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DEVELOPMENT OF A PORTABLE PNEUMATIC POWER SOURCE USING PHASE TRANSITION AT THE TRIPLE POINT

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ABSTRACT

This study is concerned with the development of a novel portable pneumatic power source applicable to self-powered mobile applications such as wearable actuator and rescue robot etc. Dry ice is chosen as a source of power for the pneumatic power source because it is nonpoisonous, easy to obtain and it expands 750 times in volume after being vaporized into gas. When dry ice is stored in the confined pressure container, it begins to liquefy after the pressure reaches the triple point (0.52[MPa(abs)], -56.6℃). In this process the pressure remains constant until all the dry ice melt into the liquid. When the state remains at triple point, the pressure does not decrease even though the gas is released from pressure container. By using this physical property of carbon dioxide, and by controlling the heat transfer from the surroundings into the pressure container, a noiseless, large capacity and portable pneumatic power source is developed.

KEY WORDS

Pneumatic Power Source, Phase Transition, Dry Ice, Triple Point, Self-Powered

NOMENCLATURE

M	:	mass of dry-ice in pressure container
Q	:	volumetric flow rate
G	:	mass flow rate
q	:	heat transfer rate
T	:	output period (duration of an output flow)
T_{ALL}	:	total output period (= $\sum T_i$)
y	:	displacement of cylinder
ΔH_v	:	heat of vaporization at the triple point of carbon dioxide=348[kJ/kg](-56.6 $°C$)
ΔH_f	:	heat of fusion at the triple point of carbon dioxide=195.8[kJ/kg](-56.6 $°C$)
ΔH_s	:	heat of sublimation at the triple point of carbon dioxide=543.8[kJ/kg](-56.6 $°C$)

Subscripts

i	:	i th output

1. INTRODUCTION

The lack of suitable pneumatic power source is one of the dominant bottlenecks preventing the more widespread appearance of self-powered mobile applications such as wearable actuator and rescue robot etc. The pneumatic power source in these fields should achieve the following capabilities: 1) lightweight; 2) portable-size; 3) large capacity; 4) long life; 5) noiseless; 6) nonpoisonous; 7) low-price and 8) safety. This is a challenging list, and no current pneumatic power source possesses all of these desirable characteristics. To solve the pneumatic power supply problem, many researches have been done in recently years[1) ~3)]. However, new advances in portable pneumatic power source are still required.

This paper presents a novel portable pneumatic power source which is called Dry Ice Power Cell. Dry ice, which is the solid phase of the carbon dioxide, is chosen as the source of the power because it is nonpoisonous, easy to obtain, low in price and it expands 750 times in volume after being vaporized into gas. By using physical phase transition property of carbon dioxide at the triple point, and by controlling the heat transfer from the surroundings, a noiseless, large capacity, light and portable pneumatic source is developed. In this paper, the structure and the flow characteristic of the pneumatic power source is described in detail.

2. BASIC PRINCIPLE

The phase diagram for CO_2 is shown in Fig.1. Point O is the triple point of CO_2 (0.52[MPa(abs)],-56.6 ℃) where solid, liquid and gas phases all coexist in equilibrium. Notice that the pressure at the point O is higher than atmosphere pressure. This means that the solid phase (dry ice) sublimes, that is it passes directly from the solid to the gas when left open to the atmosphere (point D), and liquid CO_2 cannot exist in this situation.

As illustrated in Fig.1 and Fig.2 (a) ~ (e), when dry ice is stored in the confined pressure container, the pressure increases steadily along the DO line (solid-gas boundary) because heat is added from the environment (a). When the pressure reaches triple point O, it stops increasing and solid begins to melt (b). In this situations, the heat addition results in change in internal energy, but no change in temperature and pressure. The heat addition from surroundings is saved in the liquid phase as the latent heat. Once all the solid has melted, no phase change occurs and the pressure rises farther along the OFA line (liquid-gas boundary) (c). At room temperature (25 °C), the pressure reaches 6.4[MPa (abs)] which is the pressure in cylinder of liquid carbon dioxide for daily use (point A).

When gas in the pressure container is released (for example, from point F), the pressure drops back down to point O along the FO line (d). Then the pressure holds constant at point O for a while. In this situation, the liquid begins to boil quite rapidly and also solid begins to reform (e). When all the liquid is gone and only reformed solid left, the pressure eventually drops back down to D along the OD line to normal atmospheric pressure (point D).

Notice that when the state remains at triple point, the pressure does not decrease even though the gas is released from pressure container. This is a useful property for pneumatic power source where a steady pressure is always required.

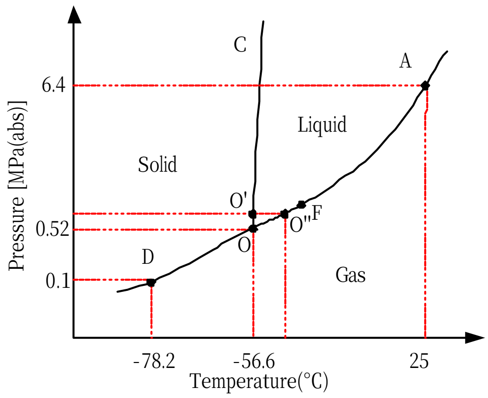

Fig.1 Sketch of the phase diagram for carbon dioxide (not to scale)

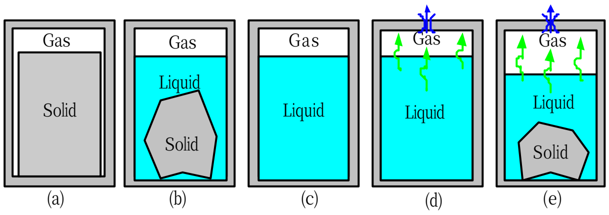

Fig.2 Phase transition process of the dry-ice in closed container

From the viewpoint of energy transfer, when gas is released at triple point pressure, part of the liquid changes to solid and emits the saved latent heat while other part absorbs this latent heat to improve its vaporization thus can hold the pressure. On the other hand, when liquid is gone, the pressure drops because of the required heat of vaporization for steady output flow rate can not be offered at that time. In other words, the liquid at the triple point acts just like an energy buffer, that is it saves energy transferred from the environment when solid melts and emits the saved heat when the output flow rate is released. The more the liquid, the longer the release duration can be achieved.

Making use of the physical property of carbon dioxide at the triple point, a novel pneumatic power source can be developed. By controlling the heat transfer from the surroundings, the developed pneumatic power source can hold the carbon dioxide in a pressure container at the state of triple point for a long time, thus achieves a fixed pressure (0.42[MPa]) pneumatic power source which can offer various output flow rate. The following describes the structure and the flow characteristic of the developed pneumatic power source in detail.

3. DESCRIPTION OF THE STRUCTURE

Developed Dry Ice Power Cell is illustrated in Fig.3. The dry ice (F) is stored in pressure container (E) which is surrounded by a can with composite wall consisting of an inner insulate layer (G) and an outer aluminum can (H) with fin (I). The control mechanics consist of a double-acting cylinder (J), a pressure switch (D), a solenoid valve (A) and its drive circuit.

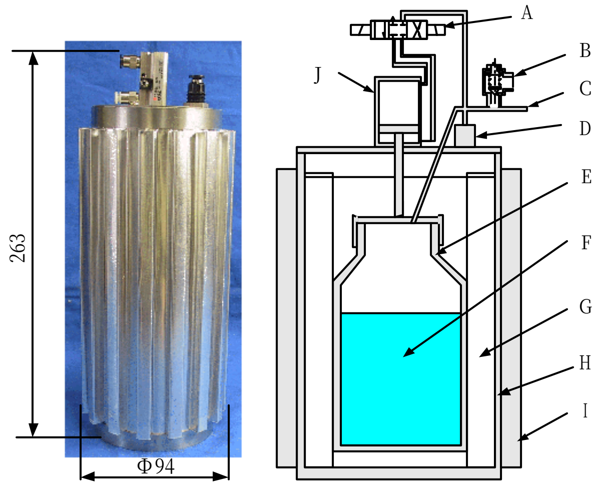

Fig.3 Photo and Model of Dry-ice Power Cell

When the pressure in the pressure container (E) falls below 0.42[MPa], solenoid valve (A) is switched on by pressure switch (D) and cylinder (J) extends to push the pressure container (E) down to contact closely with the bottom of the aluminum can (I). This position is called contact position later. On the other hand, when the pressure is higher than 0.45[MPa], solenoid valve (A) is switched off by pressure switch (D), and cylinder (J) retracts to lift the pressure container (E) up to separate it from the bottom of the aluminum can (I). This position is called separate position later. Because thermal resistance is small in the contact position and large in the separate position where an air space is inserted, the heat transfer rate from the environment to the pressure container can be controlled by this two position control.
From the viewpoint of energy transfer, when the pressure reaches 0.45[MPa], a little higher than triple point pressure, all the dry ice in the pressure container has melted into liquid CO_2 which shows sufficient latent heat has been saved and no more heat transfer from the environment is needed. At this pressure, the separate position where heat transfer is not a lot is selected. Moreover, because the pressure rises slowly even in the separate position, the relief valve (B) is needed (setting pressure 0.5[MPa]) to prevent the pressure from rising farther.
The developed Dry Ice Power Cell weighs 600g, and can store 430g dry ice, thus the total weight is about 1kg. In order to explain the action of the Dry Ice Power Cell, the phase change and pressure change inside the pressure container is shown in Fig.4.
Firstly, pressure rises as the solid sublimes①, then it stops rising and the solid begins to melt②. The pressure rises again as all the solid melts to liquid③. When the pressure reaches 0.45[MPa], the pressure container is switched to the separate position and the heat transfer from the environment is slowed down. When the pressure reaches 0.5[MPa], the gas is released from relief valve to prevent the pressure from rising farther. After that, the outlet valve may be open to give the output④. When the gas flows out⑤, the pressure drops down to the pressure of the triple point and holds there the period of T_1. During this process, the pressure container is switched back to the contact position and the liquid boils quite rapidly and the solid reforms ⑥ ⑦. When all the liquid is gone and only reformed solid survives, the pressure drops again and the output flow has to be shut off ⑧. Then the survival melts again, thus the second output period T_2 is given during a process just like② ~⑧. Accordingly, the third period T_3, the forth period T_4 … output periods can be obtained if the solid reformed from previous output exists.

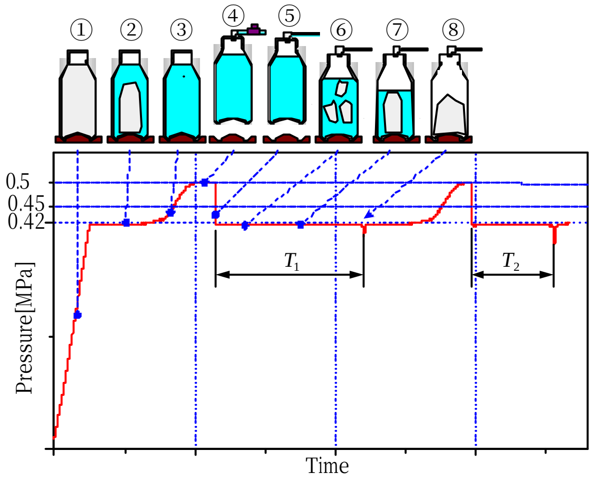

Fig.4 Principle of the Dry-ice Power Cell

4. EXPERIMENT

The experimental setup for flow characteristic of the Dry Ice Power Cell is illustrated in Fig.5.

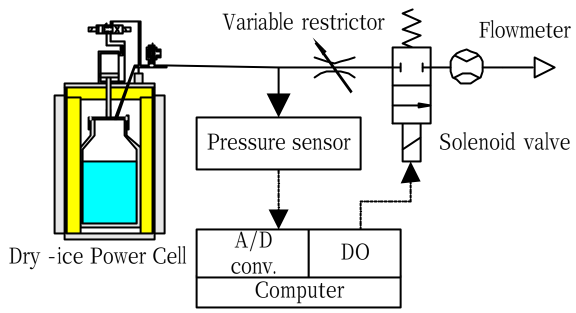

Fig.5 Schematic diagram of experimental setup

430g dry ice is stored in its pressure container. The output flow rate is controlled by a variable restrictor and a solenoid valve to give an on/off output control. The output flow rate and the pressure in the pressure container are measured by a flowmeter and a pressure sensor. When the gas is released at flow rate Q at the pressure of triple point 0.42[MPa], the output period $T_1, T_2 \ldots$ are measured.

As shown in Fig.6, when output flow rate is 5, 7and 20[L/min (nor)], experimental results show that as the output flow rate is increased, the first output period T_1 becomes shorter. This is because both vaporization and freezing occur more rapidly in larger output flow rate.

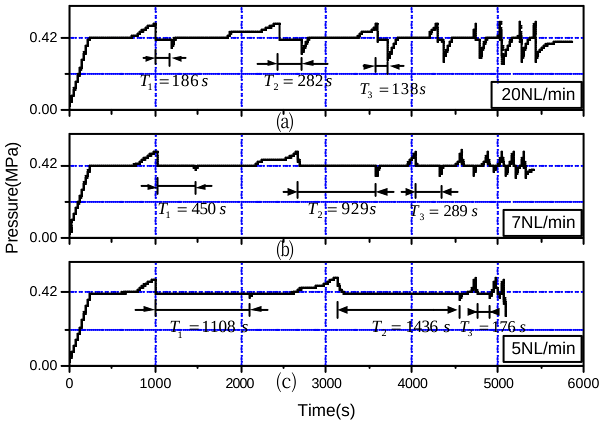

Fig.6 Experimental results of pressure with time

As shown in Fig.7, when output flow rate is 2, 3 and 4[L/min (nor)], all the gas is released at only one period T_1. This means the immediate heat transfer alone is enough for offering these small flow rates and no solid reforms throughout the output period. Notice that only the contact position is selected throughout the output at 4[L/min (nor)] (Fig.6 (a)). However, when the output flow rate is less than 4[L/min (nor)], the separate position is needed because the heat transfer at the contact position is too large for that flow rate. The smaller the out flow rate, the more the separate positions.

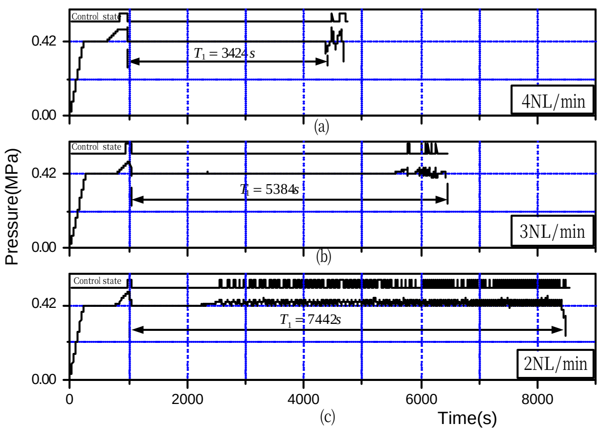

Fig.7 Experimental results of pressure with time

As shown in Fig.8, when Dry Ice Power Cell does not give any output flow, the liquid CO_2 can be preserved at the separate position for about 7.5 hours. The flow rate released from the relief valve during this process is about 0.4[L/min (nor)].

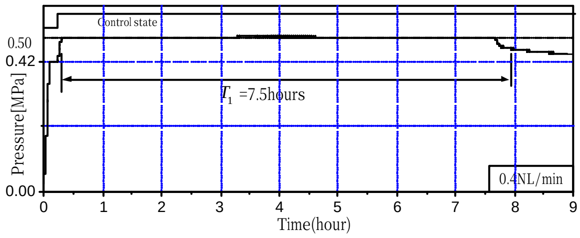

Fig.8 Experimental results of pressure with time

5. DISCUSSION

5.1 ENERGETICS

A simplified calculation can be given for roughly estimating the output capability of Dry Ice Power Cell. From neglecting the heat transfer during the output process, the heat emitted from the freezing process (195.8kJ/kg) simply equals the heat for vaporization (348kJ/kg), so that the mass of the output gas should be 36% (about 1/3) of the total initial liquid mass, and the rest 64% (about 2/3) should reform to solid. However, as illustrated in Fig.6, the experimental result shows that the first output period T_1 is less than not only 1/3 of the total output period T_{ALL} but also the second output period T_2. The conflict between the calculation and the experiment is caused by uneven temperature distribution in the pressure container.

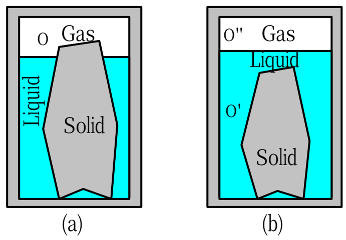

Fig.9 Temperature deviation near triple point

As illustrated in Fig.9, when the solid melts in the pressure container, the solid change it position from above liquid level (a) to sinking in liquid (b). This causes the boundary face which solid, liquid and gas phase all coexist to disappear. Although the pressure is even, the temperature distribution is not even and different temperatures can exist at the point O' and O'' as shown in Fig.1. The pressure rises even though the solid still exists in the pressure container.

In order to prove this explanation, the pressure container is shaked to make the temperature distribution even and enable to achieve a complete liquefaction. As shown in

Fig.10, (b) is from the experiment which pressure container is shaked to achieve complete liquefaction, while (a) is shown for comparison (the same as Fig.6 (a)) which the experiment is just done on a still table without any shake movement. When the pressure rises above the triple point pressure (Point A in Fig.10 (b)), the pressure container is hold to be shaked to make the temperature distribution even, thus the pressure drops down to triple point pressure. After that, the pressure rises again and again and needs to be shaked repeatedly. The existence of the solid can be confirmed in this process from the knocking sound inside the pressure container. At last, the pressure does not drop (point B) even though the pressure container is strongly shaked and no knocking sound occurs. This shows solid is not exist, and the complete liquefaction is achieved.

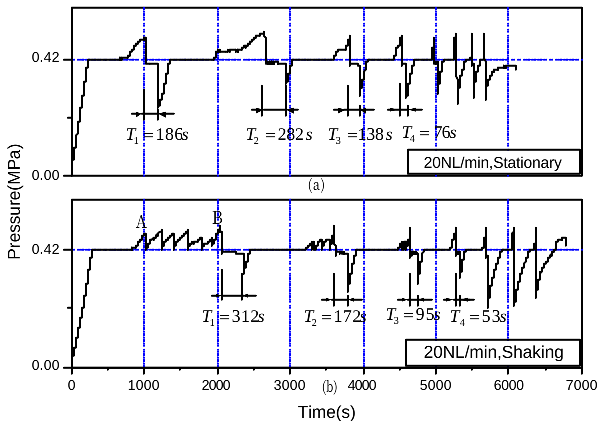

Fig.10 Experimental results of pressure with time

When the complete liquefaction is achieved, the output period at the flow rate of 20[L/min (nor)] is T_1=312s, T_2=172s, T_3=95s…, as shown in the Fig.10 (b), which is a geometric progression with the ratio of 0.55.

Since the temperature inside the pressure container is always constant at the triple point, the temperature of the environment does not change very much either, thus the heat transfer rate q should be almost constant. Therefore, the energy balance can be expressed in equation (1) which shows the heat emitted from freezing process plus the heat transferred from the environment equals the heat of vaporization. The conservation of mass can be expressed in the equation (2).

$$G\Delta H_s = q + \frac{M_i \Delta H_f}{T_i} \qquad (1)$$

$$M_{i+1} = M_i - GT_i \qquad (2)$$

So the ratio of output period geometric progression can be given by equation (3), which shows a constant ratio when the gas flows out at a constant mass flow rate G .

$$\frac{T_{i+1}}{T_i} = 1 - \frac{G\Delta H_f}{G\Delta H_S - q} \qquad (3)$$

When flow rate is 20[L/min (nor)] and the ratio is 0.55, and heat transfer rate q equals 4.5[kJ/min]. However, the heat transfer rate q measured in this way shows that q is about in the range of 3.5~4.5 [kJ/min] as shown in Fig.11, which shows some increasing tendency as the output flow rate increases.

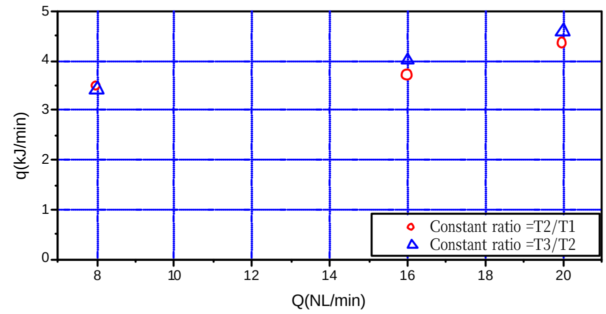

Fig.11 Experimental results of q vs. vario us flow rates Q

When the Dry Ice Power Cell is carried by a person, because there are often shake movement accompany by walking movement, the actual using condition of Dry Ice Power Cell is believed near the condition of complete liquefaction.

Developed pneumatic power source stores 430g dry ice, which can evaporate to 218L (nor) gas or 42L at pressure of 0.42[MPa]. The pressurized gas can do 18[kJ] (5Wh) work, and can give power as shown in Table 1. For example, when the output valve is full opened and 110L/min (nor) flow rate can be obtained for about 40 seconds, thus can output 150W power in 40 seconds.

Table 1 Output power of Dry-ice Power Cell

Q (L/min(nor))	T_1	T_{ALL}	Power(W)
0.4	7.5 hour	7.5 hour	0.6
4	57 min	57 min	5
20	5 min	11 min	27
110	40 second	2 min	150

5.2 APPLICATION TEST

The Dry Ice Power Cell is applied to the driving of a cylinder. The experimental setup is shown in Fig.12.

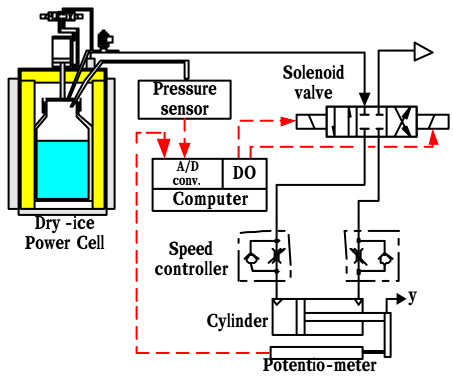

Fig.12 Setup of experiment

The cylinder is controlled by meter-out circuit, and the displacement of the cylinder y and the pressure in the pressure container are measured by potentiometer and pressure sensor. The working period of the cylinder is recorded.

Table 2 Parameters of experiments and T_i

No	Diameter (mm)	Stroke (mm)	Period (s)	T_i (min)	Mean flow rate (L/min(nor))
1	10	45	1	40, 6, 2	5
2	10	45	2	90	2.5
3	25	255	5	6.2,3.4,1.9,1.1	16

The experimental results of two cylinders in three conditions are listed in table 2. A cylinder of 10mm in diameter, 45mm in stroke is driven at a period of 1 second, and three periods of T_1, T_2, T_3 is achieved. The same cylinder is driven at a period of 2 second, only one period of 90 minutes output is achieved. A cylinder of 25mm in diameter, 255mm in stroke is driven at a period of 5 second, and output periods of $T_1 \sim T_4$ are achieved.

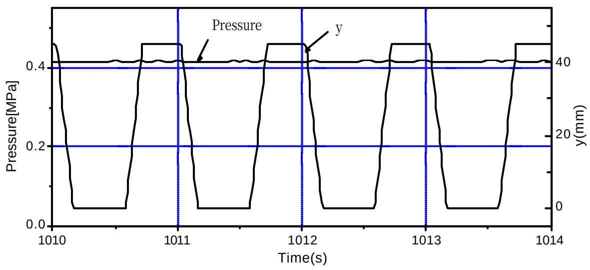

Fig.13 Experimental results (No.1)

The pressure in the pressure container and the displacement of the cylinder y of the experiment No.1 is shown in Fig.13. Notice that the pressure has only small fluctuation even though the output flow has an intermittent change. This shows the Dry Ice Power Cell can give intermittent output flow at a constant pressure and the air receiver is not necessary which is often necessary in the pneumatic system. This makes it very convenient for the pneumatic system to achieve small size and light weight.

5.3 SAFETY CONSIDERATIONS

Although the gas CO_2 is nonpoisonous, it causes some health problems when people breathe it in at high concentration. However, an adult in quiet breathe blows out CO_2 at the flow rate of nearly 0.45L/min, which is near 0.4 L/min (nor) the output of the Dry Ice Power Cell at separate position. A 2.4kW/h gas-heater generates 220L CO_2 within one hour, which is near the amount of the CO_2 generated by 430g dry ice. Therefore, Dry Ice Power Cell is safe even for using at home.

Because dry ice is obtained fom by-product stream from manufacturing processes, the Dry Ice Power Cell makes no more CO_2, and is considered to have little effect on increasing the amount of CO_2 in the atmosphere which can cause global warming.

6. CONCLUSIONS

A novel pneumatic power source is proposed in this paper. By using the physical property of carbon dioxide at the triple point, and by controlling the heat transfer from the environment into the pressure container, a noiseless, large capacity and portable power source which is named Dry Ice Power Cell is developed. Proposed pneumatic power source can be widely used in self-powered mobile applications such as wearable actuator and rescue robot etc.

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