Numerical analysis of molten droplets in a rarefied gas flow

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Chondritic meteorites contain a large amount of millimeter-sized, spherical-shaped igneous grains mainly composed of silicate material, which are called as chondrules. They are considered to have formed from chondrule precursor particles that were heated and melted through flash heating events in the solar nebula and cooled again to solidify in a short period of time. One of the most plausible model for chondrule formation is shock-wave heating model (e.g., Iida et al. 2001, Icarus 153, 430-450). If shock waves were generated in the solar nebula, the nebula gas is suddenly accelerated by the gas pressure, while precursor dust particles tend to keep their initial position. The relative velocity between gas and dust particles causes the gas frictional force and the gas drag heating on the surface of dust particles. If the shock waves are strong enough, it is possible to melt dust particles and form chondrules. The dynamics of molten droplets in the high velocity gas flow (deformation, internal flow, and fragmentation caused by ram pressure of the gas) is thought to be important for shape and size of chondrules (Susa & Nakamoto 2002, ApJ 564, L57-L60), though it has been still unknown.

We developed a numerical hydrodynamic simulation code to investigate the behavior of molten droplet in a rarefied gas flow. The motion of molten droplet is mainly governed by three factors; viscosity, ram pressure, and surface tension. In order to introduce the surface tension, it is needed to capture the interface between a droplet and rarefied gas sharply. We applied CIP method (Yabe et al. 2001, J. Comp. Phys. 169, 556-593) to this problem and confirmed that the interface can be easily detected even after sufficient calculation steps proceed. We simulate a capillary wave of molten droplets due to the surface tension in order to confirm the validity of our code. The calculated vibration period is well matched with an analytic solution.

Using this code, we investigate the dynamics of molten droplets in a rarefied gas flow. It is well known that two dimensionless numbers classify the destruction process of droplets; Weber number (ratio of ram pressure to surface tension, We) and Ohnesorge number (ratio of viscosity to surface tension, Oh). We simulated various systems that are specified by We and Oh and succeeded to obtain numerical solutions (internal velocity, pressure, and deformation of droplet). In cases that deformation of the droplet is small, our results show the similar patterns of shape and velocity field to that obtained from analysis of linearized hydrodynamic equations (Sekiya et al. 2003, Prog. Theo. Phys. 109, 717-728). We can also obtain plausible results in cases of large deformation, which cannot be treated by linear analysis. Moreover, our calculations indicated the fission of molten droplets if We is greater than about 10, which matches well with previous experiments. Therefore, it is thought that our numerical code is valid for analysis of such problems and can be applied to advanced situation.

Finally, we describe the future direction of our study. In above calculations, we assumed that the physical parameters in droplets (temperature, viscosity, and so forth) are constant. In reality, however, droplets are heated from one side on their surface by gas drag heating, so the temperature distribution will be inhomogeneous. Moreover, viscosity and surface tension strongly depend on temperature. We are going to introduce thermal advection/diffusion equation to our current code in order to analyze above problem. Additionally, in this study, we consider the initially all-molten particles. However, dust particles are initially solid and gradually melted from the surface where the gas drag heating takes place. We are planning to solve such complicated problems and investigate the dynamics of molten droplets in a high-velocity gas flow.