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Design and experimental performance verification of a thermal property test-bed for lunar drilling exploration

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Abstract Chinese Chang'e lunar exploration project aims to collect and return subsurface lunar soil samples at a minimum penetration depth of 2 m in 2017. However, in contrast to those on the Earth, automated drilling and sampling missions on the Moon raise the risk of burning bits. Test-beds are required for testing the thermal properties of drill tools in a lunar environment. In this paper, a novel temperature measuring method based on thermocouples and a slip ring was proposed. Furthermore, a data acquisition system for a drilling process was designed. A vacuous, cryogenic, and anhydrous soil environment simulating the lunar surface was established. A drilling test-bed that can reach a depth of 2.2 m was developed. A control strategy based on online monitoring signals was proposed to improve the drilling performance. Vacuum and non-vacuum experiments were performed to test the temperature rising effect on drill tools. When compared with the non-vacuum experiment, the vacuum temperature rise resulted in a 12 °C increase. These experimental results provide significant support for Chinese lunar exploration missions.

1. Introduction

Our understanding of extraterrestrial regolith properties can be greatly enhanced by analyzing soil samples collected from celestial bodies. The method of drilling and sampling is the most direct approach to explore subsurface soil layers, and has been widely used to explore extraterrestrial soils for decades.[1] Automated drilling on the Moon and samples return missions were first accomplished in 1970 by the Soviet's robotic Lunar 16 lander.[2] In 1971, the Apollo Lunar Surface

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Drill (ALSD) was first deployed to extract soil column samples by American astronauts on Apollo 15.[3,4] The Sampler, Drill and Distribution System (SD2) was developed in 2001 by the European Space Agency (ESA) for a comet exploration mission named Rosetta.[5–7] The Curiosity rover was equipped with the Mars Science Laboratory (MSL) drill to collect Martian rocks and sand, and successfully landed on the Mars in 2012.[8–10] For the first mission of the ESA's Aurora Exploration Program, a 2-m long multi-auger drilling sampler will be employed to collect soil at a specified depth.[11] NASA's Mars2020 Sample Acquisition and Caching Technologies and Architectures, currently under development, will be used to acquire Mars rock samples in 2020.[12,13] For Chinese extraterrestrial exploration project, lots of drilling samplers have been proposed in recent years.[14–17]

Most planetary drilling will be performed blindly, i.e., without any precursor seismic imaging of substrates typically used on the Earth when drilling for hydrocarbons.[18] On the Earth, geologic formation drilling is a mature technology; however, extraterrestrial drilling entails challenges that are significantly more complex. In the former Soviet Union's three lunar soil sampling and return missions, Luna-20 encountered a hard formation and rebooted three times during drilling to depths of 90, 150, and 340 mm (drilling was abandoned at this depth). Similarly, Luna-24 was obstructed twice during drilling and coring.[19] To reduce the risk of mission failure, a number of tests should be performed to improve the safety and reliability of automated extraterrestrial drilling samplers. Test rigs and methods have been proposed and developed in recent years. However, each testing equipment and the corresponding test method are only applicable to specific tests. For example, the LunarVader was developed to test the drilling performance of water-saturated soils that may occur in lunar polar regions.[20] CRUX was designed to demonstrate the efficiencies in breaking through hard ice-soil layers.[21] MARTE was designed to verify remote command sequences for future Mars explorations.[21,22] DAME was developed for fully hands-off drilling, including fault dictation, recovery, and resumption of drilling.[21,22] A drilling and coring test-bed was developed to validate the flexible tube coring method, which may be used in Chinese Chang'e lunar exploration.[23] A drilling and sampling test-bed was designed to test various drilling and sampling parameters.[24] An on-line temperature-measuring system based on fiber Bragg grating sensors was employed to test the drill bit temperature against rocks in vacuum.[25]

The Moon has an atmosphere so tenuous as to be considered nearly a vacuum. The gas conduction effect does not exist in lunar soil, and the thermal conductivity of the soil is much lower than that on the Earth.[26,27] The temperature of the top 300-mm layer of the lunar regolith varies greatly with time in a lunar day. The maximum temperature difference of the surface nearly reaches 300 °C. However, the temperature of the lower layer dose not fluctuate and is approximately −30 °C at the lunar equator.[28,29] For Chinese Chang'e lunar exploration, a 2-m sample of subsurface lunar soil will be acquired with an automated drilling sampler.[30] The lunar exploration drill will work in extreme environments, i.e., airless (without convection cooling), dry (without drilling muds or lubricants), blind (no prior local or regional seismic or other surveys), and weak (very downward force on the bit).[1] There is no effective way to dissipate the heat generated during the drilling process due to the poor thermal conductivity of lunar soil. Therefore, drilling in the lunar environment may lead to higher equipment temperatures, thereby greatly increasing the risk of burning the drill bit. The temperature performance of the drill bit must be confirmed by ground tests.

This paper aims to describe the design and experimental verification of a thermal property test-bed. Section 2 shows the test-bed scheme. Sections 3 and 4 discuss the designs of a lunar environment simulator and a drilling test-bed, respectively. A control system is introduced in Section 5. Section 6 presents experimental results. Finally, Section 7 summarizes the findings of this study.

2. Scheme of the test-bed

The thermal property test-bed was designed based on the drilling requirements of a simulated lunar environment and involves three components: the lunar environment simulator, the drilling test-bed, and the control system, as shown in Fig. 1. The lunar environment simulator contains a vacuum chamber and a pump system (to simulate a lunar vacuum environment), a cooling and heating system (to control the environment temperature), and a specimen holder. The drilling test-bed was developed for testing drilling in a simulated lunar environment. The control system is divided into three sub-controllers, i.e., the vacuum pump controller, the cooling and heating controller, and the drilling controller. Each sub-controller is individually controlled.

3. Lunar environment simulator

The thermal properties of a powder or granular material are highly dependent on ambient gas pressures. This is because a significant amount of heat within the powder is transferred by gaseous conduction within the inter-particle space. Only a relatively small amount of heat is transferred by conduction through soil particles.[31,32] However, the approximately 10^{-10} Pa pressure on the surface of the Moon is impossible to achieve on the Earth.[26] For pressures below 10 Pa, Bernett et al.,[33] Wechsler and Glaser,[34,35] Fountain and West,[36] and Tien and Nayak[37] showed that the thermal properties of a powdered material were independent of the ambient pressure. Therefore, to simulate the vacuum conditions of the Moon, thermal property measurements were conducted at pressures below this 10 Pa.

A general view of the lunar environment simulator design is presented in Fig. 2. The simulator is comprised of a vacuum pump system, a vacuum chamber, a specimen holder (inside the chamber), and a cooling and heating system. Two vacuum gauges were used for the measurement of the pressure inside the chamber.

3.1. Vacuum pump system and vacuum chamber

The vacuum pump system is comprised of an oil diffusion pump (1.8×10^4 L/s pumping speed at 6×10^0 Pa), a roots pump (6×10^2 L/s pumping speed at 5×10^2 Pa), and three rotary-vane vacuum pumps (7×10^1 L/s pumping speed at 1×10^5 Pa).

The vacuum chamber is comprised of three components as shown in Fig. 3: the top component holds the drill tool, the middle component holds the specimen holder for drilling