EXPERIMENTAL INVESTIGATION ON THE PERFORMANCE OF COMPRESSED AIR ENERGY STORAGE USING SPRAY-BASED HEAT TRANSFER

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Near-isothermal compression and expansion may be accomplished by injecting water droplets into the air during the process to increase the overall efficiency. However, little is known about the relationship between spray system parameters and compressed air energy storage (CAES). Furthermore, the experiments about compressed air energy storage using spray-based heat transfer have not been investigated. The aim of this paper is to study the relationship between the performance of CAES and the spray system parameters by experimentally. The parameters including the spray closing time, the spray opening time, and the nozzle diameter are discussed. Results show that under the same operating conditions, the maximum air pressure in compression chamber reach to constant value when the spray closing time is 0.6 s; and spraying water mist within 0.6-1.2 s has no heat exchange effect on the air in the cylinder. During the compression process, the smaller the nozzle diameter is, the higher maximum pressure in compression chamber is. During the expansion process, if we ignore the energy consumption of spray system, the larger the nozzle diameter is, the more the expansion output is. Further investigation is recommended to optimize spray parameters based on different CAES systems.

Keywords: compressed air energy storage system;spray-based heat transfer; the spray closing time; the spray opening time; the nozzle diameter

1. Introduction

According to the 14th Five-Year Plan for national economic and social development and the long-range goals for the 2030s and the 75th session of the United Nations General Assembly agreement, China has a target to carbon peak by 2030 and to carbon neutral by 2060. The government is strongly supporting renewable energy incentive policies. The newly installed wind power capacity and solar power capacity have rapidly grown since 2012. In 2022, China's newly installed wind and solar PV power generation capacity exceeded 12 GW, accounting for 60% of the newly installed power generation capacity [1]. Because of the inherent intermittency of renewable energy, power generation in renewable energy plants fluctuates over many time scales, from seconds to days which restricts direct wind power penetration into power systems. To mitigate the problem, energy storage technologies are focused on. Compressed air energy

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storage (CAES) technology has the advantages of large scale, environmental friendliness, long service life, and large energy storage capacity, and has broad application prospects [2].

Conventional CAES systems that burn fossil fuel have been put into commercial operation in Germany (Huntorf CAES power station which was built 1978) and USA (McIntosh CAES power station which was built in 1991) [3, 4]. The heat is recovered in compression process and reused to preheat the compressed air during expansion process in McIntosh CAES power station. So compared with Huntorf CAES power station, the plant efficiency increases 12% [5]. Currently, no fossil burning CAES systems have been proposed and applied to achieve zero carbon emission. The salt cavern CAES national pilot demonstration project in Jintan, Jiangsu Province, China, is based on the Advance Adiabatic Compressed Air Energy Storage (AA-CAES) system. The AA-CAES system can recover and stored heat which is generated during the compression process using heat exchangers. Then, the heat is used to heat the high-pressure air during expansion. The total system efficiency of 55%-61% [6]. However, most large scale CAES requires suitable geography which becomes the limiting factors, and lower efficiency affects its profitability. High pressure CAES has a high energy density and decreases the volume of compressed air which allows CAES to be free from geographical constraints [7]. Vessels with storage pressures of up to 75 MPa are already in use, and hydrogen can be stored at pressures of up to 100 MPa in hydrogen refueling stations. The work done to compress air to a pressure-ratio r and discharge it into a high pressure store depends on whether the air is kept cool during compression. To compress $1 m^3/s$ of ambient air to 75 MPa, the mechanical power to the compressor is equal to 1996 kW based on adiabatic condition. But under the isothermal condition, the required mechanical power is reduced to 670.8 kW. And the expander output power will increased by increasing air temperature during expansion process. So isothermal compression and expansion are an efficient method to improve CAES system efficiency due to the minimum work input and the maximum work output associated with the isothermal process.

Clearly, heat transfer plays an important role in achieving near-isothermal compression and expansion. For the isothermal compression, the instantaneous rates of heat transfer should be equal to the instantaneous mechanical power to the compressor [8]. For the isothermal expansion, the instantaneous rates of heat transfer should be equal to the expander instantaneous mechanical power output. In general, the mechanical power to the compressor and the expander instantaneous mechanical power output are significantly higher than the instantaneous rate of heat transfer. This results in a near-adiabatic process in the compressors and expanders. So convective heat transfer coefficient and area of heat transfer should be increased drastically to achieve the near-isothermal compression and expansion. Various methods for enhancing heat transfer have been investigated. Liquid piston, spray, aqueous foam, and combination of multiple methods have been focused to improve the instantaneous rate of heat transfer. Table 1 shows the comparison of various methods.

Water droplet is an effective form of heat transfer due to the high heat capacity of water and the high surface area of sprays of droplets. So water spray can significantly improve rate of heat exchange, and can be used alone or in conjunction with other methods with solid or liquid piston. For a low compression ratio of two, experimental results show that spray cooling can increase compressor efficiency into the range of 88-97%. To obtain an accurate heat transfer process model, the area of water mist heat transfer in the cylinder are divided into two parts, and the spray angle and nozzle diameter are considered [16]. Odukomaiy et al. used spray cooling to achieve near isothermal compression and the system round-trip efficiency is up to 82% and the energy density is 3.59 MJ/m^3 [17]. The performance of a water spray cooling system was investigated by experimentally and theory [18].

Table 1 Comparison of various heat transfer methods

Method	Instantaneous rate of heat transfer	Advantage	Disadvantage
Liquid piston	Less than 1000 W/m2·K[9]	Good sealing performance and no pollution.	Air will inevitably dissolve into liquid which leads hydraulic system elastic modulus decreases, and a series of problems such as noise, vibration and cavitation in the low-pressure area occurs[10]
Water spray	Heat transfer coefficients of droplets with diameters of 20 μm and 50 μm are 6000 W/m2·K and 5000 W/m2·K.[12]	Faster heat exchange rate and being clean and pollution-free to the environment.	Certain amount of energy to make water spray[11]
Liquid piston and water spray	More than 5000 W/m2·K[13]	Good sealing performance and faster heat exchange rate.	Air is dissolved in liquid, resulting in energy waste and high energy consumption in making water spray[10]
Liquid piston and porous media	N.A.-Not Available	Faster heat exchange rate	Porous media has high cost and occupies a certain volume, which has a certain impact on compression; Air dissolves in liquid, resulting in energy waste[14]
Aqueous foam	N.A.-Not Available	Large heat exchange area and fast heat exchange rate.	Difficult to make water foam, and it cannot be fully converted into air and water after heat exchange [15]

Most previous studies of near-isothermal CAES focused on spray cooling system. Few studies focus on spray heating system. In fact, spray heating needs to be applied during expansion process to achieve near-isothermal expansion. Zhang et al. conducted a numerical study on the spray heating expansion process and found that it is 12% higher than the adiabatic expansion work [19]. To realize the isothermal expansion process of piston expander, Qihui et al proposed a method to inject micron water mist at high temperature into the cylinder. Simulation results showed the average air temperature in cylinder increased by 24.7%. But the output power/efficiency of the expansion process is reduced by 7.7%/12.3% [20].

Though the above studies have considered many aspects, they lack some experimental study of parameters influence especially for the expansion process. Additionally, there is also a lack of experimental studies of the effect of droplet size, spray time. And the results of previous numerical studies are inconsistent. Previous studies on near-isothermal CAES have focused on analyzing droplet heat transfer and the compression/expansion process separately, taking into consideration multiple factors such as droplet size, flowrate, pressure ratio, cycle frequency, and chamber configuration. However, up to now, the design and optimization near-isothermal CAES system is a challenging task based on spray. The main objectives of this study was to further investigate the relationship between spray parameters including the spray closing time, the spray opening time, and the nozzle diameter and pressure in cylinder during compression/expansion process of a isothermal compressed air energy system using experimental results. The experimental results is valuable to further investigate and optimize the near-isothermal CAES system based on spray transfer.

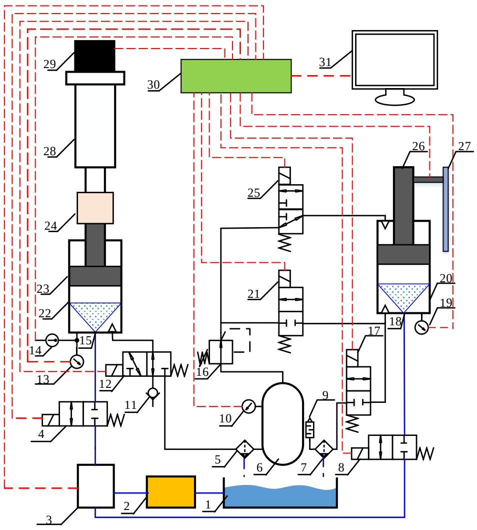
This is the first paper to the authors' knowledge to investigate the relationship between the spray parameters and pressure in cylinder during compression/expansion process using experimental results. Importantly, this is the first paper to identify the spray closing time and the spray opening time as the key spray parameters for compression/expansion process of a near-isothermal compressed air energy system. Furthermore, the spray closing time and the spray opening time was optimized based on specific experimental conditions. Thus, it fills an important gap in the literature, as would be need to implement near-isothermal CAES based on spray transfer.

The paper was organized as follows: in Section 2, the experiment platform is introduced and the experiment process is described. Section 3 contains experimental results and discussion, and Section 4 provides the conclusions.

2. Experiments

2.1. Experimental apparatus and procedure

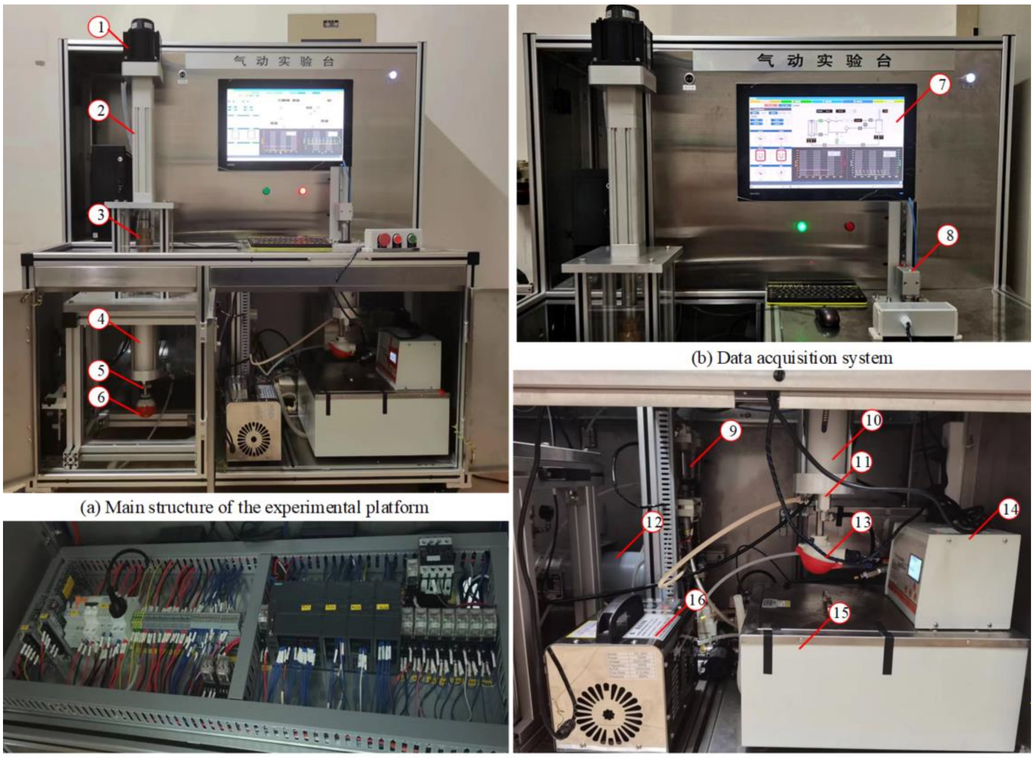
Fig.1 shows the schematic of the near-isothermal CAES system, which is composed of a compression system, a spray generator system, an expansion system, and a data acquisition system.



1 water tank; 2 constant temperature box; 3 water mist generator; 4,8,17,21 2/2 solenoid valve;5,7 water mist separator; 6 air storage tank; 9 muffler; 10 flowmeter; 11 check valve;12,25 2/3 solenoid valve; 13,19 pressure sensor; 14 temperature sensor; 15 atomizing nozzle 16,18 nozzle;20 expansion cylinder; 22 compression cylinder; 23,26 piston rod; 24 coupling;27 magnetic railing ruler; 28 electric actuator; 29 servo motor; 30 DAQ card; 31 computer

Fig.1 Schematic of the experimental apparatus

Water droplets are sprayed into the compression chamber or expansion chamber which enhances the heat transfer from the air to the surrounding water. The water in the constant temperature container also provides a large heat sink during the operation of the compressor or expander. The inlet and outlet solenoid valves are installed in the passage connected to the compression chamber and expansion chamber. A water mist generator is used to control the supply of water mist inside the compression/expansion chamber. The pressure of the water mist can be adjusted by the water mist generator, and the temperature of the water was controlled by a constant temperature tank. Spray size can be adjusted by changing different nozzles. A programmable logic controller (PLC 200 smart) is used to control the operation of solenoid valves.



(a) Main structure of the experimental platform

(b) Data acquisition system

(c) Control system

(d) Spray system

1 servo motor; 2 electric actuator; 3 coupling; 4 compression cylinder; 5 pressure sensor; 6 temperature sensor;7 computer; 8 magnetic railing ruler; 9 water mist separator; 10 expansion cylinder; 11 nozzle; 12 air storage tank;13 temperature sensor; 14 constant temperature equipment; 15 water tank; 16 water mist generator

Fig.2 Experimental platform photographs

The experimental apparatus shown in Fig.2. consists of servo motor (MDME202GCG) by Panasonic, an electric actuator (SDG63-006) by Shanghai Yinghao electromechanical Equipment Co., LTD, two stainless-steel pressure transducer which uses high accuracy silicon sensor (PR-25, 0~1 MPa, ±0.5% FS) by Keller, two K-type thermocouples (pt100, 0~100℃, ±1.5℃) by MEACON ， a magnetic railing ruler (MB500-10-0.05-ST, linear error ±35 μm) by SIKO, a water mist separator by SMC, two high pressure atomizing nozzle by Shenzhen Hanbo Environmental Protection Equipement Co., LTD, an air storage tank by SMC, a constant temperature equipment (DHC-05-A, 0-99.9℃, Temperature fluctuation ±0.2℃) and water tank (5L) by Hangzhou Qiwei Instrument Co. LTD, a water mist generator (PC-2801, flow rate 0.3 L/min) by Suzhou HAIGINT electromechanical Co. LTD.

Pressure sensors are installed at the bottom dead center of the compression chamber and expansion chamber to measure the instantaneous pressure of the air during the compression process and expansion process. Two K-type thermocouples are placed inside the compression chamber and expansion chamber to measure the instantaneous temperature of the air. The structure of the atomizing nozzle is described in the previous literature of the research group [21]. Fig.2 shows pictures of this study's quasi-isothermal CAES system setup. The compression chamber and expansion chamber are modified based on existing pneumatic cylinder. So, the diameter and height of the compression chamber are 100 mm and 150 mm, respectively, and the diameter and height of the expansion chamber are 100 mm and 125 mm, respectively.

A Labview program was used to program the operation of solenoid valves. Instantaneous pressure and temperature data during compression and expansion cycles are recorded using a data acquisition device (DAQ) through the LabVIEW program. The measurement devices were calibrated repeatedly to maintain measurement accuracy.

Spray nozzles are attached to the bottom of the compression chamber and expansion chamber to generate spray inside the chamber as shown in Fig. 3.

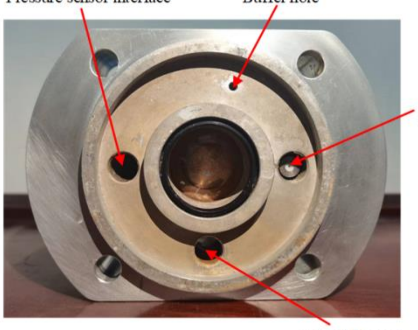


Fig.3 Structure diagram of the spray nozzle installation

2.2. Parameter definition

In the present study, we first studied the influences of the spray system on the compression and expansion process. Then the influences of the spray time and the nozzle size on the pressure in the compression or expansion chamber were investigated subsequently while keeping other operating parameters invariable. The nozzle inlet heating or cooling degree was precisely controlled. The spray time can be adjusted by program control. To change the nozzle size, different types of nozzles were applied. To study the effect of spray time, the spray opening time and closing time need to be defined based on compression process.

$$t_{op} = \frac{y_{so}}{v_p} \tag{1}$$

$$t_{cl} = \frac{y_{sc}}{v_p} \tag{2}$$

where, y_{so} is the position of the piston when the spray control valve is energized. y_{sc} is the position of the piston when the spray control valve is de-energized. v_p is the velocity of the piston.

The compression ratio, R_p, is described as

$$R_p = \frac{V_{ic}}{V_c} \tag{3}$$

where, V_{ic} is the initial air volume of compression chamber, V_c is the volume of air being compressed.

The expansion ratio, R_{ex}, is defined by

$$R_{ex} = \frac{V_{ie}}{V_e} \tag{4}$$

where, V_{ie} is the initial air volume of expansion chamber, V_e is the volume of supply air during expansion process.

The schematic of the piston movement during the compression process and expansion process can be shown in Fig.4. The initial position of the piston is the top dead center (TDC). The final position of the piston is the bottom dead center (BDC).

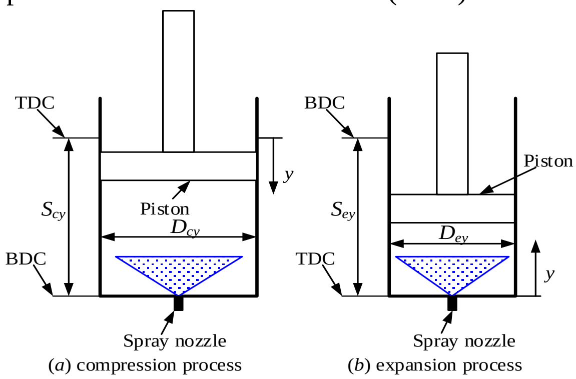


Fig.4 Schematic of piston moving

3. Experimental results and discussion

3.1. Influence of spray system

Table 2 Experimental conditions

Case	Parameters	Value
Compression process without water spray	Diameter of compression cylinder D_{cy}	100 mm
	Stroke of compression cylinder S_{cy}	150 mm
	Compression ratio R_p	2
	Velocity of piston v_p	0.1 m/s
Compression process with water spray	Compression ratio R_p	2
	Velocity of piston v_p	0.1 m/s
	Spray pressure p_{sw}	2 MPa
	Diameter of nozzle D_{nc}	0.6 mm
	Spray opening time t_{op}	0 s
	Spray closing time t_{cl}	1.2 s
	Water mist temperature T_{mc}	288 K
Expansion process without water spray	Expansion cylinder diameter D_{ey}	100 mm
	Expansion cylinder stroke S_{ey}	125 mm

	Expansion ratio R_{ex}	3
	Intake pressure p_s	0.4 MPa
	Intake air temperature T_s	293 K
Expansion process with water spray	Expansion cylinder diameter D_{ey}	100 mm
	Expansion cylinder stroke S_{ey}	125 mm
	Expansion ratio R_{ex}	3
	Intake pressure p_s	0.4 MPa
	Intake air temperature T_s	293 K
	Diameter of nozzle D_{ne}	0.8 mm
	Spray pressure p_{sp}	6 MPa
	Water mist temperature T_{we}	363 K

During the process of experiment, the environment pressure, environment temperature are 0.1 MPa and 293 K, respectively. To obtain the influence of the spray system, with and without water spray experiment were performed during the compression process and expansion process. The experimental conditions are summarized in Table 2.

During the compression process, the spray inlet pressure is set to 2 MPa, and the inlet water temperature is kept at 288 K. The diameter of the nozzle is 0.6 mm. The solenoid valve which controls the water spray is energized when the air starts to compress by the piston. When the piston reaches the BDC, the solenoid valve is de-energized. The velocity of the piston is equal to 0.1 m/s. During the expansion process, the spray inlet pressure is set to 6 MPa, and the inlet water temperature is kept at 363 K. The diameter of the nozzle is 0.8 mm. The compressed air flows into the expansion chamber, meanwhile, the water is sprayed into the expansion chamber until the piston reaches the BDC.

Variations of the pressure in the compression chamber and expansion chamber with spray and without spray are shown in Figs.5.

From Fig.5(a) , we can see that whole compression process can be described by the following processes:

The A-B curve denotes the suction stage. In this stage, the pressure in the compression chamber decreases owing to the piston's upward leading to the volume of the chamber increase.

The B-C curve denotes the stable stage. In this stage, the pressure in the compression chamber keeps constant pressure.

The C-D curve denotes the compression stage. The pressure in the compression chamber sharply increases owing to the piston's rapid downward. In this stage, the water spray at 288 K is injected into the compression chamber. Obviously, the pressure in the compression chamber with spray is lower than that without spray.

The D-E curve denotes the exhaust air stage. In this stage, the pressure in the compression chamber exhaust into the air storage tank. As the number of cycles increasing, the exhaust pressure gradually increases.

The maximum pressure in the compression chamber is about 0.212 MPa with spray enhanced heat transfer. The maximum pressure in the compression chamber decreases by 19.8% without spray-enhanced heat transfer. This means that the spray-enhanced heat transfer can reduce the work consumption during the compression process.

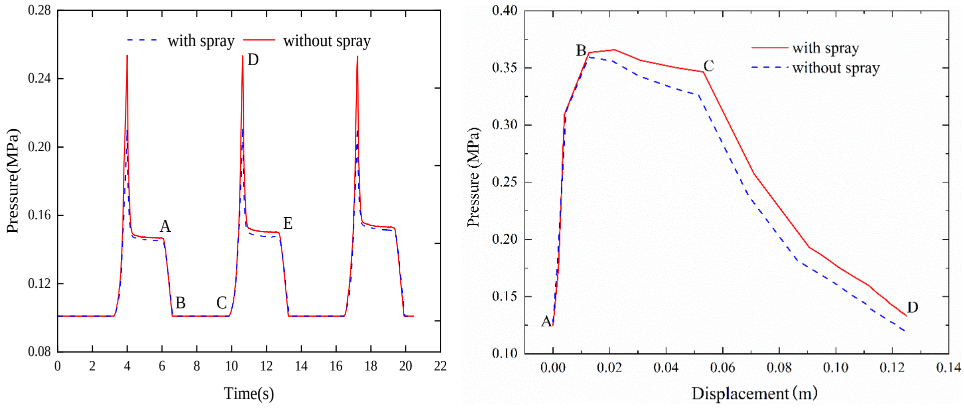
From Fig.5(b), we can see that the whole expansion process can be expressed by the following process:

The A-B curve denotes the inlet air stage. In this stage, compressed air flows into the expansion chamber and the pressure in the expansion chamber increases.

The B-C curve denotes the expansion process. The intake valve is closed. The compressed air continues expansion and the pressure in the expansion chamber decreases. In this stage, the water spray at 363 K is injected into the expansion chamber. It is obvious that the pressure in the compression chamber is higher with spray than without spray.

The C-D curve denotes the exhaust process. In this stage, the exhaust valve is opened. The residual compressed gas exhausts into the environment by piston drive.

Generally, the area contained in the *p-V* diagram is regarded as output work. It is obvious that the output work with spray enhanced heat transfer is larger than without spray enhancing heat transfer.



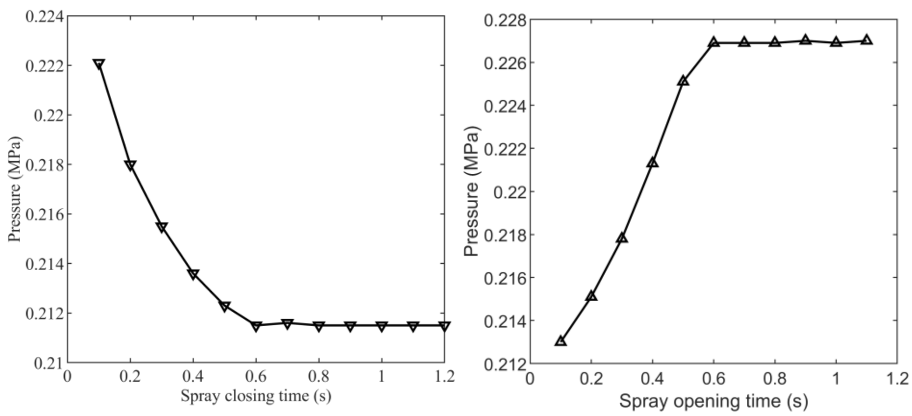
(a) compression chamber (b) expansion chamber

Fig.5 Variation of pressure

3.2. Influence of spray closing time and opening time during compression process

Based on the experimental platform, the maximum stroke of the compression cylinder is 150 mm. The velocity of the piston's movement is equal to 0.1 m/s. It takes the piston from the TDC to the BDC spends 1.2 s. When the position of the piston is at the TDC and starts to compress, the moment is defined as the initial moment. The Fig.6(a) shows the relationship between spray closing times and the maximum air pressure in the compression chamber under with a compression ratio of 2.

It can be seen from the Fig.6(a) that the changing trend of the gas pressure in the cylinder obtained by the experiment at differences spray closing time. The maximum air pressure of gas in the compression chamber will remain unchanged after the spray closing time is 0.6 s, and will only increase when it is less than 0.6 s. This shows that the mass of water mist injected at the stage of 0.6-1.2 s at the time of spray closing is excessive, and the heat exchange between water mist and air is not affected by closing the water mist in advance. With the closing time of spray less than 0.6 s, the mass of sprayed water mist is less than the saturation value, and there is not sufficient heat exchange with air, so the gas pressure increases due to limited heat exchange.



(a) different spray closing time (b) different spray opening time

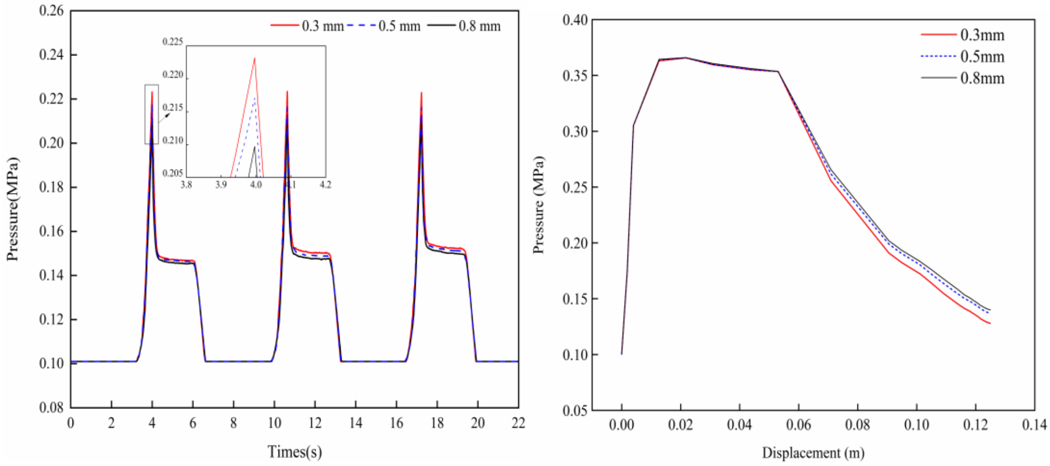
Fig.6 Maximum air pressure in the compression chamber

It can be seen from the Fig.6(b) that the changing trend of the gas pressure in the cylinder obtained from the experiment at different spray opening times. The pressure of gas in the compression chamber increases with the increase of spray opening time and remains unchanged after 0.6 s, which shows that spraying water mist within 0.6-1.2 s has no heat exchange effect on the air in the cylinder. Therefore, spraying water mist into the compression chamber after 0.6 s will not reduce the gas pressure inside the cylinder and will not improve the compression efficiency of the system.

3.3. Effect of spray size

The compression ratio is set to 2, the piston speed is set to 0.1 m/s, and the compression experiments are carried out under different nozzle diameters, and the nozzle diameters are 0.3mm, 0.5mm and 0.8mm respectively. It can be seen from the Fig.7(a) that spraying water mist particles with different nozzle diameters in the compression chamber has certain influence on the heat transfer effect between water mist and air. When the nozzle diameter is 0.3mm, the maximum pressure in three compression cycles is 0.223MPa; When the nozzle diameter is 0.5mm, the maximum pressure in three compression cycles is 0.217MPa; When the nozzle diameter is 0.8mm, the maximum pressure in three compression cycles is 0.211MPa. Therefore, it can be concluded that the smaller the nozzle diameter is, the better the heat exchange capacity of water mist is.

In order to obtain the specific changes of the air pressure in the cylinder under the fixed intake pressure and the fixed spray pressure, experiments were conducted with nozzle diameters of 0.3mm, 0.5mm and 0.8mm respectively, and the experimental study was carried out when the intake pressure was 0.4MPa, the water temperature was 363 K, and the spray pressure was 6 MPa. The Fig.9 shows the specific changes of the air pressure in the cylinder when nozzles of different diameters are used. It can be seen from the Fig.7(b) that the relationship between the specific changes of the air pressure in the cylinder. During the expansion process, the energy from water spray is injected into the expansion chamber. The larger the nozzle diameter is, the more water flows into the expansion chamber. So if we ignore the energy consumption of spray system, the larger the nozzle diameter is, the more the expansion output is.



(a) compression chamber (b) expansion chamber

Fig.7 Air pressure variation at different spray size

4. Conclusions

CAES system based on spray enhanced heat transfer is investigated. The influence of spray system, spray closing time, spray opening time and the diameter of the nozzle are studied experimentally. Based on thorough experiments the following conclusions can be drawn:

(1) Under same conditions, CAES system with spray heat transfer system can reduce the work consumption during the compression process compared with without spray heat transfer system. And during the expansion process, the output work will increased due to high temperature water spray injected into expansion chamber.

(2) For the same nozzle, the spray closing time and opening time have the critical value to decrease the maximum air pressure during compression process. Under the given condition, the critical spray closing time and opening time are 0.6 s, and 0.6 s, respectively.

(3) To compression process, the reduction of nozzle diameter can decrease maximum air pressure in compression chamber.

(4) To expansion process, if the energy consumption is ignored, the larger the nozzle diameter, the greater the expansion output.

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Conflicts of Interest

The authors declare no conflict of interest or personal relationships that could have appeared to influence the work reported in this paper.

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