Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

PPS020-22 Room:103 Time:May 24 16:00-16:15

Observation of Spallation Phenomena in Hypersonic Wind Tunnel Experiment Simulating Atmospheric Entry of Icy Object

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The hypersonic wind tunnel, which has been used for the research and development of high speed aircrafts and spacecrafts in the aerospace engineering, is also a useful tool to simulate the flowfield around an atmospheric entry object, such as a meteorite, and to observe the various phenomena induced by the flow (Suzuki, et al., JpGU Meeting 2010, PPS004-10, Imamura, et al., AIAA Paper 2010-4512). In this paper, we present the spallation phenomena observed in the wind tunnel experiment using an ice piece. The experiments have been conducted at the hypersonic and high-enthalpy wind tunnel (http://daedalus.k.u-tokyo.ac.jp/wt/wt_index.htm) in Graduate School of Frontier Sciences, the University of Tokyo. In this facility, the uniform flow at Mach number 7.0-7.1 is obtained in the region of about 120mm diameter around the tunnel axis for 60s at maximum. Assuming an icy object entering the atmosphere, we prepare the test piece of a 40mm-diameter sphere made from water ice around the 15mm-diameter spherical core made from acrylic resin or foam aluminum. The ice piece is set in the test section by the supporting rod via thermal insulator (bakelite rod) and is injected into the test section after the uniform flow has been established.

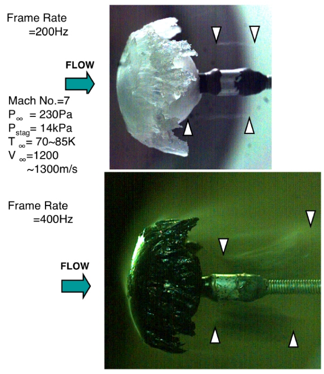
The attached figure shows the snapshots taken by the high-speed camera at about 25s from the injection into the flow. The frame rate is 200Hz and 400Hz for the upper and lower images, respectively. In both cases, the pressure and heating rate at the stagnation point on the surface are estimated as about 14kPa and 100kW/m^2, respectively. The maximum temperature of the flow is 800-920K. In the case of the lower picture, the test piece is made from black water dyed with Indian ink (5% wt.). In the stagnation region, the recession of the surface occurs by the melting and/or evaporation under the severe aerodynamic heating. The liquid water and vapor go downstream and are refrozen into ice due to the temperature decrease at the rapid expansion flow in the shoulder region. The pile of icy columns grows outward, forming a brim-like shape around the icy body. In the upper image, we successfully captured the spallation, in which very small icy pieces are ejected from tips of frost-like icy columns. The triangular symbols in the image indicate the beginning and end points of a streak of a spalled particle during the exposure time of the camera (5ms). In this case, the ejection velocity is estimated as in the order of 1-10m/s from the length of a streak. However, there are a variety of the streak shape and length. This means that the ejection speed and trajectory of the spalled particle are not uniform.

The high-speed video image shows that such spallation frequently occurs after the pile of the icy columns has been constructed. The mass loss due to the spallation is not negligible in comparison with that by the evaporation at the surface. At the tip of the icy column, the detailed shape looks similar to the frost. The size of the spalled particle is in the same order of the scale of the frost-like shape, which is much smaller than the size of the icy object. In the similar way, a large amount of small spalled particles are expected to be ejected into the wake flow of a meteorite.

The pile of icy columns in the shoulder region remains by the balance of the refreezing and spallation. After long exposure time, the breakup of a icy column occurs at some timing. The lower image shows the snapshot of the test piece just after the breakup, where the light scattering is observed due to a large amount of mist injected from cracks on the ice.

Such simulation experiments using a hypersonic wind tunnel are expected to provide useful information for understanding the phenomena of an atmospheric entry object such as meteorite.

This work is supported by Grant-in-Aid for Scientific Research (B) No. 21360413 of Japan Society for the Promotion of Science.



Keywords: atmospheric entry, ice, ablation, spallation, hypersonic flow, wind tunnel experiment