DYNAMIC PRESSURE AT ENCELADUS' VENTS AND IMPLICATIONS FOR VENT AND CONDUIT IN-SITU STUDIES.

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Introduction: In addition to being interesting in their own right, Enceladus' plumes provide a unique opportunity to sample directly a potentially habitable zone in the outer solar system. However, due to very low column densities, it is unclear orbiters or fly-by missions can sample sufficient material to detect putative life and obtain some of the more important habitability constraints. An alternative to this approach is to collect samples directly from the vents where the column density is greater or, even more ambitiously, to descend into the conduit. However, in order to address the feasibility of this concept in terms of engineering challenges, it is necessary to understand the dynamic regime that exists here.

Dynamic pressure definition: A fluid in motion exerts a pressure that depends both on the static pressure, *p,* and on the pressure caused by the energy of its motion, its dynamic pressure, *q*, where:

$$q = \tfrac{1}{2} \rho u^2, \quad (1)$$

where u is the velocity and ρ is the density. For high speed systems, however, an alternative formulation can be defined with respect to the speed of sound. By applying the ideal gas law, as well as definitions of the speed of sound and the Mach number, M, it can further be shown that:

$$q = \tfrac{1}{2} \gamma p M^2, \quad (2)$$

where γ is the ratio of specific heats. We consider three approaches to constraining upper limits to q.

Maximum exit velocity: We consider a scenario in which most of the acceleration occurs in the subsurface and water erupts at sub-triple points pressures (vapor + solid). In this case, we use eq. 2, assume $p < 611$ Pa and, from studies of the jet structures [1], $5 < M < 8$.

The ratio of specific heats of a pseudogas mixture, Γ, can be determined using adiabatic ratios of the individual components w.r.t. pressure and volume, weighted by their volumes fractions, ϕ:

$$\Gamma = \Sigma (\phi\, c_p) / \Sigma (\phi\, c_v) \quad (3)$$

Based on results from the Cassini Ion Neutral Mass Spectrometer (INMS), we can assume that a proportion of the plume is exsolvable non-water volatiles, and based on E5 and E7 compositions [2] we consider it reasonable to assume 8% (molar) CO_2 as a proxy for all non-water volatiles. CO_2 and H_2O water at 0º C have specific heats capacities at constant pressures of $c_{p,CO2v} = 800$ J kg^{-1} K^{-1}, $c_{p,H2Ov} = 1860$ J kg^{-1} K^{-1}. Specific heat capacity at constant volume, c_p, can be derived using the ratios of specific heat at 0º C, $\gamma_{CO2} = c_p / c_v = 1.31$ and $\gamma_{H2O} = c_p / c_v = 1.33$. At these pressures the volume fraction of water-ice ($c_p = c_v = 2100$ J kg^{-1} K^{-1}) is negligible, so we can ignore that contribution. Thus, making no assumptions about the relative quantities of CO_2 and H_2O, we find $1.31 < \Gamma < 1.33$, and so we assume 1.32.

Application of eq. 2 gives $q < 2.6 \times 10^4$ Pa, equivalent to a terrestrial surface wind speed of 208 m/s (466 mph). This is an over-estimate, as some acceleration will occur below triple point pressures.

Choked eruption: A more theoretical estimate can be derived by estimating the dynamic pressure at Mach 1, a likely condition at the surface (surface choked) or in at the narrowest point of a converging-diverging nozzle (the "throat"). For the same static pressure as above, the maximum value for q would 64× less that for the above scenario using eq. 2. However, in this case it is useful to determine the solution semi-analytically for higher pressures using eq. 1, as u is known to be equal to C, the mixed-phase sound speed velocity, an approximation for which is [3]:

$$C = (AB)^{-1} \quad (4)$$
$$A = [\Sigma (\phi\, \rho)]^{0.5}$$
$$B = [\Sigma (\phi / \rho c^2)]^{0.5},$$

where c and ρ are the speed of sound and densities of the individual components. As previously, we assume that CO_2 drives ascent, and additionally that it exsolves from the H_2O in equilibrium according to Henry's Law ($H^{cp} = 0.034$ mol L^{-1} atm^{-1}). Water remains in a liquid state (>611 Pa), consistent with a liquid ascent (cryovolcanic) ascent model. Results are given in fig. 1 for a range of pressures and CO_2 starting molar fractions.

In this scenario, the dynamic pressure in the throat approximates the static pressure. Eruptions may only occur if the mean fluid density integrated from ocean to surface is less than the mean crustal density, i.e. the liquid is hydraulically buoyancy, and so results with $\rho > 920$ kg m^{-3} are rejected; Further analysis will rein this in further. The highest dynamic pressures (>1 MPa) occur with high CO_2 contents and static pressures (also ~1 MPa), equivalent to a terrestrial ground wind speed of 1290 m s^{-1}. Such values may also be unrealistic if they exceed ocean pressures, or if exsolution of available CO_2 is suppressed (likely) due to supersaturation or formation of carbonic acid, which will be considered in future analyses.

Supersonic nozzle flow: Mitchell [4] proposed that abrasive erosion of conduit walls in volcanic eruptions would, given as a sufficiently long-lived eruption, as seems plausible on Enceladus, result in the fluid dynamic conditions (e.g. a de Laval nozzle) necessary to facilitate descent of the throat into the subsurface and enable supersonic flow at the surface. From conservation of mass, if we assume isentropic flow, which is reasonable for a supersonic jet, through an ideal de Laval nozzle, it has be shown [5] that:

$$\left(\frac{A}{A^*}\right)^2 = \frac{1}{M^2}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right]^{(\gamma+1)(\gamma-1)}$$

$$\frac{A^*}{A} = \frac{\rho u}{\rho^* u^*} = \frac{\left[1-\left(\frac{p}{p_0}\right)^{(\gamma-1)/\gamma}\right]^{\frac{1}{2}}\left(\frac{p}{p_0}\right)^{1/\gamma}}{\left(\frac{\gamma-1}{2}\right)^{(1/2)}\left(\frac{2}{\gamma-1}\right)^{(1/2)(\gamma+1)/(\gamma-1)}} \quad . \quad (5)$$

where A is the conduit cross-sectional area, and superscript * refers to the condition at $M = 1$.

Hence it is possible to track how pressure, Mach number and cross-sectional area change relative to their values at the throat, which was determined above (fig. 1). Dynamic pressure is presented, relative to the throat as a function of expanding vent/jet angle (fig. 2), demonstrating that the throat is likely to be the location of peak pressure (it may be a few percent higher within a few vent radii of the surface). Note that this analysis does not consider the consequences of phase change after this condition, which is inevitable during decompression through the triple point.

Summary: Our anaylsis provides critical information for the ongoing feasibility study of a robotic mission to sample at, or descend into, Enceladus vents, as one of the major challenges of such mission is the dynamic pressure. The results are preliminary, but within the scope of the assumptions made we find that the upper limit dynamic pressures are not insurmountable. They point us in the direction of anchored robots with low drag structures. Efforts continue to to rein in more extreme pressures and improve modeling assumptions.

References: [1] Hansen, C.J. et al. (2011) *GRL*, *38*, L11202; [2] Waite, J.H. et al. (2011) *EPSC Abstracts 6*, EPSC-DPS2011-61-4; [3] Lorenz, R.D. (2002) *Icarus*, *156*, 176-183; [4] Mitchell, K.L. (2005) *JVGR, 143*, 187-203; [5] Liepmann, H.W. and Roshko, A. (2001) Elements of gasdynamics. Dover, NY.

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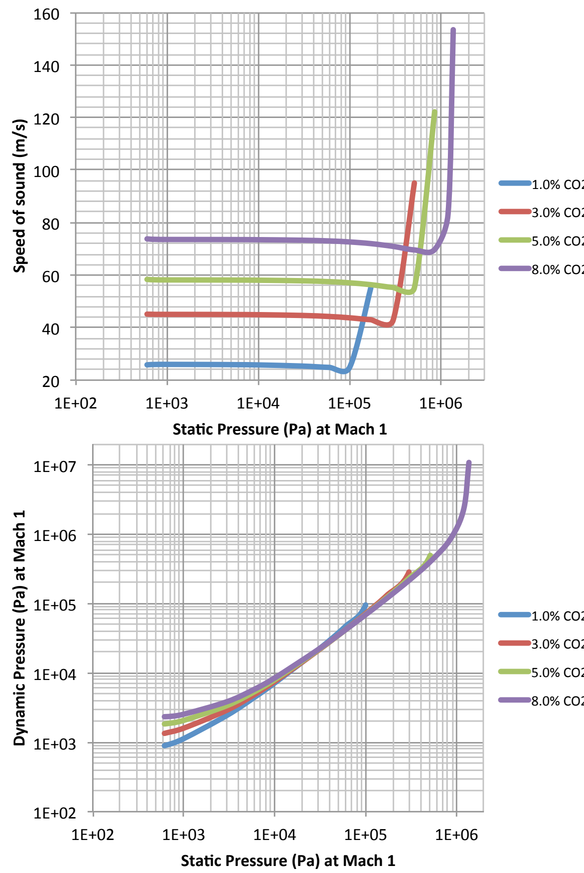

Figure 1: (top) Sound speed and (bottom) dynamic pressure for a CO_2-driven eruption at Mach 1 (surface choked or in nozzle throat). Upper limit at ρ = 920 kg m^{-3} (density of ice), lower limit at p = 610 Pa (triple point of water).

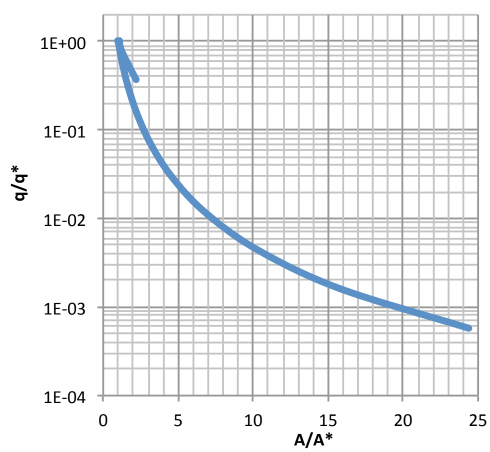

Figure 2: Relationship between dynamic pressure and conduit cross sectional area in a de Laval nozzle assuming isentropic flow and negligible phase changes, both w.r.t. the condition at Mach 1 (* annotated). The short tail is for elevations below the throat, where flow is subsonic.