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Experimental study of a pneumatic engine with heat supply to improve the overall performance

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HIGHLIGHTS

- The design of a pneumatic engine modified from diesel engine was reported
- Performance study of a pneumatic engine with and without heat supply
- Two pressure and two temperature conditions under different rotational speed

Abstract

As an environmental friendly technology, hybrid pneumatic concept regenerating the engine braking energy to boost the engine performance for better fuel economy and lower engine emissions attracts ever increasingly attentions in automotive industry. However, the pneumatic operational mode of the engine suffers from low energy efficiency, which requires more research efforts. This study presents an optimisation method for the pneumatic mode of hybrid pneumatic engine by supplying heat during the expansion process of compressed air. A pneumatic prototype engine has been designed, constructed and used to simulate the working process of the engine during pneumatic mode. Hot water has been used as the heat source to heat up the engine cylinder wall in order to study the effects of using heat supply on the performance of the pneumatic

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engine. The results show that the power and torque of the pneumatic prototype engine under the heat source temperate at 90 °C and 1 MPa intake pressure are both increased. The maximum power output of the HPE obtained is around 1.5 kW, which is 22% higher than that of the HPE without heat supply. Under the engine rotational speed at 400 r/min, the torque produced from the HPE is about 29 N m, which is 7% improvement than that without heating supply. The maximum energy efficiency of the HPE can be improved from 27 % to 35%, when the cylinder wall is heated by 90 °C water and the intake pressure is set at 1 MPa. Moreover, the effects of hot water temperature have also been investigated and in total twenty one testing points have been conducted under the engine intake pressure set at 1 MPa. The maximum power output from the HPE under water temperature at 70 °C and 90 °C can respectively be as high as 1.4 kW and 1.5 kW, which is about 14 % and 22 % improvement compared with the HPE without heat supply.

Key words: Hybrid Pneumatic Engine, heat supply or recovery, pneumatic mode, performance study

1 Introduction

The development of hybrid technologies attracts ever increasing attentions in the automotive industry because the hybrid system has been proven as an effective solution to improve the overall efficiency of the vehicle and reduce the fuel consumption [1, 2]. The most well-known hybrid technology is hybrid electric vehicle, which requires relatively complex system arrangement, higher cost of the components and is not a complete green system compared with compressed-air hybrid technology [1, 3].

The revolution of compressed-air hybrid system began with the invention of compressed air vehicle since 1880s built by the manufacture such as General Herman Haupt [3]. The concept of Hybrid Pneumatic Engine (HPE), which adds an extra charging valve on the cylinder head of Internal Combustion Engine (ICE), has first been introduced by Schechter since 1999 [4, 5]. The proposed system stores the braking energy as the

41 form of compressed air and reuses the energy during acceleration at later time [4, 5]. Higelin et al. [6-8]
42 conducted simulation on HPE and claimed that the reduction on fuel consumption can be as high as 15%
43 under New European Driving Cycle (NEDC) and even up to 31% under optimised operational conditions.
44 Trajkovic et al. [9-13] modified a single-cylinder ICE into HPE by using pneumatic valve actuator, and
45 conducted experiments to study its performance and efficiency. The results showed that the fuel consumption
46 of ICE can be reduced by 30% after applying HPE, and the extra cost of HPE was claimed to be a fraction of
47 that for an electric hybrid arrangement due to its simplicity [9, 10]. In addition, the optimisation on valve
48 parameters and timing was also conducted [11]. Zhao et al. [14-17] conducted numerical simulation on HPE
49 based on a cam profile switching device. The results showed that a 6.8% reduction in fuel consumption could
50 be achieved as a result of the application of HPE [17]. The compressed air recovered during vehicle brake was
51 also available to provide instant boost so that a highly downsized engine could be used for further
52 improvement in fuel economy without the loss in performance or greater emissions associated with turbo-lag.
53 Donitz et al. [18-20] investigated the fuel consumption reduction of HPE when it is combined with engine
54 downsizing. The results showed that a fuel consumption reduction was up to 34% for the MVEG-95 drive
55 cycle and the turbo-lag normally associated with heavy downsizing could be overcome with HPE by using
56 compressed air from the tank to supercharge the engine during the acceleration of the turbocharger [18-20].
57 Basbous et al. [21-24] and Ibrahim et al. [25, 26] applied HPE concept on wind-diesel generators to reduce
58 fuel consumption for electricity production in non-interconnected remote areas. Results showed that the fuel
59 economy generated by HPE was 10%~26% under different wind power conditions. Wang et al. [27]
60 conducted a simulation study on a HPE to regenerate the braking energy and urban driving-cycle simulation
61 results pointed out the fuel consumption of a light-duty vehicle with pneumatic hybrid system can be reduced

by 8 %. A two-stage expansion air engine, which includes one small and one large cylinder to conduct two-stage in series has been proposed and investigated by Liu et al. [28]. Results indicated the two-stage expansion air engine can generate up to 1.7 kW power and 12.42Nm torque at air pressure of 12 bar [28].

As described previously, the application of HPE enables engine to work in different modes. The waste energy is recovered from ICE and stored as compressed air in compressor mode by operating the engine as air compressor during the vehicle brake. Under conditions like vehicle start, HPE is operated in pneumatic mode and the engine works just like a pneumatic motor and the pressurised air flows into the cylinder and produces power by expansion. Some researchers reported the efficiency of the pneumatic mode of HPE is lower than 20 % [29-32]. Therefore, the performance of pneumatic mode requires research efforts in order to optimise the HPE performance. However, limited study has been reported and conducted focusing on the issues mentioned above. This study aims to experimentally investigate the effects of using heat supply on the pneumatic mode of HPE in order to improve the overall efficiency and performance of the HPE. A prototype pneumatic engine with heat supply system has been designed, built and tested to study the effects of using heat supply on the performance of the HPE. The results obtained from this study can be used as a useful reference not only for the academic but also for the engine manufacture to promote the development of the Hybrid Pneumatic Engine.

2. Methodologies

2.1 Description of the Hybrid Pneumatic Engine (HPE)

Fig. 1. Schematic diagram of the working principle of pneumatic mode (a) intake and expansion, (b) exhaust

The working principle of the HPE can be described as the following modes. In the firing mode, HPE works the same as a normal ICE, while brake energy is recovered and stored in forms of compressed air in the compressed air storage tank. When working in pneumatic mode, the engine works as a pneumatic motor with the fuel-injection being cut-off converting the compressed air energy into mechanical work. Fig. 1 illustrates the typical working process of the pneumatic mode of HPE. The two-stroke process is composed of intake, expansion and exhaust process. The intake valve opens when the piston moves to the Top Dead Centre (TDC) and closes at some time during the intake process. The compressed air flows from air tank to the cylinder during the intake process, pushing the piston to move downwards. After the intake valve is closed, the compressed air continues to expand in the cylinder until the piston reaches the Bottom Dead Centre (BDC). Then the exhaust valve opens after the expansion process and the remaining compressed air is pumped out of the cylinder by the piston.

Fig. 2. *P-V* diagram of the pneumatic mode

91 Fig. 2 illustrates the ideal thermodynamic cycle of the pneumatic mode of HPE. According to the above
 92 description, the intake process 1-3 begins when the intake valve opens at TDC. Note that the pressure rises
 93 immediately to tank pressure p_T after the opening of intake valve, and remains constant during the intake
 94 process. Therefore the intake process can be regarded as isobaric. Compressed air flows into the cylinder
 95 during the intake process and pushes the piston to move downwards to produce power. The intake valve
 96 closes at some time before the piston reaches BDC, thus changing the isobaric intake process into an
 97 expansion process 3-4. The compressed air continues to expand until the piston reaches BDC, followed by the

98 exhaust process 5-1 after the opening of the exhaust valve. Finally the compressed air is pumped out of the
99 cylinder during the upward movement of the piston.

100 The net work produced in the cycle can therefore be calculated by Eq. (1), where W_{1-3} is the work of the
101 intake process, while W_{3-4} is the work of the expansion process of compressed air.

$$W = W_{1-3} + W_{3-4} \quad (1)$$

102 The efficiency of the cycle can be expressed as Eq. (2). E is the total energy contained in the
103 compressed air, which can be calculated as Eq. (3), where m indicates the mass of compressed air flowing into
104 the cylinder per cycle. It can be noted that the total energy E remains constant if the pressure, temperature and
105 the mass of compressed air are unchanged, hence the only way to achieve an efficiency improvement is to
106 maximise the net work of the cycle.

$$\eta = \frac{W_{1-3} + W_{3-4}}{E} \quad (2)$$

$$E = mRT \ln \frac{p_r}{p_0} \quad (3)$$

107 According the thermodynamic laws, the work of the isobaric process 1-3 can be expressed as Eq. (4),
108 where V_1 is the cylinder volume when the piston is at TDC, and V_3 is the cylinder volume when the intake
109 valve is closed. It can be noted that W_{1-3} remains constant if the tank pressure and valve timing of the
110 pneumatic mode is unchanged. Therefore, the net work of the cycle depends on the expansion work of
111 compressed air W_{3-4} .

$$W_{1-3} = p_T (V_3 - V_1) \quad (4)$$

112 If there is no heat transfer during the expansion process, the expansion work W_{3-4} can be expressed as Eq.
 113 (5), where, κ ($=1.4$) is the adiabatic index of compressed air, and $\varepsilon=V_3/V_4$ is the volume ratio between the
 114 initial and final state of the expansion process.

$$W_{3-4} = \frac{p_T V_3}{\kappa - 1} [1 - \varepsilon^{\kappa-1}] \quad (5)$$

115 If the expansion process is isothermal, W_{3-4} can be expressed as

$$W_{3-4} = p_T V_3 \ln \varepsilon \quad (6)$$

116 Due to the heat absorption during the process, the work of isothermal expansion is larger than that of
 117 adiabatic expansion if the initial state and the volume ratio is fixed. For the expansion process of the
 118 pneumatic mode, the maximum and the minimum work can be achieved in the cases of isothermal and
 119 adiabatic expansion, respectively. However, neither isothermal nor adiabatic process can be achieved during
 120 practice, and the actual expansion of compressed air is a polytropic process distributing between isothermal
 121 and adiabatic expansion. Therefore, an effective way to maximise the expansion work of compressed air is to
 122 supply additional heat during the expansion, thus making the expansion process evolve towards isothermal
 123 expansion, and eventually leading to an increase in the net work of the cycle.

124 ***2.2. Experimental methods***

125 ***2.2.1 Design of Pneumatic prototype engine***

126 As mentioned above, an increase in the work output of the pneumatic mode can be potentially achieved
127 by supplying heat to the expansion process of compressed air. In order to validate the analysis above, the
128 pneumatic mode of HPE should be realized on the test bench before designing the heat supply system.
129 However, the pneumatic mode is only activated during transient conditions such as vehicle start or engine
130 acceleration, hence it is impossible to obtain its performance properties such as power and torque under steady
131 conditions. To confront this problem, a pneumatic prototype engine is developed in this study to simulate the
132 working process of pneumatic mode of HPE.

133 The two-stroke pneumatic prototype engine is re-configured based on a single-cylinder diesel engine, as
134 shown in Fig. 3. The cylinder head of the original diesel engine has been re-designed to satisfy the demand of
135 valve timing of pneumatic mode. Fig. 4 shows the rotational valve system adopted on the pneumatic prototype
136 engine. The exhaust valve is driven by a sprocket wheel system which is connected to the crankshaft, and the
137 intake valve is connected to the exhaust valve through gear transmission. The valve timing is shown in Table
138 1 along with the main specifications of the prototype, and it can be changed by adjusting the gear connection
139 between the intake and exhaust valve. The intake valve opens immediately when the piston moves to TDC,
140 and compressed air flows into the cylinder during the intake process which lasts for 72 °CA. After the intake
141 valve is closed, the compressed air in the cylinder continues to expand until the piston moves to BDC. Then
142 the exhaust valve opens and the piston moves from BDC to TDC to pump the compressed air in the cylinder
143 during the exhaust process.

Fig. 3. Photo of the prototype pneumatic engine

Fig. 4. Schematic of the rotational valve

Table 1

Specifications of the prototype pneumatic engine

Item	Value
Bore (mm)	85
Stroke (mm)	95
Displacement (L)	0.54
Intake valve open (°CA ATDC)	0 (TDC)
Intake valve close (°CA ATDC)	72
Exhaust valve open (°CA ATDC)	180 (BDC)
Exhaust valve close (°CA ATDC)	360 (TDC)

2.2.2 Description of the experimental system

As shown in Fig. 5, the experimental system is composed of three modules, including engine test, heat supply and data acquisition. The engine test module is consisted of the pneumatic prototype engine, an air

149 tank, a flowmeter, a dynamometer and sensors. During the experiment, the pneumatic prototype engine is
150 driven by the compressed air stored in the air tank with 300 L in volume and 2.5 MPa in maximum pressure.
151 A pressure regulator is placed at the outlet of the tank to adjust the intake pressure of the pneumatic prototype
152 engine. The intake pressure is always lower than the tank pressure so that a steady flow of compressed air can
153 be ensured. The power and torque of pneumatic engine are monitored by the dynamometer (DW-20, Hongxin
154 Inc., China), and the compressed air flow rate is monitored by the flowmeter (HQ-980, Huaqiang Inc., China).
155 The intake pressure and temperature of pneumatic prototype engine are measured by a pressure sensor
156 (PT-110, Qizheng Inc., China) and a thermistor, respectively. In addition, the cylinder pressure of pneumatic
157 prototype engine is measured by a transient pressure sensor (Type 6013C, Kistler Inc., Germany).

158 The heat supply module is used to provide heat to the expansion of compressed air during working
159 process of the pneumatic prototype engine. It should be noted that the water jacket of the diesel engine is
160 maintain unchanged during its modification to the pneumatic prototype engine. During the experiment, an
161 electric heater with a maximum power of 2 kW_e is placed in a water tank to heat the water. Then the hot water
162 is guided out by a pump to flow through the water jacket, thus providing heat to compressed air by raising the
163 cylinder wall temperature. After that, the water flows back to the tank, forming a complete circuit. The power
164 of the heater is controlled so that the water temperature at the outlet of the tank is maintained constant during
165 the experiment. The power of the electric heater was not considered during the calculation of the efficiency
166 since its function was to simulate the waste heat source during the practical operation of HPE. The
167 temperature difference of the water is monitored by thermistors, which are place at both inlet and outlet of the
168 water jacket of the pneumatic prototype engine. An electromagnetic flowmeter (LDCK-10, Shanghai
169 Automation Instrument co., China) is used to measure the volume flow rate of the water. It should also be

noted that the heat supply module is used to simulate the waste heat generation during the practical operation of HPE. Since the experiment was conducted on the prototype pneumatic engine, the heat supply process in the experiment was not absolutely identical to that of HPE.

Fig. 5. Schematic of the experimental system

The data acquisition module is established based on National Instrument platform (NI CDAQ-9234, USA). Different input devices are selected to collect the signals of the sensors, and all signals are eventually processed by a data acquisition program designed based on Labview. The specifications of the sensors are listed in Table 2, and it should be noted that all sensors were calibrated before the experiment.

177 **Table 2**

178 Specifications of the data acquisition equipment

	Power Supply	Output	Range	Accuracy
Dynamometer DW-20	220 V AC	Digital display	0~20 kW	$\pm 0.2\%$ FS
Flowmeter LDCK-10	220V AC	Digital display	0~18 m ³ /h	$\pm 0.5\%$ FS
Flowmeter HQ-980	24 V DC	Current, 4~20 mA	0~150 kg/h	$\pm 1\%$ FS
Thermistors	24 V DC	Voltage, 0~5 V	0~100°C	$\pm 0.5\%$ FS
Pressure sensor 6013C	24 V DC	Voltage, 0~10 V	0~15 MPa	$\pm 0.5\%$ FS
Pressure sensor PT-110	24 V DC	Voltage, 0~5 V	0~1.6 MPa	$\pm 0.5\%$ FS

179 **2.2.3 Experiment conditions**

180 The pneumatic prototype engine is operated within the speed range of 400~1000 r/min to study the
 181 performance of the pneumatic mode of HPE. As stated in the manuscript Section 2.2.2, the prototype
 182 pneumatic engine has been modified from a diesel engine. The two selected pressure conditions are the typical
 183 working conditions of the prototype pneumatic engine. When the prototype pneumatic engine is running lower
 184 than 0.6 MPa supplied pressure, the engine cannot be started smoothly and no effective data can be obtained
 185 in the experimental tests. The other testing pressure is 1 MPa, which is selected to prevent the exploration of
 186 the high pressure air tank when the prototype engine works under steady state for a period of time.

On the other hand, the structure of water jacket of the diesel engine has not been changed. The coolant temperature from a conventional ICE varies from 70 to 90 °C [33, 34]. The two selected heated temperature conditions 70 and 90 °C can be used to provide as the reference for the development of Hybrid Pneumatic Engine and validate the analysis conducted in the Section 2.1, which shown the expansion process of compressed air is adiabatic if there is no heat supply during the expansion and with the increase of the heat supply, the expansion process will develop towards isothermal, which will lead to an improvement on the performance of the pneumatic mode. Therefore the selected temperature 70 °C is used to prove the concept of adding heat into Pneumatic Engine to improve the overall system efficiency. And the selected temperature 90 °C is to prove that the expansion process can be developed towards isothermal process with the increase of heat supply as described previously.

3. Results and discussion

3.1 Effects of heat supply

Fig. 6 shows the cylinder pressure of pneumatic prototype engine acquired under the speed of 600 r/min and the intake pressure of 1 MPa. Case A indicates that the engine works when the electric heater is switched off, while case B refers to the condition that the water is heated to 90 °C and used to raise the temperature of the cylinder wall of the engine. It can be noted that the cylinder pressure is higher when the water is used to heat the cylinder wall, especially at the expansion stage of compressed air. The peak cylinder pressure of case B is above 0.8 MPa, which is approximately 10% higher than that of case A, when the cylinder wall is not heated by the water. In addition, the area surrounded by the p - V curve is also larger under case B when the cylinder wall temperature is higher, indicating the net work of engine cycle can be increased by raising the

207 cylinder wall temperature. This phenomenon can be explained by the enhancement of heat absorption of
 208 compressed air, hence the expansion process of the pneumatic mode is optimised and develops towards
 209 isothermal due to the additional heat supply under higher cylinder wall temperature. It can be concluded that
 210 the working process of the pneumatic mode of HPE can be improved when the cylinder wall temperature is
 211 raised, while the waste heat of ICE could serve as an ideal heat source and be used to increase the mechanical
 212 work output during the pneumatic mode.

Fig. 6. Cylinder pressure of pneumatic prototype engine

213 The power and torque of pneumatic prototype engine under different conditions are shown in Fig. 7 and
 214 Fig. 8, respectively. Similarly, the legend Case A in the figures indicate the condition that the engine works
 215 without the cylinder wall being heated by the water, while Case B refers to the condition that the water

216 (heated to 90 °C) is used to heat the cylinder wall. Note that the power of the pneumatic prototype engine first
 217 increases then drops with the speed, while the torque of the engine decreases monotonously with the speed.
 218 The reason can be explained by the fact that the mass of compressed air in the cylinder decreases with the rise
 219 of the engine speed due to the reduction of intake valve opening period.

Fig. 7. Pneumatic prototype engine power vs. engine speed at $p_i=0.6$ MPa, 1.0 MPa

Fig. 8. Pneumatic prototype engine torque vs. engine speed at $p_i=0.6$ MPa, 1.0 MPa

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It can be noticed that higher wall temperature has positive effect on the performance of the prototype engine. Under the intake pressure $p_i=1.0$ MPa, the maximum power of the engine is approximately 1.5 kW when the cylinder wall is heated, which is 22% higher than that of Case A. The maximum torque of the prototype engine is nearly 29 N·m when the water is used to heat the cylinder wall, which is increased by approximately 7% compared to that of Case A. In addition, the torque of the prototype engine reaches 10 N·m at the engine speed $n=1000$ r/min under Case B, indicating that the engine can slow down the performance deterioration under high speeds with heat supply to compressed air expansion. Similar trends on power and torque of the prototype engine can also be observed when the intake pressure $p_i=0.6$ MPa. The improvement on the power and torque can be attributed to the optimisation on the expansion of compressed air. When the cylinder wall is heated by the water, the heat transfer between compressed air and cylinder wall is enhanced,

231 hence the expansion of compressed air is closer to isothermal, leading to an increase in mechanical work
232 output.

233 Fig. 9 and Fig. 10 illustrate the compressed air flow rate and air consumption of the prototype engine as a
234 function of engine speed n . The air consumption of the engine is defined as the mass of compressed air
235 consumed per unit power output, and can be calculated by dividing the compressed air flow rate by the power
236 of the prototype engine. A monotonous increase in both compressed air flow rate and air consumption of the
237 prototype engine can be observed in Fig. 9 and Fig. 10. However, both air mass flow rate and air consumption
238 is lowered under Case B when the engine cylinder wall is heated by the water of 90 °C. When the intake
239 pressure $p_i=1.0$ MPa, the air consumption is 112 kg/(kW h) at the engine speed $n=980$ r/min, while it already
240 exceeds 200 kg/(kW h) at $n=890$ r/min under Case A, when the cylinder wall is not heated. Similar trends on
241 the compressed air flow rate and air consumption of the prototype engine can also be observed when the
242 intake pressure $p_i=0.6$ MPa. The reduction of compressed air flow is attributed to the increase in cylinder
243 pressure under higher wall temperature due to the enhancement of heat transfer between compressed air and
244 cylinder wall, as shown in Fig. 6. Accordingly, the pressure difference between the cylinder and the intake
245 port is reduced, leading to a lower intake flow rate of the prototype engine. The lower air consumption under
246 Case B is the combined effect of lower compressed air flow rate and higher power output when the cylinder
247 wall is heated by the water.

Fig. 9. Compressed air flow rate vs. engine speed at $p_i=0.6$ MPa, 1.0 MPa

Fig. 10. Air consumption of pneumatic prototype engine vs. engine speed at $p_i=0.6$ MPa, 1.0 MPa

249 Fig. 11 shows the efficiency of pneumatic prototype engine η as a function of engine speed n under
 250 different conditions. As mentioned above, the legends Case A and Case B refer to the conditions that the
 251 engine is operated without or with the heat supply of the water. The efficiency η is calculated by dividing the
 252 engine power by the total energy of compressed air according to the first law of thermodynamics. As shown in
 253 Fig. 11, the efficiency η decreases monotonously with engine speed, indicating better efficiency performance
 254 can be achieved in lower speeds. Efficiency improvements are observed when the cylinder wall is heated by
 255 the water under different intake pressures. The maximum efficiency is increased from approximately 27% to
 256 35% under the intake pressure $p_i=1.0$ MPa. Similar trend can also be observed when the intake pressure is
 257 $p_i=0.6$ MPa. These improvements can be explained as follows: when the cylinder wall is heated by the water,

258 the power of the pneumatic prototype engine is increased due to the enhanced heat absorption of compressed
 259 air; meanwhile, the compressed air flow rate is decreased without any change in intake pressure, indicating
 260 that the total energy of compressed air is lowered; accordingly, an efficiency improvements is observed.

Fig. 11. Pneumatic prototype engine efficiency vs. engine speed at $p_i=0.6$ MPa, 1.0 MPa

261 In summary, it can be concluded that the performance properties of pneumatic prototype engine is
 262 optimised when the cylinder wall is heated. Dynamic properties such as power and torque are increased under
 263 higher cylinder wall temperature, meanwhile economic property such as air consumption is lowered. In
 264 addition, the efficiency performance of the engine is also improved due to the enhancement of heat absorption
 265 of compressed air.

3.2 Effects of water temperature

Fig. 12 shows the power of the pneumatic prototype engine as a function of engine speed under different water temperatures t at the inlet of the water jacket. The intake pressure was maintained at $p_i=1.0$ MPa during the experiment, and the control of water temperature was realised by the program which enabled on/off switch of the heater. As mentioned above, the legend Case A refers to the conditions that the engine is operated without heat supply, while Case B represents the conditions that the engine works when the cylinder wall is heated by the water. Greater improvement on the power of the pneumatic prototype engine can be noted when the water temperature t is higher. When the water temperature $t=70$ °C, the maximum power of the engine is 1.4 kW, while it reaches 1.5 kW when the water temperature is raised to 90 °C. Compared to Case A, the maximum power is improved by 14% and 22% under the water temperature $t=70$ °C and $t=90$ °C, respectively. The trend can be explained as follows: compressed air absorbs larger amount of heat during expansion when the cylinder wall is heated, leading to an improvement in engine power; when the water temperature is higher, the heat absorption rate of compressed air is further increased due to larger temperature different between the cylinder wall and compressed air; hence greater improvement on the engine power can be observed under higher water temperatures.

Fig. 12. Pneumatic prototype engine power vs. engine speed at $t=70\text{ }^{\circ}\text{C}$, $90\text{ }^{\circ}\text{C}$

281 Fig. 13 and Fig. 14 illustrate the compressed air flow rate and air consumption of pneumatic prototype
 282 engine under different water temperatures t , respectively. The intake pressure is maintained at $p_i=1.0\text{ MPa}$
 283 during the test. Larger decrease in both compressed air flow rate and air consumption can be noticed when the
 284 water temperature is raised. When operated without heat supply (Case A), the air consumption of pneumatic
 285 engine exceeds $200\text{ kg}/(\text{kW h})$ at engine speed $n=890\text{ r/min}$, while it just reaches $140\text{ kg}/(\text{kW h})$ at engine
 286 speed $n=980\text{ r/min}$ when the cylinder is heated by the water of $70\text{ }^{\circ}\text{C}$. A further decrease of the air
 287 consumption can be observed when the water temperature is raised to $90\text{ }^{\circ}\text{C}$. As analysed above, this
 288 phenomenon is the combined effects of lower compressed air flow rate and higher power output under higher

289 water temperatures: when the cylinder wall is heated, the cylinder pressure of the prototype engine is raised,
 290 and the increase becomes larger with the rise of water temperature; accordingly, the compressed air flow rate
 291 is decreased; meanwhile, the power of the prototype engine is increased, as shown in Fig. 12; therefore, a
 292 decrease in air consumption can be observed.

Fig. 13. Compressed air flow rate vs. engine speed at $t=70\text{ }^{\circ}\text{C}$, $90\text{ }^{\circ}\text{C}$

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Fig. 14. Air consumption of pneumatic prototype engine vs. engine speed at $t=70\text{ }^{\circ}\text{C}$, $90\text{ }^{\circ}\text{C}$

294 According to the results above, it can summarised that greater improvements can be achieved by using
 295 water with higher temperature to heat the cylinder wall of the pneumatic prototype engine. For the pneumatic
 296 mode of HPE, heat source with higher temperature is also available during the operation, such as the exhaust
 297 produced in the firing mode.

298 **4. Conclusions**

299 This study aims to experimentally investigate the performance of Hybrid Pneumatic Engine (HPE)
 300 supplying with heat during the expansion of compressed air. A pneumatic prototype engine is modified from a
 301 single cylinder diesel engine to study the performance of HPE pneumatic mode at steady condition. A heat

supply system based on cylinder wall heating has been designed, established and used to study the performance of the pneumatic prototype engine with and without heat supply. The conclusions are as follows,

- The performance properties of the pneumatic prototype engine are improved when using heat supply during the operation. The power and torque of the engine are increased when the cylinder wall is heated by 90 °C water. Results indicated the peak cylinder pressure under the heated condition is around 10 % higher than that without heat supply. The maximum power produced from the prototype engine with heat supply (90 °C) is about 1.5 kW, which is 22% higher than that of the engine without heat. The experimental results also pointed out the torque output from the prototype engine heated by water at 90 °C is around 29 N m, which is 7% improvement than that without heating supply, under the engine rotational speed at 400 r/min. Moreover, results also shown adding heat supply system can potentially reduce the energy consumption of compressed air supplied from the air storage tank. When the intake pressure is set at 1.0 MPa, the air consumption is 112 kg/(kW h) at the engine rotational speed 980 r/min, while it already exceeds 200 kg/(kW h) at 890 r/min when the cylinder wall is not heated.
- The investigation on the overall energy efficiency of the pneumatic prototype engine indicated that under the engine intake pressure at 1 MPa, the maximum efficiency of the system can be improved from 27% to 35%, when the cylinder wall was heated by 90 °C water. Similar efficiency improvements have also been observed when the engine intake pressure is set at 0.6 MPa under different rotational speed.
- The effects of water temperature on the performance of the pneumatic prototype engine were experimentally studied. The supplied water temperature has been set at 70 °C and 90 °C under the

intake pressure set at 1.0 MPa. In total twenty one testing points have been conducted in order to compare the performance of the prototype engine without heating and with two different heat supply temperature. The testing results shown the maximum power output from the prototype engine under water temperature at 70 °C and 90 °C can respectively be as high as 1.4 kW and 1.5 kW, which are about 14 % and 22 % improvement compared with the engine without heat supply.

In conclusion, this paper reports an experimental study, which designed, constructed and used a piston type pneumatic engine using hot water as heat source to prove the feasibility of adding extra heating source to improve the performance of the HPE. The developed system can be potentially be integrated with Internal Combustion Engine (ICE) to recover the wasted kinetic energy during the engine brake process and reuse the wasted heat energy from the ICE such as the coolant and exhaust waste heat in order to effectively improve the overall energy efficiency of the ICE, reduce the engine emissions and increase the fuel economy.

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