CFD ANALYSIS OF WIND FLOW AROUND INDIVIDUAL YARDANGS: A COMPARISON BETWEEN EARTH AND MARS CONDITIONS.

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Introduction: Yardangs, or wind-carved ridges, are thought to form in unidirectional wind regimes. Whitney [1] put forth a qualitative model to explain the flow of wind around a single yardang, principally based on the interpretation of aeolian flute directions on a single Egyptian yardang photographed by J.F. McCauley [1]. The model includes diverging flow around the nose of the yarding, and regions with separated/recirculating (reverse) flow eroding the flanks of the yardang. Ward and Greeley [2] visualized some amount of recirculating flow occurring at low wind speeds in wind tunnel experiments, but high wind speeds quickly eroded their fragile yardang simulants, meaning that they were unable to observe the variation in the strength or presence of separated/recirculating flow regions under different conditions. They also did not observe recirculating flow around more blocky, less streamlined forms [2].

Figure 1 – Dedos observed that point in different directions, but are in close proximity on two different facets of a yardang in the CPP.

Recent works have proposed that multiple wind directions may also be present where yardangs are observed [3-4]. Multiple wind directions have the possibility to influence the evolution of yardang geometry, and may explain the formation of dedos (small protrusions that indicate wind directions) that form in a separated flow/recirculation region with respect to the primary wind direction, but are fully exposed to the secondary wind direction (e.g. Fig. 1). In this work, the commercially available computational fluid dynamics (CFD) software STAR-CCM+ is used to investigate flow around individual yardangs observed in the Campo de Piedra Pomez (CPP) Yardang fleet. CFD simulations can be compared to observed dedos patterns for a specific yardang, and can provide insight into what wind-angle is consistent with the observed dedos orientation. Furthermore, flow comparisons can made between Earth-like and Mars-like conditions.

Methods: An overview of the field work performed in 2018 and 2019 can be found in [3-5]. Detailed images of the CPP yardang fleet taken in the field are used to create 3D geometrical reconstructions of chosen individual yardangs (Fig, 2). 3D geometries are imported into STAR-CCM+ and incompressible viscous simulations are performed. Preliminary simulations are performed using the Realizable K-Epsilon Two-Layer Reynolds-Averaged Navier-Stokes (RANS) turbulence model. As yardang evolution timescales are believed to be much longer than stereotypical flow times scales, LES modeling is not currently being employed, with the understanding that RANS solutions represent temporally averaged results, and will not necessarily resolve some transient flow structures. Preliminary simulations use a mesh with 45,810,311 cells and a target resolution of ~ 15 cm for the surface of the yardang. A relatively large domain is used (Fig. 3) in order to try and minimize any influence that the uniform flow inlet/outlet boundary conditions have on flow in the vicinity of the yardang itself. Table 1 provides a summary of the initial conditions used in the simulations.

Parameter	Earth	Mars
Gas	Air	CO_2
Pressure (Pa)	~7.0*10^{4}	~6.4*10^{2}
Density (kg/m^3)	~8.2*10^{-1}	~2.0*10^{-2}
Dynamic Viscosity (Pa s)	~1.8*10^{-5}	~1.1*10^{-5}
Windspeed (m/s)	~20	~20
Re -30m length	~2.7*10^{7}	~1.1*10^{6}

Table 1 – Summary of CFD simulation parameters.

Even though Martian yardangs are observed to have different geometries than those observed on the Earth, the same geometry is used in this work in order to focus on differences in the flow field caused by the lower Reynold's number (Re) flow that is characteristic of the Martian environment.

Preliminary Results: Figs. 4-5 show sample preliminary CFD results. Fig. 4 shows a contour plot of y+

focusing on the surface of the yardang for the Earth simulation – as expected, due to the high Re of this flow, it is not computationally feasible to resolve a y+ of 1, which is another reason a RANS model is chosen for this work. Future work will attempt to increase the boundary layer resolution and perform a convergence study in order to determine the effect of boundary layer resolution on the quantities of interest. Fig. 5 shows a plot of shear stress on the surface of the yardang for Earth-like conditions (Mars-like results look qualitatively similar, when scaled appropriately).

Discussion: CFD simulation results will enable a quantitative comparison of flow around yardangs under both Earth- and Mars-like conditions, with the goal of gaining additional insight into why there are observed differences in yardang geometries between Earth and Mars. A shear stress plot is presented in Fig. 5 as erosion due to wind is likely to correlate with high regions of shear stress. However, particle-based erosion due to small particles being entrained in the high winds around yardangs is also quite likely. Future numerical work could couple gas-phase only CFD results with lagrangian particle tracking in order investigate whether or not areas of the yardang surface are consistent with areas where particles are expected to impact the yardang. CFD results will also be compared to orientation of the dedos mapped in the field for the yardangs being simulated, and the effect of changing the wind direction on the resulting flow field can be investigated numerically. An atmospheric boundary layer model will also be used in future simulations instead of a simple uniform flow initial condition which is used for the results presented in this work.

Conclusions: Preliminary work has been completed to investigate local flow around yardang geometries that have been reconstructed based on images taken in the CPP yardang field. As expected, surface shear stress compares well under the two flow conditions when scaled appropriately. This analysis will help quantify the expected flow similarities and differences for wind flow around yardangs on both Earth and Mars.

References: [1] Whitney, M.I. (1983) *Eolian Sediments and Processes,* 38, 223-245; [2] Ward, A.W. and Greeley, R. (1984) *Geol. Soc. Am. Bull.*, 95, 829–837; [3] Rabinovitch et al., (2019) *LPSC* Abstract #2250; [4] Kerber et al., (2020) *LPSC* Submitted Abstract; [5] McDougall1 et al., (2019) *LPSC* Abstract #3202.

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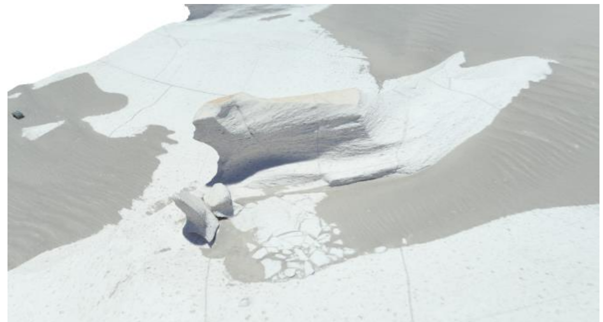

Figure 2 – Textured 3D reconstruction of CPP yardang - length is ~ 30 m for scale.

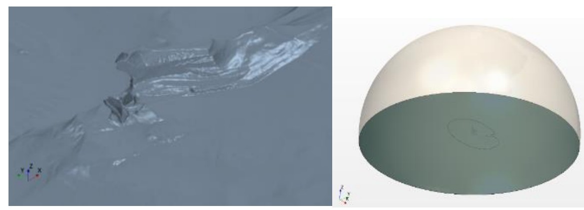

Figure 3 – CFD 3D reconstruction of a yardang from Fig.2 (left), large numerical CFD domain (right).

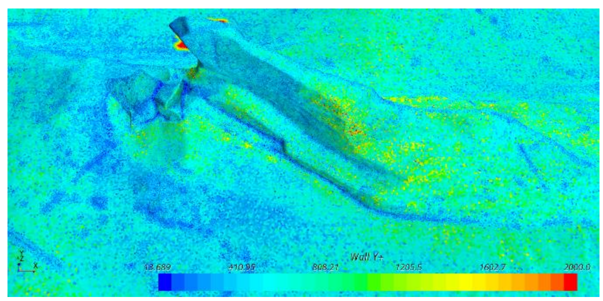

Figure 4 – y+ values shown on and around the surface of the yardang for Earth flow conditions.

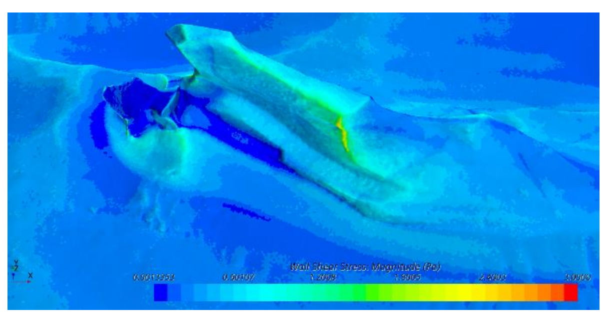

Figure 5 – Shear stress on the surface of the yardang for Earth-like flow conditions. Results are similar for Mars simulation results with the magnitude of the shear stress scaled by ~0.05, which follows the commonly used empirical turbulent boundary layer correlation of $\tau_{wall} \sim \frac{\rho}{Re^{0.2}}$**.**