A PROPOSED CRYOVOLCANIC ERUPTION MECHANISM FOR THE ENCELADUS PLUME.

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Summary: A new Enceladus ascent/eruption model is developed where the driving eruption mechanism is the exsolution of dissolved volatile gases from water during vertical ascent through conduits from Enceladus' ocean. In brief, this is similar to the mechanism that causes a carbonated beverage to overflow when opened if it has been shaken – when pressure is decreased, bubbles form, and these bubbles can then drive a mixture upwards – and shares many similarities with some forms of terrestrial volcanism, including explosive silicate volcanism, as well as cold-water geysers and "limnic" eruptions driven by rapid exsolution of dissolved CO_2. If valid, this "cryovolcanic" eruption model, referred to as the multi-component multi-phase (MPMC) model here, would have both scientific and engineering impacts to future Enceladus mission concepts. Specifically, the jet and plume composition in space is expected to be more representative of ocean composition for the MPMC model compared to models with large amounts of condensation during ascent. This implies that composition measurements made in space would be more representative of the ocean. Another outcome is that the conduit size, mixture composition, dynamic pressure, velocity, etc. are expected to be different for the MPMC model compared to previously proposed boiling interface eruption models. If a spacecraft is being designed to explore the Enceladus conduit system beneath the surface, then the requirements are expected to differ based on which eruption mechanism is dominant.

Introduction: One of the most striking discoveries of the Cassini mission was the water-dominated plume erupting from near the south pole of Enceladus [1-6]. The finding that the plume is at least in part supplied directly from a subsurface ocean [7, 8], informs a unique opportunity to sample material from a potentially-habitable environment inside an icy moon without the need for a spacecraft to land and descend through the ice shell [9-11]. However, to draw conclusions about the ocean and related interior processes on Enceladus, one must quantitatively link the composition of the plume observed in space to the composition of the ocean. This is already performed implicitly in many past studies such as [12-14], where quantities such as the composition and pH of the ocean and possible chemical reactions and interior processes are determined based on plume composition measurements. While the presence of salts in the E-ring informs us that not all involatile components are left behind, the extent to which such components are fractionated is unclear. Few models have considered it despite the incorporation of features such as static-surface boiling [15-17], which would enrich volatiles and deplete solids. Furthermore, the idea that condensation onto conduit walls would deplete water is assumed in [12], and adopted in more detail in [18], which is the only study that investigates possible fractionation in detail. However, [18] was based on a single ascent and eruption model [19] that features significant condensation of water onto the walls, so non-water components of the ocean are enriched in the plume. As noted by the authors of that work, if there were less condensation (e.g. per [17], or the MPMC model proposed in this work), the fractionation could go in the opposite direction, and H_2O concentration could be enriched. Until a consensus on eruption mechanics is reached, the role of fractionation is likely to remain uncertain, which presents a challenge for designing future life detection missions to Enceladus.

In this work, we re-assess the evidence for different ascent and eruption models in the context of investigating the possibility of fractionation. We find that no current models satisfactorily address all relevant physics and explain all relevant observations, and that the differences between them have significant impacts on fractionation, the extent to which the jets and plume sample the ocean, and hence future mission sampling strategy. We propose a new ascent model that includes physics associated with the degassing of volatile species, and still attempts to produce outputs that are consistent with physical quantities of interest previously measured at Enceladus. In this case, the excess heat observed emitting from around Enceladus' tiger stripes is not a direct result of conduction from the rising fluids, but instead must be provided independently, via e.g. localized shear heating [7]. The consequences for future missions to Enceladus that involve sampling of the erupting materials are discussed.

MPMC Model Summary: Presuming that a physical conduit exists between the Enceladus ocean and the surface, the following simplified model is proposed to demonstrate the importance of incorporating the physics of dissolved volatile gases. While the proof-of-concept MPMC model presented here provides a simplified model of the Enceladus conduit system, it does include basic physics associated with the dissolved volatile gases. In its current form, the MPMC model accounts for the conservation of mass and energy, and models an ascending multi-phase multi-component mixture. Conservation of energy is given by:

$$\underbrace{\overset{\text{Heat}}{Tds} - \overset{\text{Mechanical work}}{Pdv} + \overset{\text{Chemical potential}}{\textstyle\sum_i \mu_i dN_i}}_{\text{Specific internal energy [J/kg]}} + \underbrace{\overset{\text{Kinetic}}{udu} + \overset{\text{Gravitational potential}}{gdz}}_{\text{Specific external energy [J/kg]}} = 0,$$

where, u is the ascent velocity [m/s], T is the temperature [K], s is the specific entropy [J/(kg K)], P is Pressure [Pa], v is specific volume [1/m^3], u is the ascent velocity [m/s], g is Enceladus' gravity (~0.113 m/s^2), z is the elevation relative to the surface [m], μ is the chemical potential [J/molecule] and N_i is the number of molecules per kg of species i. The chemical potential is assumed to be dominated by the heat of exsolution of the volatile phases, where h_{ex} is the enthalpy of solution, and dm_{ex} is the amount of gas exsolving, (e.g. the mass of gas coming out of solution and undergoing a phase change). In order to calculate the amount of volatile exsolution as a function of pressure, Henry's Law for exsolution of a single non-H_2O volatile (currently H_2) is assumed, similar to [20]. For specific internal energy, all vapor and liquid phases are calculated separately, with vapor treated as an ideal gas. At the top of the conduit, the flow velocity is assumed to be Mach 1 (a standard boundary condition for compressible flow through a long duct with viscosity, or for choked flow if a converging/diverging geometry existed). We incorporate a commonly-used simplification [21-22], originally proposed in [23], to account for the multi-phase (gas and liquid) speed of sound. We assume a thermally isolated system (no heat loss through walls), and, due to the large latent heat of fusion of water and lack of consideration of solutes that deflate the liquid, also conveniently keeps the temperature constant. Internal thermodynamic energy is balanced with external (gravitational potential and kinetic) energy. Additional assumptions in the MPMC model will be described in the full work.

Summary of Preliminary Results: In brief, preliminary results from this model highlight two findings: 1) the exsolution of volatiles (known to be present in the Enceladus ocean) can drive an ascending flow if no slip is assumed between the different phases, and 2) the multi-phase speed of sound is significantly lower than a gas-phase only speed of sound. These results are illustrated in Figs. 1 and 2.

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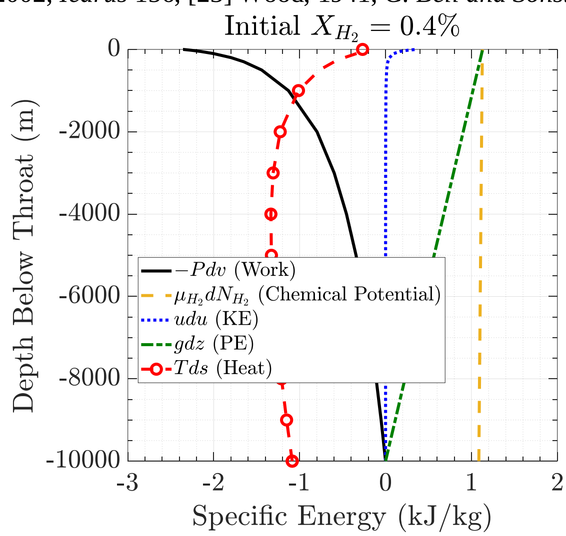

Figure 1 - Proof-of-concept MPMC model results. The different terms from conservation of energy show how energy is partitioned in the flow.

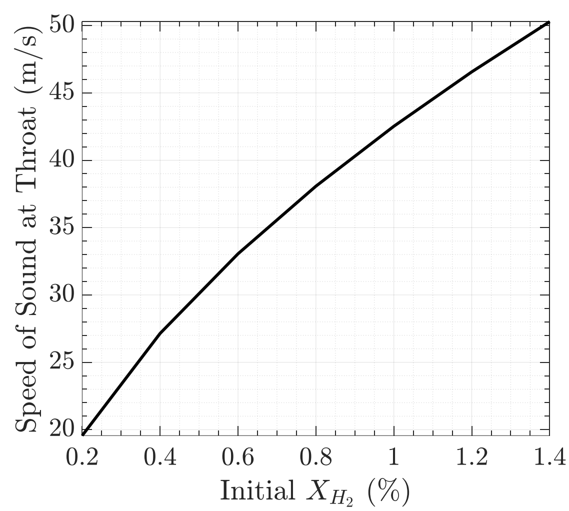

Figure 2 - The low speed of sound of a multi-phase mixture significantly limits the amount of energy that can be converted into kinetic energy (KE).