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Study of a single-valve reciprocating expander

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ABSTRACT

The reciprocating expander is a small scale power generation device which could be extensively utilized in small scale compressed air energy storage (CAES) system, distributed renewable energy utilization, uninterruptible power supply, vehicle engine etc. In this paper, a simulation work of a single-valve reciprocating expander is carried out. The working performance, flow loss mechanism and its internal flow structure are studied in details. The flow losses are analyzed. It reveals that the flow speed is very high due to the large pressure difference during the air intake period. It also causes strong vortex flow inside the cylinder leading to a big loss of the total pressure. This study provides a fundamental understanding of the single-valve reciprocating expander and a reference for further optimization design.

1. Introduction

Compressed Air Energy Storage (CAES) system is a significant Electrical Energy Storage (EES) technology, and it receives much attention around the world. The CAES system could achieve peak shaving, and it could also enable the renewable energy generation continuous and stable, which improves the renewable energy penetration in the grid. When engaging the CAES into the distributed generation (DG), it increases DG system's flexibility and economy performance. It also has advantages of relatively long life time, high efficiency, low maintenance cost and environmentally benign characteristics [1].

The small-scale CAES system could be extensively used in DG, backup power system, air powered vehicles or refrigeration system. It reveals that the small-scale CAES system is even more flexible and of low carbon feature [1–5]. In respect of the DG system, a novel CAES system was proposed to realize the customer side management (CSM) [6,7]. In reference [5], it studied a CAES system coupled with a diesel engine, which was used in DG system and small or districted grid. The hybrid system could save fuel consumption with almost 27% compared with the diesel-engine-only system. In respect of the backup power system, some researchers studied a CAES system to be used as a small backup power system. It stored compressed air of 30 MPa, and its power rating was 2 kW. The life time could be 30 years with pretty less maintenance cost. In respect of air powered vehicle, many researchers have studied compressed air engine/car both theoretically and experimentally [8–10]. They generally modified the diesel engine to make it work with compressed air to drive a car. The liquid nitrogen powered engine was also analysed in reference [11,12] for zero emission vehicle. And some methods such as to get isothermal or quasi-isothermal expansion process or recover the cooling energy of the liquid nitrogen were discussed in order to improve the engine efficiency, which could improve specific energy output by more than 200 kJ/kg [11,12].

The compressed air engine/expander is the key component of the above-mentioned small-scale CAES systems. Many types of the air expander have been proposed and studied by researchers [13,14], which included turbomachinary expander, scroll expander, screw expander, triangle rotor expander, reciprocating expander, etc. Among these expanders, reciprocating expanders could work under high pressure ratio, have a good isentropic efficiency and a good power output/size ratio. Thus it has sparked interest of many researchers to work on the reciprocating expander for power generation in a relatively small scale [13,15]. In reference [16], a reciprocating expander was utilized as a steam expander for small scale Rankine Cycle (RC). A two-cylinder double valves reciprocating expander was configured and

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studied theoretically. The results showed that the expander efficiency could be more than 60%, and the RC system efficiency was about 14% with energy utilization factor of about 78%. Knowlen has conducted the study of using liquid nitrogen as power source for an automobile [12,17]. The theoretical research results indicated that the reciprocating expander could produce 15 kW power output at 850 rpm, which could satisfy the urban transportation vehicle engine requirement [12,17]. Some researchers have carried out experimental work on a reciprocating expander [18,19]. It was a double-valve reciprocating expander modified from a diesel engine with cylinder diameter of 0.085 m and stroke distance of 0.1 m. This reciprocating expander produced shaft power of about 1 kW with air inlet pressure of 0.8 MPa and temperature of ambient condition. But the efficiency was less than 20% [18].

Previous studies are mainly about double-valve reciprocating expander. And the experimental results show that the expander efficiency is not high, and it also has a non-negligible leakage around the valves [18,19]. To enable the reciprocating expander more efficient and practical, a single-valve reciprocating expander (SVRE) is proposed in this study. The main difference is that there is only one valve (inlet valve) situated on the cylinder head. It could be sealed by inlet volume compressed air, and it is forced to open by a rod connected to the piston head. Thus there is no any leakage channel to the ambience or the cylinder. On the other hand, the SVRE does not need cam shaft to control the valve rod movement, some parts are removed compared with the double valve reciprocating expander. The SVRE has advantages such as less moving parts, avoidance of the inlet air leakage, and also the small air expander efficiency improvement.

Up to now, there is no related study about the SVRE regarding its flow features and loss mechanism. This paper will carry out simulated study of the expander's working process. Both the internal flow structure and its aerodynamic performance were obtained. This study analyzed the internal flow structure and its flow loss mechanism in detail, which was an important reference for the further study and development of the high efficiency reciprocating expander.

2. Single valve reciprocating expander (SVRE)

2.1. Expander description

The schematic diagram of the SVRE is shown in Fig. 1(a). The inlet valve is situated on the head of the cylinder. The outlet is some orifices with their circle centers at a same circumference curve of the cylinder wall near the position of bottom dead center (BDC). There are two strokes in one cycle. When the piston runs to the position near the top dead center (TDC), the inlet valve is forced to open by a certain rod on

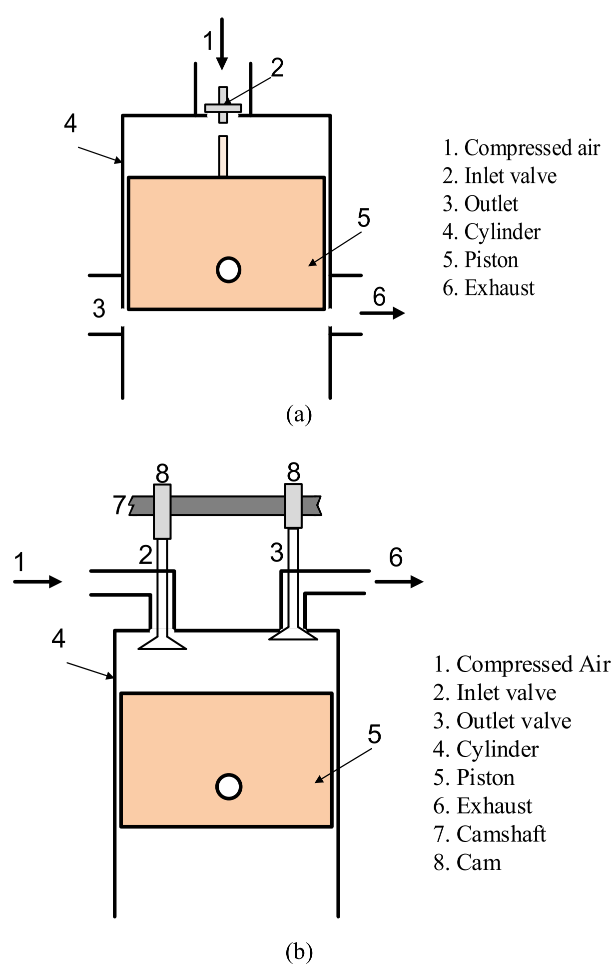

Fig. 1. Schematic diagram of the reciprocating expander. (a) single-valve reciprocating expander (b) double-valve reciprocating expander.