1D Effervescence Modeling for the Titan Submarine.

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Introduction: Concepts for an extraterrestrial submarine are currently being designed and developed to explore the seas of Saturn's moon Titan for a one year mission to investigate astrobiological and geological aspects of the moon. A stand-alone concept that relies on direct-to-Earth communication is depicted in Figure 1 [1]. The concept is a unique, fully-submersible and autonomous submarine capable of operating within the cryogenic hydrocarbon seas of Titan. Details of the mission, the submarine, and concept of operation are available in the literature [2].

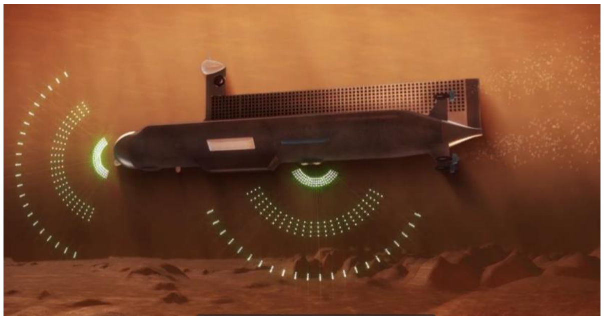

Figure 1: Concept for the Titan Submarine

Currently, a major design concern is the effect of effervescence on submarine operation. The submarine relies on a radio-isotope system for power. Along with appropriately sized insulation, waste heat from the power supply is distributed throughout the interior of the submarine to maintain electronics at ambient temperature of 297K; the rest of the heat (< 400 W/m^2) is rejected to the surrounding seas at 93K. This temperature gradient and resultant heat flux is not sufficient to boil the liquid, which is close to the freezing point of pure ethane or methane. But it may be enough to cause the nitrogen gas that is dissolved in the liquid to come out of solution [3].

On Titan, the submarine may be subject to hydrostatic pressures in excess of 1 MPa and temperatures colder than 93K. For terrestrial submarines, the solubility of air in water is < 0.1% at 1 MPa. On Titan however, atmospheric pressure is 1.5 times that of Earth, and recent solubility data taken near Titan conditions [4,5] shows that nitrogen is highly soluble in liquid ethane and liquid methane, as high as 12% at the surface of the sea. Furthermore, a universal analytical solubility model recently developed for the ternary nitrogen/ethane/methane shows that the amount of dissolved gas increases with increasing pressure and decreasing temperature [6].

Effervescence of nitrogen gas may cause issues in two operational scenarios for any submersible on Titan. In the quiescent case, bubbles that form may interfere with sensitive science measurements, such as composition measurements, in acoustic transmission for depth sounding [7], and sidescan sonar imaging. In the moving case, bubbles that form along the submarine may coalesce at the aft end of the craft and cause cavitation in the propellers, impacting propulsive performance.

Model: Computations presented here focus on the latter of the two concerns, to quantify the volume fraction of gas at the aft end of the propellers. Complete details of the effervescence model are available in [8], only a brief description is given here. Eq. 1 [6] specifies the mole fraction of dissolved nitrogen gas as a function of the location on Titan (e.g. Ligeia or Kraken Mare), which specifies the relative mole fraction ratio of ethane:methane, as well as the location within a given sea, which specifies the temperature and pressure:

$$\chi_{GN2} = f\left(\chi_{C2H6}, \chi_{CH4}, T, P\right) \qquad (1)$$

Next, the supersaturation ratio, S is determined by evaluating Eq. 1 at the bulk liquid temperature and at the submarine skin temperature based on the amount of waste trasferred into the liquid. For any bubble to grow, the initial nucleus size must be larger than some critical radius based on the surface tension γ, local pressure P_a, and supersaturation ratio:

$$R_c = \frac{2\gamma}{P_a S} \qquad (2)$$

Bubbles larger than this critical radius may form along the submarine; smaller bubbles will dissolve back into solution. Bubble incipience, the third step in the computation, is governed by the supersaturation ratio and critical bubble radius. The bubble is assumed to grow from zero size. Next, the bubble growth rate is computed from solving the implicit coupled initial and boundary value problem for concentration and radius of the bubble $C(t,r)$ for a given bubble growth constant. Fifth, now that the number of nucleation sites and the growth rate is known, one can count the number of bubbles, either on an area or volume basis.

Results: The amount of accumulation at any location is determined by the submarine velocity, as well as the nucleation and growth rates. Each bubble has had time to grow, according to the distance from its nucleation site to the position of calculation, and the total bubble coverage at any position is the sum of the coverage of all individual bubbles. In the moving case, the most important location to track accumulation is the aft end of the propellers. There are two components to the total gas volume fraction. First, bubbles that are thermally driven out of solution due to waste heat will accumulate along the length of the submarine. Second, bubbles are also pressure driven out of solution due to pressure drop across the propeller blade. Thus supersaturation, and consequently effervescence, is affected both by temperature and pressure.

Simulations were performed for two different ethane:methane concentration ratios to simulate Kraken and Ligeia Mare. Results for the high methane case (Ligeia) are shown in Figure 2, where the volume void fraction of gas at the aft end of the propellers is plotted as a function of the submarine skin temperature and the depth (pressure) within the sea, at a vehicle cruising speed of 0.5 m/s. As shown, effervescence increases with depth, due to higher solubility and thus higher supersaturation. Effervescence also increases with increasing skin temperature, which also drives the supersaturation ratio up, and the number of nucleation sites.

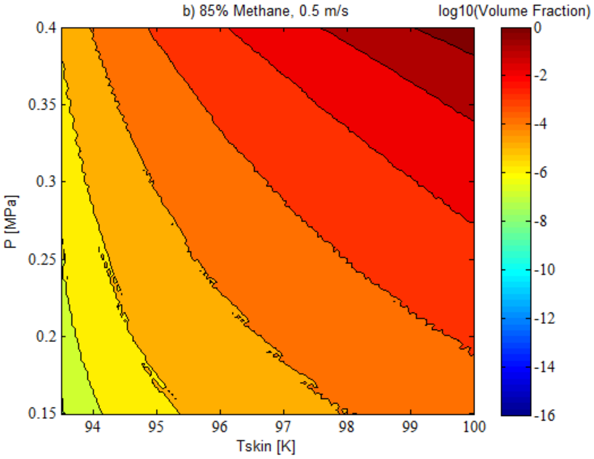

Figure 2: Log of the Volume Fraction of Gas at the Aft End of the Propellers in Ligeia Mare.

Figure 3 plots the volume fraction as a function of vehicle velocity at a fixed depth of 150 m within Ligeia Mare. At zero speed, volume fraction is at the thermally driven limit; only natural convection can sweep away bubbles that form during quiescent operation. As velocity increases, volume fraction decreases in two ways: bubbles that nucleate do not have enough residence time to grow, and forced convection sweeps some thermally induced bubbles off the sides of the submarine. However, as velocity is further increased, pressure drop through the propellers increases, causing more nucleation sites, and thus more bubbles to come out of solution. Therefore, operationally for the submarine, there is an optimal velocity which minimizes both the thermally and pressure induced components of effervescence.

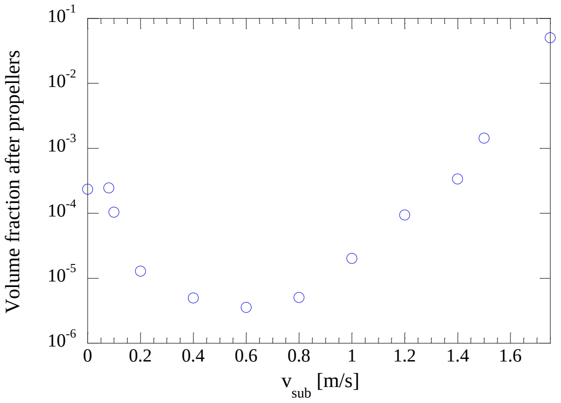

Figure 3: Volume fraction after propellers as a function of the vehicle velocity.

Acknowledgements: The authors wish to acknowledge the NASA Innovative Advanced Concepts office for funding this study, as well as Justin Walsh for discussion on cavitation.

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