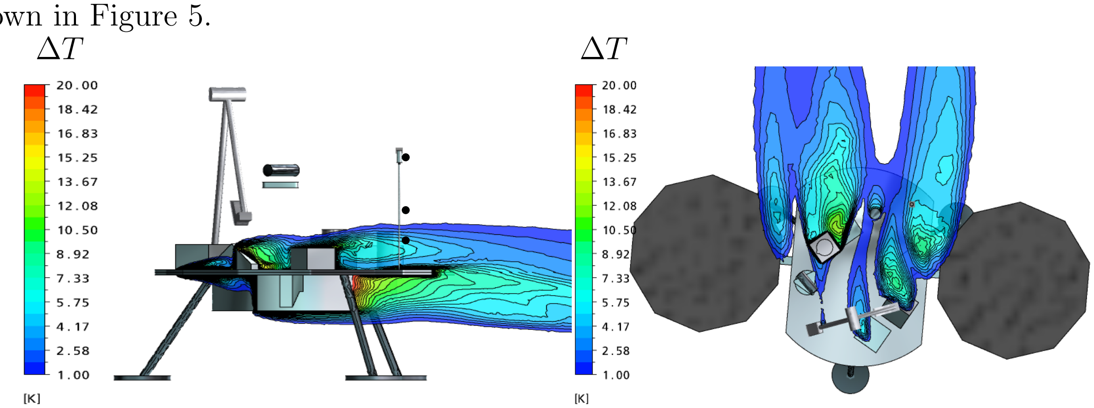

Figure 5: Temperature contours showing the effect of the lander heating on the thermocouples on a vertical plane (Left) and a horizontal plane (Right) for $\alpha = 5°$.

Here, heating of the lander is found to affect the lowest thermocouple as heat is convected over the instruments towards the mast. The upper two thermocouples, however, remained relatively unaffected. Conditions can occasionally arise, where the upper two thermocouples could be affected when the camera is aligned with the mast or under quiescent conditions [5], although the latter were not observed during the mission. Some results of the parametric study focusing on the effects of wind direction are summarized in Table 1. The differences between the measured temperature and the actual undisturbed air temperature are divided by the temperature difference between the lander and the upstream air, T_e, to facilitate comparison between the two cases included in the Table.

As might be expected, the temperature difference between the environment and that of the lowest thermocouple was strongly dependent on the wind direction. In particular,

Wind Dir. °	355	5	15	25	35	45	55	60*	80*
h=1.00 m	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00
h=0.50 m	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.00
h=0.25 m	0.20	0.05	0.01	0.07	0.17	0.01	0.29	0.15	0.08

Table 1: Temperature differences between the upstream air and the thermocouple locations normalized with ΔT for a range of flow directions. h is the height above the deck, $U = 4.14$ m/s, most cases $\Delta T = 40$ K except cases with * $\Delta T = 20$K.

we notice the effect of the wake of TEGA and MECA instruments on the deck for winds from 355°-5° and from the robotic arm, when lifted, for winds around 35°. No significant temperature differences, however, were found for the upper two thermocouples, located outside of the lander's wake, except for angles between 45°-55° when the mast and the camera were aligned. The high temperature difference found for 55°-60° is a result of the alignment of the mast with the camera, Lidar, and the antenna.

3.3 Comparison with Mission data

A comparison of these results with Phoenix mission data was difficult, due to limited, continuous, wind measurements. However, impacts of deck and instrument heating can be seen in Figure 6, during an evening period in sol 52, when the wind direction was measured by the telltale to be in the range 65° - 85°, i.e. blowing across the lander.

The wind speed was estimated in the range of 5 to 7 m/s . The Figure reveals a temperature anomaly in the lowest thermocouple, when the wind direction was around 70°, but a much lower or no effect when its direction was around 85°.In this case, the Lidar and antenna are upstream of the mast in the range of 55° - 80° and their wake could significantly disturb the flow and temperature field in this direction range, contributing to the temperature anomaly. Results from the simulations in Table 1 support this argument and show the reduced effect expected for winds at 80°. In agreement with the data in Figure 6, these effects are expected to decrease further for angles above 80°, as the only obstacle upstream in that range, the electronics board unit (PEBU), has a much lower height. This particular example demonstrates how elevated temperatures frequently shown by the lowest thermocouple in the evening were likely associated with effects from the lander.

4 CONCLUSIONS

Simulations of the heat and mass transfer over the Phoenix lander show that the lander's elevated temperature can affect the atmospheric measurements taken by its meteorological station. For the thermocouples, the simulations indicate that the lowest

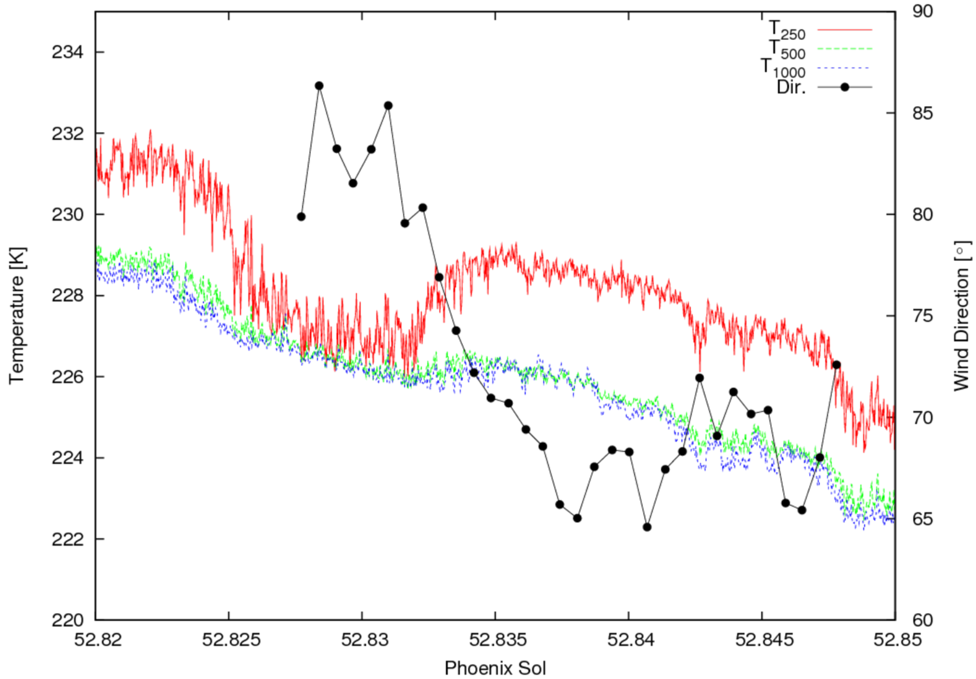

Figure 6: Temperatures of the three thermocouples (at 0.25 m (red), 0.5 m (green) and 1.0 m (blue) above the deck) plotted along side of the wind measurements.

thermocouple can be affected by the decks heating, whereas the two thermocouples at 0.5 m and 1.0 m above the deck were found to be unaffected by the lander. For the velocity measurements, limited effects are expected since under quiescent conditions the mirror shelters the Telltale from the effects of natural convection.

ACKNOWLEDGMENTS

Funding from the Canadian Space Agency is gratefully Acknowledged. The design of the Open lander model of the Phoenix lander was performed by J. Boddez and G. Heacock at the University of Alberta.

REFERENCES

[1] Smith, P.H. et. al., Introduction to special section on the Phoenix Mission:Landing Site Characterization Experiments, Mission Overviews, and Expected Science, *J. Geophys. Res.*, **114**, 00A18 doi:10.1029/2008JE00308 (2008).

[2] Davy, R., J. A. Davis, P. A. Taylor, C. F. Lange, W. Weng, J. Whiteway, and H. P. Gunnlauggson, Initial analysis of air temperature and related data from the Phoenix

MET station and their use in estimating turbulent heat fluxes, *J. Geophys. Res.*, 115, E00E13 doi:10.1029/2009JE003444 (2009).

[3] J. Whiteway, M. Daly, A. Carswell, C. Dickinson, T. Duck, L. Komguem, C. Cook, Lidar on the Phoenix Mars Mission, *J. Geophys. Res.*, **114**, E00A10, doi:10.1029/2007JE003015 (2008).

[4] Holstein-Rathlou, C., H. P. Gunnlauggson, J. P. Merrison, K. M. Bean, B. A. Cantor, J. A. Davis, R. Davy, N. B. Drake, M.D. Ellehoj, W. Goetz, S.F. Hviid, C. F. Lange, S. E. Larsen, M. T. Lemmon, M. B. Madsen, M. Malin, J. E. Moores, P. Nornberg, P. H. Smith, L. K. Tamppari, and P. A. Taylor (2010), Winds at the Phoenix Landing Site, *J. Geophys. Res.*, doi:10.1029/2009JE003411, in press.

[5] J.A. Davis and C.F. Lange, Simulation of the momentum transfer over the Phoenix Mars Lander, Proc. of the 16th Annual Conf. of the CFD Society of Canada, CFDSC2008, Saskatoon, Canada.