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Review

A review of compressed air energy systems in vehicle transport

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ABSTRACT

Emission free compressed air powered energy system can be used as the main power source or as an auxiliary power unit in vehicular transportation with advantages of zero carbon emissions and improved the overall energy efficiency of the integrated energy system. This work presented a detailed technological development of compressed-air energy systems. The studies on compressed-air powered powertrain in transport sector are summarised including the design of new valve technologies, prototype developments, and integration of the system. Furthermore, compressed-air based hybrid technologies using different pneumatic hybridisation methods are comprehensively presented aiming to provide in-depth insight on the advantages and limitations of different pneumatic hybridisation. The opportunities and challenges for the compressed-air based technology in transport application are discussed. It can be expected the transformation of energy systems to a cleaner and more sustainable future would promote the technological development and implementation of Zero-Emission compressed air solutions.

1. Introduction

As one of the potential technologies potentially achieving zero emissions target, compressed air powered propulsion systems for transport application have attracted increasing research focuses [1]. Alternatively, the compressed air energy unit can be integrated with conventional Internal Combustion Engine (ICE) forming a hybrid system [2,3]. The hybrid powertrain system can be recognised as a transition vehicle propulsion system between the fossil-fuelled combustion engine and zero-emission propulsion system such as electric power unit or compressed air powered unit [4]. The hybrid powertrain is currently one of the most feasible solutions to improve fuel economy and reduce the emissions with relatively overall low capital cost compared to the electric powertrains using Lithium-ion batteries. A hybrid powertrain consists of two power units, including an internal combustion engine and an auxiliary power unit with a clean energy source such as a battery or compressed air unit. The hybrid powertrain enables conventional fossil-fuelled ICE to be operated at optimised conditions with lower fuel consumption and reduced pollutant emissions [5].

This study aims to present a comprehensive review addressing the research challenges and potential future development strategies on the application of compressed air energy technology in the vehicle propulsion system. Differently as two previously published articles by Mavarnia et al. [1], who reviewed the layout of compressed air propulsion system with the major focuses on the working principle and structure of the compressed air powered engine, and Wasbari et al. [5], who focused on the structural design, components and technical breakthrough of compressed air hybrid technology for the vehicle application, this article provides a comprehensive discussion on the compressed air power generation technology and summarises its historical and state-of-art applications in the transport sector.

2. Compressed air powertrain

2.1. Historical development of compressed air powertrain

Before the invention of the fossil-fuelled Internal Combustion Engine (ICE), compressed air powertrain was widely used as the power source in locomotive transportation for over half a century due to its simplicity, safety and low cost. Locomotive engines driven by compressed air were extensively developed during the 1880s and 1890s by companies such as General Herman Haupt. In 1886, Louis Mekarski developed the Mekarski locomotive system as illustrated in Fig. 1 using a single-cylinder compressed air engine, which a hot water tank heater was

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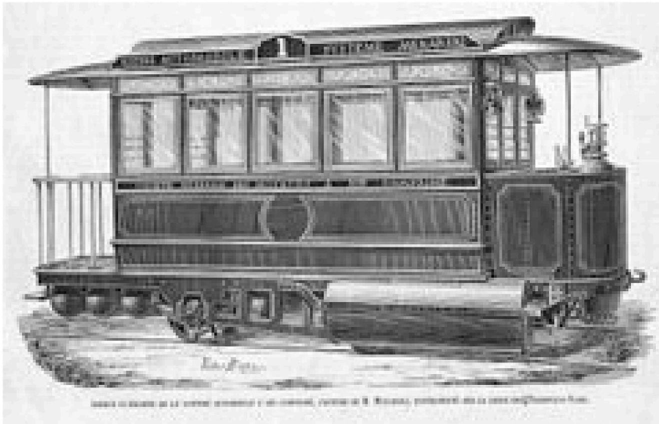

Fig. 1. Compressed air locomotive by Mekarski [6].

used to heat compressed air before the expansion in the engine cylinder [6]. Robert Hardie further developed the concept by adopting an advanced re-heating system on a one-stage expansion engine with the capability of regenerating engine brake energy [7]. A two-stage air--powered engine called Hoadley-Knight system was developed for the purpose of extending the operating distance of the locomotive before recharging the system [8]. The Hardie system and Hoadley-Knight system were both operated in New York USA during 1880–1900, and the compressed air was supplied from a 1500 horsepower steam-powered air compressor station. During that time, the air-driven locomotive was also used in coal mines. The compressed air-driven locomotive will not generate enormous heat or spark during the operation, which eliminate the risk of explosion and therefore safer than its main competitor the Internal Combustion Engine.

The application of compressed air in the transport application began to shrink in the 1930s due to the emergence of highly efficient fossil-fuelled ICE. After the World War II, the dramatical reduction of fossil fuel price promotes the commercialisation and development of gasoline and diesel engines for the vehicle or locomotive application leading to the disappear and replacing of the compressed air driven engines from the road. However, the research interests and technological developments on the compressed air propulsion system emerged once again in the 1970s because of the concerns on the energy crisis and environmental problems. Table 1 shows the inventions of compressed air powered vehicles during the 1970s. The first compressed air-powered vehicle is called the Troyan air mobile developed by the inventor Joseph P. Troyan using the air-powered flywheel in a closed system. Willard Truitt presented his aircar invention in the late 1970s, which was later sold to the U.S Army and NASA in 1982. In 1974, Russel R. Brown of Texas claimed to have invented the first compressed air-powered vehicle. Sorgato invented a compressed air driven the car in Italy that used 9 air bottles with the pressure of 2840 psi in 1975. In 1976, Ray Starbard invented a compressed air truck in Vacaville, California [9]. In 1979, Terry Miller designed a spring-powered car and demonstrated that compressed air was the ideal energy storage medium. In 1993, Terry Miller jointly developed an air-driven engine with Toby Butterfield and the car was named as the Spirit of Joplin air car. Terry Miller's invention is a milestone for the research on the application of compressed air propulsion on vehicles. Inspired by Terry Miller's work, several studies have conducted in the following decades. The interests on the compressed air-powered vehicle were stimulated by the announcement of a prototype for commercial production. In 1992, French engineer Guy Negre proposed the design of a compressed air-powered vehicle. As described in the design, the prototype vehicle could run 200 km using 300 L of compressed air (300 bar) stored in either carbon or glass fibre tanks. It was estimated to take about 2–3 min at a price of 1.5 euros to fill up the air tank [10].

Table 1
Inventions of compressed air propulsion system during the 1970s.

	Inventor	Year	Nation
1	Joseph P. Troyan	The 1970s	USA
2	Willard Truitt	The 1970s	USA
3	Russel R. Brown	1974	USA
5	Vittorio Sorgato	1975	Italy
6	Ray Starbard	1976	USA
7	Terry Miller	1979	USA

2.2. Working principles of compressed air powered engines

In a compressed air propulsion system, the energy is usually converted by the engine into mechanical power through the expansion of compressed air in the cylinder. Fig. 2 illustrates the working process of a common compressed air powered engine. The reciprocating piston structure is similar to that of a conventional internal combustion engine except that compressed air powered engine has no fuel injector or spark plug. The working cycle of the engine is composed of 2 strokes, known as expansion and exhaust. It should be noted that the intake process happens at the beginning of the expansion stroke. The intake valve usually opens when the piston moves to the Top Dead Centre (TDC), and the compressed air flows into the cylinder from the air tank. After the intake valve is closed, the compressed air trapped in the cylinder continues to expand until the piston reaches the Bottom Dead Centre (BDC). The exhaust valve opens after the expansion process, and the compressed air is pumped out of the cylinder with the upwards movement of the piston.

The majority of studies conducted on compressed air powered engine were based on the reciprocating piston structure during the past decade. Liu et al. [11,12] established the mathematical models for compressed air powered engine and analysed the working characteristics of the engine under both single-stage and two-stage expansion. The results presented that an engine with reciprocate piston was the ideal structure for a compressed air powered engine. Yu et al. [13] analysed the theoretical cycle of compressed air powered engine and concluded that the work output of the engine was in linear positive correlation with the initial temperature of the expansion process, and a possible method to increase the work output of the engine was to introduce a multi-stage, quasi-isothermal expansion of compressed air. Liu et al. [14] reported the optimisation design on the theoretical cycle of the compressed air powered engine using multi-objective optimisation method. The study demonstrated the maximum cycle efficiency can be obtained under the engine intake pressure ratio and the compression ratio respectively at 32 and 13. Optimal design for the trajectory of the reciprocating piston was also proposed by introducing a dual crankshaft mechanism [15]. The simulation showed that the piston could remain still before the

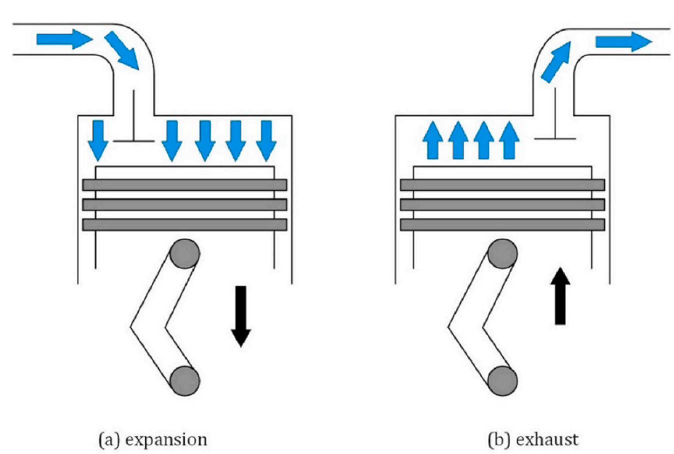

Fig. 2. Working process of a reciprocating piston compressed air engine [2].

in-cylinder pressure rose to the intake pressure when the optimised piston trajectory was adopted. In addition, the piston velocity could be linearly dependent on the flow area of the intake valve until the in-cylinder pressure of the engine reached the maximum and then remained constant after the intake valve was closed. Hu et al. [16] conducted transient analysis on the in-cylinder flow field of the compressed air powered engine to study the energy distribution during its working process and found that the turbulence near the intake port could lead to the severe energy loss of compressed air. A research group from Beijing University of Aeronautics and Astronautics conducted virtual modelling and performance analysis on the compressed air powered engine [17,18]. The simulation model developed [17] by this team was validated by an Air-Powered Engine (APE) [18]. A virtual prototype with a newly developed valve system was developed to study the dynamic performance of the air-power engine and optimised valve controlling strategies were investigated, making contributions towards the theoretical understandings on air-power engine technology. Following the previous progress, the team further developed the dynamic heat transfer to investigate the temperature drop during operational conditions of the air-powered engine [19]. Additionally, a temperature compensation technology [20] was proposed to eliminate the risk of ice blocking as a consequence of the throttling effect during the flow of compressed air. Ethanol alcohol was used as the heat exchange medium in the temperature compensation system, and the simulation results showed that the efficiency of the compressed air powered engine could be improved by almost 30% when temperature compensation was adopted. Yu et al. [21] designed a double crank link mechanism to optimise the performance of reciprocating piston engine. The results showed that the in-cylinder pressure was barely influenced by the engine speed when equipped with a double crank mechanism, meanwhile, the energy efficiency could be improved by 1.86–2.86 times. Except for the reciprocating piston type engine, research attempts have also been made on other types of compressed air powered engines. Selected compressed air engines with different types of expansion machines previously reported are listed in Table 2.

Positive displacement machinery such as piston expanded, scroll expander and screw expander are popular as a power generation unit. However, the piston expander suffers from the disadvantages due to its low overall efficiency, complex structure, easy wearing and high noise issues. Therefore, He et al. [23] adopted and designed a single screw expander to potentially solve the above problems. The working process of the single screw expander (see Fig. 3) was composed of three stages: air admission, air expansion and air discharge. In the beginning, the inlet compressed air with a certain pressure pushed rotor running in the revolution, and the gate rotor rotated with the rotor at the same time. During the expansion process, compressed air expanded in the closed volume formed by a spiral groove, gate rotor tooth and bodyshell as the rotor rotated. A prototype screw expander as shown in Fig. 4 was manufactured based on the principle described above, and an experimental system was established for the performance study [26]. The results showed that the highest overall efficiency could reach 55% under the intake pressure of 1.5 MPa at the speed of 2800 r/min, meanwhile the largest torque could nearly reach 100 N m, and the biggest power output could amount to about 22 kW with the lowest air consumption of about 60 kg/kW·h.

As illustrated in Fig. 5, Xu et al. [25] proposed a novel type of compressed air powered engine based on a twin-rotor mechanism. Results indicated that the prior advantage of the twin-rotor structure was that it allowed the volume of each cylinder varies four times during one revolution of the output shaft due to the special differential velocity driving system. Therefore, the twin-rotor piston engine was equivalent to an air-powered reciprocating engine with 32 cylinders of the same cylinder displacement. The simulation results showed the maximum torque of the twin-rotor compressed air powered engine was 100 N m at 450 r/min under the intake pressure of 0.6 MPa, which was nearly three times of a reciprocating piston engine.

Table 2
Compressed air engines with different types of expansion machines.

Item	Year	Author	Type[a]	Engine type	Conclusions
1	2009	Shen et al. [22]	E	vane type air motor	The efficiency is above 70% when the motorcycle speed is over 20 km/h. The power consumption is about 0.073 kWh per kilometre compared to 0.127 kWh per kilometre for conventional d internal combusting engine motorcycle. Transportation distance should be improved.
2	2010	He et al. [23]	E	single screw expander	The highest overall efficiency is 55%, the largest torque is nearly 100 N m, the biggest power output is about 22 kW and the lowest gas consumption is about 60 kg/kW h.
3	2012	Zhang et al. [24]	E	scroll expander	The maximum air mass consumption rate is 800 kg/h, the maximum power is 8.112 kW, and the maximum efficiency is only 0.26
4	2015	Xu et al. [25]	N	twin rotor piston engine	The maximum output torque is 100 N m at 450 r/min under the gas pressure of 0.6 MPa.

[a] N: Numerical simulation; E: Experimental study.

2.3. Design and optimisation of the valve system

The energy conversion processes of the compressed air determine the performance of the compressed air powered engine. It is therefore critical to control and optimise the intake and exhaust process to reduce the flow losses. Many studies were conducted on the design, simulation and experiment of the valve system to achieve an optimised performance and efficiency of the compressed air powered engine.

For example, Jia et al. [27] studied the pressure reduction process of compressed air during the intake process and concluded that the energy efficiency could be improved by 15–40% when adopting pressure reduction by expander instead of throttling depressurisation, and the energy conversion capability of compressed air could be increased by 10–60% if a two-stage pressure reduction was adopted. In addition, high pressure on/off valve with its relative control algorithm was designed for the compressed air powered vehicle system. Cai et al. [28] proposed a rotational valve system driven by a sprocket wheel connected to the crankshaft. A mathematical model of the intake and exhaust process was established based on the rotational valve system, and the influence of the valve timing on the performance of compressed air powered engine was studied. The results showed that the most optimised valve timing is that the intake valve opened at the Top Dead Centre (TDC). Zhang et al. [29] designed a valve system with a polynomial cam profile and simulated the influences of the half wrap angle and the maximum valve lift to the fullness coefficient. It was concluded that designed cam profile should use the minimum valve lift to receive the maximum fullness coefficient. Xu et al. [18] applied the orthogonal design with grey relation analysis to optimise the valve timing parameters of the compressed air powered engine and proposed the ideal values of cam rise angle and cam return angle. Yu et al. [30,31] developed a mathematical model of a compressed air powered engine and validated the simulation in an experiental prototype. A pressure-compensated intake valve was designed and introduced to study the structural parameters design method. They concluded the efficiency of the compressed air power engine is by the dimensionless exhaust pressure, the intake duration angle and the dimensionless cylinder clearance. Results indicated under

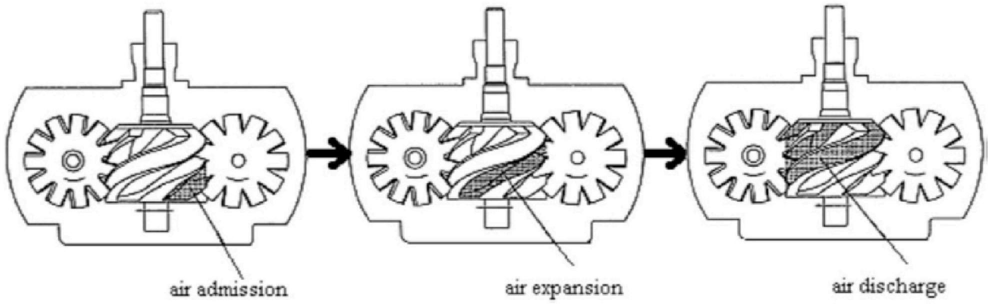

Fig. 3. Working process of a single screw expander [26].

Fig. 4. Photo of a single screw expander prototype [26].

the optimal working condition, the performance of the air-powered engine could be improved from an original 21.95%–50.1%, and the average output torque increases from 22.047 5 N m to 22.439 N m [31].

Full Variable Valve Actuation (FVVA) can also be applied for the valve system design of the compressed air powered engine. An FVVA system can change valve timing flexibly according to the working condition of the engine. The schematic diagram of such system is illustrated in Fig. 6. Chen et al. [32] designed an electro-pneumatic variable valve system driven by waste energy during the pressure-reduction process of compressed air. As shown in Fig. 7, the system composed of a piston, a pneumatic cylinder, two standard three-way solenoid valves, piston rings and springs. Before the operation, one of the solenoid valves was set to open, and the other was set to close. When the solenoid valves were energised, the control air, produced during the pressure-reduction process, would flow into the chamber B and push the piston to the left end, forming a flow path of compressed air from the air tank to the engine cylinder. When both solenoid valves were de-energised, the control air flowed into chamber A to push the piston to the right side, thus cutting off the air supply of the engine. The valve timing could be adjusted by changing the time of the electrical pulse applied to the

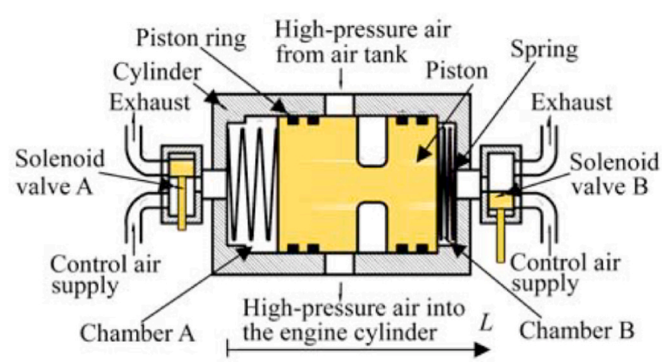

Fig. 6. Schematics of the electro-pneumatic variable valve system [32].

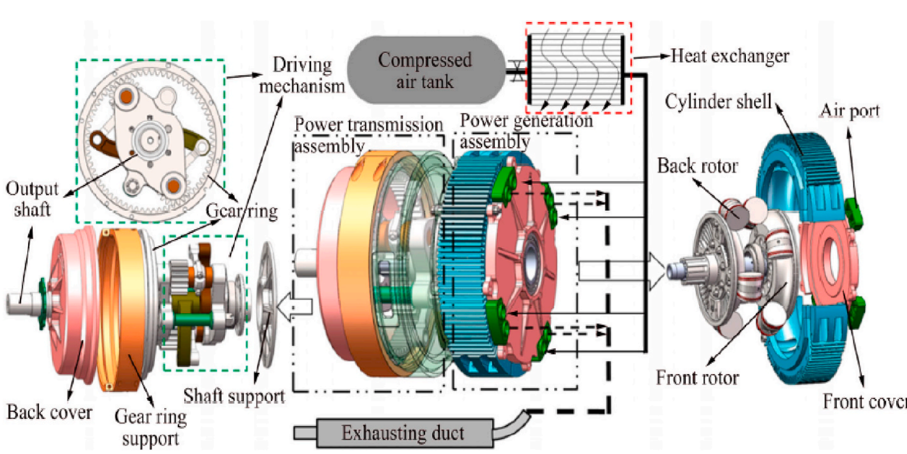

Fig. 5. Schematic of the twin-rotor air-powered engine [25].

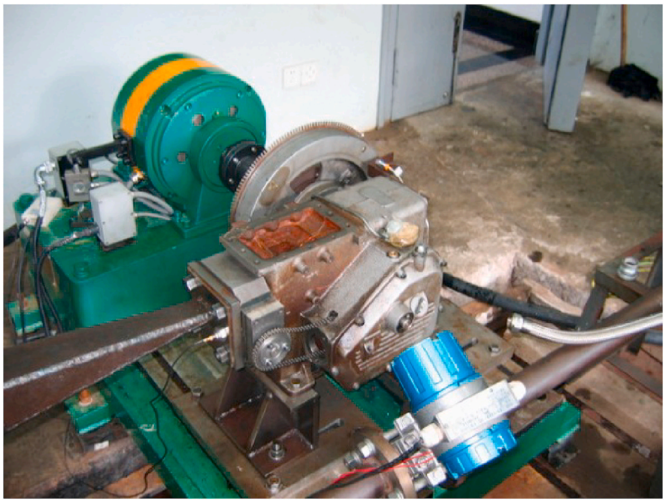

Fig. 7. Prototype of compressed air powered engine at Zhejiang University [35].

solenoid valves. An experimental system was established to verify the flexibility of the electro-pneumatic valve system. The results showed that the working frequency of the valve system was observed to reach 30 Hz, corresponding to the engine speed of 2000 r/min, almost covering the whole speed range of the compressed air powered engine. Koca et al. [33] and Lian et al. [34] also conducted studies on the design and control strategy of FVVA for the compressed air powered engine.

2.4. Experimental studies of prototypes

The experimental studies on the compressed air powered engine are important providing valuable quantitative data to validate the theoretical investigation on the system and optimise the valve control strategies and design. The majority of prototypes are constructed in the research intuitions by the modifications of conventional ICEs. For example, the authors' team at Zhejiang University modified a single-cylinder diesel engine into a compressed air engine prototype [35]. The engine had a bore of 85 mm, with natural inspiration intake system. During the modification, the cylinder head of the original engine was removed and replaced by a rotational valve system [28]. An experimental system was established to study the performance of the prototype as shown in Fig. 8. The results showed that the maximum power reached was 2.6 kW under the intake pressure of 0.8 MPa, and the power decreased linearly with the speed when the prototype worked under constant intake pressure, while the air consumption increased dramatically with the speed. While working under constant speed, the power increased with the rise of intake pressure, meanwhile a drop of air consumption was observed. It was concluded that compressed air powered engine could achieve best performance when it was operated in low speed and high load regions.

Huang et al. [36] from National Tsing Hua University developed a prototype compressed air engine modified from a 100 cm^3 ICE originally used on a motorcycle. The original cam mechanism of the ICE was kept for the valve system of the prototype. The cam profile was modified to be conjugate to change the engine from 4-stoke to 2-stroke operation, with the maximum valve lift reduced from 5 mm to 2 mm. The experimental results showed that the maximum power reached at 0.96 kW under the intake pressure of 0.9 MPa, while the flow rate of compressed air varied from 500 L/min to 1050 L/min as the speed changed from 500 r/min to 2000 r/min. The highest efficiency observed during the experiments was 13%, which was possibly caused by the restriction of the valve system on the intake and exhaust flows. In addition, the under-expansion of compressed air inside the cylinder was concluded as the main effect leading to the limited efficiency of the prototype. In order to solve the problem, and optimisation design on the valve system was proposed by replacing the original camshaft with a rotary intake and exhaust system [37]. The new valve system was operated at air pressures as high as 1.3 MPa, and the operating cylinder pressure rose faster than that of the previous system featuring the conventional cam mechanism. The prototype engine installed with the new rotary intake and exhaust system yielded an output power of 2.15 kW and a torque of 15.97 Nm under the intake pressure of 1.3 MPa. And it was installed on a motorcycle to conduct road tests [38]. The test results showed that the motorcycle installed with the compressed air engine could operate at the maximum speed around 38.2 km/h for 5 km.

Although other approaches by using alternative expansion machines for compressed air powered engines were also conducted by the researchers, the mainstream of this research topic is still focusing on recuperating piston engine. For example, Zhang et al. [24] developed a prototype compressed air powered engine based on a scroll expander. An experimental system was established to study the performance characteristics of the prototype. The results showed that the air mass consumption rate and the output power both increased with the engine speed. The maximum air mass consumption rate was 800 kg/h and the maximum power achieved 8.112 kW when the intake pressure was 2 MPa. The maximum efficiency was limited to 26%, which was concluded because of the manufacturing limitation and assembly accuracy of the prototype.

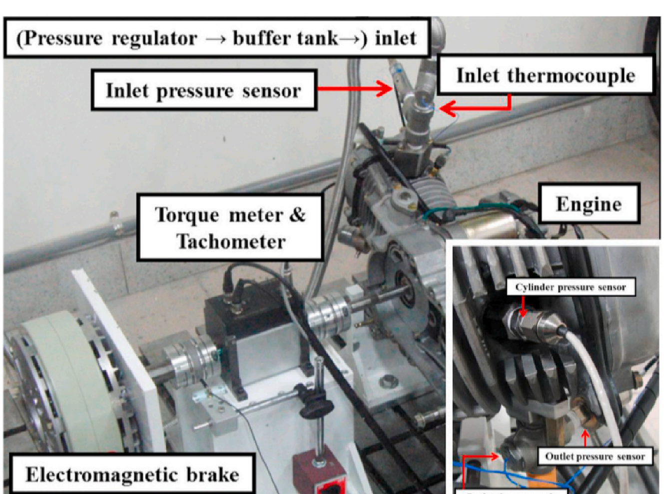

Fig. 8. Prototype compressed air engine at National Tsing Hua University [36].

2.5. Integration for vehicle application-the current commercialisation status

Various attempts have been made on the development of compressed air vehicles by some car manufacturers. The first prototype of a compressed air vehicle named AIRPod shown in Fig. 9, was released by MDI in 1998, later MDI released a series prototypes including OneFlowAir, CityFlowAir, MiniFlowAir and MultiFlowAir. MDI claimed that the compressed air vehicle would be under production in 2000, however further information has been released. Tata Motors of India is another car manufacturer working on the compressed air-powered vehicle. In 2009, Tata planned to launch an air-powered vehicle with an MDI compressed air engine. In February 2017, Tim Leverton, president and head at Advanced and Product Engineering, Tata Motors announced to commercialise the concept and target to release the first vehicle by 2020 [39].

Other reports indicate Tata is also looking at reviving plans for a compressed air version of the Tata Nano [41], which had previously been under consideration as part of their collaboration with MDI. Except for MDI and Tata Motors, there were other companies that have worked on compressed air powered engine. For Example, EngineAir of Australia

Fig. 9. AirPod, the compressed air-powered vehicle by MDI.

developed a rotary air engine called 'Di Pietro motor' based on a rotary piston [40] (see Fig. 10). Different from existing rotary engines, the Di Pietro motor uses a simple cylindrical rotary piston (shaft driver) which rolls without any friction inside the cylindrical stator.

Prototypes of compressed air vehicle were also developed in research institutes. The State Key Lab of Fluid Power Transmission and Control at Zhejiang University designed and manufactured the first compressed air-powered vehicle in 2004 [42]. The prototype vehicle as shown in Fig. 11 had a mass of 1820 kg and was equipped with 4 air tanks with a volume of 50 L. A compressed air powered engine, modified from a 4-cylinder gasoline engine, was installed on the vehicle to supply power. During the road test, the initial tank pressure was 12 MPa, and the intake pressure of the engine was 1.2 MPa. The results showed that the average power of the vehicle was 2.673 kW under the speed of 30 km/h, and the adiabatic thermal efficiency reached 24.15%. The prototype vehicle could run for 1870 m without charging compressed air. In addition to the studies mentioned above, there are other studies included the simulation of compressed air vehicle [43] and the development of fuzzy-logic control [44].

2.6. Summary

In summary, several studies were conducted on compressed air powered propulsion since the 1990s, resulting in the release of various prototype engines and vehicles. However, the application of compressed air propulsion on vehicles is not that popular compared to other alternative energy technologies such as BEV or HEV. A few technological barriers as summarised below.

Fig. 10. Compressed air-powered vehicle by EngineAir, Australia [40].

Fig. 11. The first compressed air-powered vehicle in China developed and tested at Zhejiang University [42].

- The relatively low energy density of compressed air could lead to a poor dynamic performance of the engine or vehicle. Liu et al. [45] calculated the energy density of compressed air to be 370 kJ/kg under the storage pressure of 20 MPa, which is much lower than that of diesel or gasoline. To ensure the continuous supply of compressed air during the operation, the power of the engine or the vehicle speed must be limited. Meanwhile, the volume of the air tank must be large to contain enough amount of compressed air, leading to difficulties in the spatial arrangement.
- The high energy loss of compressed air during the operation is the other main technical barrier. Due to the low energy density, it is necessary to increase the storage pressure of compressed air to ensure the air supply, which could lead to severe throttle loss of compressed air when it is released from the air tank. During the working process of the compressed air powered engine, the in-cylinder pressure is usually higher than the ambient after the expansion of compressed air, which means that the energy of compressed air is not sufficiently converted to power output, which could also lead to the pump loss of the engine during the exhaust process. In addition, compressed air could experience high flow loss during the intake process due to the high flow velocity and structure of the valve system [46].
- Due to various energy losses, the efficiency of the compressed air powered engine is rather low compared to conventional ICE. Both simulations and experiments showed that the efficiency of the compressed air powered engine is around 20%, which is the main disadvantage of compressed air powered systems compared to that of BEV and HEV.
- The throttling process of compressed air produces low temperature at certain spots of the pipes or valves according to the Joule-Thomson effect, which may result in ice-blocking problems of the engine after long-term operation.

3. Compressed air hybrid powertrain

Compressed air powered powertrain shows unique advantage due to its environmental benefit since air is the only emission. However, the application of compressed air powered engine is limited due to several technical flaws including low efficiency and the source of compressed air. Compressed air powered powertrain could be more suitable to serve as an auxiliary power unit in a hybrid powertrain. Such compressed air hybrid system can be realised on the vehicle by combining two independent types of propulsion subsystems including a compressed air powered engine and a conventional ICE. During the past a few decades, various studies have been reported on different kinds of compressed air hybrid systems. For example, a prototype 'hybrid compressed air' vehicle, developed by PSA Peugeot Citroen, was demonstrated in Geneva Auto show in 2013 [5]. PSA claimed that this technology has the same effect on the fuel economy as the hybrid electric, with less complexity in system arrangement and lower cost. This technology is not the only attempt to use compressed air as an alternative energy source for vehicle propulsion, which will be further explained in the following sections.

3.1. Regenerative braking energy from the vehicle

The principle of regenerative braking is to recover the waste kinetic energy of the vehicle during the braking phase and transform into available energy, such as battery power. Similarly, regenerative braking can be used to produce compressed air in a compressed air hybrid system. The main difference is that battery energy is recovered through the charging process based on chemical reaction, while compressed air is produced by the compression process of a compressor. Compared to the hybrid electric powertrain, a compressed air hybrid system is more compact because the compression and power output can be realised on the same engine.

Schechter [49] introduced a new thermodynamic cycle that could provide a substantial improvement in automobile fuel economy in 1999, which is considered as the first researcher working on the compressed air hybrid propulsion system. The new cycle could realise the conversion of the kinetic energy of the vehicle into the compressed air. The converted compressed air was stored in an air tank and was used to assist in vehicle acceleration later. The braking process of the vehicle was replaced by compression braking, during which the fuel injection of the engine was paused, and the engine was operated as a reciprocating-piston two-stroke compressor driven from the driving wheels by vehicle motion. Air was inducted from the outside atmosphere into the cylinder, compressed and displaced in the air tank. Work performed by the piston absorbed the kinetic energy of the vehicle and realised the deceleration, thus transforming the kinetic energy of the vehicle into the compressed air. The engine could be completely shut down during the stoppage time. During acceleration, the engine could be operated as both air motor and internal combustion engine in a four-stroke air assisted power cycle. While working under air assisted power cycle, the compressed air in the air tank was inducted to the engine cylinder, expanded and performed work during the first down-stroke of the piston. Then the same air charge was used in the following combustion process, performing additional work on the piston during its second down-stroke. The engine could also be operated as a two-stroke air motor by deactivating the fuel injection and inducting the compressed air into the cylinder for expansion and work output. Schechter [47,48] proposed and conducted modifications on an engine to realise the new cycle. As shown in Fig. 12, an additional charging valve was added to each cylinder, which was connected to a charging manifold and air tank. Electronic and variable control strategies were recommended in the valve system. The simulation results showed that a 50% of fuel consumption reduction could be achieved by using the compressed air hybrid propulsion in a 45 s urban driving cycle, and the efficiency of a 'round-trip' energy conversion and recovery was estimated at 60–65% [49,50]. However, it is worth noting hereby the round trip efficiency highly relies on the pressure of the stored air. The relatively high overall round trip efficiency can only be achievable when the stored air is within the low-pressure region (for example, below 5 bar). When the stored compressed air is operating in the high-pressure region, the majority of mechanical energy would be lost as heat during the compression process. It is therefore necessary to include thermal energy storage technology to ensure a high performance compressed air energy system.

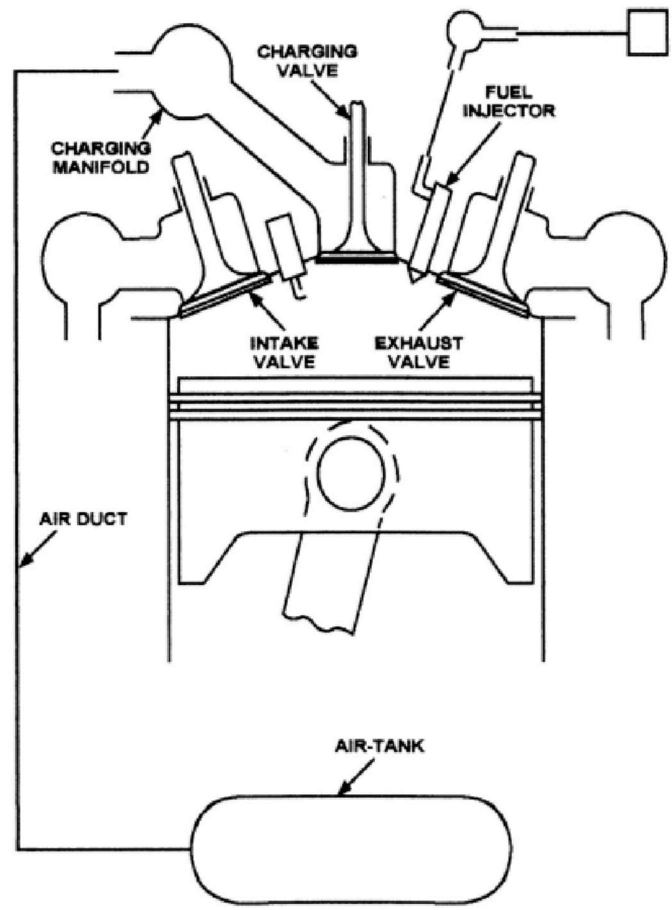

Fig. 12. Schematic of compressed air hybrid engine by Schechter [47,48].

Higelin et al. [51] furthered Schechter's study on the compressed air hybrid propulsion system. Except for the regenerative braking and pneumatic motor driving, the compressed air recovered during the braking phase could be used for engine supercharge to provide short-term boosting power output during transient acceleration in Hegelian's system. The positive effect of the pneumatic supercharging was that engine design could be optimised for the maximum power meeting 80–90% of the driving situations without supercharging, hence a downsized design could be achieved to save fuel consumption. The numerical calculation was completed based on a J4S Renault engine, and the results showed that global fuel consumption could be reduced by 15% under the New European Driving Cycle (NEDC) [52]. The fuel economy improvement could be improved to 31% by optimising the maximum tank pressure, tank volume and engine displacement [53]. However, Higelin pointed out that the regenerative braking was only applicable for harsh braking conditions since the engine friction was enough to dissipate the kinetic energy during the deceleration phase. Brejaud et al. [54–56] improved Higelin's work by proposing an intermediate heated tank on the pneumatic hybrid combustion engine design. The exhaust gas produced during the conventional internal combustion engine mode was used to raise the temperature of the compressed air. The simulation showed that the fuel consumption saving could reach 26% under NEDC and 46% under the Worldwide Harmonized Light Vehicles Test Procedure (WLTP). An experimental study was also conducted on a single-cylinder spark-ignition engine with a displacement of 347 cm^3.

Andersson et al. [57] announced that the compressed air hybrid concept by Schechter could only absorb and produce low power levels, hence its application was limited to a passenger car. In order to expand its application to heavy-duty vehicles, the original compressed air hybrid design was improved by placing two air tanks with different pressure levels. The simulation showed that a city bus with the compressed air hybrid propulsion system could achieve a fuel consumption reduction of approximately 23% under Braunschweig cycle. Trajkovic et al. [58,59] designed pneumatic valve actuators and converted a Scania D12 single-cylinder diesel engine for compressed air hybrid operation (see Fig. 13). Both compression-braking mode and air motor mode were tested on the laboratory setup. The regenerative efficiency, defined as the ratio between the energy produced in air motor mode and the energy recovered during compression braking, was around 33%. A pressure compensated tank valve with a larger valve head diameter (28 mm) was also equipped on the tested engine. The results showed that the regenerative efficiency could be improved to 48% if the tank valve diameter was enlarged.

Based on the experimental results, Trajkovic et al. [60–64] conducted modelling investigation on the compressed air hybrid system using GT-Power software. The simulation results showed that a reduction in fuel economy of up to about 30% could be achieved for a pneumatic hybrid bus on the Braunschweig duty cycle. According to the conclusion, the main part of the fuel consumption reduction was contributed by the stop/start functionality of the system, while regenerative braking only contributed 8.4%. In addition, about 87% of braking power could be absorbed and converted to compressed air, however only 20% of this part of energy could be converted to effective work.

Donitz et al. [65–68] proposed that the most ideal compressed air hybrid engine concept was to combine pneumatic hybridisation and engine downsizing. Based on the thermodynamic modelling, analyses were conducted on both two-stroke and the four-stroke working process of the engine when driven by pure compressed air. The results showed that the results of the four-stroke pneumatic driven process were not significantly lower than those of the two-stroke counterpart. Due to its similarity to a conventional engine, the four-stroke concept of compressed air hybrid propulsion with fixed camshafts for intake and exhaust valves could easily be realised in practice. The concept was later validated after a two-cylinder gasoline engine was modified into a prototype compressed air hybrid engine MPE750, with the initial measurement completed on the test bench. The simulation showed that the combination of engine downsizing and pneumatic hybridisation achieved a fuel consumption reduction of 34% under the MVEG-95 driving cycle. Additionally, the 'turbo-lag' normally associated with heavy downsizing could be overcome with this concept by using compressed

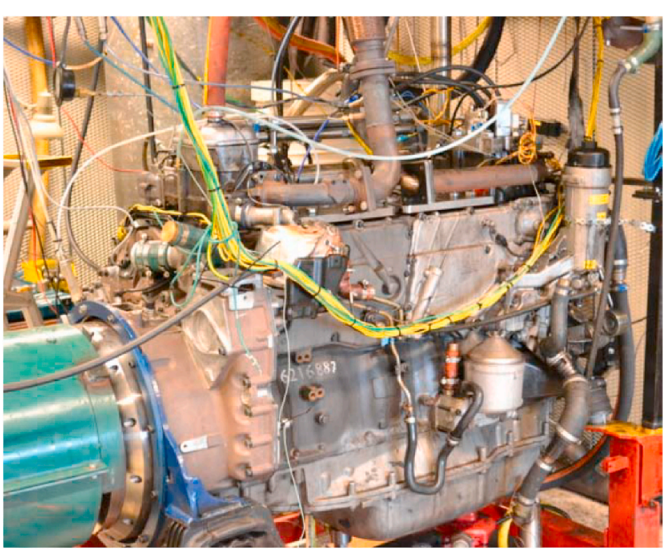

Fig. 13. Modified Scania D12 compressed air hybrid engine by Trajkovic [58,59].

air from the tank to supercharge the engine during the speed-up of the turbocharger. Later vehicle emulation tests were conducted on two compact-class series production passenger vehicles, Volkswagen Polo and Nissan Micra. Both vehicles were equipped with engines that exhibit approximately the same rated power as the MPE750. The experiment results showed that the fuel consumption of the test vehicles could be reduced by 35% and 30% under MVEG-95 cycle and FTP cycle, respectively. Voser et al. [69,70] further studied the compressed air in-cylinder boosting for the supercharged spark-ignition engine. Based on a deactivated camshaft-driven valve system, a torque control strategy was designed to compensate the turbo-lag during transient conditions, and later experimentally verified at several engine speeds and for various torque steps.

Lee et al. [71–75] studied a cost-effective mild compressed air hybrid engine concept for buses and commercial vehicles. Like the studies described above, the compressed air was converted from the braking process of the vehicle and could be used to drive an air starter and achieve regenerative braking for buses and delivery vehicles with frequent stop-start operations. The regenerative braking could also provide service air required for braking and pneumatic operations and reduce the usage of the engine-driven compressor. In addition, the compressed air could realise an instant boost to a turbocharged engine during start-up and acceleration for better performance and improved fuel economy. Based on a six-cylinder diesel engine, the potential for fuel consumption reduction was evaluated. The results showed that the fuel mass consumed during NEDC cycle was 677 g for a standard vehicle and 631.2 g for a compressed air hybrid vehicle, indicating a fuel-saving effect of 6.8% could be achieved. Furthermore, the idle process of the conventional engine could be eliminated. A single-cylinder engine equipped with Fully Variable Valve Actuator (FVVA) was also constructed to verify the feasibility of the compressed air engine concept [76].

Table 3 lists other studies on compressed air hybrid powertrains based on vehicle regenerative braking. As previously discussed, it can be summarised that the compressed air regenerative braking was mostly applied to diesel engines. It can be attributed to the fact that both the diesel engine and compressed air engine are operated at relatively low speed. It should also be noted that most studies are based on simulations rather than experiments, with few prototypes of compressed air hybrid engine reported in recent years.

3.2. Waste heat recovery from the ICE

As previously discussed, regenerative braking is the main form of pneumatic hybridisation of vehicle, which can recover brake energy stored as compressed air, then reuse this part of energy during vehicle acceleration. The pneumatic hybridisation is not limited to regenerative braking, and other energy recovery methods were also attempted during the past decades. For example, the waste heat produced during the fuel combustion of the conventional engine occupies approximately 60% of the total fuel energy in the form of engine coolant and exhaust energy [87,88], showing great potential in waste heat recovery. The compressed air could benefit from recovering the waste heat since its availability was raised after absorbing heat, leading to better performance when the engine was driven by compressed air [2].

Zhai et al. [89] proposed the compressed air hybrid system to recover the waste heat from a conventional engine for the purpose to improve the efficiency of a compressed air engine. The conventional engine and compressed air engine worked separately in the system. Different hybrid forms were modelled using simulation tools, including series, parallel and mixed-mode. Zhai et al. [89] concluded that about 13.5% and 6.7% energy from the exhaust and coolant of the conventional engine could be absorbed by compressed air when a series hybrid system was applied, while a parallel system enabled compressed air to recover 26% and 20% energy from the exhaust and coolant, respectively. In addition, cooling fan and radiator of the conventional engine could be dispensed due to

Table 3
Studies on compressed air hybrid powertrain based on vehicle regenerative braking.

Item	Year	Author	Type[a]	Subjective	Conclusions
1	2008	Hyungsuk et al. [77]	N	heavy-duty diesel engine	Efficiency improvement was 4%–18% over a wide range of applications.
2	2009	Wang et al. [78]	N	10.8 L diesel engine	A potential 4–18% fuel economy improvement over the truck equipped with the conventional baseline diesel engine was evaluated depending on the particular driving cycle.
3	2009	Ivanco et al. [79]	N	middle-class vehicle with 1.6 L gasoline engine	Different energy management strategies on compressed air hybrid powertrain were compared, and the strategy based on pattern recognition with an associated variable penalty coefficient showed the best performance.
4	2010	Basbous et al. [80]	N	wind-diesel generation system	A significant fuel economy up to 60% was obtained, especially at low loads. Using the engine cooling system to heat the compressed air before admitting it in the engine was recommended.
5	2011	Ibrahim et al. [81]	N	wind-diesel generation system	A fuel consumption reduction of 50% was expected, however there were some limits on the system, including the permeability limit of the intake valves and the mechanical limit.
6	2012	Lu et al. [82]	N	motorcycle engine	The pneumatic hybrid motorcycle can improve efficiency with an appropriate control strategy for driving operation.
7	2014	Li et al. [83]	N	7 L commercial vehicle diesel engine	The total fuel consumption could be reduced by 5.3% when applying compressed air hybrid powertrain on a 16,550 kg city bus with a six-cylinder diesel engine.
8	2015	Dimitrova et al. [84]	N	C Segment commercial vehicle with a 3-cylinder gasoline engine	An efficiency improvement of 20–50% was observed after the adoption of compressed air hybrid powertrain, and the fuel consumption results for the urban usage was 51 g CO_2/km.
9	2016	Li et al. [85]	N	diesel generator	The fuel consumption of the compressed air hybrid system was only 50% of the single-diesel unit and 77% of the dual-diesel unit.
10	2016	Wang et al. [86]	N	2-cylinder diesel engine	Urban driving-cycle simulation results showed that the fuel consumption of a light-duty vehicle with a pneumatic hybrid system could be reduced by 8%.

[a] N: Numerical simulation; E: Experimental study.

the existence of a compressed air engine. Hu et al. [90,91] and Nie et al. [92,93] followed Zhai's study by modelling the compressed air hybrid system based on exhaust and coolant heat recovery separately, proving that the performance and efficiency of compressed air engine could be improved by recovering the waste heat from the conventional ICE. The authors [94] evaluated the energy-saving potential of the compressed air hybrid system by modelling the cooling system of a 4-cylinder diesel engine and concluded that the application of pneumatic hybridisation could save 50% of cooling fan power since the waste heat contained in the coolant was recovered by compressed air.

Huang et al. [95–97] introduced another kind of compressed air hybrid system that composed of a gasoline engine, an air compressor and a pneumatic motor, as shown in Fig. 14. During the operation of the system, the gasoline engine worked at a steady speed to drive the air compressor. To realise the waste heat recovery, the exhaust of the engine was mixed with the compressed air produced by the air compressor, then the mixture entered the pneumatic motor for expansion. The advantage of the system was that the fuel economy of the gasoline engine could be optimised due to the absence of working condition variation, meanwhile the pollutant emission could be minimised. The energy merger, which connected the exhaust pipe of the engine and the outlet of the air compressor, was also studied using both CFD simulation and experiments. It was concluded that the energy merge process was significantly influenced by the cross-section area of the merging pipe, and about 80% of exhaust waste heat could be recovered under the optimised cross-section area [98,99]. The hybrid system was evaluated and demonstrated in the experiment, which has the potential to improve the vehicle efficiency to approximately 40% when the pressure of the compressed air was stabled at 8 bar [100–102].

3.3. Compressed air jet-controlled combustion

Compared to the regenerative braking and waste heat recovery, compressed air jet-controlled combustion is a different mode of pneumatic hybridisation since the compressed air is not directly involved in mechanical work output. The idea of compressed air jet-controlled combustion is a branch of jet-controlled compression ignition to realise combustion phase control in diesel hot premixed combustion system. Unlike conventional diesel diffusion combustion, the fuel and air are premixed by an advanced fuel injection timing, then the mixture is ignited by external stimulator such as LPG flame jet [103]. This kind of combustion was proved of higher thermal efficiency and lower pollutant emission. Compressed air could serve as one of the external stimulations to ignite the premixed diesel-air mixture since the high-pressure jet

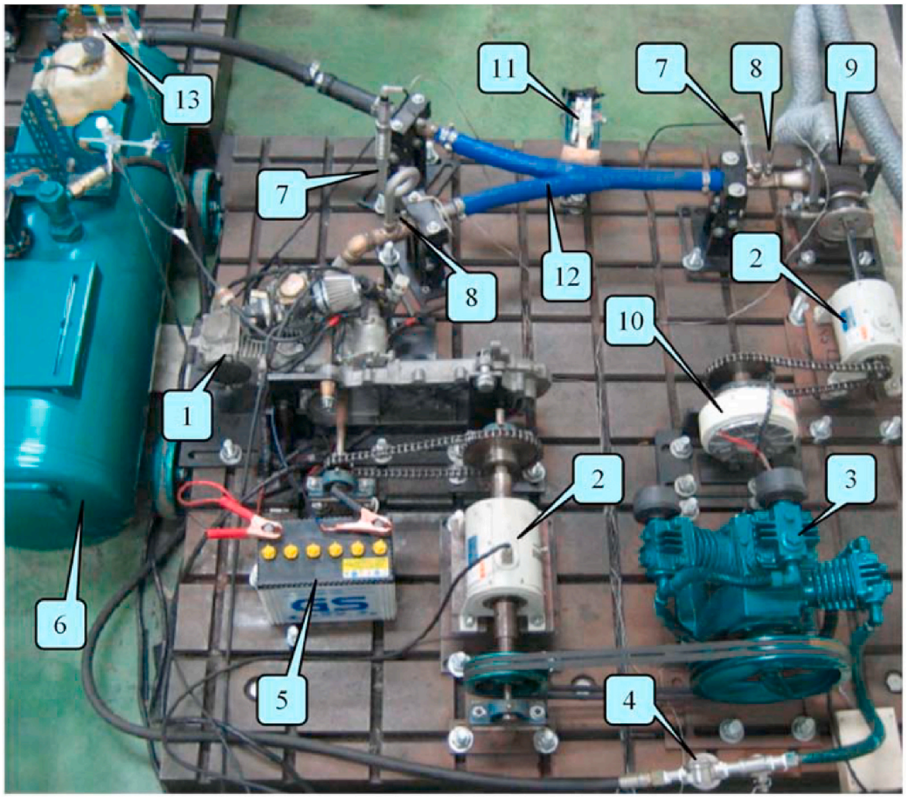

Fig. 14. Hybrid pneumatic power system by Huang et al. [95–97]. (1) Gasoline engine; (2) Torque sensor; (3) Air compressor; (4) Voltage stabilizer valve; (5) Battery; (6) Air storage tank; (7) Pressure sensor; (8) Temperature sensor; (9) Turbine; (10) Load cell; (11) Electric motor; (12) Energy merger pipe; (13) Control valve.

could dramatically raise the in-cylinder pressure and satisfy the ignition limit.

Meng et al. [104,105] established the model of compressed air jet-controlled combustion based on a single-cylinder diesel engine with a displacement of 0.418 L. The compression ratio of the diesel engine was reduced to 12 to avoid auto-ignition. Compressed air was jetted into the combustion chamber from a check valve placed vertically in the central position of the cylinder head. Effects of compressed air jet temperature and pressure, jet duration and timing were analysed using simulation methods. It was concluded that low jet pressure and high jet temperature could lead to an optimised thermal efficiency of the engine, while long compressed air jet duration could result in high peak pressure in the first-stage high-temperature reaction, and the short air-jet duration could lead to high combustion efficiency. In addition, there exists an optimum timing for obtaining the highest combustion efficiency and shortest burning duration.

3.4. Summary

Compared to the compressed powered powertrain, compressed air hybrid powertrain combined compressed air engine and conventional ICE by modifying conventional ICE system for pneumatic hybridisation. Fuel injection is paused during the braking phase, and the intake of the engine is compressed into an air tank through an additional charge valve placed on the cylinder head, and the compressed air could be used to drive the engine during start-up phase or acceleration. Such pneumatic regenerative braking is the key to pneumatic hybridisation since it is the only source of compressed air during the operation of compressed air hybrid engine. Other methods to produce compressed air might also be feasible, such as a combustion engine-driven compressor.

A direct expansion is considered the major energy conversion method for compressed air recovered during the braking phase. Current studies focused on the evaluation of fuel consumption reduction effect of pneumatic hybridisation, while a few researchers considered the performance optimisation during compressed air driven period by waste heat recovery from the conventional ICE. In addition, compressed air jet could be used to control the combustion phase of the premixed diesel-air mixture. The low-efficiency issue of compressed air expansion can potentially be eliminated by the innovative compressed air jet-controlled compression ignition. Table 4 summarises the features of different compressed air hybrid powertrains discussed previously. It can be concluded that compressed air-based regenerative braking should be an essential element for the compressed air hybrid powertrain, while the methods of compressed air energy utilisation can be combined or selected according to different conditions.

4. Challenges and opportunities for the compressed air energy systems in vehicle transport

A purely compressed air powertrain may not be feasible for vehicle propulsion system due to its low efficiency and low energy density while applying compressed air hybrid powertrain can reduce the fuel consumption of conventional ICE by methods such as regenerative braking and pneumatic driving. Interests in compressed air hybrid powertrain are much fewer than other electrical counterparts since electricity is considered as the next-generation power source for the vehicle. Some critics even argue that conventional ICEV will be completely replaced by BEV in the future since the latter produce zero tailpipe pollution, therefore the studies on fuel-saving technology for the conventional ICE are meaningless. In the authors' opinion, the actual effect of BEV on the environment should be assessed based on 'Well to Wheel' (WTW) lifecycle. Woo et al. [106] analysed the WTW greenhouse gas (GHG) emission of BEV based on electricity generation mix and concluded that the GHG emission for BEV was higher than ICEV in countries with high

Table 4
Comparison between different compressed air hybrid powertrains.

Item	Type	Advantages	Limits
1	Compressed air-based regenerative braking	Compressed air can be produced during vehicle brake, with no extra requirement on air compressors. Vehicle fuel consumption can be reduced.	Engine efficiency under compressed air driven mode is still lower than 20%.
2	A hybrid system based on waste heat recovery	Efficiency under compressed air-driven mode can be improved by recovering waste heat from the conventional engine. The conventional engine can work at stable conditions to reduce fuel consumption and pollutant emission.	The source of compressed air remains unsolved, an engine-driven compressor might be needed. The system complexity is increased since the conventional engine and compressed air engine are separated.
3	Compressed air jet-controlled compression ignition	Compressed air is not involved in direct power output, eliminating low-efficiency issues.	The effect of compressed air jet compression ignition requires more validation since current studies are limited to simulation.

fossil fuel ratios in their power generation mix such as China, India and Australia. Similarly, an analysis on the cradle to gate GHG emission conducted by Qiao et al. [107] showed that the total energy consumption and GHG emission for BEV were 50% higher than that of ICEV [107]. Additionally, the role of ICE is still unshakeable on heavy-duty commercial vehicles. Considering the practical application of vehicles like cargo trucks, using the battery as a sole power source is not feasible at all because the heavyweight of batteries would dramatically reduce the cargo capacity. The complete replacement of ICEV with BEV is not that feasible unless dramatically technological developments of batteries will happen in the next few decades. As an energy-saving and environmentally friendly technology, compressed air hybrid powertrain still has its potential value in the transport sector.

The major challenge for compressed air hybrid powertrain is the overall energy efficiency since the engine performance under pneumatic driven mode is determined by the mass and pressure of compressed air recovered during the braking phase, as well as the energy conversion process of compressed air. According to current studies, a passenger vehicle with a tank volume less than 50 L could only run a short distance using compressed air, while the tank volume is strictly limited due to the reason of spatial arrangement. For a heavy-duty commercial vehicle, it is possible to place an air tank with a larger volume, when carefully determine the storage pressure for transport application. The reliability of the air tank could be achieved with the progress in the material development of storage tanks. Recently new materials such as carbon fibre composite are under development by companies for high-pressure hydrogen storage for FCV, and the storage pressure can be as high as 70 MPa [108]. The high-pressure storage technology can also be applied for compressed air storage owing to its non-flammability. Except for the storage pressure, the recovery process of compressed air energy should also be considered since compressed air suffers great energy loss during the flowing from cylinder to tank. Unfortunately, limited studies have been reported and focused on the physic mechanisms of the compressed air flow process, therefore none relative theoretical guidance can be referred to reduce the energy loss and realise a more efficient regenerative braking. Further studies on the compressed air flow process based on compressible fluid and shock wave theory might be a possible solution.

5. Conclusions

The history and state-of-art of the compressed air energy systems and its potential applications in vehicle propulsion system are reviewed and summarised. Findings and conclusions demonstrated that a purely compressed air powertrain is difficult to be achieved for the vehicle application, despite its unique advantage of environmental benefit. Technical flaws including the low efficiency and low energy density issues of compressed air propulsion still require extensive research efforts to promote the technology developments. Compressed air hybrid propulsion, which combines compressed air propulsion with a conventional internal combustion engine, can be a potential method to avoid the technical flaws. By adopting pneumatic regenerative braking, the energy dissipated during the vehicle brake phase can be recovered and stored as compressed air and converted into mechanical power during vehicle acceleration. Meanwhile, the source of compressed air can be secured during the vehicle start-stop process. Using compressed air to recover the waste heat from the conventional internal combustion engine is another hybridisation method, which can improve the performance of the engine system when driven by purely compressed air. When compressed air jet-controlled combustion technology is used, the low efficiency of pneumatic propulsion is eliminated since compressed air does not expand for mechanical work output. This innovative combustion process can also be considered as a solution for compressed air hybridisation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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