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Evaluation of ideal double-tank hybrid pneumatic engine system under different compression cycle scenarios

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Abstract

A double-tank hybrid pneumatic engine system, with one low pressure tank and one high pressure tank has been proposed to improve the energy conversion efficiency and auxiliary braking power output of regenerative braking of vehicles. The performance of three ideal compression cycle scenarios for the double-tank system has been investigated and the results are compared with that of ideal one-tank scenario in order to identify the optimal compression cycle under different primary performance requirements. Results indicate the maximum brake mean effective pressure can be improved to not over 0.2 MPa less than the HP tank pressure and the highest improvement of total air mass recovered can reach over 40% utilising the double-tank scenarios. Scenario 3 performs the best at the braking power output ability, while scenario 4 shows the greatest high pressure compressed air recovery potential. Considering about the LP tank air sources, scenario 2 is the only one that can operate independently without other air complements, which also performs the best at the energy conversion efficiency among the three double-tank scenarios.

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Keywords: regenerative braking, hybrid pneumatic engine, double-tank compression cycle scenarios, energy efficiency analysis

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1. Introduction

Regenerative braking technology draws increasing attentions because of the urgent demand to improve the energy efficiency of conventional Internal Combustion Engine (ICE) [1-3]. Hybrid Pneumatic Engine (HPE) system is one of the available approaches, having the advantages of lightness, simplicity, pollution-free and low cost, that attracts researchers to study [4-6]. The conventional ICE can be easily adopted as a compressor by modifying the ICE valve system, which can also run the ICE as an air motor by changing the valve timing [7, 8]. The energy of the compressed air can also be used for supercharging system or supplying other pneumatic accessories [9-11]. Most previously proposed and studied hybrid pneumatic systems are focused on the one-tank system, which is easy to be fully filled and therefore limits the energy storage capacity. Several researchers proposed to use double-tank system to improve the system performance [12, 13]. However, the optimal compression cycle strategy using double-tank system has not been comprehensively studied and analysed. And the energy recovering improvements and braking effect improvements are required to be evaluated. In this paper, a double-tank hybrid pneumatic engine system based on the conventional one-tank system is proposed. Three ideal compression cycle scenarios for the double-tank system are described, analysed and compared in order to identify the optimal compression cycle scenario under different system demands.

2. System concepts

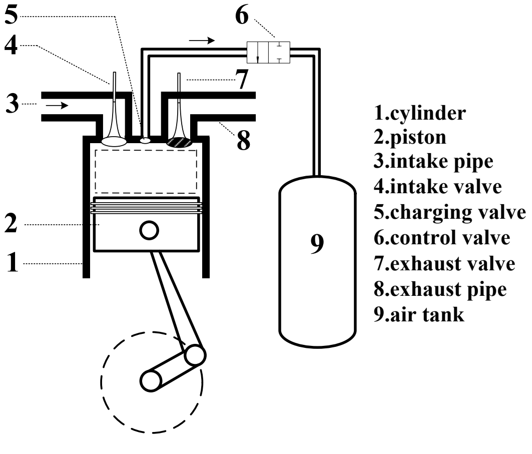


Fig.1. Schematic diagram of a one-tank HPE system

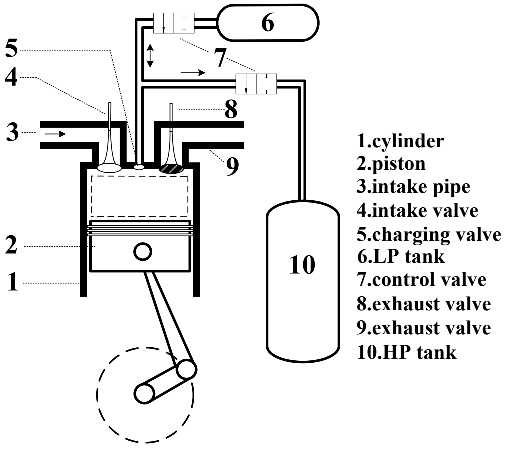


Fig.2. Schematic diagram of a double-tank HPE system

Figure 1 shows a schematic diagram of a one-tank hybrid pneumatic engine system. The engine cylinder is modified by adding a charging valve on the cylinder head which is connected to the air tank. Four modes, including the ICE mode, the compression mode, the air motor mode and the supercharging mode, can be achieved by controlling the fuel injection and the opening and closing times of the valves. Based on this configuration, a double-tank hybrid pneumatic engine system (Figure 2), with one low pressure (LP) tank and one high pressure (HP) tank, is proposed to further improve the amount of the compressed air that can be recovered in the tank, meanwhile to achieve a better braking effect.

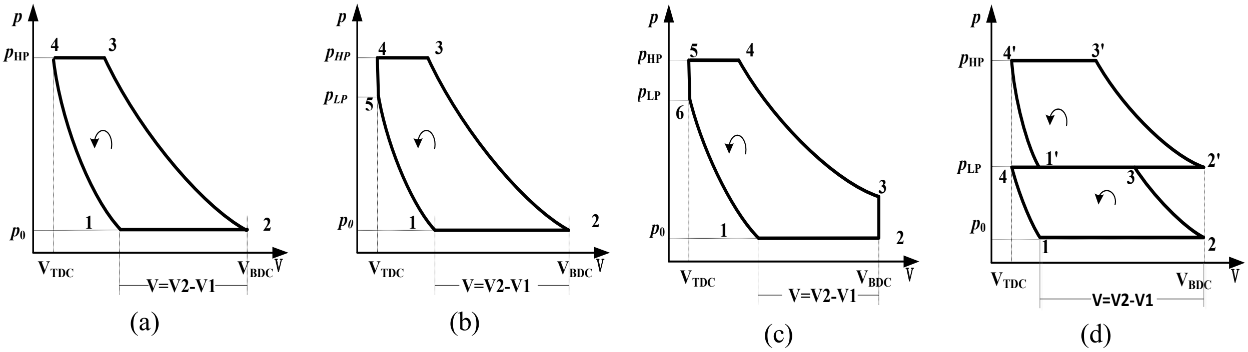
Three ideal compression cycle scenarios for the double-tank hybrid pneumatic engine system are shown in Figure 3. As a comparison, the ideal compression cycle scenario for the one-tank system is also presented (Figure3 (a)). Detailed working processes are defined as follows:

Scenario 1: 1-2: Intake valve opens and atmosphere air is sucked into the cylinder till the Bottom Dead Center (BDC); 2-3: Air is compressed in the cylinder; 3-4: Charging valve and the control valve open, the pressurized air is charged into the air tank till the Top Dead Center (TDC); 4-1: Both the charging valve and the intake valve are closed and the residual air in the cylinder expands to the atmosphere pressure.

Scenario 2: On the basis of working process of scenario 1, an air charged into the LP tank process 4-5 is added. 4-5: The HP control valve closes and the LP tank control valve opens, the remaining pressurized air is charged into the LP tank till the cylinder pressure equals to the LP tank pressure.

Scenario 3: An air from the LP tank injected into the cylinder process 2-3 is added based on scenario 2. 2-3: Intake valve closes, charging valve and the LP tank control valve open, compressed air from the LP tank enters the cylinder till the cylinder pressure equals to the LP tank pressure.

Scenario 4: Two cycles as in scenario 1 operate in turn. In the first 1-2-3-4-1 cycle, atmosphere air is sucked into the cylinder, and the pressurized air is charged into the LP tank. While in the second 1'-2'-3'-4'-1' cycle, the air of the LP tank is taken as the air supply, and the higher pressurized air is charged into the HP tank.



(a) (b) (c) (d)

Fig. 3. Scenarios of ideal compression cycle (a) Scenario 1; (b) Scenario 2; (c) Scenario 3; (d) Scenario 4

3. Evaluation methods

Thermodynamic analysis has been applied to the above four compression cycle scenarios, underlying the following assumptions.

1. Air is an ideal and calorically perfect gas, and the state parameters distributes uniformly.
2. Opening and closing times as well as flow restrictions of the valves are neglected.
3. Both the cylinder and tanks are considered as adiabatic.
4. The volumes of the tanks are far greater than the cylinder-swept volume. The tank pressure and temperature changes during one cycle are therefore neglected.

Considering that the concept of hybrid pneumatic is proposed to fulfil the requirement of braking energy recovery and braking power output, three performance indicators of the thermodynamic cycles are selected for evaluating and comparing the four scenarios, as listed in Table 1.

Brake Mean Effective Pressure $(BMEP)$ $P_{bmep}$is the work expended in one compression cycle W divided by displacement volumeV_d, which can reflect the braking ability of the hybrid pneumatic system. Mass of compressed air recovered per cycleΔm is the total of compressed air recovered by the LP tank Δm_{LP} and the HP tank Δm_{HP}. Energy conversion efficiency expressed by COP equals to the energy of compressed air recovered ΔH divided by the work expended W [14]. Mass recovered per cycleΔm and energy conversion efficiency COP can be used to demonstrate the hybrid system's energy recovery ability.

The parameters of the geometric model built to calculate these performance indicators are listed in Table 2.

Table 1. Performance indicators

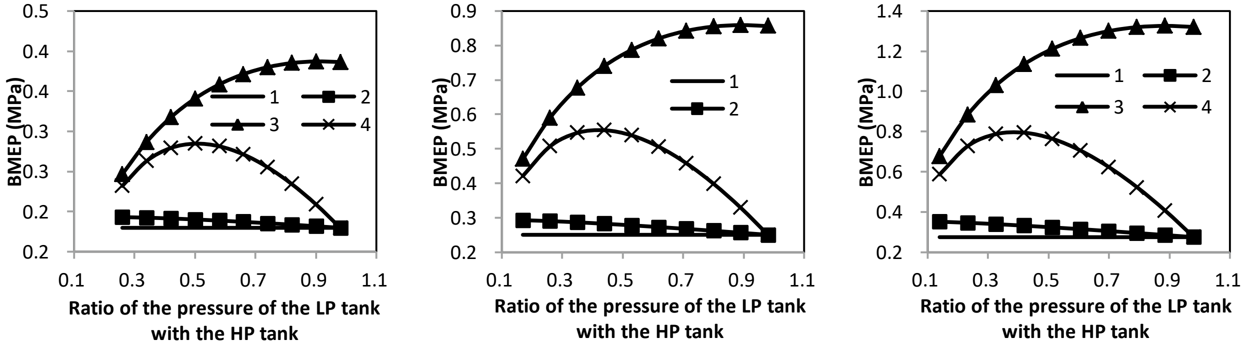
Indicator	Calculation equation
Brake Mean Effective Pressure (*BMEP)*	$BMEP = -W/V_d$
Mass of compressed air recovered per cycle（Δm）	$\Delta m = \Delta m_{LP} + \Delta m_{HP}$
Energy conversion efficiency (*COP*)	$COP = -\Delta H/W$

Table 2. Modified engine parameter

Name	Value
Engine type	290F
Cylinder bore	90mm
Cylinder stroke	75mm
Single-cylinder displacement	477cm^3
Original compression ratio	19:1
Ratio of the crank radius to the connecting-rod length	0.333

4. Results and discussion

As in the four scenarios, tank pressure is the main effecting factors. Only variation laws of *BMEP*, Δm, and COP with tank pressure are evaluated in detail below. Considering that the LP tank pressure is designed to be lower than the HP tank pressure, the ratio of the pressure of the LP tank with the HP tank is introduced as one independent variable. Another independent variable is the HP tank pressure, which only takes three cases of 0.5 MPa, 1.0 MPa, 1.5 MPa into account.



(a) (b) (c)

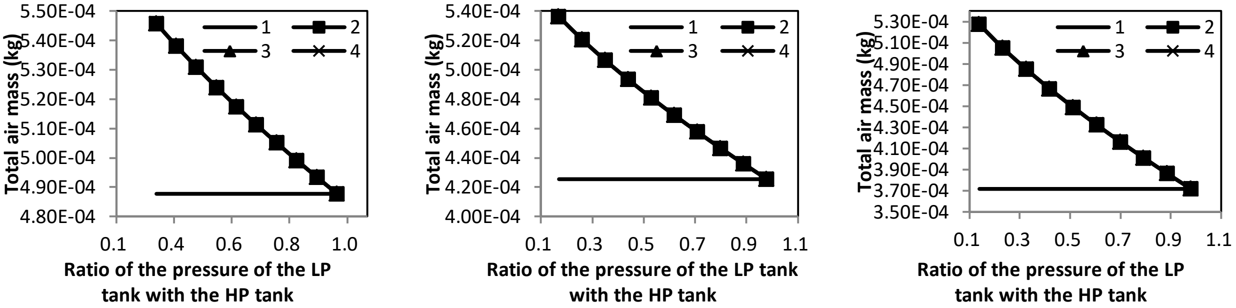
Fig.4. Evaluation of BMEP under various LP and HP tank pressure (a) HP=0.5MPa; (b) HP=1.0MPa; (c) HP=1.5MPa

4.1. Evaluation of Brake Mean Effective Pressure (BMEP)

The comparison of *BMEP* of the four scenarios is shown in Fig.4. The increase of HP tank pressure can significantly promote *BMEP* of all scenarios which means the braking ability can be improved. All the three scenarios for double-tank can produce more braking power than the ideal one-tank scenario. However, the effect of LP tank pressure is not consistent. Scenario 3 performs the best braking ability among all scenarios under the same conditions. The maximum value, which can reach not over 0.2 MPa less than the HP tank pressure, occurs when the ratio of the pressure of the LP tank with the HP tank is around 0.9.

4.2. Evaluation of total air mass

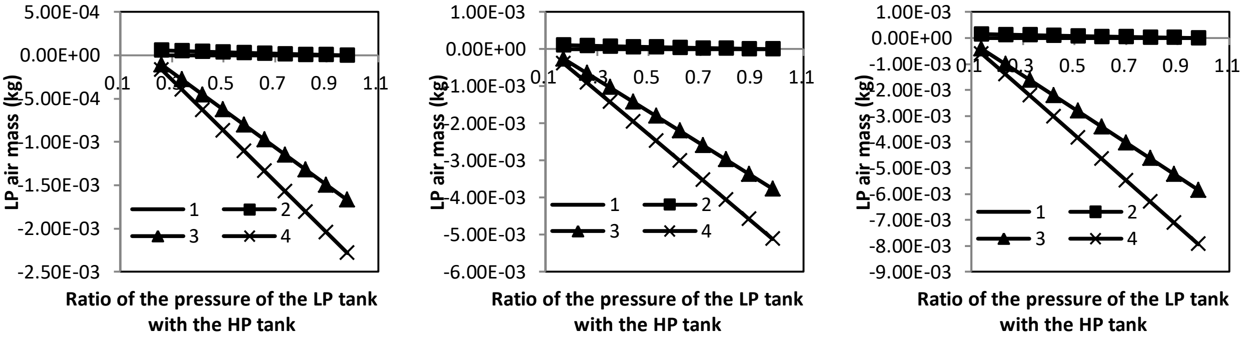
Different from the variation laws of BMEP, the higher the HP or LP tank pressure is, the less the total air can be recovered. As can be seen in Fig.5, the highest improvement of Δm in the double-tank scenarios compared with that in the one-tank scenario can reach over 40%. However, there is no difference among the three scenarios under the same HP tank pressure.



(a) (b) (c)

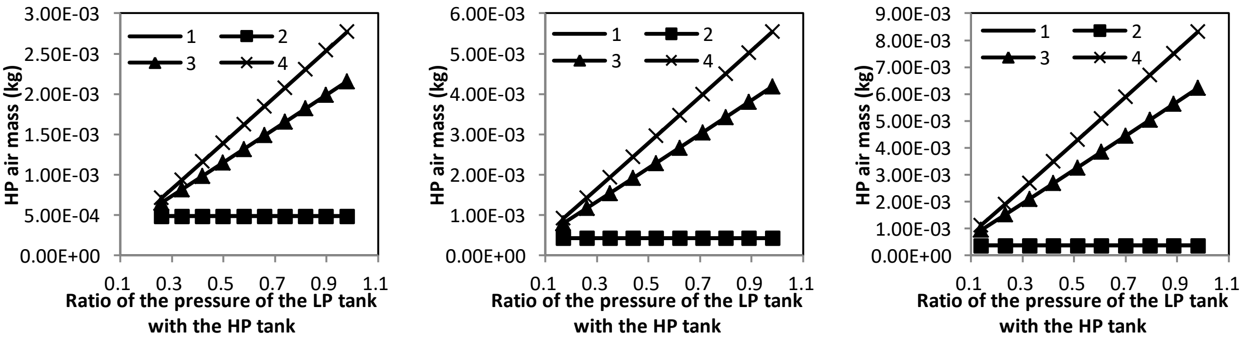
Fig.5. Evaluation of total mass recovered per cycle under various LP and HP tank pressure
(a) HP=0.5MPa; (b) HP=1.0MPa; (c) HP=1.5MPa

Thus the air mass of LP tank and HP tank recovered per cycle are also presented in Fig.6 and Fig.7, respectively. Scenario 2 is the only scenario that can increase but not consume the air of LP tank, and the air recovered of HP tank is same to that of the ideal one-tank scenario. Air recovered of HP tank in scenario 3 and 4 increases greatly with increasing HP or LP tank pressure, while air consumed from LP tank increases greatly, too. Scenario 4 shows the greatest potential among the three double-tank scenarios of 1.4 to 22 times as much HP air amount recovered as that in the one-tank scenario 1. But if air sources of LP tank are taken into consideration, scenario 2 is the only one that can operate independently without other air complements.



(a) (b) (c)

Fig.6. Evaluation of LP air mass recovered per cycle under various LP and HP tank pressure
(a) HP=0.5MPa; (b) HP=1.0MPa; (c) HP=1.5MPa

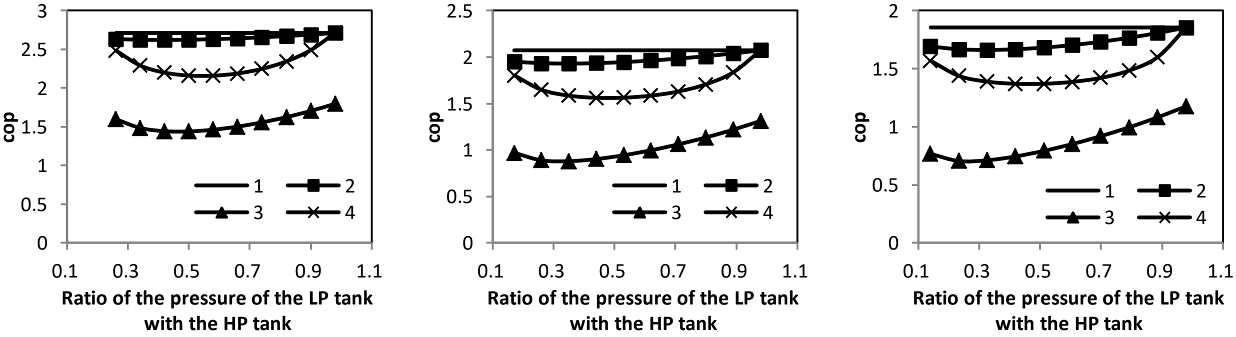


(a) (b) (c)

Fig.7. Evaluation of HP air mass recovered per cycle under various LP and HP tank pressure
(a) HP=0.5MPa; (b) HP=1.0MPa; (c) HP=1.5MPa.

4.3. Evaluation of COP

Results in Fig.8 indicate the double-tank scenarios cannot do any favour to the improvements of energy conversion efficiency COP. And COP of all double-tank scenarios shows a variation law of first decreasing and then increasing when the LP tank pressure increases. The poorest performances occur when the ratio of the pressure of the LP tank with the HP tank is about 0.3 to 0.5. Scenario 2 shows a better energy conversion performance compared with the other two double-tank scenarios, which is close to the ideal one-tank scenario.



(a) (b) (c)

Fig.8. Evaluation of COP under various LP and HP tank pressure (a) HP=0.5MPa; (b) HP=1.0MPa; (c) HP=1.5MPa

5. Conclusions

This paper proposes three ideal double-tank compression cycle scenarios for the hybrid pneumatic engine system and reports the thermodynamics cycle analysis and comparisons results. The cycle performance evaluating, including brake mean effective pressure$BMEP$, mass of compressed air recovered per cycle Δm and Energy conversion efficiencyCOP, are conducted in order to identify the optimal compression cycle under the different primary requirement of improving the braking energy recovery or braking power output. Main conclusions can be drawn as follows

1. The introduction of double-tank compression cycle can help to improve the braking power output and the total air mass recovered of the hybrid pneumatic system. However, the energy conversion efficiency cannot be improved. The highest improvement of Δm in the double-tank scenarios compared with that in the one-tank scenario can reach over 40%.

2. Scenario 3 performs the best braking ability among all scenarios, which can reach not over 0.2 MPa less than the HP tank pressure. Scenario 4 shows the greatest potential of 1.4 to 22 times as much HP air amount recovered as that in the one-tank scenario 1. If air sources of LP tank are taken into consideration, scenario 2 is the only one that can operate independently without other air complements. At the same time, scenario 2 also performs the best at the energy conversion efficiency among the three double-tank scenarios, which is close to the ideal one-tank scenario.

3. Optimal braking ability and optimal braking energy recovery ability cannot occur on the same compression cycle scenario, and cannot occur under the same tank pressure conditions, either. In an actual application, the choices of the compression cycle scenarios must have their own emphasis according to the requirement of the hybrid pneumatic system.

Acknowledgements

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