Comparing Particle Flow Regimes in the L2K Arcjet with Martian Entry Conditions

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Nomenclature

d_p = particle diameter, m
Kn = Knudsen number
M = Mach number
Re = Reynolds number
v = velocity, m/s
μ = viscosity, kg/m-s
ρ = density, kg/m^3

Subscripts
g = gas
p = particle

I. Introduction

In recent years, there has been renewed scientific interest in studying particle-laden flows. One application of this work is to assess the effect of dust particles in the shock layer on a spacecraft entering the Martian atmosphere, where dust is always present. Depending on their size and relative velocity, dust particles can travel through the shock layer and strike the heatshield with sufficient kinetic energy to create impact craters in the thermal protection system (TPS) material. In addition, if the entry occurs during a significant regional or global dust storm, dust particle impacts on the heatshield of the spacecraft can cause erosion of the vehicle thermal protection system (TPS) that can be equivalent to that caused by thermochemical ablation [1]. Other effects of dust particles in the shock layer include augmented surface heating rates and changes to radiative heating.

Since 2017 there has been a successful partnership between the NASA Entry Systems Modeling (ESM) project under the NASA Game Changing Development (GCD) program and the German Aerospace Center (DLR). The DLR L2K arcjet facility is uniquely qualified to conduct dusty-flow experiments at relevant Martian conditions because it is possible to inject particles into a high-enthalpy CO2-N2 test gas in the L2K [2]. In addition, DLR test engineers are currently working on advanced diagnostic techniques in the DLR GBK facility to provide accurate simultaneous measurements of particle size ad velocity [3]. These new diagnostic techniques will be incorporated into the L2K to provide highly-accurate flow measurements of particles in a Martian-relevant test gas.

Another element of the ESM project has been the development of an integrated CFD-particle trajectory code named US3D-DUST [4]. The code uses a Lagrangian-based framework that computes the trajectories of individual particles in the flow. The US3D-DUST code is applicable to dust particles traveling through a Martian shock layer and dusty-flow experiments conducted in ground-based facilities such as the L2K. In addition, the code can model momentum and energy transfer between the particles and surrounding fluid and can simulate physical effects such as surface heating augmentation due to particle impacts.

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An important consideration when designing and interpreting ground-based experimental data is traceability to flight. In the case of L2K dusty-flow experiments, the question is how well and to what extent the experimental conditions in the L2K will match those experienced in the shock layer of a spacecraft entering the Martian atmosphere. The flow environments in the L2K are defined by the arc heater settings that determine the reservoir pressure and temperature and by the mass flow rates of CO2 and N2. These quantities in turn determine the flow quantities in the shock layer that forms in front of the test article.

In this study, the US3D-DUST code will be used to simulate particles in the L2K dusty-flow test environments and compare them to conditions in the shock layer of the Schiaparelli capsule during its entry into the Martian atmosphere in 2016 [5]. The particle Reynolds, Mach, and Knudsen numbers, key non-dimensional numbers that characterize the dusty-flow environments, will be compared between the L2K and Martian shock layers. This study will provide a preliminary assessment of how well-suited L2K dusty-flow conditions are for particle drag model validation and the development of particle impact surface damage correlations. The results of this study may help to guide the design of future dusty flow environments in the L2K facility.

II. The US3D-DUST Code

The US3D code is a Navier-Stokes flow solver that was developed at the University of Minnesota in collaboration with the NASA Ames Research Center for the simulation of compressible and reacting flows [6]. The US3D code has been applied to a wide range of aeronautical and aerothermal flow problems and is one of the main CFD codes used by NASA. Recently as part of the ESM project, a Lagrangian particle solver named DUst Simulation and Tracking (DUST) [4] has been integrated into the US3D flow code.

The DUST solver provides a time-varying solution for particle attributes such as location, velocity, temperature, and diameter using the point-particle discrete element method. Inter-phase and intra-phase interactions, characterized as one, two, or four way coupling between carrier and dispersed phase, can be modeled to varying levels of completeness based on problem requirements within the same framework. A central component of this solver is the particle mesh-location algorithm which utilizes standard unstructured mesh connectivity information to efficiently identify the sequence of Eulerian cells a particle traverses through during the simulation. The time-driven hard-sphere approach is adopted to speed up calculations for resolving particle-particle collisions. Time-stepping is performed using Adams-Bashforth methods which balances temporal accuracy and computational costs.

The DUST library in conjunction with US3D has been applied to study a range of problems. These include verification tests involving hypersonic planetary entry, flow through a converging-diverging nozzle, and the impingement of dust particles on a flat plate [4]. Additionally, surface heat-flux augmentation due to particle impacts has been numerically investigated for the Mars 2020 spacecraft during its descent through the dusty Martian atmosphere.

III. Characterizing Dusty Flow Environments

The dusty flow environment experienced by a particle traveling through a shock layer can be characterized in terms of the particle Mach, Reynolds, and Knudsen numbers. These non-dimensional numbers are similar to the standard definitions applied to gas flows, with the difference being that the particle non-dimensional numbers are based on the relative particle velocity, $\Delta\vec{V} = \overrightarrow{v_g} - \overrightarrow{v_p}$, between the particle and surrounding fluid.

A. Reynolds Number

The particle Reynolds is a function of the relative particle velocity, the particle diameter, and the density and viscosity of the fluid surrounding the particle.

$$Re = \frac{\rho_g|\Delta\vec{V}|d_p}{\mu_g} \tag{1}$$

The particle Reynolds number determines the nature of the boundary layer flow around the particle. The boundary layer around the particle will be laminar and attached for particle Reynolds numbers less than 20 [7]. For Reynolds numbers between 20 and about 130, the wake flow behind the particle is separated but steady. As Reynolds number continues to increase, the wake flow becomes unsteady and transitional until finally becoming fully turbulent at Reynolds numbers above 2000. The Reynolds number can have a strong effect on the drag coefficient and drag force experienced by the particle.

B. Mach Number

The particle Mach number characterizes the extent of compressibility effects on the flow around the particle and is equal to the magnitude of the relative particle velocity divided by the speed of sound, c, in the fluid surrounding the particle.

$$M = \frac{|\Delta \vec{V}|}{c} \tag{2}$$

Because the particle Mach number is based on the relative particle velocity, a slow-moving particle striking a fast-moving shock layer (e.g., in front of a spacecraft) and a fast-moving particle striking a stationary shock wave (e.g., in front of a model in an arcjet experiment) can both experience supersonic particle Mach numbers. For particle Reynolds numbers above 45, the flow is in the compression-dominated drag regime and particle Mach number will have a strong influence on the drag coefficient.

C. Knudsen Number

The particle Knudsen number is defined as the ratio of the mean free path of the fluid surrounding the particle to the particle diameter. The Knudsen number can be expressed in terms of the particle Mach and Reynolds numbers [7].

$$Kn = \sqrt{\frac{\pi\gamma}{2}}\left(\frac{M}{Re}\right) \tag{3}$$

The γ term in Eq. (3) is the specific heat ratio of the surrounding fluid. Since the Knudsen number is a function of the Mach and Reynolds numbers, the three quantities are not mutually independent. Specifying the values of two of them will define the third. The are four general flow regimes defined in terms of the particle Knudsen number. Values less than 0.01, where the particle Reynolds number is much larger than the particle Mach number, represent continuum flow conditions. The slip regime is defined by Knudsen numbers between 0.01 and 0.1. At higher Knudsen numbers between 0.1 and 10, the particle is in the transitional flow regime. Free molecular flow occurs when the Knudsen number is greater than 10.

D. General Trends in Drag Coefficient

The general trends of drag coefficient of spherical particles with regards to Reynolds, Mach, and Knudsen number are shown in Fig. 1. As presented by Loth [7], there are two distinct regions of drag coefficient for Reynolds numbers separated at a “nexus” point value of Re = 45. For Reynolds numbers less than 45, the particles are in the rarefaction-dominated regime where Knudsen number has a strong effect on drag coefficient. Increasing Knudsen number indicates that the flow regime is moving from continuum flow towards rarefied conditions, and the drag coefficient decreases. For Reynolds numbers larger than 45, the particles are the compression-dominated regime where the drag coefficient is primarily influenced by compressibility (i.e., Mach number) effects. Increasing Mach number in this regime results in a higher drag coefficient.

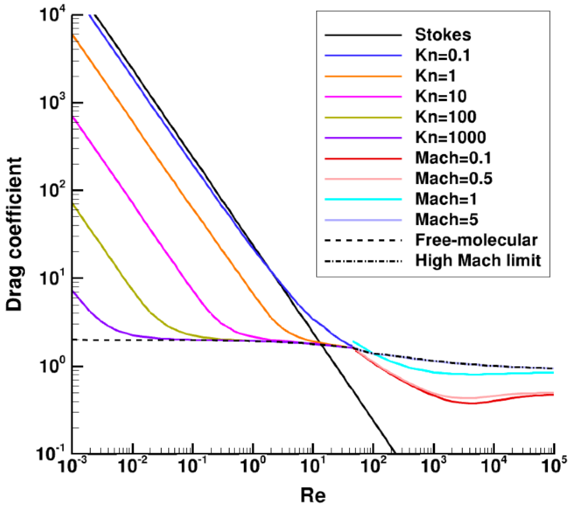

Figure 1. General trends of particle drag coefficient.

IV. Martian Shock Layer Environments

To determine representative dusty-flow conditions in the shock layer of a spacecraft entering the Martian atmosphere, the US3D-DUST code was applied to dust particles traveling through the shock layer of the Schiaparelli capsule during its 2016 entry into the Martian atmosphere [5]. As part of a dusty-flow analysis in the Martian atmosphere, Palmer, et al. [1] generated a series of CFD solutions over the Schiaparelli entry capsule at four trajectory points ranging from 25 to 40 km in altitude. The freestream conditions for the four trajectory points are shown in Table 1. These trajectory points were chosen for the current analysis because results from Ref. [1] indicate that this altitude range is where the majority of the heatshield erosion due to dust particle impact damage will occur. Simulations were performed using 2- and 10-micron diameter particles initially starting at the outer (i.e. freestream) boundary of the CFD grids. The particles were assumed to be spherical with a material density of 2940 kg/m^3. The Loth 2021 drag model [7] was used to compare the particle drag coefficient.

Table 1. Schiaparelli CFD trajectory points.

Altitude, km	Density, kg/m^3	Velocity, m/s	Temperature, K	Mach	Angle of attack, deg
40.0	4.825e-4	4689.0	182.4	21.5	7.2
35.0	7.717e-4	4016.9	186.3	18.3	7.2
30.0	1.322e-3	2913.7	190.1	13.1	6.0
25.5	1.979e-3	2013.8	195.4	9.0	5.0

The results of the Martian shock layer dusty flow analysis are shown in Fig. 2. Because the shock standoff distance is different for each case, the x-axis in the figures is the normalized distance from the wall to the shock. As shown in Fig. 2a, the particle Reynolds number values vary from about 0.4 to 6 in the shock layer, with the larger 10-micron particles having higher Re values. Based on these Reynolds number values, Martian dust particles are in the rarefaction-dominated drag regime.

The Knudsen numbers in the Martian shock layers, shown in Fig. 2b, vary from about 0.8 to 10 indicating that the particles are in the transitional flow regime. Martian dust particles wil not be in the continuum flow regime due to their small size (generally less than 10-micron in diameter) and the low density of the Martian atmosphere, both of these factors contribute to small particle Reynolds numbers. The particle Mach numbers in the shock layer, shown in Fig. 2c, exhibit a fairly narrow range with values between 2 and 4, indicating that the particles are in the compressible, supersonic regime.

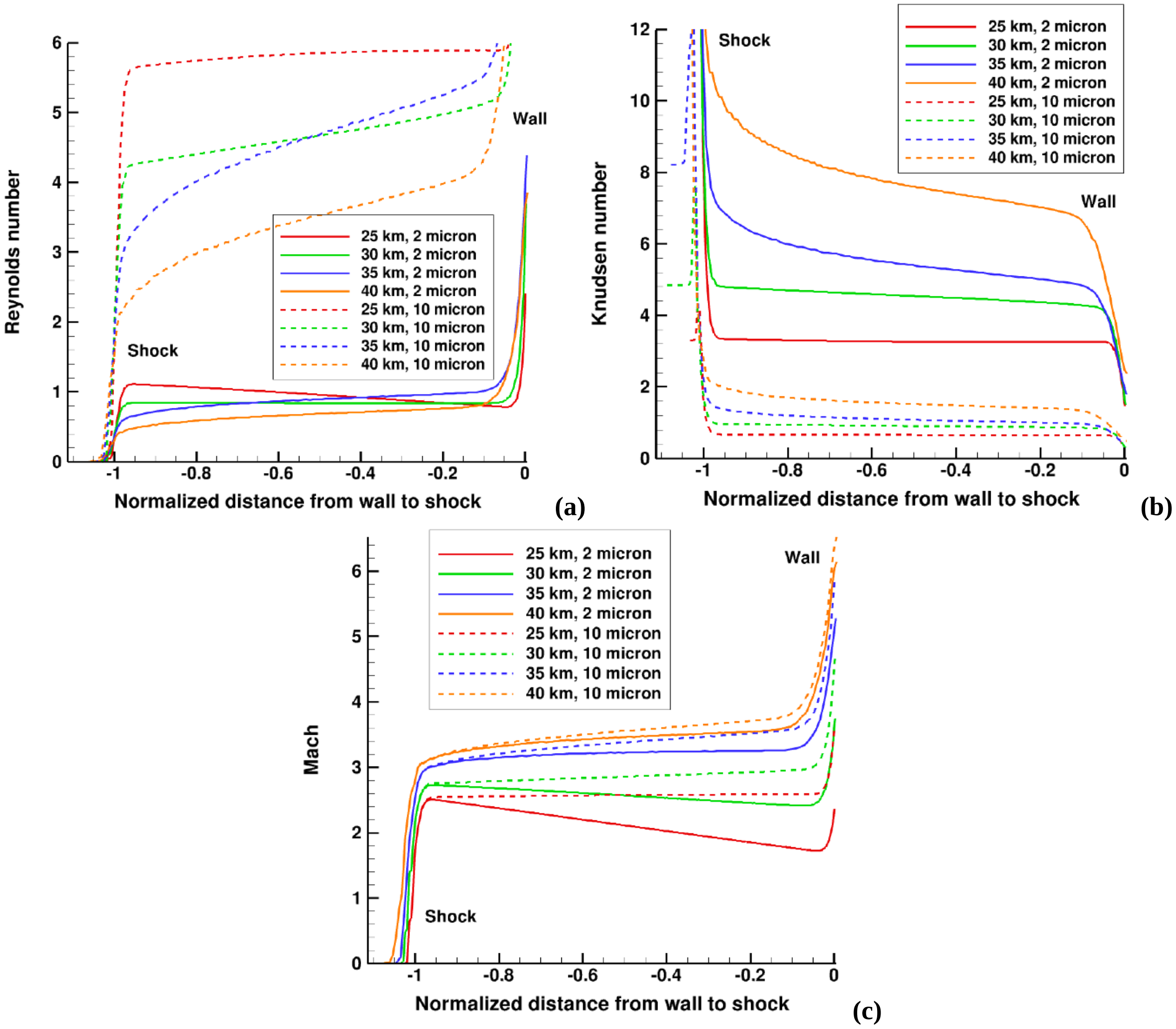

Figure 2. Particle flow characteristics in Martian shock layers as a function of normalized distance from the wall. (a) Reynolds number (b) Knudsen number (c) Mach number.

V. Comparing L2K and Mars Dusty-Flow Environments

The DLR L2K is one of the two arcjet test facilities that comprise the DLR LBK arc heated facility [8]. The L2K is powered by a Huels type arc heater with a maximum electrical power of 1.4 MW. The arc heater heats the test gas to a high enthalpy state, and the test gas then travels through a converging-diverging nozzle. The L2K nozzle throat is 0.029 m in diameter. The expansion part of the nozzle is conical with a 12-degree half angle. As previously stated, the L2K has two key features for experiments of dusty flow environments in support of future Mars missions – the ability to use a CO_2-N_2 mixture as the test gas and the ability to inject particles into the flow

Two different test environments were provided by the DLR test engineers for this analysis representing low-enthalpy and high-enthalpy conditions. The arc heater settings for the two conditions are shown in Table 2. In both conditions the mass flow rates of CO_2 and N_2 were 40 and 1.2 gm/sec respectively. For the US3D-DUST simulations, the CFD grid included the stagnation chamber, the converging-diverging nozzle, and a 100-mm diameter flat-faced model located 0.5 m downstream of the L2K nozzle exit. This model and standoff combination was used in the 2010 L2K dusty flow experiments [2].

Table 2. L2K arc heater settings.

Condition	p_0, bar	T0, K	Specific enthalpy, MJ/kg
Low-enthalpy	0.79	2815	5.6
High-enthalpy	0.93	3283	9.2

A comparison of Reynolds, Knudsen, and Mach number in the Mars and L2K shock layers is shown in Fig. 3. Only the high- and low-bounding curves of the Martian data are shown in Fig. 3. The complete set of Martian shock layer data was previously presented in Fig. 2. In terms of Reynolds number the L2K values are lower than the Martian results by an order of magnitude, but since all of the particle Reynolds numbers for the L2K and Martian results are less than 45, both the L2K and Martian shock layers are in the rarefaction dominated drag regime.

The Knudsen numbers in the Mars shock layers vary between about 0.8 and 10 indicating the particles are in the transitional flow regime. For the L2K environments, the 10-micron particles have Knudsen numbers close to 10, at the upper end of the transitional flow regime, but the 2-micron particles show Knudsen numbers between 60 and 70, indicating that the smaller particles in the L2K will be in the rarefied flow regime. The particle Mach numbers in the L2K shock layers range in values from 0.4 to about 1.1, which is smaller than that seen in the Martian shock layers, but both the Mars and L2K flow environments are in the compressible flow regime.

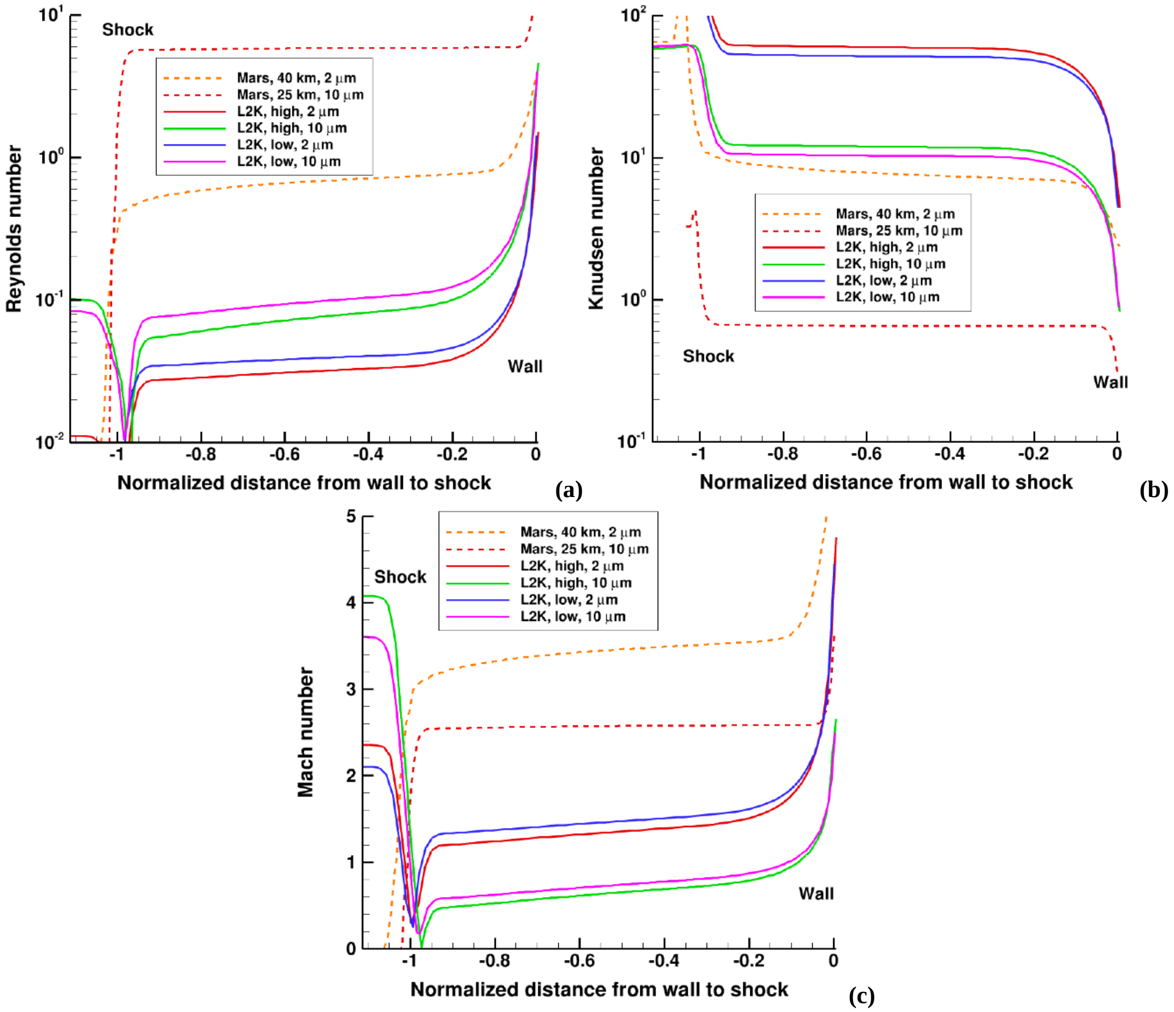

Fig. 3. Comparison of dusty flow conditions in L2K and Mars shock layers as a function of normalized distance from the wall. (a) Reynolds number (b) Knudsen number (c) Mach number

The results for the dusty-flow analysis of the L2K and Schiaparelli shock layers are summarized in Table 3. Martian dust particles wil not be in the continuum flow regime due to their small size (generally less than 10-micron in diameter) and the low density of the Martian atmosphere, both of these factors contribute to small particle Reynolds numbers. Continuum flow requires large Reynolds numbers and/or Mach numbers much less than 1. The larger, 10-micron particles in the L2K experiments will result in higher Reynolds numbers and lower Knudsen numbers and will better match the Martian shock layer conditions compared to the smaller, 2-micron particles.

Table 3. Summary of particle flow conditions in Martian shock layer.

Quantity	Mars	L2K	Regime
Re	0.4 – 6	0.03 – 2	Rarefaction-dominated
Mach	2 – 4	0.4 – 1.1	Compressible
Kn	0.8 – 10	10 – 70	Transitional or Free-Molecular (L2K, 2-micron)

One of the uses for L2K dusty-flow experiments is to validate particle drag models. Recent improvements in diagnostic capability at DLR allow the simultaneous measurement of particle size and velocity. This experimental particle-size data can be compared against simulations from codes like US3D-DUST to determine if the drag models in the code are under- or over-predicting the drag force on the particles. With enough experimental data, the particle drag models could be updated for greater accuracy.

Ovals representing the L2K and Mars shock layer environments are overlaid on the theoretical spherical drag coefficient curves in Fig. 4. Only the rarefaction-dominated part of the particle drag regime where Re < 45 is shown in the figure. The Stokes and Clift-Gauvin curves represent the upper-limit to drag coefficient for continuum, incompressible flow. The lower-limit to drag coefficient is the curve for free molecular flow. Although the L2K and Mars environments do not overlap, particles in both the Mars and L2K shock layers are in the rarefaction-dominated drag regime, and if larger particles are used in the L2K experiments (10-microns or larger) they will be in the transitional flow regime. From this preliminary analysis, it appears that the L2K dusty-flow environments are applicable for drag model validation efforts.

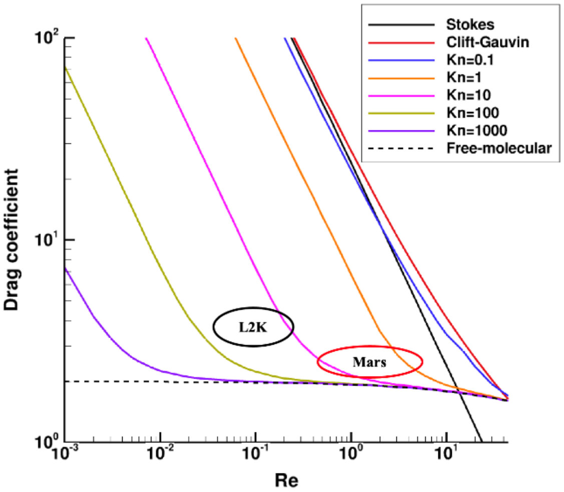

Fig. 4. Comparison of L2K and Mars drag regimes.

Another possible objective for dusty-flow experiments in the L2K facility would be to measure surface recession data due to particle impacts in thermal protection system (TPS) materials such as Norcoat-Liege [2] or PICA [9]. Based on previous dusty-flow experiments in the L2K [2], Palmer, et al., derived a surface damage correlation for Norcoat-Liege [1] that has been incorporated into the US3D-DUST code. Previous work on impact cratering performed during the Apollo era [10] suggest that the crater diameter is proportional to the cube root of the particle kinetic energy. This scaling relationship was found to be approximately valid over orders of magnitude of both energy and particle size. For spherical particles, the size of the impact crater is proportional to the particle diameter, material density, and the velocity of the particle at impact.

$$D_c \propto \rho_p^{0.33} d_p v_p^{0.667} \tag{4}$$

A plot of the quantity, $d_p v_p^{0.667}$, which is proportional to the cube root of particle kinetic energy, as a function of particle impact velocity is shown in Fig. 5. The particle impact velocities in the L2K simulations are at the low end of the expected values at Mars, but the cube root of the particle kinetic energy values at impact in the L2K are largely in between the data for the Mars simulations. Since the L2K kinetic energy values are in-family with conditions seen at Mars, this preliminary study indicates the the dusty-flow conditions achievable in the L2K can be used to develop surface damage correlations that will be relevant for Martian entry conditions.

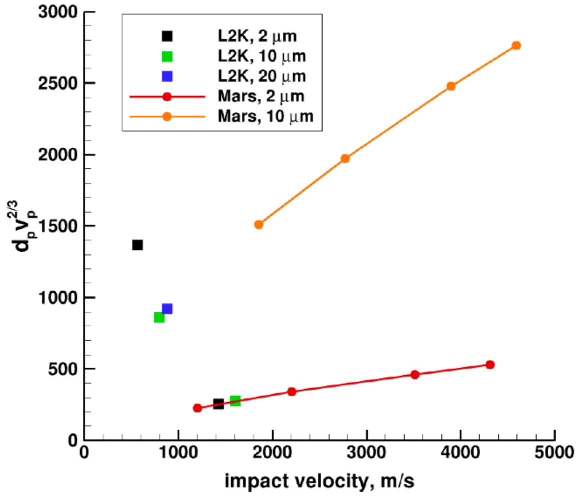

Fig. 5. Comparison of paricle impact kinetic energy between L2K and Mars

VI. Concluding Remarks

The integrated CFD-particle trajectory code US3D-DUST was used to compare the dusty-flow environments in the DLR L2K arcjet test facility with conditions that will be experienced by particles traveling through a shock layer around a Martian entry spacecraft. The US3D-DUST code simulated trajectories for 2- and 10-micron diameter particles traveling through a shock layer in front of a 100-mm diameter flat-face model in the L2K arcjet at low- and high-enthalpy conditions. Values of particle Reynolds, Knudsen, and Mach number in the L2K shock layers were compared against results from particles traveling through the shock layer around the Schiaparelli entry capsule during its entry into the Martian atmosphere. The Reynolds numbers for both the L2K and Mars simulations were less than 45 in all cases, indicating that the L2K and Martian shock layers are in the rarefaction-dominated drag regime. The Knudsen numbers in the Martian shock layers were between 0.8 and 10 signifying transitional flow conditions. The 10-micron particles in the L2K flow simulations were also in the transitional flow regime. Based on this preliminary study, it appears as though dusty-flow experiments in the L2K facility should be able to generate data relevant to drag model validation and surface impact damage correlation development.

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