**Introduction**

**Cometary Knudsen layer**

Ice sublimating from nucleus surface into vacuum forms a Knudsen layer, which is a non-equilibrium boundary layer with a scale height of about 20 mean free paths (mfp) [1] (Fig. 1). Within this region, the velocity distribution function (VDF) is strongly non-Maxwellian [2]. The thickness of the Knudsen layer depends on the gas production rate of the nucleus. When Rosetta encounters Comet Churyumov-Gerasimenko (C-G), the mfp will be of the order of meters to kilometers [3, 4]. A numerical model of the non-equilibrium innermost coma of C-G is necessary for the Rosetta mission to understand the physics of the outflow immediately above the surface.

**DSMC**

Direct Simulation Monte Carlo (DSMC) [5] is a very powerful numerical method to study gas flows inside non-equilibrium regions and has been applied to study cometary outflows by many authors [4, 6]. The basic idea of DSMC is to represent many real gas molecules by a few model particles and apply statistical collision models to them. The gas parameters such as density, velocity, and temperatures are obtained by averaging the properties of the particles in sampling cells. The DSMC program used in this study is PDS*C++ developed by Wu and coworkers [7-9]. PDS*C allows a parallel simulation of 3D flows on hybrid unstructured grids. The code is especially useful when treating the large density gradients by implementation of a variable time-step and a transient adaptive sub-cell technique to increase computational speed and accuracy in the regions of high density [10].

**Objectives**

- To determine the gas field-flow in the innermost coma and to place constraints on the surface outgassing properties from analysis of the flow-field.
- To prepare for comparisons with Rosetta observations over a range of heliocentric distances.

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**Method**

A complete simulation of the innermost coma of C-G involves the details of the nucleus surface (shape model, thermal model) and the gas dynamics variables. Brief descriptions of the models are listed as follows:

**Shape model (Unstructured grid)**

A nucleus shape model constructed and released by ESA/Rosetta/MPS determines the geometry of C-G. The model has a surface area of 3.93 km². The simulation domain extends out to 10 km from the center of the nucleus (Fig. 2). The dimensions of the surface facets are chosen to be comparable to the mfp when C-G is around the perihelion.

**Thermal model**

A thermal model can give the gas temperature and density distributions upon the nucleus surface as the initial boundary conditions. The thermal model here is based on a simple 1D energy balance equation neglecting the thermal conductivity $S(1 - A_0) \cos \theta = c_0 + \frac{I \cos \theta}{d t}$ and applied to each facet of the shape model. Constants for albedo and IR emissivity are assumed.

**Gas Dynamics Variables**

Gas dynamics variables such as outgassing forms, heliocentric distances ($r_h$), production rates ($Q$), velocity distribution functions (VDF) and gas species are also important factors affecting the innermost coma. Several test cases designed to investigate the influence of the parameters are shown in Table 1.

**Results**

**Initial boundary conditions**

Temperature and number density distributions (Fig. 3) upon the nucleus surface obtained from the thermal model are the major initial boundary conditions for the simulation. They are the main constraints for the outgassing results.

**Distributions of the inner coma**

The difference caused by outgassing forms is clear. The VDF imposed by the initial outgassing shown in Fig. 4(b) has more gas over the number density distributions as shown in the coma regions. The energy is redistributed through the gas and the mass conservation will be investigated in the future, and our DSMC code will be compared to measurements obtained by the Rosetta instrumentation, both in situ and remote sensing, using more sophisticated gas and velocity models.

**Conclusions**

We have simulated the gas kinetics in the innermost coma of C-G and identified to what extent modification of parameters influences the gas flow field. For cases of single species outgassing ($H_2O$), the production rate $Q$ ($kg/s$) is the most influential parameter. Differences of the gas distributions between homogenized and inhomogeneous outgassing are evident but would be less clear in the coma 10 km away from the nucleus as the gas expands. The cosine law velocity distribution function imposes some changes in the flow field. The collimation effect of the gas is not clearly seen in the number density distributions but evident in the velocity distribution. In general, the cosine law distribution function should change significantly the flow field of the free molecular flow. It is the collimation between the gas particles that may help to explain why the collimation effect resulted from the cosine law distribution is not so strong. The energy is redistributed through collisions and reaches a Maxwell-Boltzmann distribution when the flow field is in equilibrium. For cases of multispecies outgassing ($H_2O$ and $CO_2$), the amount of the two species depends on the initial boundary conditions. As for the velocity distribution, $CO_2$ is apparently slower than $H_2O$ as expected. More variables will be investigated in the future, and our DSMC code will be compared to experiments obtained by the Rosetta instrumentation, both in situ and remote sensing, using more sophisticated gas and shape thermal models.

**Reference**


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