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# Performance of radial piston type reciprocating expander for $CO_2$ refrigeration cycle

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ABSTRACT

Various types of expanders have been investigated to recover a throttling loss and to improve the performance of $CO_2$ refrigeration cycle. However, the capacity of the expander studied so far is so large that it cannot be used for a small cycle such as a vending machine, since the performance of small expander tends to get worse due to influence of leakage. In this paper, a novel reciprocating expander which can be applied to the small cycle is designed and its performance is examined. The expander has four cylinders and pistons arranged radially, and controls supply and discharge of refrigerant by a reciprocating motion of an adjacent piston. It is found that the developed expander can be operated with a small flow rate and the total efficiency attains to 0.4 over the wide range of rotational speed.



# Performance du détendeur à piston radial pour un cycle frigorifique au $CO_2$

*Mots clés :* Détendeur ; Cycle frigorifique au $CO_2$ ; Récupération d'énergie ; Perte due au laminage ; Détendeur à piston

## 1. Introduction

Carbon dioxide ($CO_2$) is natural refrigerant and an alternative candidate to hydro fluorocarbon (HFC) refrigerants in refrigeration or heat pump cycles, because it has no flammability and no toxicity. In recent years, the $CO_2$ cycle is used for water heaters and vending machines. However, the inherent performance of air cooled $CO_2$ cycle is lower than that of HFCs due to large throttling loss occurred in the isenthalpic expansion process (Lorentzen, 1995; Robinson and Groll, 1998) and it is important to recover the loss in order to improve the performance of the $CO_2$ cycle. Using an expander as an expansion device is one way to recover the throttling loss.

Various types of expander have been developed and investigated for the $CO_2$ cycle. A scroll mechanism is suited to

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**Nomenclature**

*Latin letters*

| | |
|---|---|
| $d$ | diameter [m] |
| $G$ | mass flow rate [kg s$^{-1}$] |
| $l$ | length of connecting rod [m] |
| $n$ | rotational speed [s$^{-1}$] |
| $P$ | pressure [Pa] |
| $r$ | crank radius [m] |
| $T$ | torque [Nm] |
| $V$ | volume [m$^3$] |
| $W$ | $P$–$V$ work [J] |

*Greeks*

| | |
|---|---|
| $\eta$ | efficiency |
| $\theta$ | rotational angle [rad] |
| $\rho$ | density [kg m$^{-3}$] |
| $\omega$ | angular velocity [rad s$^{-1}$] |

*Subscripts*

| | |
|---|---|
| cyl | cylinder |
| exp | expander, experiment |
| i | ith cylinder |
| in | inlet |
| ind | indicated |
| is | isentropic |
| m | mechanical |
| out | outlet |
| st | stroke |
| t | total |
| th | theoretical |
| top | top clearance |
| v | volumetric |

the expander and many researchers studied about the scroll expander for the $CO_2$ cycle (Huff et al., 2003; Fukuta et al., 2006; Kohsokabe et al., 2008a; Hiwata et al., 2009). Vane expanders have the almost the same structure with vane compressors, and therefore have simple structure. The performance of the vane expander is examined by Fukuta et al. (2009), Yang et al. (2009) and Jia et al. (2009). Two-cylinder rotary expander is proposed in which one of the cylinders is used to control a supply process of the expander and design parameters are optimized (Matsui et al., 2009). A revolving vane expander is developed by Subiantoro and Ooi (2009, 2012a,b) and its performance is investigated both experimentally and theoretically. Although the control of the supply and discharge process is necessary in a reciprocating mechanism in case of the expander, reciprocating machines are considered as the expander (Kruse et al., 2006; Baek et al., 2002, 2005a,b). Free piston expander is a kind of the reciprocating expander and developed by Heyl and Quack (1999), Nickl et al. (2002, 2005) and Zhang et al. (2007). Driving an auxiliary compressor directly by the recovered power of the expander or using the recovered power as a part of driving power of the compressor is discussed by combining the expander with the compressor (Fukuta et al., 2001; Okamoto et al., 2005; Kim et al., 2006; Kohsokabe et al., 2006, 2008b; Kakuda et al., 2009).

The expanders studied so far has relatively big capacity and cannot be applied to a refrigeration cycle having small capacity such as vending machines. The same structures of the expander described above are hardly adaptable to the small size expander, since the influence of leakage becomes severe in the small expander. Among the expander types, the reciprocating expander seems to be feasible to have a good performance in the small capacity refrigeration cycle, since some kinds of seal device such as a piston ring can be applicable to reduce the leakage. On the other hand, the controls of supply and discharge process are needed in the reciprocating expander.

In this study, a novel reciprocating expander which can be operated with small flow rate is developed. It has four pistons and cylinders arranged radially. The controls of supply and discharge of refrigerant are done by reciprocating motion of an adjacent piston as a spool valve. The performance of the expander is measured and examined experimentally.

## 2. Experiment

In this study, the reciprocating expander is developed and the performance of expander is measured with a test $CO_2$ refrigeration cycle.

### 2.1. Reciprocating expander

Fig. 1 shows appearance of the radial piston type expander and a piston with a connecting plate. Fig. 2 shows a schematic of inner structure of the expander and working principle. The four cylinders labeled C1–C4 are arranged radially. The pistons are connected to a one crank arm via the connecting plate. Each cylinder has a flow channel connected to a side wall of an adjacent cylinder. The piston has a groove sealed by O-rings at both ends of the groove. The reciprocating motion of the adjacent piston controls supply and discharge of refrigerant as a spool valve. An inlet port is connected to four

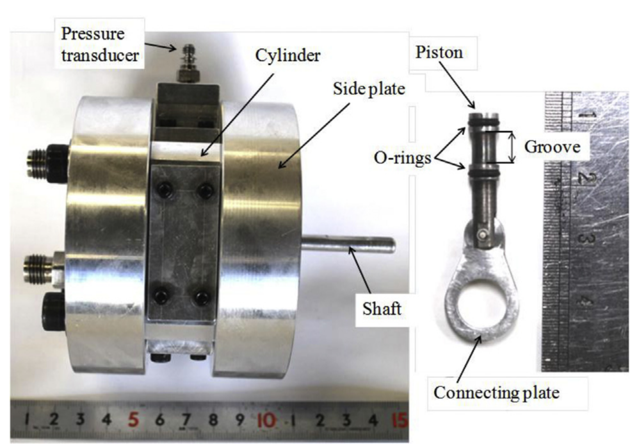


**Fig. 1 – Appearance of radial piston type expander and piston.**