Study of Energy Merger Management of a Hybrid Pneumatic Power System

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Abstract: - One characteristic of a hybrid pneumatic power system (HPPS) is that it enables an internal combustion engine (ICE) to operate at its sweet spot of maximum efficiency. Using an energy merger device, an HPPS can both recycle the exhaust-gas energy of an internal combustion engine and compress air to activate the air motor. The HPPS can increase the thermal efficiency of the ICE and help reduce exhaust emissions. Using a data collection device (NI-USB-6229), the data were collected and then conveyed to the computer operations, recorded, and shown on the human–machine interface. The main aim of this research is to experimentally investigate the process of energy merging. The results show that compressed air energy influences the ICE exhaust gas energy in the merger process. It affects the air motor output power considerably. Modulating the diameter of the energy merger pipe improves the backflow phenomenon in the tube and promotes greater efficiency. The compressed air energy and air motor are tested under different load conditions to optimize the energy merger, control the tube diameter, and establish the HPPS management strategy.

Key-Words: - Hybrid Pneumatic Power System (HPPS), Exhaust Gas Recycling, Energy Merger Management

1 Introduction

To respond to the driver's demands and the roadway load, current Internal Combustion Engine (ICE) power systems usually have to be constantly in accelerating or decelerating state, which causes the fuel consumption to fail to maintain its sweet spot of maximum efficiency. This not only leads to a waste of energy but also raises the serious question of exhaust emission and causes the ICE vehicle to have only 15% power efficiency. However, since the exhaust-gas energy discharged from the ICE represents more than one third of the total energy, recycling the exhaust-gas energy can not only avoid wasting energy but also reduce exhaust emission and pollution. With regard to the issue of exhaust-gas recycling, most of the current researches employ heat exchangers to recycle thermal energy. Based on this viewpoint, the aim of this research is to propose an innovative idea: "a Hybrid Pneumatic Power System (HPPS) that can completely recycle the waste energy of the engine". This system adopts the following components: (1) a new and active airflow converger which can completely recycle the high-temperature and high-pressure exhaust-gas discharged from the ICE; moreover, it can produce the Venturi effect by using an active mechanism to adjust the converging tube to various diameters, and in so doing it transforms the exhaust-gas energy discharged from the ICE into effective power and thus increases the heating effect of the engine and decreases its exhaust pollution, fuel consumption, and manufacturing cost; (2) an air compressor which provides a fixed load to the ICE, causing it to operate in its sweet spot of maximum efficiency with low fuel-consumption and low pollution, effectively reducing the emission of harmful gas. This thesis applies an experimental method of testing the HPPS platform and builds up a management strategy through analysing the statistics of the energy merger under different operating modes, and in this way efficiently reduces the exhaust backpressure of the ICE, smoothens the processes of the energy merger, and, most importantly, reduces exhaust emission and resultant pollution of the environment.

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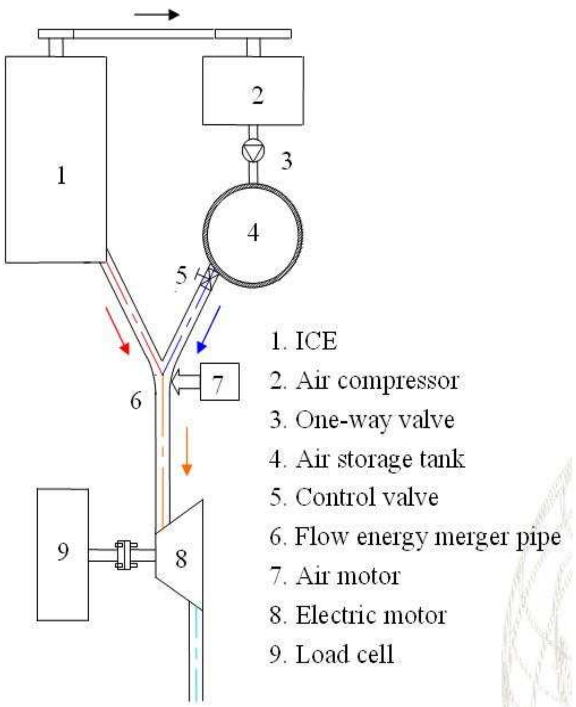

Fig. 1. Structure and operating principle of HPPS

2 Design of the Experimental Platform

2.1 System Components

The design of the experimental platform adopts the hydraulic-pneumatic pressure components available on the market. The components include the ICE, air compressor, air storage tank, energy merger pipe, and air motor. The air compressor converts the mechanical energy outputted by the ICE into high-pressure pneumatic energy and saves it in the air storage tank. The energy merger pipe is a Y-tube with two inlets and one outlet: one inlet carries the high-temperature exhaust discharged from the ICE and the other inlet carries the compressed air adjusted by the electronic throttle. These two energies are converged in the tube and produce power to drive the air motor. The purpose of converging these two energies is to recycle the enormous waste energy of the ICE and also to control the merging processes in order to maintain the exhaust backpressure of the ICE and decrease the energy loss.

Table 1. System Components

Component	Type specification
ICE	125 cc, 4-stroke Gasoline engine
Air compressor	Rotorcomp NK40
Air motor	GAST 8AM

2.2 Establishment of Experimental Platform

The HPPS experimental platform gradually realizes the concept of the system, its design ideas, hardware planning and design, writing of the monitor interface, hardware/software installation, testing, and analysis, and the complete experimental platform is shown in Figure 2. After being tested under actual operation, the results of the analysis show that all components are working normally and no mistakes are found in the piping or transmission lines; moreover, the monitor interface and signal communication control both work normally, allowing the system to be understood, analysed, and debugged and making it easier for the system to make adjustments and design changes. This platform can help carry out further analysis and research on the key techniques of the system.

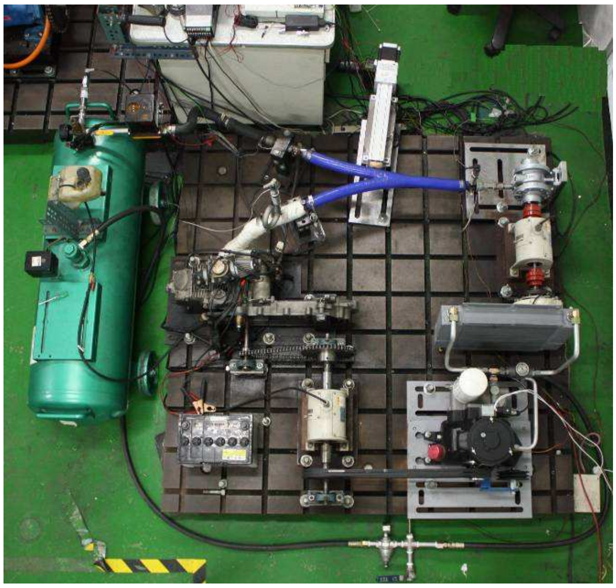

Fig. 2. Experimental platform of the HPPS

3 Research Method and Procedure

3.1 Control Modes of Experimental Platforms

The operation of the HPPS can be categorized into ICE mode, hybrid power mode, and compressed air mode. When the vehicle is under low load, the system switches to ICE mode, which uses the exhaust-gas energy to drive the air motor, and saves the air compressed by the compressor in the air storage tank. When the load demand is higher than the power provided by ICE mode, the system switches to hybrid power mode, which drives the air motor by converging the exhaust-gas energy of the ICE and the high-pressure pneumatic power; it also

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adjusts the throttle valve of the air storage tank according to the load demand and then adjusts the diameter of the energy merger pipe to reduce the exhaust backpressure of the ICE, and in this way smoothens the processes of the energy merger. When the pressure of the air storage tank reaches a default value, it switches to compressed air mode. In this mode, the ICE is turned off, so the air motor is driven solely by the compressed air stored in the air storage tank; in addition, the throttle valve of the air storage tank is adjusted according to the load demand until the pressure of the air storage tank is below the default value, at which point the system switches back to ICE mode or hybrid power mode.

3.2 Experimental Parameters

This research mainly discusses the processes of the energy merger. During the processes, if the exhaust backpressure of the ICE is too high, the merger will not be able to take place smoothly like the operation of the ICE. With regard to this situation, this research attempts to produce the Venturi effect by adjusting the diameter of the energy merger pipe to change the cross-sectional area of the converging spot, thus reducing the exhaust backpressure of the ICE and decreasing the energy loss.

The major factors which affect the pressure within the energy merger pipe are: (1) pressure of the air storage tank, (2) the throttle valve of the air storage tank, (3) the load of the air motor. This experiment applies different parameter settings to test the platform data, and the processes of the energy merger are discussed. The parameter settings are shown in Table 2. The optimum adjustment of energy merger pipe diameter is analysed to build up the HPPS management strategy.

Table 2. Experimental Parameters

Parameter	Setting value
Pressure of air storage tank	1, 2, 3, 4, 5 (bar)
Throttle valve of air storage tank	15, 20, 25, 30 (^{o})
Load of air motor	1, 2, 3 (Nm)
Adjustment of energy merger pipe diameter	0, 3, 6, 9, 12 (mm)

3.3 Experimental Processes

The experimental processes of this research can be discussed with respect to three different operation modes. The discussion of ICE mode mainly concerns the loading processes of using ICE exhaust-gas energy to drive the air motor and testing of the ICE mode to analyse the changing of pressure within the energy merger pipe as well as the rotational speed and torsion of the air motor under different loading conditions. To prevent unsuccessful operation or even stalling of the ICE, the load of the air motor and the upper limit of its output power must be understood clearly.

The discussion of hybrid power mode mainly concerns the converging processes of the exhaust-gas energy of the ICE and high-pressure pneumatic energy. To produce the Venturi effect, which reduces the exhaust backpressure of the ICE, it is necessary to adjust the diameter of the energy merger pipe according to different air storage tank pressures, the throttle valve of the air storage tank, and the load of the air motor in order to analyse the optimum adjustment of the energy merger pipe diameter and therefore smoothen the processes of the merger and decrease the energy loss and to understand the load of the air motor and its upper limit of output power under every condition.

The discussion of compressed air mode focuses on the processes of using compressed air to drive the air motor. Since the ICE is turned off in this mode, the ICE exhaust backpressure does not need to be taken into consideration. Thus, the focus will be on different air storage tank pressures, the throttle valve of the air storage tank, and the load of the air motor in order to understand the load of the air motor and its upper limit of output power under every condition. After testing and analysing these three modes, the energy merger management strategy can be built.

4 Results and Discussion

4.1 Component Testing and Analysis

4.1.1 ICE Test

The purpose of the ICE test is to determine whether the ICE can be operated at a fixed rotational speed and also to test its fuel consumption; in addition, the ICE needs to be tested repeatedly in order to show the experimental precision and system stability. Figure 3 shows the relation between ICE rotational speed, torsion, and time; its testing conditions comprise setting the one way valve at 10 bar load and maintaining a damper opening degree of 85%. From Figure 4.1 we can observe that when the system is started, it can maintain its operation in a fixed spot and its output torsion stably, which proves that the compressor with a backpressure valve designed for this system can provide a regular load to the engine, thus keeping the damper in a fixed position and maintaining the operation of the ICE at a stable rotational speed, and furthermore keeping the ICE operating in its sweet spot of maximum efficiency by using this characteristic.

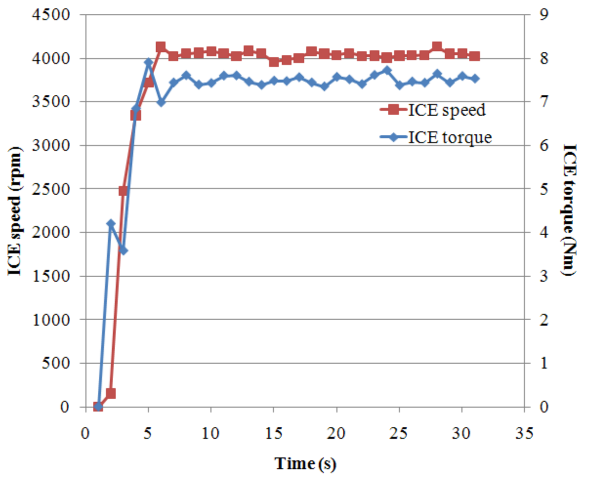

Fig. 3. ICE speed and torque versus time

In order to ensure that the system possesses higher energy density, the analysis of ICE rotational speed is set at 3000 rpm, 4000 rpm, and 5000 rpm brake specific fuel consumption. The test results (shown in Figure 4) demonstrate that when the ICE is operating at 4000 rpm and the pressure stabilizer valve is set at 10 bar, it has the lowest brake specific fuel consumption of 288 g/kW-h, and thus this system will cause the ICE to be operated at this fixed rotational speed.

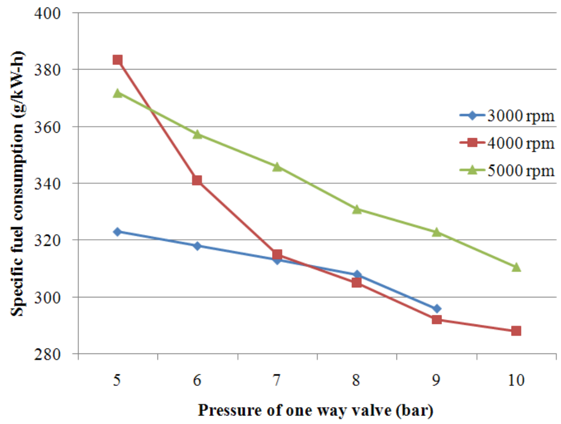

Fig. 4. Specific fuel consumption

4.1.2 Compressor Test

With regard to testing the compressor, since the ICE test is complete, the compressor will be operated under a stable condition after the system turned on, and thus this section will focus on analysing the compressed air produced by the compressor.

The results show that once the system is started, the compressor will produce stable pressure in the air storage tank, and it takes about 175 seconds to pressurize the tank to 10 bar (gauge pressure). The test results demonstrate the stability of the compressor and also prove that the system can store energy quickly.

4.2 Energy Merger Test

4.2.1 ICE Mode Test

The content of the ICE mode test mainly concerns the relation between the air motor load, air motor speed, and ICE exhaust backpressure while in the ICE mode. The air motor load is experimentally adjusted while maintaining the ICE in exhausting condition, and the results are shown in Table 3.

Table 3. Results of ICE mode test

Load of air motor	Air motor speed	ICE exhaust backpressure
0.5 Nm	360 rpm	0.8 bar
1 Nm	200 rpm	1.2 bar
1.5 Nm	Cannot drive the load	

4.2.2 Compressed Air Mode Test

In the compressed air mode test, since the ICE is turned off and the air motor load is driven solely by high-pressure pneumatic energy, the adjustment of the energy merger pipe diameter does not need to be taken into consideration. The experiment mainly investigates the possible influences on the air motor output with different testing parameters. Figures 5–7 demonstrate how the air storage tank pressure and the throttle valve of the air storage tank affect the air motor speed under different load settings.

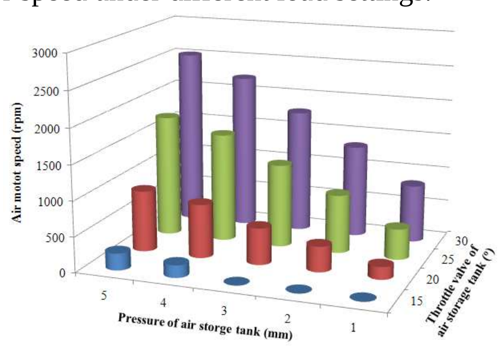

Fig. 5. Air motor speed (load of 1 Nm)

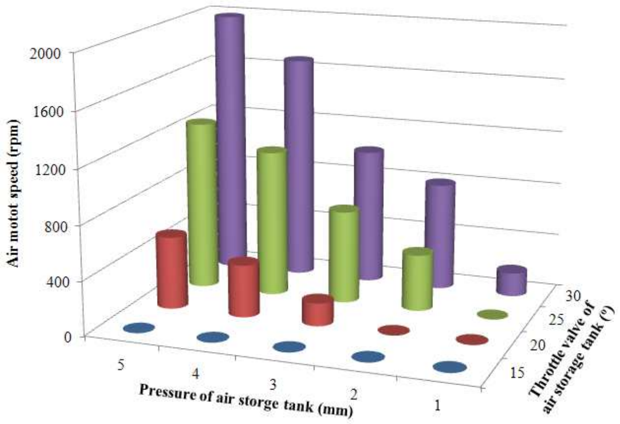

Fig. 6. Air motor speed (load of 2 Nm)

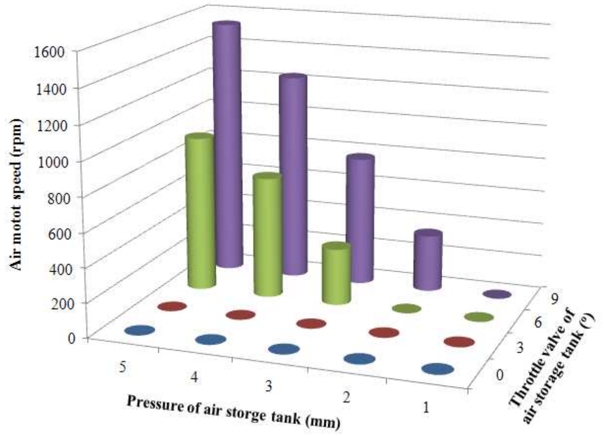

Fig. 7. Air motor speed (load of 3 Nm)

4.2.3 Hybrid Power Mode Test

In this experiment, the ICE exhaust-gas inlet end of the energy merger pipe should be maintained in the exhausting condition in order to examine the effects on the air motor output when the parameters of the test are varied. The experimental results show that the Venturi effect can be produced by adjusting the diameter of the energy merger pipe, thus influencing the air motor speed, since it would directly reflect whether the merger is successful or not. If the converging tube diameter is not adjusted, the compressed air end will extrude the ICE exhausting end, causing difficulty in exhausting. This condition can be improved by adjusting the energy merger pipe; however, if the tube diameter is over-adjusted, it may extrude the compressed air end and decrease the output rotational speed. The energy merger pipe diameter and its corresponding air motor speed are varied to find the optimum adjustment of the energy merger pipe diameter, and the optimum adjustment of the energy merger pipe diameter with its corresponding air motor speed are found by the observing air storage tank pressure under different air storage tank throttle valves and air motor loads.

For instance, if the pressure of the air storage tank is 3 bar, and the load is set as 1 Nm, the energy merger pipe diameter does not need to be adjusted while the degree of opening of the air storage tank throttle is 15%, but when the degree of throttle opening is 20^o and 25^o, the optimum adjustment of the energy merger pipe diameter is 3 mm. If the opening degree of the air storage tank throttle is 30^o, since the energy from the compressed air end is above 25^o, the tube diameter needs to be adjusted more, and thus the optimum adjustment increases to 6 mm. If the load is set as 2 Nm, when the throttle opening degree is 15^o, 20^o, and 25^o, the optimum adjustment of the energy merger pipe diameter is 3 mm; when the throttle opening degree is 30^o, the optimum adjustment of the energy merger pipe diameter should be increased to 6 mm. If the load is set as 3 Nm, a throttle opening degree of 15% will not be able to provide sufficient power to drive the load; when the throttle opening degree is 20^o, the optimum adjustment of the energy merger pipe diameter is 3 mm. When the throttle opening degree is 25^o, the load and the high-pressure pneumatic energy will be too high and will cause the pressure within the converging tube to seriously affect the ICE exhaust, and thus it is necessary to adjust the tube diameter to prevent the ICE from being turned off; the optimum adjustment is 6 mm. When the throttle opening degree is 30^o, the diameter of the energy merger pipe also needs to be adjusted, otherwise the ICE will be turned off; the optimum adjustment is 9 mm. Once again, too much adjustment will affect the compressed air end and decrease the rotational speed.

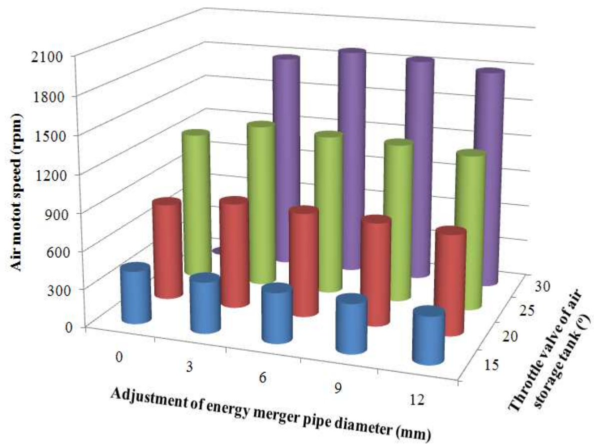

Fig. 8. Air motor speed (load of 1 Nm)

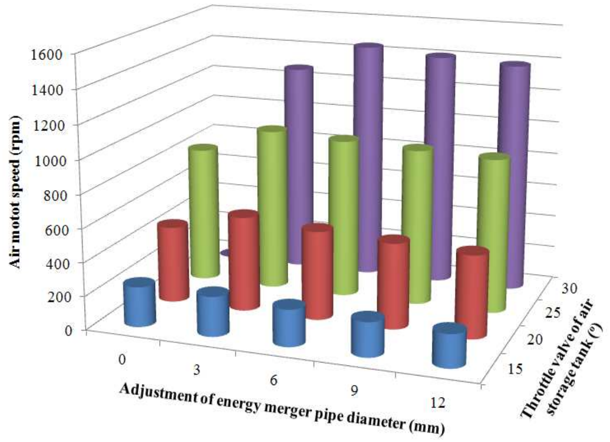

Fig. 9. Air motor speed (load of 2 Nm)

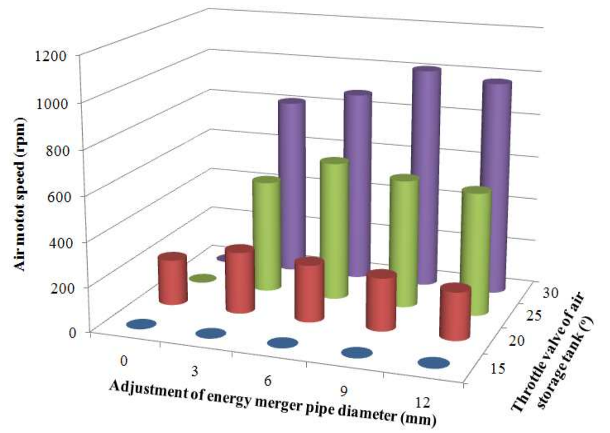

Fig. 10. Air motor speed (load of 3 Nm)

From the optimum adjustment of the energy merger pipe diameter and its corresponding air motor speed, which are found by observing the pressure of each air storage tank with different air storage tank throttle valves and air motor loads in the hybrid power mode, we can determine clearly the ideal air storage tank throttle valve settings and energy merger pipe diameters when the air storage tank is facing different load and air motor speed demands. These can be the basis of energy merger management.

4.3 Energy Merger Management Strategy

The HPPS energy management strategy aims to provide a way to manage the power of the HPPS. The merger device is used to integrate the two pneumatic energies according to different driving demands, adjust the throttle valve of the air storage tank to control the pressure of its compressed air, and then alter the diameter of the energy merger pipe to produce the Venturi effect in order to control the flow speed of converged energy at the air compressing end, thus avoiding backflow caused by too much backpressure at the ICE waste energy end while inletting the high-pressure pneumatic energy and further recycling the ICE waste energy to increase the density of pneumatic energy, ultimately increasing the overall efficiency of the system.

Once the system has been started, it firstly judges whether the pressure of the air storage tank has reached the default value; if it has, the system will switch to air storage tank mode, turn off the ICE, and then control the air storage tank throttle to drive the high-pressure pneumatic energy to meet the system demand. If the air storage tank does not reach the default value, the system will judge whether the ICE exhaust energy can meet the load demand or not; if it can, then the system will switch to ICE mode, turn off the air storage tank throttle, and then store the compressed air produced by the air compressor in the air storage tank, using only the ICE exhaust energy to drive the load. If the ICE exhaust energy is not sufficient to drive the load, the system will switch to hybrid power mode, using the air storage tank throttle to control the high-pressure pneumatic energy and ICE exhaust energy; it will detect the pressure of the air storage tank and its throttle valve and air motor load and then actively adjust the diameter of the converging tube to smoothen the processes, which finally drive the load and meet the system demand.

5 Conclusion

The main purpose of this thesis is to conduct research on the energy converging processes of HPPS using experimental parameters to investigate different system operating modes and their energy converging conditions by analysing the energy consuming condition of each system component as well as the optimum adjustment of the energy merger pipe diameter under different parameter settings and then to build up an energy merger management strategy for the HPPS. The conclusions of this research and possible directions and suggestions for future research are as follows:

i. By analysing ICE rotational speed and torsion, this research has proved that the ICE in this system can be operated in a fixed operating spot.
ii. Through careful experimentation, this research has proved that if the opening degree of the air storage tank throttle is too large, the pressure of the compressed air will affect the processes of the ICE exhaust merger within the converging tube and decrease the output power of the air motor.

iii. Through careful experimentation, this research has proved that adjusting the diameter of the energy merger pipe can produce the Venturi effect, which can smoothen the converging processes; in addition, the experiment also tested the optimum adjustment of the tube diameter and its corresponding air motor speed while varying the air storage tank conditions, throttle valves, and loads, and then built an energy merger management strategy based on the results.

iv. Due to the restrictions of material quality, if the pressure of the air storage tank, its throttle opening degree, and the load of the air motor are set too high, there will be too much pressure within the energy merger pipe and damage to the tube may occur. The material of the energy merger pipe must be high-temperature and high-pressure resistant and flexible for diameter adjustment. Future research should seek improvements in the material quality in this direction in order to carry out a complete experiment.

v. Since the components of the ICE, compressor, and air motor in this experimental platform all adopt ready-made products available on the market there are many restrictions with regard to the function and efficiency of components, making it difficult for them to meet the system requirements. If future research can find components which meet the system requirements more closely in terms of system running rate, pressure, and temperature, the energy consumption efficiency will be closer to our expectations.

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