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Fluid Flow and Particle Motion Behaviors During Seabed Nodule Pickup: An Experimental Study

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In this study, two nodule pickup device models were designed and tested, based on the suction effect and Coandă effect. The collection flow fields were measured using a particle image velocimetry system. The nodule motions were captured utilizing the visual object tracking method based on the open-source computer vision library OpenCV. Similarities and differences between the suction effect-based and Coandă effect-based hydraulic-type collection methods are revealed. The results show that the Coandă effect-based model requires a smaller flow rate but causes a larger flow field disturbance to achieve a comparable nodule collection rate. This study aims to provide a clearer understanding of the hydraulic collection mechanism and to aid in optimizing the design of nodule pickup devices.

INTRODUCTION

There has been a resurgence in the interest in deep-sea mining, as recent technological advances and an increasing demand for metals and rare-earth elements (REEs) could make deep-sea mining economically viable in the near future (Wedding et al., 2015). The three mineral resources most proposed in the deep ocean are seafloor massive sulfides, ferromanganese crusts, and polymetallic (manganese) nodules (Boschenetal et al., 2013; Hein and Koschinsky, 2014). Among them, manganese nodules have great potential for exploitation and utilization, owing to their promising economic value, massive reserves, and high grades (Hein et al., 2013). International consortia and enterprises have invested in the exploration of manganese nodules and the development of mining technologies since the 1960s (Chung and Tsurusaki, 1994; Chung, 1996). Meanwhile, prototypes of mining systems are also under way (Chung, 1999, 2005, 2009). Full-scale at-sea tests of the mining system using the Hughes Glomar Explorer were conducted in the north Pacific Ocean in the 1970s (Chung, 2010). However, commercial mining has not commenced owing to many obstacles and challenges. Technically speaking, improving the benefit-cost ratio of mining projects and limiting environmental impacts to minimum levels are the main considerations (Chung, 1985; Boetius and Haeckel, 2018).

A deep-sea mining system that consists of a mining vehicle subsystem, a hydraulic lifting subsystem, and a mining vessel subsystem has received growing attention (Chung, 1994). The self-propelled miner collects manganese nodules on the seabed, and the lifting system transfers the nodules continuously from the miner to the vessel. In the deep-sea mining system, the technique used for nodule pickup near the seabed is considered one of the most critical aspects of deep-sea mining because effective collection of manganese nodules from the sediment surface layer of a deep seafloor is necessary for an economically and environmentally acceptable mining operation (Hong et al., 1999). Ecological preservation is very important, as improper deep-sea mining methods can lead to serious biodiversity losses (Van Dover et al., 2017). The impact of nodule mining could potentially lead to an irreversible loss of some ecosystem functions, especially in directly disturbed areas (Simon-Lledó et al., 2019). Several groups of mining engineers and environmental scientists have been conducting studies for the assessment of environmental impact and additional disturbance on the deep seabed. Potential effects, environmental considerations, and engineering considerations of deep seabed mining are discussed (Chung et al., 2001). These studies supplement International Seafloor Authority (ISA) reports with more scientific details and technological aspects.

Nodule pickup methods have been studied and optimized regarding efficiency and reliability. Various nodule pickup methods, such as hydraulic collection, mechanical collection, and hybrid collection, have been developed (Min et al., 1997). As the hydraulic collection method has no mechanical components acting directly on the surface of the seabed, the disturbance to the seabed is relatively small. The results from a real sea experiment conducted by "Ocean Management Incorporated" in 1978 revealed that the hydraulic collection method has a simple structure, high reliability, and acceptable pickup efficiency, and it generates a relatively small disturbance on the seabed (McFarlane et al., 2008). Three kinds of hydraulic nodule pickup methods have been tested and evaluated in real sea experiments—namely, the suction effect-based method, Coandă effect-based method, and water-jetting-based method. Oh et al. (2018) tested and evaluated the collection performance of a pickup device in a real sea experiment and verified the effectiveness of a pilot mining robot. It has been difficult to find pickup devices using the water-jetting-based method that meet the requirements for ecological preservation, as very large amounts of sediment are whirled up by the scouring (Schwarz et al., 1999). The collection methods based on suction effect and Coandă effect are considered as technically and economically valuable, and they therefore are investigated in this study.

The ISA is seeking to approve exploitation regulations for manganese nodules by approximately 2021, but significant research and knowledge gaps remain, which must be addressed (Miller et al., 2018). Several studies have been conducted to investigate the process of hydraulic nodule pickup. For the method using the suction effect, Zhao et al. (2017, 2018b, 2019) carried out experimental and numerical studies to investigate the characteristics of flow field, forces, and motions of spherical particles during the process of hydraulic collection. The effects of several collecting parameters on vertical and radial force coefficients of the particles are investigated. Zhao et al. (2018a) established an empirical

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