Knudsen Compressor*

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A model pumping system without a moving part, which makes use of thermal transpiration and is operated with its ends at an equal temperature, is constructed. The system consisting of ten units, each of which is a pipe of length 30 mm and inner diameter 15 mm with a simple inner structure and a heater, reduces the pressure of a reservoir of $8 \times 10^3 \text{ cm}^3$ to a half in 200 sec when the other exit of the system is kept at a constant pressure between 10–40 Pa.

1. Introduction

In a rarefied gas, a temperature field plays an important role on gas motion. The thermal transpiration, a flow induced through a pipe with a temperature gradient along it, is a well-known example,^{1–5)} and its application to a vacuum pump without a moving part has been considered for a long time. A pressure difference is induced between two reservoirs joined by a pipe with a temperature gradient (or reservoirs of different temperatures) owing to thermal transpiration. To make the pressure difference large, the temperature difference of the reservoirs must be kept large. This is not practical and some cascade process should be devised. As early as 1910, Knudsen carried out an experiment with a cascade system and showed its effectiveness.^{2,6)} A pumping system making use of the flow attracts new attention, since the system has no moving part and no mixing process.^{7–12)}

In Ref. 9, the behavior of a rarefied gas in a two-dimensional channel between two plane walls on which a series of ditches is dug periodically and a periodic saw-like temperature distribution in harmony with the ditches is imposed, as shown in Fig. 1, was investigated numerically by the direct simulation Monte-Carlo (DSMC) method.^{13,14)} A one-way flow is shown to be induced in the channel without help of a pressure gradient for a wide range of the Knudsen number, and the pumping effect of the flow (or the average pressure gradient induced along the channel by blocking the flow) is discussed. In Ref. 12, the study is extended to the corresponding problem for a circular pipe. In these examples,

Fig. 1 Channel or pipe with ditches and its wall temperature distribution.

flows induced in the ditches, which are in the opposite direction to those on the main part, are blocked by the side walls of the ditches, and the one-way flow is induced. In the corresponding experiment (or one period of the above-mentioned pipe with its two ends at equal temperature and pressure), one-way flows are demonstrated.¹⁰⁾ The ditch is essential for induction of the one-way flows. In fact, in a straight channel or pipe, no one-way flow is shown to be induced numerically,^{9,12)} experimentally,¹⁰⁾ and mathematically.¹⁵⁾ In Ref. 11, another system where a one-way flow is induced without average pressure and temperature gradients is proposed and the flow is demonstrated experimentally. It is a straight circular pipe with a shelf or shelves being put up in its half part and with a heater at the central position along the pipe, as shown in Fig. 2. The mass flux through a pipe for small Knudsen numbers is proportional to the cross sectional area for the thermal transpiration (temperature-induced flow) but to its square for the Poiseuille flow (pressure-driven flow). The one-way flow in the second system is well understood by this difference of the

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Fig. 2 A pipe with a shelf put up partially.

Fig. 3 A unit of a pipe (Part S + Part N). (a) Overall view and (b) closer view. The wires are the leads to the heater in the middle of the pipe.

mass fluxes.¹¹⁾

In the present paper, we devise a model pumping system without a moving part by making use of the characters of the two kinds of one-way flows in the preceding paragraph and show its performance. Our aim is to present a simple model that can induce a considerable pressure difference between the two ends of the system in a practically short time.

2. Pumping System and its Experiment

We prepare a cascade pumping system consisting of ten equal units. The unit is a circular glass pipe with a heater at its central position along its axis, and the pipe is divided into several passages on one side of the heater. That is, a bundle of 18 glass pipes of inner diameter 1.6 mm and length 15 mm is inserted in a half part of a circular glass pipe of inner diameter 15 mm and length 30 mm; a heater of Nichrome wire is wound around one end of each thinner pipe, and it is situated in the central part of the pipe of length 30 mm; and a copper plate with thickness of 1 mm is attached at each end of the unit (Fig. 3). The thinner-pipe side will be called S part and the other side N part. The copper plate plays multi-roles: it is the joint to the next unit and the support, which is fixed to the base of a thick copper plate; the support serves to keep the temperature of the ends of the pipe unit at a constant temperature close to the room temperature. The unit makes use of two effects: the effects of variation of the cross section and division of the passage. The first one is

Fig. 4 Pumping system consisting of the ten units.

Fig. 5 Experimental system.

more effective to induce a one-way flow, and the second is more effective to induce pressure difference. The bundle of thinner pipes corresponds to division of the passage, and the cross section changes at the division between the S and N parts. The pump system consists of the ten units. Owing to the size of our vacuum chamber available for its performance experiment, it is the connection of two subsystems consisting of the five units connected with the copper plates in a series, as shown in Fig. 4. The two subsystems are connected with a glass pipe.

The experiment to examine the performance of the pumping system is carried out in the following system (Fig. 5). The pumping system is put in a vacuum chamber, and the N-side end of the pumping system is open in the chamber. The vacuum chamber is prepared in a glass bell jar of diameter 250 mm and height 300 mm put on a steel base. The pressure in the chamber is controlled from at-

Fig. 6 Time-variation of the pressure p (Pa) and the temperature T (K) at various parts in the system I: Stronger heating (electric supply 120 W). (a) Pressure variation and (b) temperature variation. The t is the time (sec) after the heater is put on and p_0 is the pressure in the vacuum chamber at $t=0$. The temperature difference of the two ends of the pumping system is less than 1 K. The initial pressure of the tank is slightly higher than that in the vacuum chamber. It may be attributed to desorption of gases from the tank and pumping system.

Fig. 7 Time-variation of the pressure p (Pa) and the temperature T (K) at various parts in the system II: Weaker heating (electric supply 20 W). (a) Pressure variation and (b) temperature variation. (See the caption of Fig. 6.)

mospheric pressure down to a few pascal by a rotary vacuum pump. The other end (or S-side end) of the pumping system is connected to a steel tank of $8 \times 10^3 \text{ cm}^3$ with a glass pipe of length 150 mm and a steel pipe of length 550 mm. The vacuum chamber and the tank, connected with the pumping system, serve as reservoirs. The performance of the pumping system is how fast it pumps a gas from the tank to the vacuum chamber when the heater is put on.

3. Performance of the Pumping System

The performance of the pumping system is examined in the following way. First keep the whole experimental system at a desired uniform pressure by adjusting the valve between the rotary pump and the vacuum chamber. After confirming the stationary state at a desired pressure being established, we put on the heater and observe the pressures in the

Fig. 8 Pumping speed [volume flux (cm^3/sec) from the tank] versus the pressure (Pa) in the tank during the pumping process at a constant pressure in the vacuum chamber. (a) The stronger heating and (b) the weaker heating.

vacuum chamber and in the tank and the temperatures at the heater, at the two ends of the pumping system, and in the tank. In this process, the pressure in the vacuum chamber is kept constant at the initial pressure by adjusting the valve.

The performance experiment is carried out at four different pressures (10, 20, 40, and 80 Pa) in the vacuum chamber. The time-variations of the pressures in the tank and in the vacuum chamber (bell jar) and those of temperatures at the heater, at the end of the pumping system on the vacuum-chamber side, and in the tank are plotted in **Figs. 6** and **7** for two different rates of heating (stronger and weaker heatings). The temperature difference of the two ends of the pumping system is less than 1 K. The heating is controlled by electric current supplied from the outside of the vacuum chamber. In the experiments of the stronger heating, the pressure in the tank is initially a little higher (by 0–0.3 Pa) than that in the vacuum chamber. This may be attributed to desorption of gases from the tank or pumping system, since it disappeared in the later experiments after several months. In the experiments with stronger heating, except in the case of 80 Pa in the vacuum chamber, the pressure in the tank is reduced to a half of the pressure in the vacuum chamber (or the initial pressure in the tank) in 200 sec. That is, 20 cm^3 of air at the original pressure is pumped up every second on the average in this period. At about 500–600 sec, the pressure in the tank reaches the minimum pressure attained by the pumping system. The pumping speed [or the volume flux (cm^3/sec)] from the tank versus the pressure (Pa) in the tank during the pumping process at a constant pressure in the vacuum chamber, estimated from **Figs. 6** and **7**, is shown in **Fig. 8**. In the present experiment, we used the bell jar at our hand as the vacuum chamber. Thus, there were various limitations for the construction of the sys-

tem. For example, the tank and the pumping system are connected with a long pipe and some part of it is narrow. The real performance of the pump is expected to be better than the results of the experiment.

The gas flow is visualized by a windmill at the bell-jar-side end of the pumping system. The performance (e.g., the minimum pressure) is reduced in the presence of the windmill. The results in Figs. 6–8 are for the experiments without the windmill.

4. Concluding Remarks

Making use of our previous works (Refs. 9, 11, 16, and 17), we have made a simple model of a pumping system without a moving part and examined its performance. The cascade system works effectively in the model. The pump makes use of the features of the two kinds of flows: temperature-induced flow and pressure-driven one. The present system consists of ten equal units. However, in a system consisting of many units to obtain a large pressure ratio, the pressure in a unit differs much depending on its position in the series of units. Thus, a unit should be designed so as to work effectively in its pressure range with the aid of the discussion and data in Refs. 9, 11, 16, and 17.

The purpose of the present paper is to present a simple pumping system without a moving part that has an appreciable pumping speed (volume flux) and maintains a considerable pressure ratio between two reservoirs. Thus, we have not paid attention to the energy efficiency of the system. The model designed as a vacuum pump is also used as a valve in a vacuum system owing to its simple structure and the easiness of control.

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