Energy 90 (2015) 516–524

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Modified intake and exhaust system for piston-type compressed air engines

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ARTICLE INFO

Article history:
Received 9 January 2015
Received in revised form
15 July 2015
Accepted 16 July 2015
Available online 13 August 2015

Keywords:
Rotary intake and exhaust system
Compressed air engine
Piston-type engine

ABSTRACT

This study investigated a modified intake and exhaust system for piston-type compressed air engines. A conventional 100-cm^3 four-stroke internal combustion engine was modified to a two-stroke compressed air engine and its output power and fluid properties at various intake pressures and rotational speeds were examined. The torque output, airflow rate, and cylinder pressure were recorded; these values reflected the fluid characteristics of the compressed air engine during operation. The conventional engine design uses a cam mechanism for controlling the intake and exhaust valves, wherein the valves open and close gradually. To overcome this drawback, a rotary intake and exhaust system was designed in which the valves open and close quickly. This new system is operable at air pressures as high as 13 bar, and the operating cylinder pressure rises faster than it does in systems featuring the conventional cam mechanism. Air engines installed with the new rotary intake and exhaust system yield an output power of 2.15 kW and a torque of 15.97 Nm at 13 bar.

1. Introduction

Over the recent decades, energy conservation and carbon emission reduction, crucial global concerns, have drawn considerable attention. Because exhaust from motor vehicle IC (internal combustion) engines contributes largely to carbon emissions, determining alternative energy sources for engines with reduced emissions is the focus of intense research. Hybrid electric vehicles with battery-powered electric motors are being extensively used. However, the slow recharge rates and the heaviness of electric motors have hindered their use in other applications. Compressed air engines have been studied for use in motor vehicles as the main or auxiliary power systems. The feasibility of compressed air as a vehicular energy source has been investigated; for example, conventional IC engines have been modified to create air engines driven by compressed air during the power cycle. Because air engines do not have a combustion cycle, they do not pollute the air [1]. Automotive companies, such as Motor Development International and Toyota, have developed AirPod and Ku:Rin, conceptual green energy vehicles that use compressed air as the main power source.

In addition, compressed air can serve as auxiliary energy sources and in conventional IC engines for supercharging during combustion to improve engine performance. Schechter first presented a hybrid system consisting of an air-powered engine, air compressors, and an IC engine in which the vehicular kinetic energy is converted during braking to the potential energy of compressed air stored in the air tank [2]. Higelin et al. reported that the engine compression braking method recovers a considerable amount of compressed air for starting engines in the New European Driving Cycle [3]. Andersson et al. proposed a regenerative braking system featuring two storage tanks for a typical city bus. Regenerative braking systems with only one tank were incapable of producing high torque in the compression braking and air motor modes. Thus, Andersson et al. focused on using pressurized air instead of atmospheric air for cylinder charging [4]. Lee et al. proposed a hybrid pneumatic power train in which two shutoff valves connected to a convenient access hole in the engine cylinder enable the cylinder to operate as a regenerative compressor and expander when required [5]. Tai et al. utilized four fully-flexible camless valves (two intakes and two exhausts) for each cylinder. In this configuration, one intake valve is switchable and connects either the intake manifold or the air tank to the cylinder through a three-way valve. Their air hybrid engine improved fuel efficiency by 64% for city driving and 12% for highway driving [6]. Dönitz et al. presented a modified engine with a conventional combustion mode and obtained fuel

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http://dx.doi.org/10.1016/j.energy.2015.07.085
0360-5442/

savings of as much as 35% in the NEDC-95 drive cycles [7]. Their approach enables the IC engine to operate at the optimal fuel consumption rate when powering the air compressor, which improves IC engine fuel efficiency and reduces emissions.

An advantage of compressed air engines is their ability to recover energy during braking, thereby further improving engine efficiency. Huang et al. presented a hybrid pneumatic power system, a small IC engine coupled with an air compressor, in which the waste heat from the engine is recovered and converted to mechanical energy in the pneumatic engine [8]. With optimization of IC engine and recycle of exhaust heat, Huang et al. have demonstrated 18% higher efficiency than an IC engine and 33% of the power output which is transferred to the wheels [9]. Fang et al. used waste heat to heat the cylinder walls of pneumatic engines, which optimized expansion and increased the engine efficiency by approximately 15% [10]. Compressed air can serve as the supercharging gas for improving engine performance. A similar concept was developed by Voser et al. [11]. The successful applications of compressed air systems and their ease of integration with IC engines have attracted the interests of the energy sector, in which the systems can be used as secondary power systems in the future. Kumar et al. proposed a new structure of single-stage reciprocating air-powered engine utilizing compressed air. It can convert the reciprocal motion of piston into rotary motion of the output shaft for the pneumatic transmission system [12]. Fazeli et al. proposed the enhancement of regenerative braking efficiency and energy storage capacity with additional storage tank. The experimental results show at least 70% improvement in storing pressure and 125% improvement in the capability of energy storage during the regenerative braking process using the double storage system [13]. Another application of compressed air engines is the hybrid system with conventional IC engine for low engine speed condition. It could be accomplished by injecting compressed air into the engine cylinder if the engine is operating at low speed with less power requirement. The engine can be switched back to normal combustion mode when needed [14].

To study the application of compressed air engines as main power systems in motor vehicles, a high energy density is realized by increasing their storage pressure to several hundred bar [15]. The intake and exhaust systems were examined using the conventional crankshaft-driven cam system. To ensure smooth running and fast response, airflow was controlled using a simple cam mechanism in the compressed air system [16]. Conventional mechanical valve trains generally use valve timings and lifts determined depending on the cam mechanism. The lack of flexibility in camshaft-based valve trains for varying the timing, duration, and lift of intake valves is a major disadvantage [17]. The open and close duration, angle, and pressure of the intake and exhaust valves substantially influence air engine efficiency. Thus, a novel rotary intake and exhaust system was designed for overcoming leakage under high air supply pressure in the cam system, and a quick open-and-close response was achieved during operation.

2. Theoretical analysis

A theoretical model of the air engine was developed using compressible flow [18] and thermodynamic models [19] of the piston-type air engine. The following assumptions simplified the theoretical analyses. 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 outside environment during operation. 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

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, mass flow rate is calculated via 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 ideal gas.

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

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

$$P_c = (m_c \times R \times T_c)/V_c \tag{3}$$

where M_{in} is Mach number of inlet air, P is pressure, the subscripts c and in indicate the cylinder and inlet air, respectively, γ is heat capacity, $\dot{m}_{in}$ is mass flow rate, R is air constant, A is valve area, T is temperature, and C is discharge coefficient of 0.75, in the interest of simplicity, approximation through experimental tuning of the discharge coefficients was deemed sufficient [20].

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 can be considered as isentropic processes. The pressure, temperature, and work of the whole process can be calculated by using the isentropic process formula.

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

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

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

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

2.3. Exhaust stroke

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

$$\dot{m} = \rho^{*} \times a^{*} \times A^{*}C \tag{7}$$

$$\rho^{*} = \rho_c \times (2/(1+\gamma))^{1/(\gamma-1)} \tag{8}$$

$$T^{*} = T_c \times (2/(1+\gamma)) \tag{9}$$

$$a^{*} = \sqrt{\gamma \times R \times T^{*}} \tag{10}$$

where $*$ is throat.