WEARABLE INFUSION PUMP POWERED BY SCAVENGED BODY HEAT

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Abstract: An infusion pump containing a body heat scavenging Knudsen pump was created and tested. This pump does not require electricity to operate. Using the theory of thermal transpiration, the Knudsen pump moves air across a temperature gradient, to drive a pharmaceutical agent out of a reservoir. This paper also describes a theoretical heat flow model that may be used to determine the pressure gradient of a Knudsen pump for use in a wearable infusion pump.

Keywords: Knudsen pump, infusion pump, heat scavenging

INTRODUCTION

Infusion pumps are commonly used in today's medical field. They are used to deliver medications to patients primarily intravenously [1]. Infusion Pumps are commonly used as insulin pumps and general Intravenous (IV) pumps. Infusion pumps typically utilize electricity, provided by either AC power or batteries. Infusion pumps are used in a variety of clinical care settings and home care [2]. In situations where electricity is limited or not available, such as military usage in the field, under developed countries, and emergency situations, electrical infusion pumps would be useless. The proposed infusion pump works without the use of electricity and is also wearable for ease of use and increased patient mobility.

The proposed device is targeted for low flow rate applications such pharmaceutical delivery to dermal wounds [3]. The features include no power cord or need to change batteries at regular intervals, and it delivers pharmaceuticals continuously until a refill is needed.

DESIGN AND THEORY

The proposed infusion pump contains two components. The first component is the human powered Knudsen pump. Preliminary work on a human powered Knudsen pump has been previously reported [4]. The Knudsen pump pushes air into the second component, known as the pharmaceutical reservoir. The air flow applies pressure on an IV bag holding the pharmaceuticals and the medication begins to flow to the applicator. The applicator regulates the flow of the medication to the patient and evenly distributes it. Figure 1 is a diagram showing the total infusion pump including the two main components and a potential subcutaneous applicator.

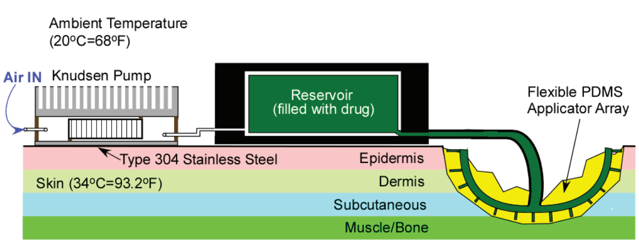

Fig. 1. Schematic of device including Knudsen pump, reservoir, and applicator. The Knudsen pump applies pneumatic pressure on a flexible inner bag of the reservoir. The pressure drives the fluid out of the reservoir at a steady flow rate.

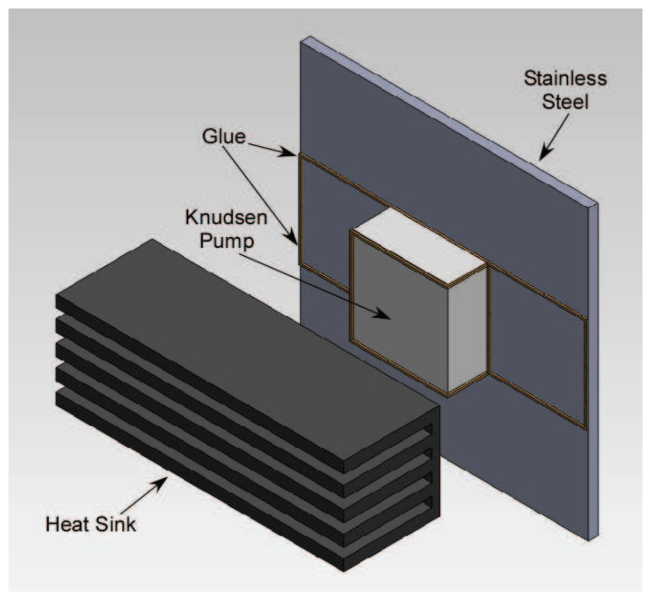

Fig. 2. Diagram of Knudsen pump, showing glue patterns and general layout. The glue pattern is used to direct the flow, preventing back flow through the device.

The Knudsen pump works on the theory of thermal transpiration. Thermal transpiration states that when a temperature difference is formed across a narrow channel a pressure gradient is generated [5]. As the temperature on one side of the narrow channel increases, the density decreases. This affects the flux of air particles entering the narrow channel from the hot side. The cold side is denser so more air flows into the channel. Therefore, when there is a temperature difference across a narrow channel, a net flow of air will occur from the cold side to the hot side. For this to occur at atmospheric pressure, the narrow channel must be very small, ideally below 100 nm in diameter. Knudsen pumps that operate at atmospheric pressure have previously been made [6-8]. Knudsen pumps have also been shown to pneumatically pump liquids. [9]

The narrow channel used for the Knudsen pump is a nanoporous membrane filter. These filters are made of mixed cellulose esters and have a pore size of 25 nm. The nanoporous filters were cut into squares and ten of them were stacked and sealed around the edges to create a thick Knudsen pump. This thick Knudsen pump was then attached to a heat sink and a thin stainless steel sheet with glue. The glue was strategically placed to direct the flow of air through the Knudsen pump and to the reservoir. Figure 2 shows the placement of the glue within the Knudsen pump.

The air flowing through the Knudsen pump will flow from the cold side of the Knudsen pump to the hot side. The stainless steel of the Knudsen pump will be in contact with the skin of the patient, and therefore will be the hot side and air will flow toward the skin. The heat sink is used to dissipate heat on the cold side.

The pressure gradient created by the temperature difference across the membrane filters will follow the relationship in Eq. 1.

$$\frac{\boldsymbol{P_h}}{\boldsymbol{P_c}} = \left(\frac{\boldsymbol{T_h}}{\boldsymbol{T_c}}\right)^{\boldsymbol{n/2}} \qquad (1)$$

where $\boldsymbol{P_h}$ is the pressure (Pa) on the hot side of the Knudsen pump; $\boldsymbol{P_c}$ is the pressure (Pa) on the cold side; $\boldsymbol{T_h}$ is the temperature (K) on the hot side of the pump; $\boldsymbol{T_c}$ is the temperature (K) on the cold side; and n is the number of pumps that are in series. Adding pumps in series will theoretically increase the pressure achievable by the Knudsen pump according to Eq. 1. To add a pump in series, one connects the outlet of the first pump to the inlet of the second pump, and so on and so forth. To increase the flow rate of a Knudsen pump, one should increase the effective area of the Knudsen pump by placing multiple pumps in parallel to one another. It is therefore possible to adjust the pressure and flow rate of a Knudsen pump by altering these characteristics.

Based on the layout of the Knudsen pump a theoretical temperature difference equation can be calculated by creating a thermal circuit. Figure 3 shows the theoretical thermal circuit used to derive Eqs. 3 and 4. The temperature drop across any element may be found from $\Delta\boldsymbol{T} = \boldsymbol{QR}$, where $\Delta\boldsymbol{T}$ is the temperature difference across a substance, $\boldsymbol{Q}$ is the heat flow through the substance, and $\boldsymbol{R}$ is the thermal resistance of the substance. Altering the geometries of Knudsen pump will change the thermal resistance of the whole device and change the temperature difference across the Knudsen pump. The thermal resistance is calculated using Eq. 2. This equation is used to calculate the thermal resistances in Eqs. 3 and 4 for every element in the thermal circuit.

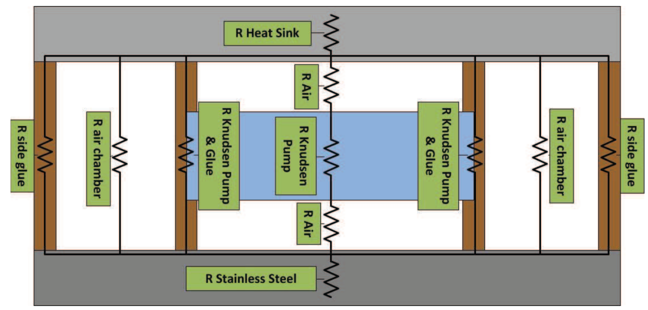

Fig. 3. Diagram of thermal circuit, which is used to estimate the temperature difference across the Knudsen pump, and which may then be used to calculate the theoretical pressure difference the pump can generate.

$$\boldsymbol{R} = \frac{\textbf{Thickness}}{\textbf{Area}*\textbf{Thermal Conductivity}} \qquad (2)$$

Eqs. 3 and 4 are used to estimate the temperature difference across the Knudsen pump, from which the pressure difference can be calculated using Eq. 1. Figure 4 shows the theoretical pressure difference that may be obtained from the Knudsen pump as a function of the thickness of the Knudsen pump, and for three heat sink configurations. A rectangular heat sink with a thermal resistance of 34°C/W, a square heat sink with a thermal resistance of 26.9°C/W, and a stainless steel sheet of thickness 0.0254 mm were evaluated. It is apparent that increasing the thickness of the Knudsen pump increases the temperature difference and therefore increases the pressure difference that may be generated. The heat sink has a significant impact on the performance of the Knudsen pump, showing that the removal of heat is a major concern during the design of the infusion pump.

$$\Delta T_{Knudsen\ Pump} = \left[R_{Knudsen\ Pump}\right] * \left[R_{middle}\right] * \left[\Delta T_{Total}\right] * \left[\left(R_{Knudsen\ Pump} + 2R_{air}\right) * \left(R_{middle} + R_{stainless\ steel} + R_{heat\ sink}\right)\right]^{-1} \qquad (3)$$

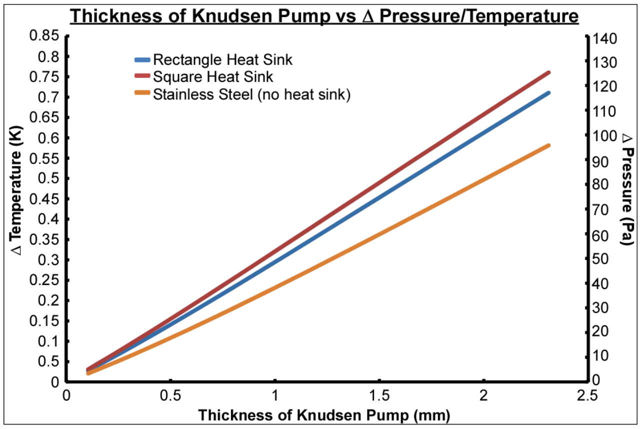

Fig. 4. Theoretical estimation of temperature and pressure difference across the Knudsen pump as a function of Knudsen pump thickness. As the thickness of the pump increases so does the temperature difference and therefore the pressure difference. These temperatures and pressures were calculated using the thermal circuit in Fig. 3 and Eqs. 1, 3 and 4.

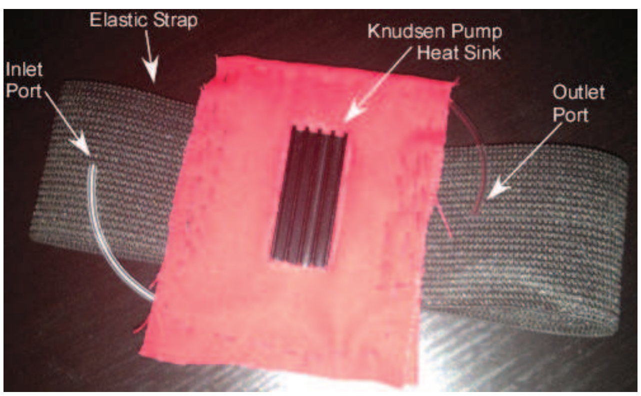

Fig. 5. Photograph of a wearable infusion pump. A stainless steel sheet (hidden from view) is in contact with the person wearing the device. This device is worn with the heat sink up.

$$R_{middle} = \left[\frac{2}{R_{side\ glue}} + \frac{2}{R_{air\ chamber}} + \frac{2}{R_{Knudsen\ pump\ \&\ glue}} + \frac{1}{R_{Knudsen\ Pump} + 2R_{air}}\right]^{-1} \tag{4}$$

FABRICATION AND TESTING

Figure 5 shows the wearable Knudsen pump that was created. The Knudsen pump is made from 10 nanoporous membranes, each of thickness 105 µm, creating a 1 mm thick Knudsen pump. The stainless steel is to be worn against the skin and the rectangular heat sink is open to air. Holes were punched in the stainless steel to allow it to be sewn into a piece of cloth. The cloth is folded over to conceal the tubing for the pump. This design will allow for multiple pumps to be connected in series, and therefore increase the pressure difference achievable by the pump. An elastic strap holds the device in contact with the person wearing the pump.

The pump was tested using two pressure sensors. One of the sensors was attached to the Knudsen pump and one is left open to air. The difference between the two pressures is measured to characterize the pump.

EXPERIMENTAL RESULTS

Figure 6 shows the pressure differences created by the Knudsen pump when the pump is strapped to an arm. On the graph are the results of a Knudsen pump with a rectangular heat sink and a sheet of stainless steel (no heat sink).

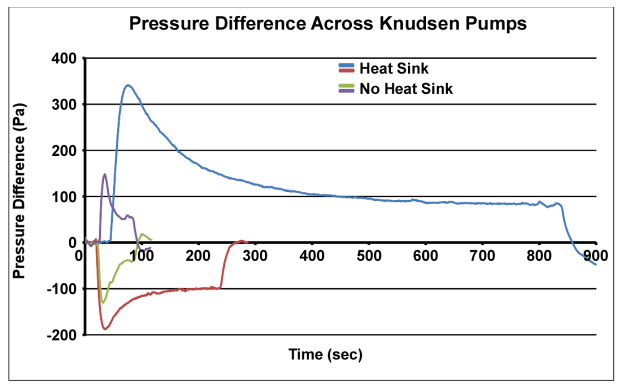

Fig. 6. Experimental results of Knudsen pump with and without heat sink. This graph shows the improvement of pressure difference when a heat sink is added. Also, this graphs shows that the device with a heat sink takes longer to reach equilibrium.

The graph shows the positive and negative pressures that were generated by the Knudsen pumps. To observe the negative pressure achievable by the Knudsen pump, the inlet port of the pump is connected to the pressure sensor. The positive pressure is observed by connecting the sensor to the outlet port of the device. The positive pressure for the heat sink Knudsen pump peaks above 300 Pa, and comes to equilibrium near 100 Pa. The Knudsen pump without the heat sink peaked at around 150 Pa and leveled out near 50 Pa. When the pump is first placed on the arm, the heat sink or stainless steel sheet is still at room temperature, resulting in an improved temperature difference and improved pressure difference. Eventually, the heat sink or stainless steel sheet heats up, reaching a steady state temperature, and a steady state pressure is obtained. Because the heat sink has a substantially larger thermal mass, it takes longer before the pump with a heat sink reaches a steady state pressure.

Based on the theoretical data in Fig. 4, the 1 mm Knudsen pump with a rectangular heat sink should achieve a pressure of 50 Pa. The experimental data is higher than theoretically predicted. This is believed to be due to error in the approximation of geometries within the device. Even though the pressure is higher, it is still only offset by less than 100 Pa, making the theoretical estimation a relevant model for approximating the pressure obtainable by the Knudsen pump.

CONCLUSIONS

A Knudsen pump for an infusion pump was designed, created, and tested. This Knudsen pump is essential for the infusion pump for the medication to be driven out of the reservoir and to the patient. The Knudsen pump was designed in such a way so that it can be adjusted to supply more or less pressure and flow rate depending on what the requirements of the reservoir.

The pump successfully scavenges heat from the human body and can be used to pneumatically drive a liquid. The pump is ideally suited for low flow rate applications.

A theoretical description of the pump performance was described that takes into account the thermal properties of all the materials used. Small discrepancies between theory and experiment are believed to be due to inaccuracies in modeling the experimental conditions, such as the thickness of the layers of glue utilized for fabrication.

DISCUSSION

The importance of this device is that it utilizes no electricity. This lack of reliance on electricity can be a real benefit in emergency situations, for use in under developed countries, and in military field operations. This device could be useful in providing a low flow supply of pharmaceuticals and potentially saving lives in these situations. There may be additional usages for this infusion pump, since infusion pumps are currently in use in clinical settings and in the home.

The addition of the heat sink to the device improves the maximum pressure differential. Once the required pressure to force pharmaceuticals out of the reservoir is known for a particular application, one can use the theory presented to calculate the optimal Knudsen pump design.

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