Modeling the water vapor plumes of Enceladus

B. J. Hanna, S. K. Yeoh, D. B. Goldstein, P. L. Varghese, L. M. Trafton
Computational Fluid Physics Laboratory, The University of Texas at Austin (ben.hanna@mail.utexas.edu, skyeoh@mail.utexas.edu)

Introduction: Cassini has detected water vapor plumes near Enceladus' warm, ice-covered south pole during its several close flybys [1]. The dynamics and structure of these plumes are important in helping us learn more about this enigmatic moon of Saturn. Two plume models are considered: the free-molecular and the collisional direct simulation Monte Carlo (DSMC) models. The non-collisional, free-molecular model is less expensive yet fairly accurate in the far-field, thus it is used to obtain a qualitative, global picture of the plumes. The collisional DSMC model is used to obtain a more accurate and detailed model of the near-source regions. The results of the simulations will be used to constrain the conditions of the sources of the plumes, such as gas temperatures, velocity and plume generation mechanisms.

DSMC Model: An axisymmetric gas plume with a single species (H_20) is simulated. DSMC uses a representative number of computational molecules to stochastically model the collisions and movements of real gas molecules [2]. The model includes planet surface curvature, variable gravity, surface frost sublimation, and internal molecular energy exchange. Since the surface vent geometry is unknown and may be complicated, the simulation employs a "virtual" vent located at an altitude where the DSMC regime becomes valid [3]. The "virtual" vent diameter is assumed to be 700m (~206 mean free paths, λ, wide) and the plume is assumed to issue from it with a uniform velocity of 200 m/s [4] in thermal equilibrium at 145 K [5]. Surface frost sublimation is negligible due to low surface temperatures of ~75 K [5]. A wedge-shaped domain of dimensions 1700 m x 1700 m x 1° and a grid size of 500 x 500 x 1 (~1 λ per cell) are employed with a time step size of 0.0015 s. About 2 x 10^6 computational molecules are used (~6-7 molecules per cell). The simulation is run until steady state is achieved.

DSMC Results: The gas emerges from the vent relatively slowly before expanding out into vacuum and accelerating to speeds in excess of 700 m/s. The difference between the translational and rotational temperatures provides a measure of the degree to which equilibrium occurs in the flow. As shown in Figure 1(a), equilbrium occurs in the core of the plume (small T difference) with large non-equilibrium (larger T difference) further out, indicating that the flow changes regimes from continuum near the vent to rarefied in the far field. This is also suggested in Figures 1(b) and (c). The gas density is highest near the vent and decreases farther away while the mean free path values are smallest close to the vent and become larger in the far field. Figure 1(d) shows the gas cooling down rapidly as it moves away from the vent.

Free-molecular Model: The free molecular model simulates non-collisional gas dynamics. As the gas undergoes a collisional expansion from the continuum near-source (DSMC) region into the far-field (free-molecular) region, it loses internal energy to directed energy and achieves an ultimate velocity of $V = [2\gamma RT/(\gamma-1)]^{1/2}$ ~ 730 m/s, where T = 145 K [6] is the temperature of the DSMC "virtual" vent from which the gas expands. Therefore, in the free molecular model, the initial velocity of every gas particle is taken to be the ultimate velocity [6]. The particles then follow a ballistic trajectory. Particle mass flux from a single vent follows a $\cos^2(\delta)$ distribution, where the angle δ is measured from the surface normal [6].

Free-molecular Results: At the simulated initial velocity of ~730 m/s, every gas particle escapes Enceladus into space to supply Saturn's E-ring. This strongly resembles Cassini observations where most of the particles leave the moon and very few return to coat the surface, increasing the moon's south polar albedo [7].

Conclusions:

- DSMC model can be used to model the plumes close to the vent where the flow is continuum and collisional while the free molecular model is suitable for modeling the far field where it becomes rarefied.
- The present free-molecular model of 8 point-like sources produce gas columns reminiscent of the Cassini particle images.

References: [1] Hansen C. J. et al. (2006) Science, 311, 1422-1425. [2] Bird, *Molecular Gas Dynamics and the Direct Simulation of Gas Flow*, Oxford University Press, 1994. [3] Zhang J. (2004) PhD dissertation, Univ. of Texas at Austin. [4] Hansen C. J. et al. (2006) Science, 311, 1422-1425. [5] Spencer J. R. et al. (2006) Science, 311, 1401-1405. [6] Goldstein D.B. (2003) AIP, 663, 712-719. [7] Porco C.C. et al. (2006) Science, 311, 1393-1401. [8] Spitale J. N. and Porco C.C. (2007) Nature, 449, 695-697.

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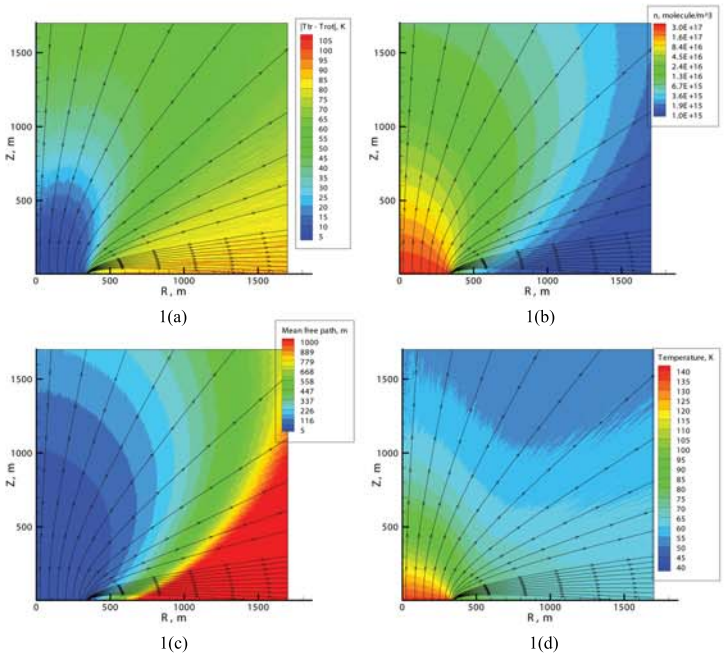

Figure 1: Close-up view of a DSMC simulation of a plume, with velocity streamlines shown. (a) The difference between the gas translational and rotational temperatures; this gives a measure of equilibrium in the flow. (b) Density of the water vapor plume. (c) Mean free path λ within the plume, indicating continuum flow (small λ ~ 3 m) near the vent to rarefied flow (large λ ~ 1000 m) in the far-field. (d) Total temperature distribution within plume.

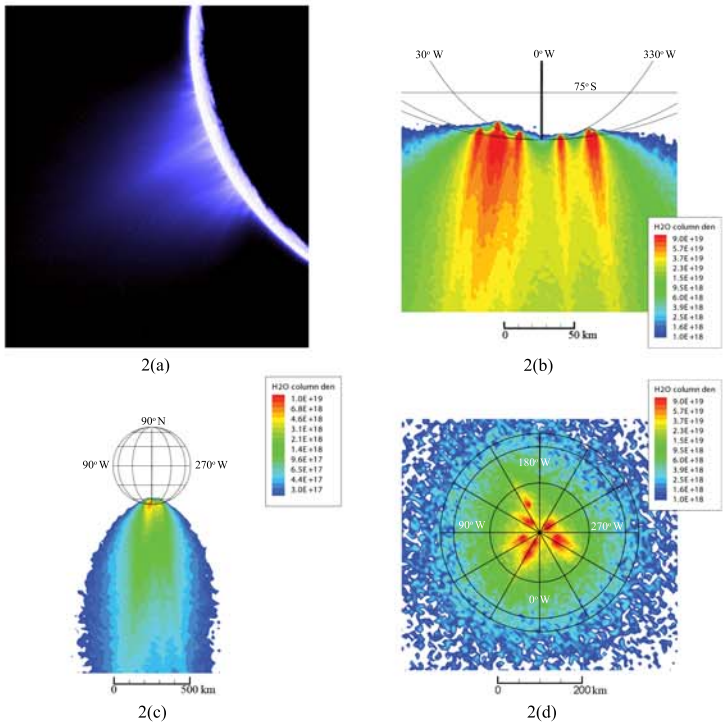

Figure 2: Spitale and Porco define eight main point-like sources based on readings from Cassini's CIRS and ISS instruments [8]. The above images depict (a) an enhanced Cassini photo [7], (b) a close-up broadside view of eight point sources, (c) a far-field broadside view, and (d) a bird's eye view of the plumes.