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Study of the creeping of irregularly shaped Martian dust particles based on DEM-CFD

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ABSTRACT

In this paper, the adhesion between irregularly shaped Martian dust particles and the Martian probe in the dust storm is studied. First, the characteristics of irregularly shaped Martian dust particles are analyzed using fractal theory and the discrete element simulation model of irregularly shaped Martian dust particles is built. Second, the mechanical model of the adhesion of Martian dust onto the Martian probe is established, and the analytical solution of the critical wind speed is calculated. Finally, a series of simulations based on DEM-CFD are performed to analyze the creeping of irregularly shaped Martian dust particles in the Martian atmospheric environment. The research can provide a theoretical basis for the processes of dust protection and cleaning in a Martian dust storm.

1. Introduction

Among the superior planets, Mars is the closest to Earth. Among the exoplanets, the natural environment of Mars, including the gravity field, atmospheric composition, temperature and rotation period, is the most similar to the Earth environment [1]. Therefore, Mars is the first target of exoplanet exploration because of its detection value and feasibility. The United States is the most successful country in terms of Mars exploration, having already sent seven Martian probes that have landed successfully on the surface of Mars. The landing time, landing area and operational states of these Martian probes are shown in Table 1 [2].

The primary method used to learn about the moon is lunar exploration with a lunar rover. Many countries have carried out the development of planet rovers and their control modes. These planet rovers are shown in Fig. 1, and their motion control technologies are shown in Table 1.

Table 1 Landing area and running states of Martian probes launched by the United States.

The special environment of the Martian surface causes a series of challenges to the operation of a Martian probe in these detection missions. Among these challenges, addressing the detrimental effects of a Martian dust storm is the most significant challenge. The Mars Exploration Rover Opportunity (MER-B) suffered a persistently enhanced dust storm in the Victoria Crater in June 2007 [3]. Compared with the state of landing on the Mars, the body of the Mars Rover Curiosity is now covered by a thick layer of Martian dust. Comparison images of parts of the Mars Rover Curiosity are shown in Fig. 1 [4].

China will conduct a Martian exploration mission in 2020. As a result, it is necessary to analyze the influence of a Martian dust storm on a Martian probe according to the relevant experience of the United States. The study of the adhesion between irregularly shaped Martian dust particles and a Martian probe in a dust storm will provide a theoretical basis for the processes of dust protection and cleaning, thereby ensuring the successful implementation of China's Martian exploration mission.

2. Study of irregularly shaped Martian dust particles based on fractal theory

Previous research shows that the particle shape has a great effect on mechanical properties of a particle. Therefore, the shape characteristics of Martian dust particles should be considered carefully in the research of adhesion between irregularly shaped Martian dust particles and a Martian probe. However, to date, a human has not obtained any Martian dust samples from Mars. Thus, the parameters of Martian dust, such as the shape parameters and the particle size distribution, can be only analyzed in situ by Martian probes [5–6].

Near the area of the landing point of the Spirit, most Martian dust is comprised of tiny particles. Almost 5% of the Martian surface is covered by clastic rock and coarse sand [7]. The Opportunity Rover landed on the Meridiani Planum. The bedrock of the Meridiani Planum, which is bright and rich in sulfate, is covered by one-meter-thick Martian soil. The soil is comprised of basalt particles and dust that is less than 0.125 mm in size. There are also some millimeter-sized meteorite fragments and other

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Table 1
Landing area and running states of Martian probes Launched by the United States.

Martian probes	Landing time	Landing area	Operational states
Viking 1	1976	Chryse Planitia	Mission complete in November 1982
Viking 2	1976	Utopia Planitia	Mission complete in May 1983
Pathfinder	1997	Ares Vallis	Mission complete in September 1997
Spirit	2004	Gusev Crater	Mission complete in May 2011
Opportunity	2004	Meridiani Planum	Orbiting
Phoenix	2008	Vastitas-Borealis Planitia	Lost contact in November 2008
Curiosity	2012	Gale Crater	Orbiting

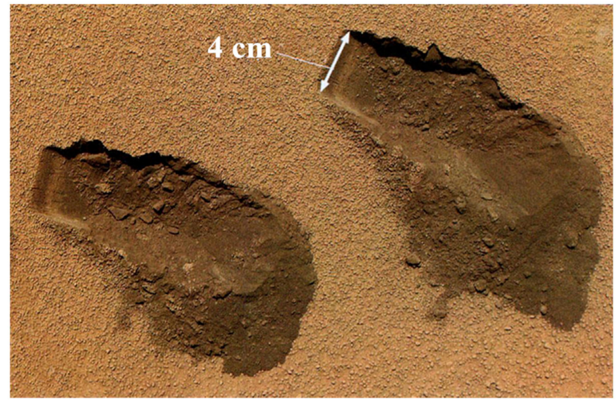

Fig. 2. Martian dust dug up by the Curiosity Rover.

debris that have irregularly shaped features [8]. The Curiosity Rover dug up 5 shovels of Martian dust for engineering tests and science observations in the Rocknest sand shadow, as shown in Fig. 2. The sample surface is covered by sand particles of diameter of 1–2 mm. The base under the sand is comprised of tiny particles. These particles are of different colors and shapes. Most of these particles are irregular in shape and no larger than 1 mm [9]. Since the process of grain rounding becomes less efficient as grain size decreases [10–12], Martian dust particles might be somewhat more angular due to decreased aeolian rounding efficiency [6]. In summary Martian dust particles have the characteristics of small size and irregular shapes.

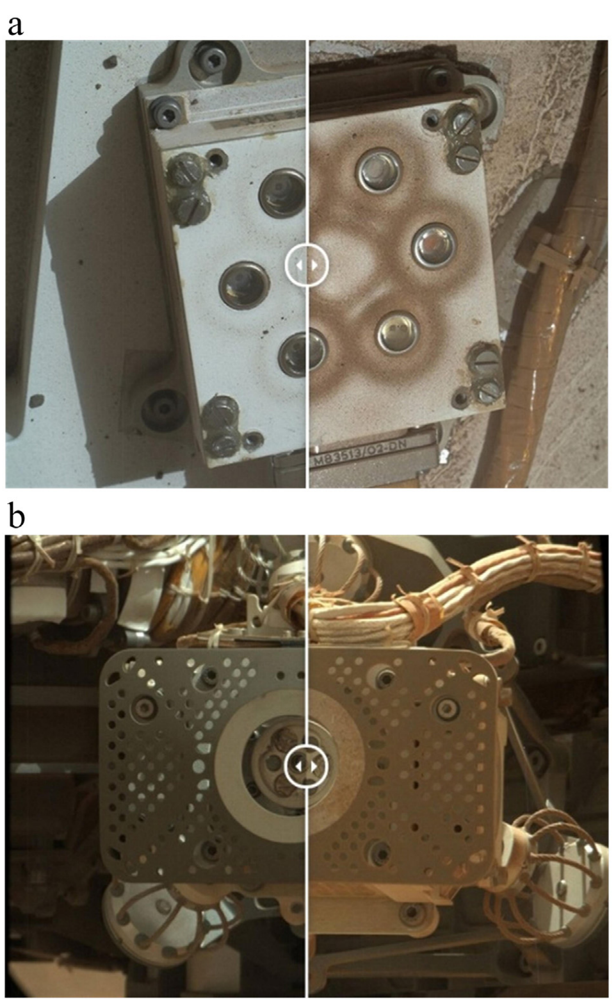

Fig. 1. Comparison images of the Curiosity Rover.

The fractal dimension is one of the most significant parameters, and quantifies the irregularity of the particles [13–16]. Fractal theory differs from traditional Euclidean geometry [17] and can be used to describe very diverse objects according to the property of interest. The shapes and volumes of Martian dust particles rarely come packaged in a neat Euclidean way. Complex systems, which cannot be precisely represented by Euclidean space, are studied by the fractal approach [18].

Mandelbrot proposed an equation describing the relationship between the perimeter P and the area A of irregular geometry in the fractal approach:

$$(P)^{1/D_L} \propto (A)^{1/2} \tag{1}$$

Thus,

$$(P)^{1/D_L} = k \times (A)^{1/2} \tag{2}$$

where k is a constant. The below equation was obtained by taking natural logarithm on both sides of Eq. (2).

$$\ln P = D_L/2(\ln A) + k_0 \tag{3}$$

A straight line, which has two variables $\ln P$ and $\ln A$, can be matched by the above equation. The value of the slope of the line is $D_L/2$. The fractal dimension of an irregular particle can be calculated using the following equation.

$$D_S = D_L + 1 \tag{4}$$

3. Theoretical modeling of the creeping of irregularly shaped Martian dust particles

The aeolian activity was first treated as an aerodynamics issue by Bagnold R.A in his famous treatise *The Physics of Blown Sand and Desert Dune* [19]. Bagnold divided aeolian activity into three parts: creeping, saltation and suspension. Creeping is the movement caused by the wind of larger particles that cannot be removed from the ground. Saltation is the movement of particles that are blown into the air from the ground and subsequently fall to the ground after gliding for a short distance. Suspension is the movement of tiny particles that are suspended in the air. According to the experimental observation, Bagnold noted that dust particles first crept for a period and later bounced from the ground after gaining enough momentum. Therefore, to analyze adhesion between irregularly shaped Martian dust particles and a Martian probe, it is necessary