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Performance analysis of a two-stage expansion air engine

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ABSTRACT

This study proposes an air engine consisting of one small and one large cylinder to conduct two-stage expansion in series, in which high-pressure air first expands in the small cylinder and then residual-pressure air is transferred to the large cylinder for another expansion, by fully using the high-pressure air and increasing the power output and efficiency of the engine. First, mathematical models of a single-cylinder engine and a two-stage expansion engine were constructed. Second, the relations between the rotational speed and the output power, torque, efficiency, and cylinder pressure were established using MATLAB simulation software for analyzing the air engine in comparison with experimental approaches. The experimental results indicated that the two-stage expansion engine generated up to 1.7 kW of power and 12.42 Nm of torque at air pressure of 12 bar, which was superior to the performance of a single-cylinder engine. By varying the intake and exhaust timing sequences, the relations among the rotational speed, output power, torque, efficiency, and cylinder pressure were investigated. The results showed that early intake in the first cylinder improved power output by 5.3% as the speed increased, whereas early intake and exhaust in the second cylinder increased power output by 7%.

1. Introduction

Reducing carbon dioxide (CO_2) emissions is a crucial challenge worldwide. A major source of CO_2 emissions is the exhaust gas of internal combustion (IC) engines. Studies have explored alternative energy sources that can be used in engines to reduce emissions [1]. Compressed air, as a type of medium, can be easily obtained from the power generation process of renewable energies such as solar energy, wind energy, and tidal energy [2]. In addition, compressed air is a potential alternative to battery electric systems because of its high power density, low cost, and minimal environmental impact [3]. Air engines that use compressed air as fuel have attracted substantial attention and have been investigated for feasibility in vehicles [4]. Compressed air expands in the engine cylinder, driving the piston to output work, and discharges in the form of breathable gas at low temperature. A compressed-air engine, when used as the main engine of a motor vehicle, can produce power with zero CO_2 emissions [5].

Compressed air can also be used as an auxiliary energy source to enable an IC engine to operate at the optimal fuel consumption rate when powering the air compressor, thus improving the IC engine fuel efficiency and reducing CO_2 emissions [6]. Compressed-air engines use a conventional IC engine to activate an onboard air compressor that provides compressed air to an onboard air motor, which serves as the main power system for motor vehicles. This approach allows the IC engine to operate at the optimal fuel consumption rate to improve its efficiency and reduce emissions while powering the air compressor [7]. This combination of an IC engine and an air motor can improve fuel efficiency by up to 22% compared with conventional IC engines [8]. A favorable feature of the compressed-air engine is its capability of recovering energy during braking to further improve the engine efficiency by using approaches such as heat recovery [9]. The success of applications using a compressed-air system, especially with regard to its advantage of easy integration with IC engines, has attracted great attention from the energy sector. The applications of a compressed-air system can be further extended to a hybrid system with IC engines or electric motors, where it can serve as a secondary power system [10].

As described previously, a simple air-powered engine can provide sufficient power output to drive motor vehicle, and its energy efficiency is more favorable than that of an IC engine [11]. For full use of the air pressure, the intake stroke of an air-powered engine is shorter, which extends the expansion stroke and avoids incomplete

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expansion caused by taking in excessive high-pressure air. However, the high-pressure air in a single-cylinder engine cannot be reduced to atmosphere pressure after the expansion stroke. With a higher power output, the air-powered engine requires a higher intake of air pressure, and the residual pressure increases after the expansion stroke, resulting in wastage of energy if air with residual pressure is directly exhausted to the atmosphere. Liu et al. presented the architecture of an air-powered engine consisting of a large cylinder in series with a small cylinder. The exhaust of the small cylinder passed through a heat exchanger and then flowed into the large cylinder. A simulation showed that the two-cylinder design was more favorable than a single-cylinder engine when the intake pressure was 10 bar, rotation speed was 1000 rpm, phase difference between the two cylinders was 180°, and intake stroke exceeded90° [12]. The Scuderi Group designed a hybrid pneumatic engine (HPE) that divides the four strokes of a conventional internal combustion engine cycle over two paired cylinders, i.e., one compression cylinder and one power cylinder, connected by an air tank [13]. However, no experiments or in-depth discussion was reported for this special design. Therefore, this study proposes a method to improve the efficiency of air-powered engines by constructing an engine with two single cylinders in series, one small and one large, to form a two-stage expansion engine. The residual-pressure air after the expansion stroke in the small cylinder is transferred to the large one, where it undergoes another expansion and performs work, resulting in two air-powered engine cycles that use high-pressure air more effectively.

2. Thermodynamic model

Fig. 1 shows a two-stage expansion engine. The exhaust process in the first cylinder completely overlaps with the intake process in the second cylinder to avoid the compression caused by the exhaust stroke in the first cylinder. Because the second cylinder reuses the gas exhausted by the first cylinder, the first cylinder must produce more output to push the gas into the second cylinder if its volume is smaller than that of the second one. Assuming that the two cylinders have the same pressure while the first cylinder is exhausting gas to the second cylinder, if the first cylinder is larger than the second cylinder, then the negative torque produced by the exhaust in the first cylinder is greater than the positive torque produced by the intake in the second cylinder. Therefore, the first cylinder should be smaller than the second one. Accordingly, the volumes of the first and second cylinders were taken as 50 and 100 cm^3, respectively.

A thermodynamic model of the air engine is developed using compressible flow [14] and the thermodynamic models [15] of the piston-type air engine. The following assumptions are made [16].

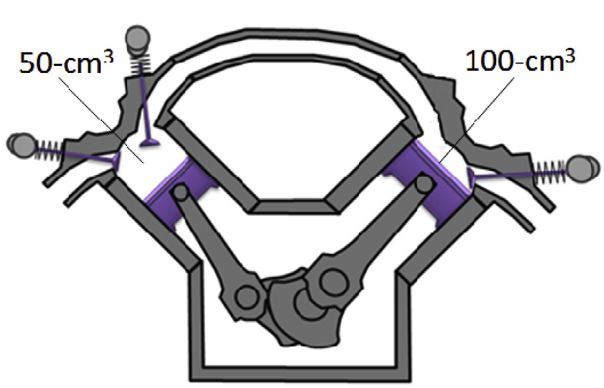

Fig. 1. Schematic of two-stage expansion engine.

First, the tank supplies high-pressure air at a fixed pressure and temperature. Second, the piston-type air engine has no heat exchange with the external environment during the expansion and compression stokes. Third, the piston operates with a simple harmonic motion. Finally, the model ignores the influence of flow resistance, leakage, and friction.

2.1. Intake stroke

The Mach number is calculated by using the pressure ratio before and after the intake valve, which can be approximated as the pressure in the high-pressure air source and the pressure inside the cylinder, respectively. Then, the mass flow rate is calculated using the Mach number. The intake amount is determined from the mass flow rate multiplied by time. The cylinder pressure is then calculated by using the equation of state for an ideal gas.

$$M_{in} = \left\{ \left[\left(\frac{P_{tank}}{P_c} \right)^{\left[\frac{\gamma-1}{\gamma}\right]} \right] \times \frac{2}{\gamma - 1} \right\}^{\frac{1}{2}} \tag{1}$$

$$\dot{m}_{in} = P_{tank} \times \sqrt{\frac{\gamma}{RT_{tank}}} \times A \times C \left(1 + \frac{\gamma - 1}{2M_{in}^2} \right)^{\frac{1+\gamma}{2(1-\gamma)}} \tag{2}$$

$$P_c = \frac{m_c \times R \times T_c}{V_c} \tag{3}$$

where M_{in} is the Mach number of inlet air, P is the pressure, the subscripts c and in respectively indicate the cylinder and inlet air, γ is the heat capacity, $\dot{m}_{in}$ is the mass flow rate, R is the air constant, A is the valve area, T is the temperature, and C is the discharge coefficient (=0.75).In the interest of simplicity, approximation through experimental tuning of the discharge coefficients was deemed sufficient [17].

2.2. Expansion and compression strokes

Because it is assumed that gas has no heat exchange with the exterior, the processes of expansion and compression are considered as isentropic processes. The pressure, temperature, and work of the whole process can be calculated by using the isentropic process formula.

$$P_{fi} = P_c \times \left(\frac{V_{st}}{V_{fi}} \right)^{\gamma} \tag{4}$$

$$T_{fi} = T_c \times \left(\frac{P_{fi}}{P_c} \right)^{\frac{\gamma-1}{\gamma}} \tag{5}$$

$$W = \frac{1}{1-\gamma} \times \left(P_{fi}V_{fi} - P_{st}V_{st} \right) \tag{6}$$

where W is work, the subscripts fi and st respectively indicates the end and start of the isentropic process.

2.3. Exhaust stroke

Because there is a greater pressure difference between the cylinder pressure and the atmospheric pressure during the exhaust process, fluid resistance is generated. Therefore, the mass flow rate is calculated by the fluid resistance method.