LABORATORY STUDIES ON THE RHEOLOGY OF CRYOGENIC SLURRIES WITH IMPLICATIONS FOR ICY SATELLITES.
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Introduction: Interpretation of Cassini RADAR and VIMS data has suggested some landforms on Titan may be due to effusive cryovolcanic processes that created cones, craters and flows [1]. High-resolution Voyager 2 images of Triton also show strong evidence of cryovolcanic features [2]. Fundamental to modeling of cryovolcanic features is the understanding of the rheological properties of cryogenic icy slurries in a thermodynamic and fluid mechanical context, i.e., how they deform and flow or stall under an applied stress. A series of measurements were performed on a 40 wt% methanol-water solution measuring the rheology of the slurries as a function of temperature and strain rate, which revealed development of yield stress-like behaviors, shear-rate dependence, and thixotropic behavior, even at relatively low crystal fractions. Analysis of these measurements revealed that rheological properties of methanol-water slurries are strongly history dependent [3]. This prompted an improved design of the experimental set up for visulaization of the cryogenic slurries. Visualization of icy slurries provides the capability to optically assess crystal size, crystal orientation and 3D crystal structure of the icy slurry samples during experiments, which strongly dominate rheological properties.

Methods: *Improved apparatus.* The improvements made since Zhong et al., (2009) are shown in Figure 1 and include:

- New vacuum jacket and liquid nitrogen (LN2) dewar with an optical window at the bottom for visualization of icy slurries within the sample cell

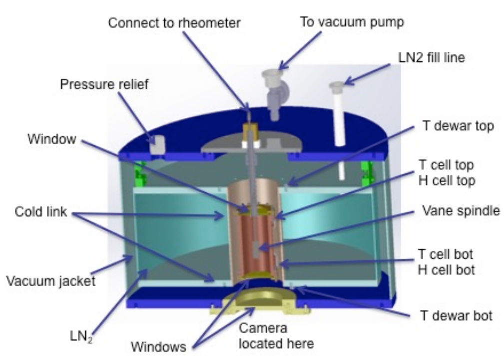

Figure 1. Cross sectional view of the cryogenic slurries sample cell and LN2 dewar.

- Thermally conductive and corrosion resistant sample cell and rheometer spindle
- Light source and camera capable of recording crystal growth within the sample cell
- Brookfield DV-III Programmable Rheometer with finer resolution and a dual thermistor RTD probe for thermal conductivity and diffusivity measurements

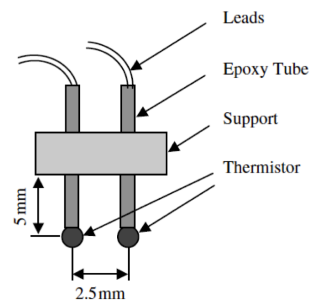

Figure 2. Schematic of the dual thermistor probe.

At the base of the sample cell is the dual thermistor probe (Figure 2) consisting of two thermistor beads that serve as a point heater and a point temperature sensor in a 3D space. This method is based on a transient thermal model of a point heat pulse [4]. With this configuration, measurements of viscoscity, thermal conductivity, and thermal diffusivity may be obtained at same temperature, concentration, solid volume fraction, and crystal structure.

Experimental Procedure. At the start of an experiment, the vacuum jacket is pumped down to 10^{-3} Torr, after which the LN2 dewar is filled. The vacuum jacket provides adequate insulation for improved longevity of the LN2 supply during the experiment. The cell temperature is recorded and maintained using PID control loop within a LabVIEW program. The sample cell is maintained slightly above the melting temperature of methanol-water or ammonia-water of a fixed concentration. The methanol-water or ammonia-water solution is quickly transferred to the sample cell in order to minimize the vaporization of the methanol or ammonia.

The spindle vane is connected to the rheometer and set to 10 rpm. Spindle torque and temperature data are recorded using a LabVIEW program. The vacuum jacket, dewar and sample cell sit on a 80-20 frame which allows the camera to be placed beneath the sample cell and centered relative to the window at the bottom of the cell. Stress is calculated from the torque and dimensions of the spindle vane, when the spindle vane is treated as a concentric cylinder. End effects can be ignored since the distance between the ends of the spindle vane and sample verticle boundaries is larger than twice the spindle vane diameter. The shear rate is determined by the angular velocity of the spindle vane and the diameters of the spindle vane and sample cell. Viscoscity is determined from the ratio of stress to shear rate.

Figure 3. Image of 40 wt% methanol-water slurry in sample cell at T = -45° C showing water ice crystal formation.

Preliminary Results: Using the improved apparatus described here, new experiments were run on 40 wt% methanol-water solutions. Results confirmed the relationship between viscoscity and temperature established in [3]. In addition to temperature and spindle data, optical observations of water ice crystal formation were recorded showing the onset of water ice crystals in the solution concurrent with an increase in spindle torque (Figure 3).

Additional experiments were conducted on 29 wt% ammonia-water solutions, which is very close to the eutectic concentration. For these initial experiments, temperature and spindle data were recorded and water-ice crystal formation was optically observed. The stress, σ, under a constant strain, $\dot{\gamma}$, was measured as temperature slowly decreased. The increase in stress due to the onset of crystal formation is clearly seen for the two solutions (Figure 4). The onset temperatures for given concentrations agreed well with previously published data by Kargel [5]. Optical observations of water-ice crystal formation agree with the stress data shown in Figure 4. As time and resources allow, additional studies of the viscoscity and thermal properties with temperature of ammonia-water cryogenic slurries will be conducted.

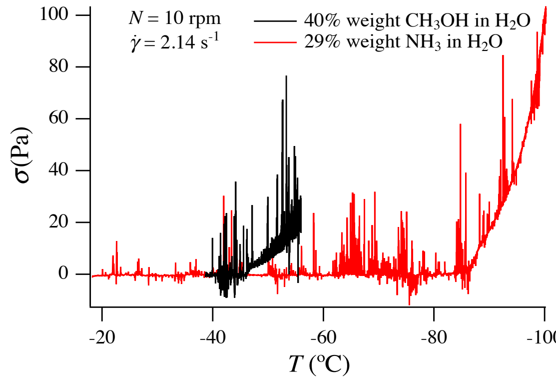

Figure 4. The stress under a constant strain versus temperature for 40 wt% methanol-water and 29 wt% ammonia-water mixtures.

References: [1] Lopes, R. M. C., et al. (2013) J. Geo. Res. 118, 416-435. [2] Smith, B. A., et al. (1989) Science 246, 1422-1450. [3] Zhong, F., et al. (2009) *Icarus* 202, 607-619. [4] Zhang, H., *et al.,* (2003) Meas. Sci. Technol. 14**,** 1396–1401. [5] Kargel, J. S., (1992) Icarus 100, 556-574.

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