Simulation of H_2 in the Conduits of Enceladus. M.C. Zaharias[1] and A. Mahieux[1,3], D. B. Goldstein[1], P. L. Varghese[1], L. M. Trafton[2] [1]Department of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin, Austin, TX 78712, mczaharias@utexas.edu, [2]McDonald Observatory, The University of Texas at Austin, [3]Belgian Royal Institute for Space Aeronomy, Brussels, Belgium

Introduction: The detection of molecular hydrogen during Cassini's final 'E21' dive through the Enceladus plume [1] was one of the most consequential discoveries of the spacecraft's mission to Saturn since the emission of H_2 from Enceladus' subsurface ocean constitutes the most compelling evidence yet found of extraterrestrial chemical disequilibrium and habitability at an icy ocean world. The data captured by the Ion Neutral Mass Spectrometer (INMS) are remarkable, showing dramatic and unexplained variability and 'spikes' in the H_2 density along the E21 trajectory, the origin of which is still entirely unknown. We aim to explore the interaction of H_2 arising from the supposed liquid reservoir under the surface of Enceladus to examine explanations for the spikes. Here, we use a Direct Simulation Monte Carlo (DSMC) [2] model to recreate what is hypothesized to be happening in the icy conduits beneath the surface.

Reference [1] studied the Cassini data captured during its flybys over the surface of Enceladus, specifically in the south polar region. During the E21 flyby the spacecraft traveled parallel along the Tiger Stripes with a speed of 8.5 km/s, roughly 50 km above the surface. The INMS was used in its Open Source Neutral Beam (OSNB) mode to find H_2 above the surface. The data shows pulses of molecular hydrogen along the trajectory ejecting from the Tiger Stripes, but the source and cause of such narrow H_2 jets remain unknown. In particular, it is not obvious how the low mass H_2 molecules can be constrained into a few very narrow sheets or beams. The most likely of several hypotheses for the ultimate source of H_2 is Enceladus being a hydrothermally active [1]. Our goal here is to further investigate the chemistry and physics of the Enceladus ocean via its plumes and jets just before they breach the surface.

Methodology: We assume there is a liquid reservoir [3] underneath the surface of the ice shell that then feeds into the conduits below the visible Tiger Stripes. The gas pressure builds due to a boiling liquid-gas interface [4] that allows for the H_2 and water vapor to travel up the conduit into vacuum. Perhaps the H_2 arises from the boiling water surface in a de-gassing process, entrained in the water vapor. The section of the conduit above the boiling liquid interface is suggested to converge to ~0.5 m in width and be ~1 km in depth [5].

The simulation/modeling of observed plumes is much more advanced for the flow above the surface compared to the flow below because we know much more about the conditions above ground. Additionally, modeling gas/particle interactions without boundaries is well understood.

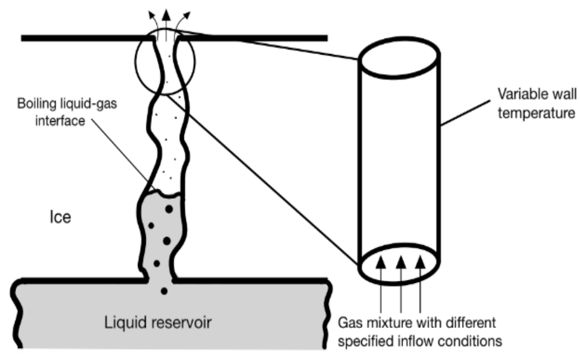

Figure 1: Schematic illustration of a conduit with an underground liquid reservoir and boiling liquid-gas interface. Our models simulate the top portion just before the gas expands into vacuum. The icy walls can vary in temperature and we can vary our inflow conditions as we study the effect of each condition within the model.

We will use a DSMC model [2] to simulate the flow of water vapor and hydrogen through the conduit, specifically studying the interaction between the species and how side-wall condensation can affect that interaction. Figure 1 illustrates the physical domain of our DSMC simulation. While the conduits extend deep underground, our model only simulates the gas flow towards the top of the conduit, just before the gas mixture exits into vacuum. Our model is simplified, as we simulate a straight, round conduit, using a nominal case 4 m wide and 20 m in height, giving a final aspect ratio of 5. In the nominal case, the wall of the conduit is 160 K at the bottom and increases linearly to 260 K at the top, reflecting the molecules diffusely. The inlet speed is Mach 2, our mixing ratio is 99% H_2O and 1% H_2 by mass, with a gas temperature of 53 K. We assign the sticking coefficient of H_2O (probability of condensation) from 0 to 1. H_2 does not condense.

Each of the mentioned parameters is varied to focus on the impact each has on the flow. We expected to see a build up of H_2 along the wall when condensation is taking place, creating a segregation effect between the two species. Our goal is to quantify to what degree this segregation effect takes place.

Results: We find that the H_2O and H_2 nearly fully separate at the wall of the conduit, over the entire parameter space when the water sticking coefficient is greater than 0. Through the process of differential diffusion over the ice, where, the water vapor 'drags'

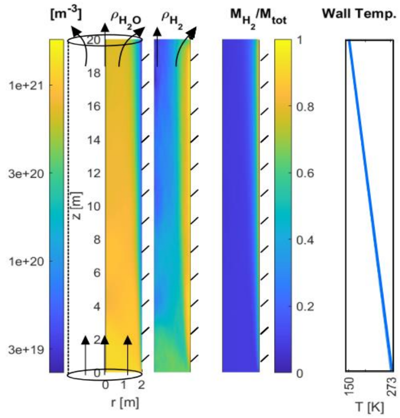

Figure 2: DSMC simulation with an inflow of 99% H_2O, 1% H_2 by mass, flowing through a straight round conduit with inflow speed of Mach 2. The temperature varies linearly along the side wall from 260 K at the bottom, reaching 160 K at the top, near the surface of Enceladus. The adopted wall sticking coefficient is 1.0 for H_2O and 0.0 for H_2. Shown is number density for each species, as well as mole-fraction of H_2. Note the huge concentration of non-condensable H_2 on the wall.

the H_2 towards the wall. The hydrogen builds up along the wall and creates a thin layer, impeding subsequent the water vapor from breaking through the H_2 layer to condense. Figure 2 shows a side by side comparison of H_2 and H_2O number densities and the mole fraction of H_2. We are able to see the decrease in H_2O fraction in the same place as the blanketing of H_2 along the wall.

The mass flux of H_2O to the wall decreases from the model inlet to the surface of Enceladus, even though the top of the conduit sidewalls is colder than the bottom. We find that the thin layer of H_2 blocks the water vapor from interacting with the wall and hence condensing.

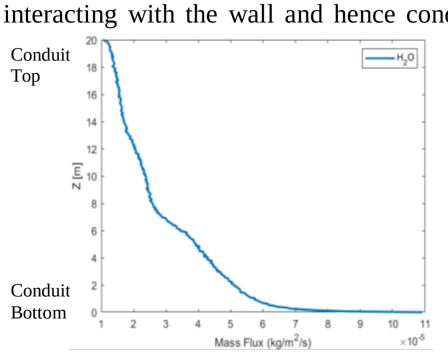

Figure 3: Mass flux water vapor molecules as they interact with the physical wall of the icy conduit.

Figure 3 depicts a time-averaged mass flux of H_2O molecules as they condense on the wall as a function of height along the conduit.

The pattern of H_2 accumulation along the physical wall remains present. In changing the wall temperature, we simulated 4 cases: 160 K at base of model increasing to 260 K at top of model (shown), and 260 K at base decreasing to 160 K at the top, 160 K constant, 260 K constant. We found that varying the wall temperature only created an effect on the bottom half of the flow, as the flux for each case coalesced into the same values at around 8 m above the model inlet.

The mixing ratio (H_2O:H_2) was varied among 3 cases: 99:1 (shown), 95:5, and 90:10. The effect of increasing the amount of H_2 in the gas mixture emphasized the blanketing affect along the icy wall. The layer of H_2 grew thicker, causing the mass flux of water vapor to the wall to taper to a lower value towards the top of the conduit.

In addition to the wall temperature and mixing ratio, we also varied the aspect ratio. Our nominal height to width ratio is 5 (shown), and this was varied to consider ratios of 10 and 50. In increasing the height, the H_2 blanketing effect was present, but less potent. The layer of hydrogen was thinner, allowing more H_2O to break through and condense at the wall.

As we further explore the Tiger Stripes on Enceladus we aim to investigate the cause in the apparent variability of H_2 along the conduit. Future work includes modeling alternative processes and to determine the most likely cause of distinct H_2 regions within the overall plume. The modeling includes intersecting multiple gas jets in the plume potentially leading to H_2 gas sheets, as well as time variable H_2 emissions from trapped gas that builds up and eventually 'pops' within the vent conduit.

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