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A novel heat pump system using a multi-stage Knudsen compressor

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ABSTRACT

A novel heat pump system is proposed using a multi-stage Knudsen compressor in the cycle between the evaporator and condenser. The proposed Knudsen heat pump is driven by thermal energy, and it is able to utilize waste heat. There are no moving parts in a Knudsen compressor, leading to several advantages, including a lack of vibration and noise, and high durability. In this study, the configuration necessary to achieve a performance such that it can be used as a practical heat pump (output power $\geq$1 kW, temperature difference $\geq$6 K) is considered. The performance of this heat pump is predicted by a one-dimensional analytical model coupled with a simple experimental result. This method is based on our previously constructed method to predict the performance of a multi-stage Knudsen compressor, and the evaporation and condensation and the time variations of temperature in the evaporator and condenser are newly considered. A heat pump with a 30-stage Knudsen compressor using glass-fiber filters with an area of 4.00 m^2 is predicted to generate an output power of 1.27 kW and a temperature difference of 6.00 K.

1. Introduction

In a rarefied gas regime, a temperature gradient of a channel wall induces a flow, which is called a thermal transpiration [1]. Knudsen initially observed experimentally the phenomenon at low pressures [2,3], and many studies were performed for academic interest after the first report [4–10]. Recently, the utilization of microporous materials and microfabrication technology has enabled the generation of thermal transpiration at high pressures, such as at atmospheric pressure. This phenomenon is utilized to realize a pump/compressor, which is called a Knudsen pump/compressor. A Knudsen compressor is driven by thermal energy, and it is able to utilize waste heat or environmental heat energy as a driving source, so it is expected to be a new class of heat recovery device. In addition, it has various advantages, such as a lack of vibration and noise, high durability, and easy miniaturization compared to other existing compressors because it has no mechanically moving parts.

Several practical applications of a Knudsen pump/compressor have been proposed [11–19]. For example, Liu et al. and Qin and Gianchandani investigated a micro-gas chromatography system with a miniature Knudsen pump [11,12]. Nakaye and Sugimoto demonstrated a gas separator composed of Knudsen pumps [15]. However, applications of Knudsen pumps/compressors are still limited.

One engineering product that uses a gas compressor is a heat pump. A heat pump system performs cooling and heating using the latent heat of a refrigerant, and it is used for air-conditioners, refrigerators, and the like. In general, an electrical compressor is used to generate a pressure difference between the evaporator and condenser so as to circulate the refrigerant vapor and to promote evaporation and condensation of the refrigerant. For heat recovery purposes, a heat-driven gas compressor may be used. An adsorption heat pump (AHP) is one such system [20]. In this system, the refrigerant vapor is sucked from the evaporator by adsorption of the adsorbent, and it is discharged to the condenser by desorption. The adsorbent is cooled with cooling water during adsorption, and it is heated with a waste heat medium during desorption. Therefore, it is necessary for AHP to repeatedly switch the gas flow path and the temperature control liquid flow path of the adsorbent, so many switching mechanisms are required. It may be possible to create a heat pump system with a simpler mechanism for heat recovery purposes by using a Knudsen compressor which can generate a practical pressure difference and mass flow.

This study proposes a novel heat pump system using a multi-stage Knudsen compressor with porous materials as a compressor in the heat pump cycle, with water vapor as a refrigerant. The

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transport of water vapor by a compressor was verified by our previous measurements [21]. However, the throughput of the Knudsen compressor is known to be low compared with a conventional mechanical compressor in a meter-scale system. Therefore, we predict the performance of the proposed heat pump system and clarify the configuration necessary to achieve the practical output power and temperature difference of conventional systems (e.g., ≥1 kW, ≥6 K). This prediction is made using the method for the multi-stage Knudsen compressor proposed in our previous study [22], with some refinements. This method was based on the one-dimensional analytical model from the mass conservation law for a multi-stage Knudsen compressor combined with a simple experimental result for a single stage, aiming to simulate a realistic performance of a high flow rate Knudsen compressor using a porous material with complicated aggregate channels. In this study, the prediction method is modified by adding the evaporation/condensation and the temperature time variations of the evaporator/condenser. The output power of the proposed heat pump depends on the mass flow rate generated by the Knudsen compressor, while the temperature difference depends on the pressure difference. Therefore, the performance is evaluated to clarify the area of the porous material and the number of stages necessary to achieve a practical performance of an output power ≥1 kW and a temperature difference ≥6 K.

2. Heat pump system using a multi-stage Knudsen compressor

2.1. Knudsen compressor

The degree of rarefaction of gas is expressed by the Knudsen number *Kn*. The Knudsen number of a gas in a channel is defined by the ratio of the mean free path of gas *l* to the characteristic length of the channel *D*.

$$Kn = \frac{l}{D}. \quad (1)$$

The gas whose *Kn* is larger than 0.1 is considered to be a rarefied gas. Under this condition, a one-way gas flow is induced by the temperature difference between the two ends of the channel from the cold to hot side, which is called the thermal transpiration.

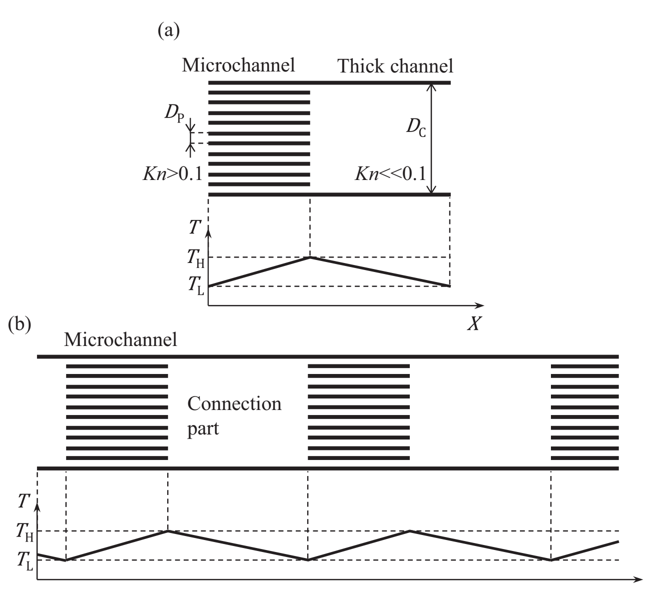

Fig. 1. (a) Illustrative single-stage Knudsen compressor. (b) Illustrative multi-stage Knudsen compressor. The pressure difference is amplified by combining multiple single-stage Knudsen compressors in series.

An illustrative single-stage Knudsen compressor is shown in Fig. 1a. A single-stage Knudsen compressor is composed of a microchannel having a diameter D_P of the same order of magnitude or less compared with the mean free path of gas and a channel having a diameter D_C sufficiently larger than the mean free path. When given a mountain-shaped temperature gradient with a high temperature T_H and a low temperature T_C as in the lower figure of Fig. 1a, thermal transpirations are induced in both of the microchannel and thick channel, but a pressure-gradient driven counterflow results in no net flow only in the thick channel. Thereby, the Knudsen compressor can generate a one-way flow and a pressure difference between the inlet and outlet of the compressor, although there is no temperature difference between the inlet and outlet. Then, a multi-stage Knudsen compressor can be built by connecting multiple single-stage Knudsen compressors in series as in Fig. 1b. The possible pressure difference increases as the number of stages increases, while the mass flow rate is determined by the performance of the single stage.

2.2. Novel heat pump system

The configuration of our novel heat pump system is shown in Fig. 2. Two chambers, referred to hereinafter as the evaporator and condenser, are filled with liquid water and water vapor as a refrigerant. A heat exchanger is installed within each chamber in order to take the heat inside the system to the outside. The evaporator and condenser are connected to each other by two channels to form a cycle: one channel in a vapor phase consists of the multi-stage Knudsen compressor, and the other in a liquid phase has a valve.

When the Knudsen compressor is operated, vapor is made to flow by means of the compressor from the evaporator to the condenser. In the evaporator, the pressure drop due to the flow induced by the compressor promotes water evaporation and heat absorption due to the latent heat of water. Then, the temperature in the evaporator T_E decreases corresponding to the decrease in the pressure in the evaporator P_E from the saturated vapor pressure curve of water in Fig. 3, which is a monotonically increasing function. In contrast, in the condenser, the pressure increase promotes vapor condensation and heat generation. Then, the increase in the pressure in the condenser P_C induces the increase in the temperature in the condenser T_C. When the evaporator water decreases, the valve at the channel in a liquid phase is opened and liquid water is supplied from the condenser. As a result, it is possible to operate continuously in a completely isolated state from the outside, and there is no concern that dust will clog microchannels inside the Knudsen compressor.

From the operating mechanism, the performance of the heat pump system is determined by the performance of the Knudsen compressor being used. The temperature difference obtained in this heat pump system depends on the pressure difference generated by the Knudsen compressors. The pressure difference can be amplified by cascading compressor units [14]. On the other hand, the power output Q depends on the mass flow rate of vapor $\dot{M}$. In terms of the latent heat of water, L, Q is calculated as $Q = L\dot{M}$.

3. Performance prediction method

3.1. Outline

The performance is predicted by modifying the prediction method for the multi-stage Knudsen pump/compressor in our previous study [22], where the practical performance was well predicted by the 1D analytical model based on the mass conservation law using the single-stage experimental results. The