Thermophysics

This year saw significant advances in thermophysics, particularly in areas related to space, high-power electronics and weapons systems, storage and transfer of energy in supersonic flows, and state-to-state kinetics.

Stardust airborne observation
In the early morning of January 15, the Stardust sample return capsule (SRC) successfully delivered its precious cargo of cometary particles to the recovery team at the Utah Test and Training Range. As the SRC entered at 12.8 km/sec, the fastest man-made object to traverse our atmosphere, a team of researchers managed by NASA Ames observed the event aboard the NASA DC-8 airborne observatory using an array of spectroscopic instruments. As the SRC did not have any onboard flight instrumentation, these data are the only time-resolved record of the entry system’s performance.

The Stardust Observation Campaign was sponsored by the NASA Engineering and Safety Center and the Crew Exploration Vehicle Thermal Protection System Advanced Development Project. The objective was to obtain data to help validate the aerothermodynamic and thermal protection system material response codes to be used in the CEV design.

The campaign’s primary objectives were to obtain total radiated power emitted from the SRC and shock layer along the entry trajectory, spectrally resolved radiated power from the SRC and shock layer along the trajectory, and evolution of structures in the near wake and entry trail. With principal investigation by the SETI Institute, researchers assembled a diverse mix of spectroscopic instruments to record the SRC entry. This team had previously flown in the DC-8 to observe the Leonid meteor shower in 2002 and in another research aircraft, the Air Force Flying Infrared Signature Technology Aircraft, to observe the Genesis sample return entry. Taken as a whole, the instruments provided overlapping views of the entry emission signature. Any single camera had a unique view in terms of temporal and spatial resolution; however, the entire suite was intended to be robust to any one or two cameras failing to acquire data.

The observation mission was flown from Moffett Field at NASA Ames. The SRC entry was viewed by instruments peering through port windows at an altitude of 38,500 ft at a location outside the western border of the Utah Test and Training Range SRC landing site. This location positioned the aircraft south of the ground track with the full Moon oriented toward the starboard side. The flight path was designed so that views to the oncoming SRC were to be as head-on as possible, thereby imaging the shock layer and forebody heatshield thermal radiation. During peak aerodynamic heating, the view angle was approximately 18° from head-on at a range of 200 km.

The incoming SRC was first acquired about 18 sec after atmospheric interface and tracked for approximately 60 sec, which is roughly centered in time around predicted peak aerodynamic heating. The radiative signal from the SRC and surrounding shock layer gases were measured by 15 of 18 instruments that had various combinations of spectral range, spectral resolution, and temporal resolution. The data, assessed to be of very good quality, were sufficient to address all observation objectives.

Initial assessments of the data reveal interesting features of the emission, including signatures of potassium and zinc, believed to be from the forebody heatshield thermal control paint burning off during entry, and a cyanogen intensity profile consistent with expected forebody heatshield ablation rate evolution. Further analysis of these data and the recovered SRC heatshield will provide an assessment of the fidelity of the aerodynamic, aerothermodynamic, and thermal protection system material response models and ground tests used to design the SRC. This assessment directly supports the Vision for Space Exploration in that the same models and tests are being used to design the crew exploration vehicle.

Spray cooling modeling and experiments
AFRL Power Div. (AFRL/PRP) is continuing to develop spray cooling technologies for high-power electronics and weapon power systems. The Power Div. is also working with NASA Glenn and NASA Goddard, the Office of Naval Research, industry (CFD Research), the University of Arkansas Computational Mechanics Laboratory, and West Virginia University on various experimental and modeling efforts.

The numerical modeling of spray cooling investigates vapor bubble growth in very thin liquid film (50-100 μm) and merger with the
vapor region above the film, and liquid droplet impact on the thin film. The modeling can simulate both 2D and 3D environments using the level set method to identify the liquid and vapor interface. The Navier-Stokes equations, including surface tension and phase change, are approximated by the finite difference method. The equations are solved by either preconditioned conjugate gradient procedure or multigrid conjugate gradient procedure.

Through this modeling effort, it has been shown that high heat flux in spray cooling is derived because of transient heat transfer rather than the phase change phenomenon assumed traditionally. The model also clearly showed that heat flux during droplet impact is much larger than during bubble growth and bubble merger events. Building on the knowledge gained from previous studies, future work will focus on multiple droplets and multiple vapor bubble growth effects.

In parallel, centrifuge and flight test experiments are conducted to determine the acceleration effects on spray cooling thermophysics. The objectives have been to determine the variation in spray cooling heat transfer performance and address fluid management issues in dynamic and static acceleration environments, and to provide well-posed experimental data to validate spray cooling models. Flight tests using the NASA Johnson Reduced Gravity Office KC-135 and C-9 aircraft began in October 2003 and have continued through July of this year. Centrifuge testing has supported the flight testing in the evaluation of liquid-vapor separator concepts. To date, AFRL/PRP has conducted 27 flight tests and 1,175 parabolas with a subscale thermal management system incorporating spray cooling.

**Storage and transfer of vibrational energy**

In high-speed flows, a considerable fraction of the flow energy can be “frozen” in the internal vibrational motion of the gas molecules. The storage and transfer of this energy with the external modes of molecular motion (translation, rotation) strongly influences the flow field temperature, the heat transfer rates, and the position of bow shocks on reentry vehicles.

**State-to-state kinetics**

The Institute of Inorganic Methodologies and Plasmas of Consiglio Nazionale delle Ricerche in Italy and the University of Bari, Italy, made advancements in the development of state-to-state kinetics for describing hypersonic flows. Quantitative improvements were made by using QCT (quasiclassical trajectory) methods and quantum mechanical approaches for the calculations of relevant cross sections including gas-surface interaction. Strongly nonequilibrium vibrational distributions and non-Arrhenius behavior of the dissociation constants were found in the boundary layer of a reentry body as well as in the nozzle expansion of high enthalpy flows.

For the nozzle expansion, the appropriate Boltzmann equation for the electron energy distribution function coupled to the electronic and vibrational excited-state kinetics signifies the non-Maxwellian electron energy distribution function along the nozzle axis. Other results include thermodynamic and transport properties of high-temperature plasmas in the presence of magnetic fields suitable for Mars’ atmosphere. Particular attention focused on the influence of electronically excited states on the transport coefficients of thermal plasmas, emphasizing the strong decrease of thermal conductivity, viscosity, and electrical conductivity.