Marangoni Effect on Molten Lunar Regolith

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Summary

Experimental research work on thermophysical properties of molten lunar regolith using JSC-1A simulant under vacuum has revealed an unexpected phenomenon apparently due to thermal Marangoni effect, spontaneous upwards migration of a uniform molten thin-film front that climbs the side of the crucible wall covering the entire wall's surface and reaching the top end of the crucible [1][2]. Temperature gradient within the melt's bulk and along the crucible's wall generates a surface tension large enough not only to form a meniscus within the three-phase junction between the crucible's wall, bulk melt, and vacuum but also to supersede the gravitational force to create the migration of a thin film front originated on the meniscus. The observed extensive wettability of the melt with the alumina crucible surface, an additional key factor besides surface tension necessary to sustain upwards migration in the thermal-driven Marangoni effect, is atypical to what it has been witnessed on molten JSC-1A simulant under non-vacuum conditions and smaller sample sizes.

The Artemis III human crew might conduct experimental corroboration and complete assessment of the thermal Marangoni effect on lunar molten regolith, the moon has more favorable conditions for the Marangoni effect than those used to observe the thermal-driven Marangoni effect on molten regolith simulant in earth, 1/6 of the gravity force and thousands of times higher vacuum. The science of thermal Marangoni effect on lunar molten regolith might lead to important In Situ Resource Utilization (ISRU) applications such as, fractional generation of oxygen and metals/alloys, protective thin-film coating, and additive 3D-printing feedstock with the benefit of minimal need for terrestrial precursors.

Terrestrial Experimental Evidence

Molten samples of JSC-1A lunar regolith simulant consistently experienced evenly distributed upwards migration along the originally bare crucible's wall. A 0.5-mm-thick thin melt film originally generated at the meniscus migrated upwards covering the entire surface of the initially bared alumina crucible wall and reaching the top end of the 146-mm-height crucible's wall [1].

Figure 1 depicts two crucibles both cut across to illustrate the outcome before (Figure 1a) and after (Figure 1b) thermal upwards migration on 150 grams of JSC-1A lunar regolith simulant at (a) 1,065 C and (b) 1,200 C respectively under 10^{-2} torr both. In Figure 1a, the surface of the sample remained mostly in the sinter phase. A 35-C temperature increment (from 1,065 to 1,200 C) happened to be sufficient to melt completely the JSC-1A sample and generate uniform upwards migration of a thin film front along the 146-mm height of the crucible's wall as depicted in Figure 1b [1][2].

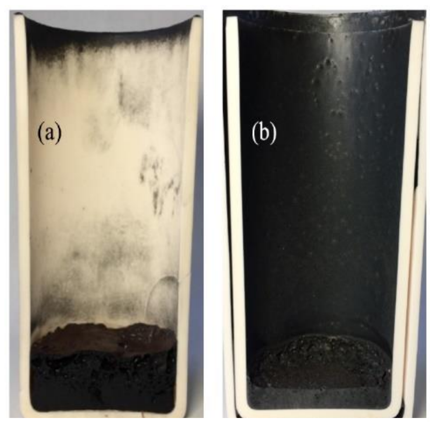

Fig. 1. JSC-1 melt thermal migration tests at (a) 1,065 C and (b) 1,200 C under 10^{-2} torr both.

Figure 2 depicts a magnification of a cropped area of Figure 1b showing the interface of the JSC-1A melt thin film and the alumina-made crucible wall. The thin film has a thickness of 0.5 mm (500 µm) measured directly from the image and remains with this thickness throughout the crucible's wall. As illustrated in Figure 2, the thin-film is compact and most important, smoothly adhered to the substrate (in this case alumina-made crucible's wall) with no eroding of or reaction with the alumina's substrate (crucible wall). The affinity of the melt with the crucible surface, clearly shown in Figure 2, leads to a wettability that sustains upwards migration in the thermal-driven Marangoni effect. This wettability/affinity is atypical to what it has been witnessed on molten JSC-1A simulant generated under non-vacuum conditions, lesser temperature gradient, and smaller sample sizes.

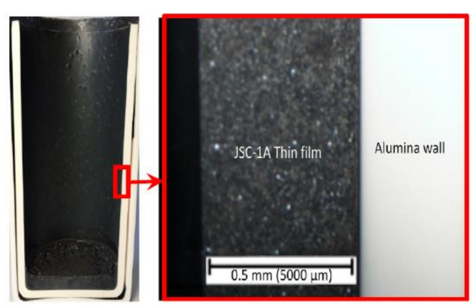

Fig. 2. Interface of molten JSC-1A thin film and crucible wall (Figure 1b).

Figure 3 depicts different views of JSC-1A melt sample after conducting the experimental run at 1,350 C and 10^{-4} torr. As expected meniscus formation and thermal-driven upwards thin-film migration occurred but in this case, the migration phenomenon is coupled with decomposition/vaporization of some JSC-1A melt thin-film components. The color change in the thin film, from black (Figure 2) to brown (Figure 3) is due to decomposition and partial evaporation of the iron oxide present in the JSC-1A sample as corroborated by SEM/EDX analysis on the thin film [1][2].

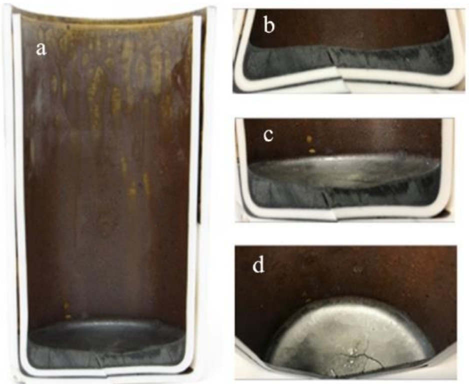

Fig. 3. Views of JSC-1A melt sample yielded at 1,350 C and 10-4 torr.

Figure 4 depicts a slide cut on the crucible housing the sample of Figure 3. In Figure 4a the meniscus is clearly differentiated from the thin film on the wall as the meniscus (and the bulk) is black and the thin film brown. Figures 4b and 5c depict a cross front view of the meniscus clearly showing two different patterns within the melt's bulk, a dark pattern surrounded by a lighter one is marked with a red dash line in Figure 4c. The formation of two-melt patterns might be due to Marangoni convection that is the tendency for heat and mass to travel to areas of higher surface tension within a liquid. It is worth stating that the Marangoni effect seems to be the source of not only the formation of the meniscus coupled with upwards migration of the thin-film melt but also the convective formation of patterns within the bulk of the melt.

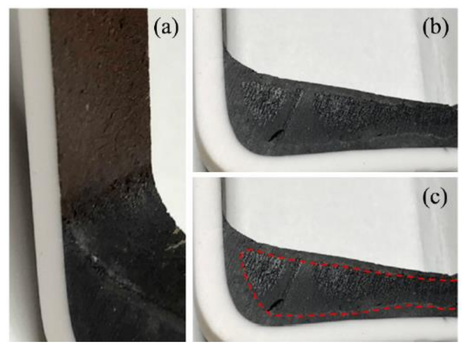

Fig. 4. Three views of JSC-1A melt sample of Figure 3.

Lunar Experiment

In the moon, the experimental unit required to corroborate the Marangoni effect on molten regolith should be relatively simpler than it is in earth on molten lunar regolith simulant, as the lunar experiment would not require vacuum generation. The experimental unit to conduct science assessment would be equipped with a tall vertical column open at the top, heating elements around the column, an insulation layer wrapping the heating elements and the column, and the required automation and temperature control hardware.

The vertical column would house crucibles as tall as 24 inches with the capacity of holding at least 125 grams of regolith samples. Figure 5 depicts the conceptual rendering of two experimental units on the moon intended to conduct direct corroboration (Fig. 5a) and fully assessment (Fig. 5b) on the science. Corroboration of the science observed in earth will be also by observation in the moon; science assessment will require in-situ real-time data acquisition as well as post processing analyses on the samples returned to earth including thin film thickness and its composition along the crucible wall.

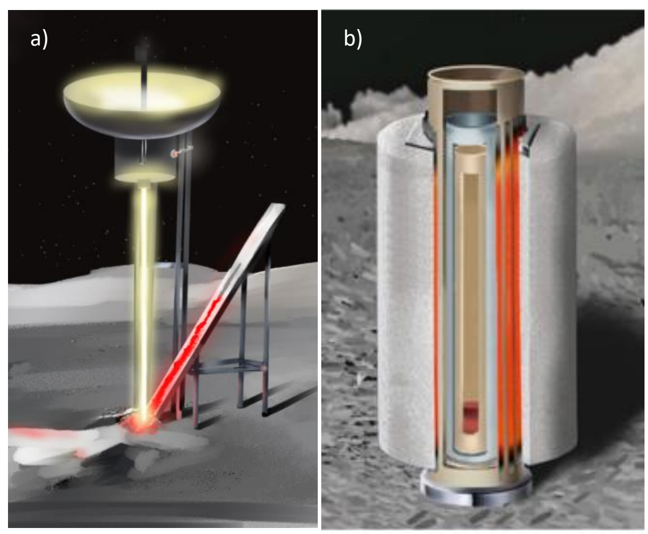

Fig. 5. Conceptual rendering of the key lunar experimental corroboration (a) and science assessment (b)..

References

[1] Dominguez J. A., ISRU Thermal-driven Processes on Interplanetary Surfaces and Characteristics on Production of Commodities, Dissertation Florida Institute of Technology, Melbourne Florida, June 24, 2018.

[2] Dominguez J. A., Whitlow J., Upwards Migration Phenomenon on Molten Lunar Regolith: New Challenges and Prospects for ISRU, Advances in Space Research 63 (2019) 2220–2228.