Summary of thesis: Studies of non-equilibrium fluctuating motion as a rectifier

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The fluctuating motion of a tracer attached to non-equilibrium environments is theoretically studied as the rectifier. We clarify three properties (1)-(3) of the fluctuating motion under non-equilibrium conditions in the thesis (Chapter 5-7).

In Chapter 1, motivation of our research for fluctuating motion under non-equilibrium situations is briefly explained. Studies on fluctuating motion have a history of nearly 200 years. Since Einstein proposed the theory on the Brownian motion using a stochastic theory in 1905, theory of Brownian motion has been developed by many researchers, including Langevin, Smoluchowski, Ornstein, and Uhlenbeck. Nowadays, non-equilibrium Feynman-Smoluchowski ratchet is experimentally realized in a granular gas environment, where the asymmetric vanes having coated the surfaces of different restitution coefficients are placed in the granular gas. The difference of restitution coefficients corresponds to the pawl in the original Feynman-Smoluchowski ratchet, and thus, the vanes can rotate in one direction. It is essential that the ratchet is attached on a non-equilibrium environment. Because the kinetic energy of the granular gas is much higher than the room temperature and the asymmetric vanes can be regarded as the system attached to the zero-temperature environment, where thermalization of the pawl can be ignored. The realization of such a non-equilibrium Feynman-Smoluchowski ratchet has raised the natural question: what can we rectify from the fluctuating motion under non-equilibrium? This is the question addressed in the thesis.

In Chapter 2-4, we review recent progress of non-equilibrium statistical mechanics related to the thesis. In Chapter 2, we review equilibrium thermodynamics and finite time thermodynamics focusing on thermodynamic efficiency. We derive the Carnot efficiency and the Chambadal-Novikov-Curzon-Ahlborn (CNCA) efficiency. In Chapter 3, we briefly summarize the formulas of stochastic analysis, such as stochastic integrals, master equations, and system size expansion methods. In Chapter 4, we explain the stochastic energetics. We discuss the attainability of the Carnot efficiency and a recent experimental result on the finite-time thermodynamics on the basis of stochastic energetics.

(1) In Chapter 5, we consider the motion of an adiabatic piston under sliding friction, which is located between two ideal gases in equilibrium characterized by two different temperatures and densities. In the absence of the sliding friction, the direction of the piston motion is known to be determined from the difference of temperature of two gases. However, if the sliding friction exists, we find that the direction of motion depends on the amplitude of the friction, and nonlinearity

of the friction. Thus, the direction of momentum flux rectified from the fluctuation piston is not determined by temperature difference if the piston is attached to non-equilibrium environments. The fluctuation theorem under dry friction, which deviates from the conventional fluctuation theorem, is derived.

(2) In Chapter 6, the dynamics of a rotor under viscous or dry friction is investigated as a non-equilibrium probe of a granular gas numerically and analytically. To demonstrate a role of the rotor as a probe for a non-equilibrium bath, we perform the molecular dynamics (MD) simulation of the rotor under viscous or dry friction surrounded by a steady granular gas under gravity. We theoretically derive a one-to-one map between the velocity distribution function (VDF) for the granular gas and the angular one for the rotor. Through the MD simulation, we find that the one-to-one map works well to infer the local VDF of the granular gas from the angular one of the rotor, and vice versa.

(3) In Chapter 7, we consider the cycle containing heating and cooling processes for an elastic hard core gas enclosed by a fluctuating piston. We study the efficiency at maximum power output (MP) for a passive engine without mechanical controls between two reservoirs. We enclose a hard core gas partitioned by a massive piston in a temperature-controlled container and theoretically analyze the efficiency at MP for heating and cooling protocols without controlling the pressure acting on the piston from outside. We find the following three results. The efficiency at MP for a dilute gas is close to the CNCA efficiency, while the efficiency for a moderately dense gas becomes smaller than the CNCA efficiency even when the temperature difference of reservoirs is small. Introducing the Onsager matrix for passive engines, we verify that the tight coupling condition for the matrix of the dilute gas is satisfied, while that of the moderately dense gas is not satisfied because of the inevitable heat leak. We clarify these results using the MD simulation and introducing an effective mean-field-like model which we call stochastic mean field model.

In Chapter 8, the thesis is concluded with several remarks and possible extensions of results are discussed.