INFLUENCE OF POROUS MEDIA PARAMETERS ON ISOTHERMAL PISTON COMPRESSION SYSTEM

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Compressed air energy storage is considered a promising one to serve as high energy capacity and power rating energy storage systems. As a crucial part, efficient compressors are needed to realize a high compression efficiency. An isothermal piston composed of a solid-piston and porous media is highly effective in achieving efficient near-isothermal compression. The large heat transfer area between the porous media and the air can effectively improve the compression efficiency. Specific surface area and porosity are two key parameters of a porous media and their influence on the performance of isothermal piston compression system is analyzed. Geometric characteristics of porous media is investigated and the flow resistance model is established. The influence of the two key parameters of porous media on resistance is discussed, and a comprehensive energy conservation performance assessment of the isothermal piston is analyzed. The results show that when the porosity is maintained at 0.92 and the specific surface area increases from 860 m^{-1} to 2980 m^{-1}, the total work of the isothermal piston system decreases by 14.6×10^3 J/kg and the system efficiency improves by 6.8%, despite the resistance work increasing from 9.4 J/kg to 48.5 J/kg. When the specific surface area is maintained at 2980 m^{-1} and the porosity increases from 0.6 to 0.92, the resistance work decreases from 17.5×10^3 J/kg to 57.9 J/kg, the total work of the isothermal piston system reduces by 17.4×10^3 J/kg, and the system efficiency improves by 8%.

Key words: *compressed air energy storage, isothermal piston, porous media, specific surface area, porosity*

1. Introduction

Renewable energy development has become the key to solving the global energy and climate crisis, and countries worldwide are focusing heavily on developing and utilizing renewable energy. However, renewable energy sources such as solar photovoltaic, wind, and tidal energy are unevenly distributed in time and space, resulting in the inability to utilize renewable energy sources optimally [1]. Compressed air energy storage (CAES) technology is considered very promising for large-scale energy storage, characterized by large storage capacity, high energy density, long storage time, and high-power rating [2].

CAES can be classified into Diabatic compressed air energy storage (D-CAES), Adiabatic compressed air energy storage (A-CAES), and Isothermal compressed air energy storage (I-CAES) concepts depending on the target idealization process [3]. The two commercial power plants operating in the world now are Huntorf and McIntosh. The Huntorf power plant in Germany is a typical D-CAES, which will affect the efficiency of the system as the compression heat generated in the compression process is not stored, and additional fossil fuels need to be added to provide energy for the expansion process. In addition, the combustion exhaust gases are vented directly into the atmosphere still having high temperature, resulting in a partial waste of energy. As a result, the system cycle efficiency of the Huntorf power plant is only 42% [4, 5]. McIntosh Power Plant in Alabama, USA, introduced a return heater based on the Huntorf power plant to absorb the waste's heat and heat the compressed air before it enters the combustion chamber. The overall cycle efficiency of the system has been improved compared to that of the Huntorf power plant, reaching 54% [5-7]. On the other hand, both Huntorf and McIntosh power stations store compressed air in underground salt caverns, and since the above two power stations do not transfer the compression heat generated during compression to the outside environment quickly, the compressed air stored in underground salt caverns has a high temperature. The temperature has a significant influence on the stresses generated in underground caverns. As a result, the long-term stability and durability of underground salt caverns can be affected [2, 8, 9].

I-CAES is a new type of CAES technology. In the compression process, the I-CAES system can transfer a large amount of compression heat to the outside world, thereby inhibiting the rise of compressed air temperature and reducing the input of compression work. After the compression heat is transferred to the outside environment, the heat exchanger in the I-CAES system can store it and heat the compressed air before expansion. Since the compressed air temperature remains almost constant during the compression and expansion phases, without additional fuel, the ideal round-trip efficiency of an I-CAES system can reach 100% [10-12].

The liquid piston realizes air compression through the rise or fall of the liquid column, which is an effective way to enhance the heat transfer of compression. The liquid has a large specific surface area and specific heat capacity, which can effectively absorb the compression heat and transfer it to the outside environment. This significantly improves the compression efficiency compared with the traditional mechanical reciprocating piston. Due to the use of a hydraulic system to drive the liquid piston, the compression process may be limited to a lower speed [13]. Another way to enhance compression heat transfer is to inject water droplets into the compression chamber, through which the compression heat is absorbed. The smaller the water droplets are, the greater the specific surface area in contact with the compressed air. However, they also require a more significant injection pressure, which means more additional energy input [14]. In addition, water foam, hollow spheres, and changing the shape of the compression chamber can also be used to strengthen the transfer of compression heat, and this method can effectively improve the compression efficiency [15-17]. Overall, improving the heat transfer efficiency is the key point to realize isothermal compression.

We presented an isothermal piston compression system in a previous study [14, 18-20]. The innovation of this system lies in the combination of the traditional mechanical reciprocating piston and the porous media. The special structure of the porous media is sparse and porous, resulting in a large heat transfer area and can improve the heat transfer efficiency between the porous media and air [21, 22]. Moreover, copper foam with better thermal conductivity is selected as the material of the porous media. When the motor drives the isothermal piston up and down through the crank rod mechanism for compression, the compression heat generated by the compressed air will be rapidly transferred to the porous media, and the temperature of the porous media will rise sharply. In order to maintain a certain temperature difference between the porous media and the air, a certain liquid (usually water) is placed below the compression chamber to absorb the heat in the porous media. In addition, the liquid can be circulated to the outside of the compression chamber through the circulation pump to dissipate the heat from the fluid to the outside world. The schematic diagram of the isothermal piston compression system is shown in Fig. 1.

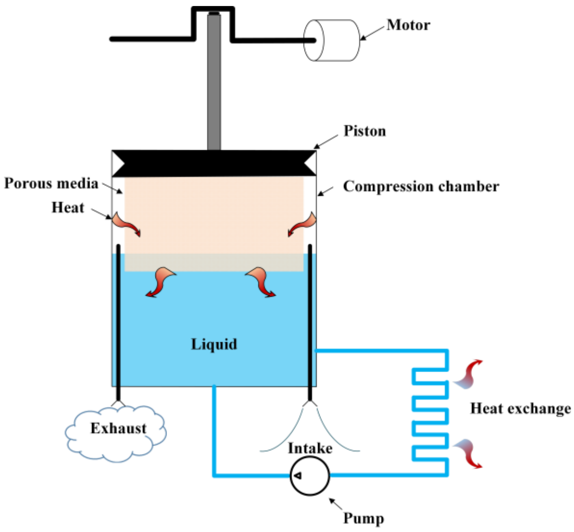

Figure 1. Diagram of the isothermal piston compression system

However, the complex porous structure of porous media also has a certain damping effect on the fluid [23]. As discussed in our previous studies, flow resistance between the isothermal piston and the fluid will be introduced, causing additional energy consumption [14, 18, 20]. The effect of rotational speed on the performance of the isothermal piston was discussed in [18]. In this paper, copper foam with excellent thermal conductivity is selected as the material of porous media. During a single compression stroke, the influence of the specific surface area and porosity of porous media on the performance of isothermal piston is analyzed when the compression ratio is 7, the motor speed is 100 r/min, and the liquid is water.

2. Geometric Characteristics of Porous Media

Due to the complex interconnections between pores in the porous media, it is extremely difficult to construct the resistance model of porous media. In this study, in order to simplify the resistance model, the face-centered cubic structure will be used for the analysis. At the same time, the porous media diameter is assumed to be the same as the compression chamber diameter.

The face-centered cubic structure is shown in Fig. 2. It can be obtained from a sphere in Fig. 3. It satisfies the relationship that $l < d_s < \sqrt{2}l$ to ensure face-centered cubic unit inside the porous media is connected and the pores are interlinked. The smaller portion of a sphere cut off by a plane is called a segment. The volume of a segment can be expressed as:

$$V_{seg} = \pi H^2 \left(\frac{1}{2} d_s - \frac{H}{3} \right) \tag{1}$$

Note that the height of a segment H can be expressed by the diameter of the sphere d_s and the side length of a cube l:

$$H = \frac{d_s - l}{2} \tag{2}$$

Substituting Eq. (2) into Eq. (1), the segment volume is:

$$V_{seg} = \frac{\pi \left(d_s - l \right)^2 \left(2d_s + l \right)}{24} \tag{3}$$

In a face-centered cubic unit, the volume occupied by the air portion can be obtained as the volume of a sphere with diameter d_s minus the 6 segments:

$$V_{hollow} = \frac{4\pi}{3} \left(\frac{d_s}{2} \right)^3 - 6V_{seg} \tag{4}$$

Substituting Eq. (3) into Eq. (4), the volume occupied by the air portion is:

$$V_{hollow} = -\frac{\pi d_s^3}{3} + \frac{3\pi d_s^2 l}{4} - \frac{\pi l^3}{4} \tag{5}$$

The apparent volume of a face-centered cubic element is:

$$V_{cubic} = l^3 \tag{6}$$

The porosity ε can be expressed as:

$$\varepsilon = \frac{V_{hollow}}{V_{cubic}} \tag{7}$$

Substituting Eq. (5) and Eq. (6) into Eq. (7), the porosity is related to d_s and l:

$$\varepsilon = -\frac{\pi}{3} \left(\frac{d_s}{l} \right)^3 + \frac{3\pi}{4} \left(\frac{d_s}{l} \right)^2 - \frac{\pi}{4} \tag{8}$$

As the porosity is determined by the ratio of the side length of the cubic to the radius of the sphere, a dimensionless quantity λ is defined which determines the structural characteristics of face-centered cubic model:

$$\lambda = \frac{d_s}{l} \tag{9}$$

Therefore, the porosity of face-centered cubic model can be expressed as:

$$\varepsilon = -\frac{1}{3}\pi\lambda^3 + \frac{3}{4}\pi\lambda^2 - \frac{\pi}{4} \tag{10}$$

Because the porous media is regarded as a face-centered cubic unit stacked, only the inner hollow part contacts the air and participates in heat transfer. The heat transfer area of the face-centered cubic unit S_{hollow} can be expressed as:

$$S_{hollow} = 4\pi\left(\frac{d_s}{2}\right)^2 - 6S_{seg} \tag{11}$$

where S_{seg} is the surface area of segment:

$$S_{seg} = \frac{\pi d_s\left(d_s - l\right)}{2} \tag{12}$$

Substituting Eq. (12) into Eq. (11), the heat transfer area of face-centered cubic unit S_{hollow} is:

$$S_{hollow} = \pi d_s\left(3l - 2d_s\right) \tag{13}$$

Specific surface area of the face-centered cubic unit is expressed as:

$$S_v = \frac{S_{hollow}}{V_{cubic}} \tag{14}$$

Substituting Eq. (6), Eq. (9) and Eq. (13) into Eq. (14), the relation between the specific surface area of face-centered cubic unit and its geometric dimensioning is:

$$S_v = \frac{\pi\lambda\left(3 - 2\lambda\right)}{l} \tag{15}$$

Therefore, based on Eq. (7) and (15), the geometric dimension of face-centered cubic unit can be determined according to the porosity and specific surface area of the porous media.

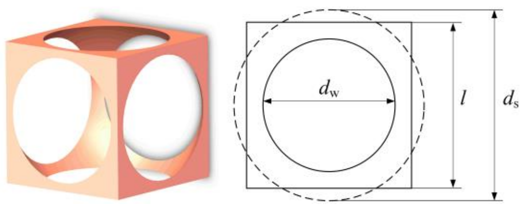

Figure 2.　Face-centered cubic structure

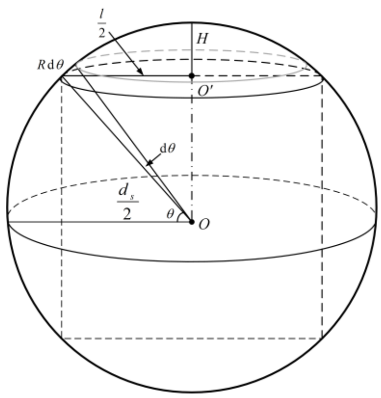

Figure 3.　Model of a sphere

3. Resistance Model and Energy Efficiency Calculation

During compression, the porous media will move up and down reciprocating with the piston. When the porous media moves down and gradually immerses in the liquid, there is a certain flow resistance between the porous media and the liquid due to the relative movement. Moreover, the complex three-dimensional structure of the porous media will further increase the flow resistance. The resistance pressure gradient $\mathrm{d}p_{liq}/\mathrm{d}l_{por}$ is given by Ergun surface cube model [24, 25]:

$$\frac{\mathrm{d}p_{liq}}{\mathrm{d}l_{por}} = \frac{\mu}{K} \cdot u + \rho \cdot C_c \cdot u^2 \tag{16}$$

The piston moves in the opposite direction to $\mathrm{d}l_{por}$, the symbol of the dynamic viscosity of the liquid is μ, the symbol of permeability of porous media is K, the symbol of the relative velocity between the porous media and the liquid is u, the symbol of the liquid density is ρ, the inertia coefficient (or form factor) of a porous media has the symbol C_c. K and C_c are defined as follows:

$$K = \frac{\varepsilon^3 d_p^{\ 2}}{a(1-\varepsilon)^2} \tag{17}$$

$$C_c = \frac{b(1-\varepsilon)}{\varepsilon^3 d_p} \tag{18}$$

The constants related with viscosity and inertia are a and b, which have values of 180 and 1.75, respectively, the equivalent spherical particle diameter symbol is d_p and is defined as follows:

$$d_p = \frac{6}{S_v} \tag{19}$$

Substituting Eq. (17) and Eq. (18) into Eq. (16), it is the classical Ergun equation

$$\frac{\mathrm{d}p_{liq}}{\mathrm{d}L} = \frac{a(1-\varepsilon)^2 \mu}{\varepsilon^3 d_p^{\ 2}} \cdot u + \frac{b(1-\varepsilon)}{\varepsilon^3 d_p} \cdot \rho \cdot u^2 \tag{20}$$

The properties of water and air are quite different, the viscosity of water (1.01×10^{-3} Pa·s) is three orders of magnitude greater than the viscosity of air (17.9×10^{-6} Pa·s), and the density of water (1×10^{3} kg/m^3) is also three orders of magnitude greater than the density of air (1.18 kg/m^3). Therefore, the drag effect caused by water on the porous media during compression is much greater than that caused by air. In this study, the flow resistance caused by the relative motion between air and porous media is not considered, only the flow resistance caused by the relative motion between water and porous media is considered.

The isothermal piston can reduce the compression work required in the compression process by maintaining the constant temperature of the compressed air, thus improving the compression efficiency of the system. The required compression work during compression can be obtained by integrating the air volume with the air pressure：

$$W = -\int_{V_0}^{V} p \cdot \mathrm{d}V \tag{21}$$

The air pressure symbol is p, at the beginning and end of compression, the air volume sign is V_0 and V, respectively. During the compression process, as the air volume decreases, the air pressure gradually increases. The negative sign used in Eq. (21) indicates that the gas volume change is opposite to the gas pressure change in the compression process, so the sign of the compression work is positive.

Eq. (22) and Eq. (23) represent the compression work consumed by isothermal and adiabatic compression within the closed system, respectively.

$$W_{iso} = m_{air} \cdot R \cdot T_0 \cdot \ln \frac{p}{p_0} \tag{22}$$

$$W_{adi} = \frac{1}{\kappa - 1} \cdot m_{air} \cdot R \cdot T_0 \cdot \left[\left(\frac{V_0}{V} \right)^{\kappa - 1} - 1 \right] \tag{23}$$

The adiabatic exponent symbol is κ, and its value is 1.4. The mass of air in the closed system is m_{air}. T_0 represents the temperature of air when it is not compressed, and the air pressure symbols at the beginning and end of compression are p_0 and p, respectively.

In this study, only the drag effect between water and porous media is considered, the flow resistance generated by the relative movement of porous media and water is linearly related, and the diameter of porous media is equal to the diameter of the compression chamber. In this case, Eq. (24) can represent the flow resistance work W_{por} generated by the relative motion between water and porous media.

$$W_{por} = \frac{1}{2} \cdot \frac{\mathrm{d}p_{liq}}{\mathrm{d}L} \cdot l_{por} \cdot V_{cy} \cdot (1 - \varepsilon) \tag{24}$$

The symbol for the length of the porous media is l_{por}, and the symbol for the volume of the compression chamber is V_{cy}.

In isothermal piston compression systems, the total system energy consumption W_{+por} is defined as the sum of compression work and flow resistance work:

$$W_{+por} = W + W_{por} \tag{25}$$

In this study, the efficiency η_s of the isothermal piston compression system is defined by Eq. (26).

$$\eta_s = \frac{W_{iso}}{W_{+por}} \tag{27}$$

The better the heat transfer performance of the isothermal piston, the higher is the system efficiency and is closer to isothermal compression. Therefore, the highest compression efficiency of an isothermal piston is isothermal compression efficiency. The minimum efficiency η_{min} of an isothermal piston is defined as the ratio of isothermal compression work to adiabatic compression work:

$$\eta_{\min} = \frac{W_{iso}}{W_{adi}} \quad (28)$$

4. Results and Discussion

The specific surface area and porosity of porous media not only greatly affects the heat transfer rate between porous media and air, but also have a non-negligible effect on the flow resistance caused by the relative motion between porous media and liquid. Therefore, in case of friction, the effect of porous media parameters on the performance of an isothermal piston compression system is analyzed in this section.

4.1. *Effect of Specific Surface Area*

The change of the specific surface area of the porous media will also change the contact area between the porous media and water. Therefore, the flow resistance generated between porous media with different specific surface areas and water also differs [19, 20].

The resistance work generated by the relative motion between porous media and water is calculated according to Eq. (20) and Eq. (24). When the porosity of the porous media is 0.92, Fig. 4 shows the relationship between the specific surface area of the porous media and the resistance work. When the specific surface area increases from 860 m^{-1} to 2980 m^{-1}, at the end of the compression stroke, the resistance work of the isothermal compression system increases from 9.4 J/kg to 57.9 J/kg, and the resistance work increases 6.1 times. It can be seen that the increase of the specific surface area of the porous media makes the flow resistance between the porous media and water increase significantly. This is because an increase in the specific surface area will make the connection between pores inside the porous media more complex, thus making the flow of water in the pores more difficult. In addition, the contact area between the porous media and water will increase with the increase of the specific surface area of the porous media, which increases the friction force between the porous media and water to some extent and further increases the resistance work.

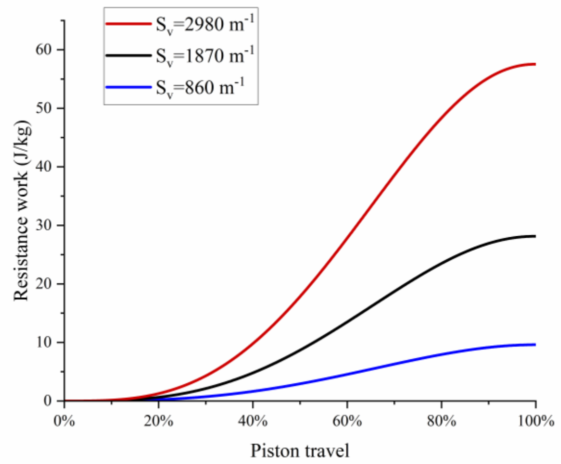

Figure 4. Relation of resistance work and compression stroke at different specific surface areas

Fig. 5 shows the influence of the specific surface area of the porous media on the total work. When the specific surface area is increased from 860 m^{-1} to 2980 m^{-1}, the total work decreases from 184×10^3 J/kg to 169×10^3 J/kg at the end of the compression stroke, resulting in total work reduction of 7.9%. This is because the increase in specific surface area accelerates the heat transfer rate between the air and the porous media, bringing the compression process closer to isothermal compression and thereby reducing the compression work by 14.6 J/kg. This indicates that when the specific surface area of the porous media increases, the positive effect of heat transfer outweighs the negative effect of resistance work. Therefore, increasing the specific surface area of the porous media can effectively reduce the system's total energy consumption.

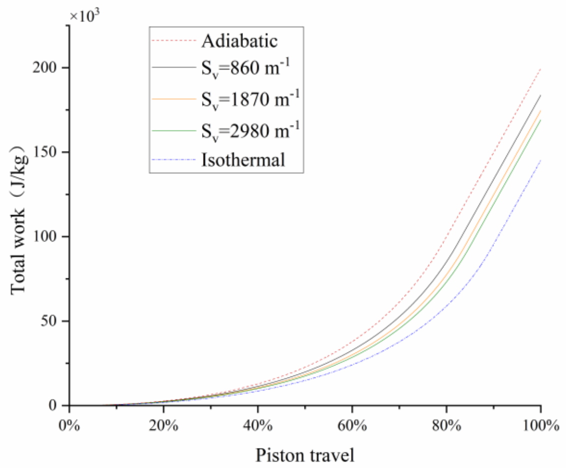

Figure 5. Relation of total work and compression stroke at different specific surface areas

Fig. 6 shows the relationship between the specific surface area of the porous media and the efficiency of isothermal piston compression. When the specific surface area of the porous media increases from 860 m^{-1} to 2980 m^{-1}, the system efficiency rises from 79% to 85.9%, an increase of 6.8%. Therefore, increasing the specific surface area of the porous media contributes to enhancing the efficiency of isothermal piston compression.

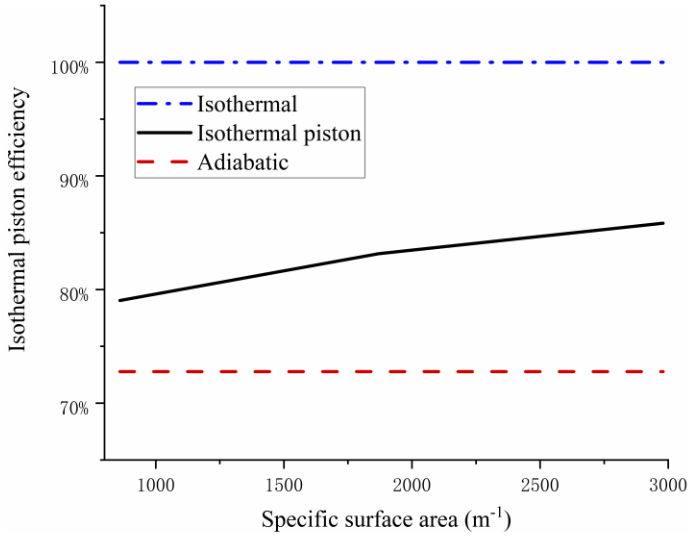

Figure 6. Relation between isothermal piston efficiency and specific surface area

4.2. *Effect of Porosity*

When the porosity of the porous media changes, the proportion of its internal solid part also changes, which affects the friction characteristics between the solid and water and further changes the resistance relationship between the porous media and water [19, 20].

When the specific surface area of the porous media is 2980 m^{-1}, Fig. 7 shows the relationship between porosity and resistance work of the porous media. After the compression, when the porosity increases from 0.6 to 0.92, the resistance work of the system decreases from 17.5×10^{3} J/kg to 57.9 J/kg, which means that the increase of porosity will reduce the flow resistance between the porous media and water. Porosity has greater influence on the resistance work than the specific surface area. The reason is that under a certain apparent volume, when the porosity increases, the proportion of the solid part in the porous media will decrease, which will result in a smaller contact area between the solid part and the water, thereby reducing the friction between the two and reducing the resistance work.

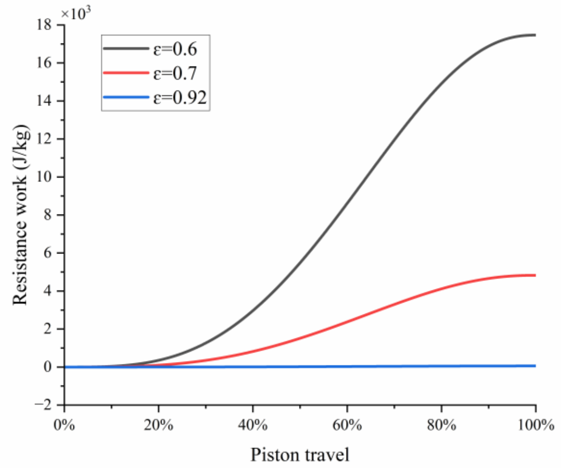

Figure 7. Relation of resistance work and compression stroke at different porosity

Fig. 8 shows the relationship between porosity of porous media and total work of isothermal piston compression system. At the end of the compression stroke, when the porosity of the porous media increases from 0.6 to 0.92, the total work of the isothermal piston compression system decreases from 187×10^3 J/kg to 169×10^3 J/kg, reducing the system's total energy consumption by 9.4%. The primary reason for this reduction is the decrease in resistance work due to the increased porosity. Additionally, the increase in porosity has a minimal effect on heat transfer, so the compression work remains nearly constant.

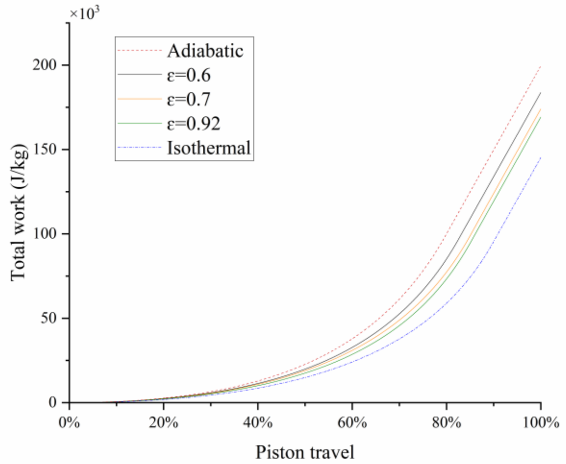

Figure 8. Relation of total work and compression stroke at different porosity

Fig. 9 shows the relationship between porosity of porous media and isothermal piston efficiency. When the porosity of the porous media increases from 0.6 to 0.92, the efficiency of the isothermal piston compression system rises from 77.8% to 85.8%, which is an increase of 8%.

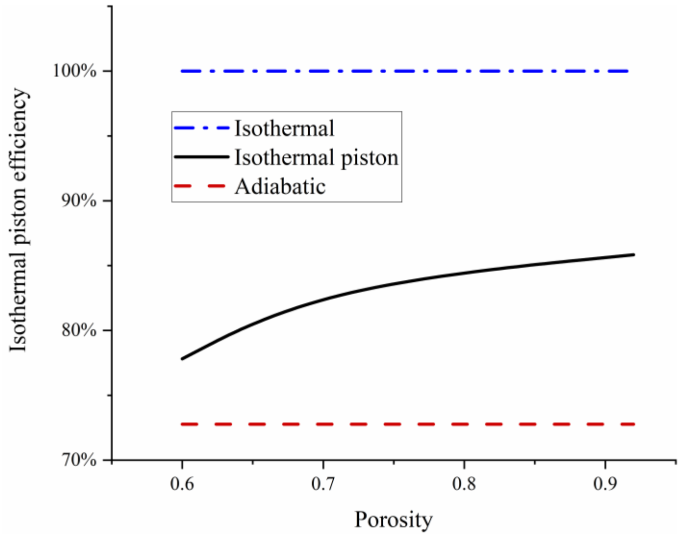

Figure 9. Relation between isothermal piston efficiency and porosity

5. Conclusions

The isothermal piston composed of a porous media can quickly absorb the compression heat in compressed air. As key parameters of a porous media, porosity and specific surface area not only affect the heat transfer of porous media and liquid, but also affect the flow resistance generated between porous media and liquid. In this paper, the face-centered cubic structure is used to simplify the analysis of porous media model, and on this basis, the effects of porosity and specific surface area of porous media on the system resistance work and total work are analyzed. The main points of this paper can be summarized as follows:

(1) When the porosity of the porous media is 0.92 and the specific surface area is 860 m^{-1}, the system resistance work is 9.4 J/kg. When the specific surface area increases to 2980 m^{-1}, the resistance work of the system is only increased by 48.5 J/kg. However, the compression work of the system decreases by 14.6×10^3 J/kg due to the increase in the specific surface area, leading to a total work reduction of 14.6×10^3 J/kg and an improvement in system efficiency by 6.8%. These results indicate that increasing the specific surface area of the porous media can effectively enhance the efficiency of the isothermal piston compression system.

(2) When the specific surface area of the porous media is 2980 m^{-1} and the porosity is 0.6, the system resistance work is 17.5×10^3 J/kg. As the porosity increases to 0.92, the system resistance work decreases by 17.4×10^3 J/kg, the total system work decreases by 17.3×10^3 J/kg, and the system efficiency improves by 8%. These results indicate that increasing the porosity of the porous media can effectively enhance the efficiency of the isothermal piston compression system.

(3) In this study, the total work of the isothermal piston compression system is between the adiabatic work and the isothermal work. When the specific surface area and porosity of the porous media are increased, the total work of the isothermal piston compression system will be reduced and come close to the isothermal work.

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Nomenclature

Cc	*Inertia coefficient of porous media(m-1)*	*Greek symbols*	
Cv	*Specific heat at constant volume (J·kg-1·K-1)*	ε	*Porosity (%)*
dw	*Diameter of inner circle forming the face-centered cubic (m)*	λ	*ratio of ds and l*
ds	*Diameter of outer circle forming the face-centered cubic (m)*	η	*Isothermal piston efficiency*
dp	*Equivalent spherical particle diameter (m)*	κ	*Adiabatic exponent*
d*pliq*	*Flow pressure of the liquid during the porous media*	μ	*Dynamic viscosity (Pa·s)*
H	*Height of a segment (m)*	ρ	*Density of fluids (kg/m3)*
K	*Permeability of porous media (m2)*		
l	*Cube edge length forming the face-centered cubic (m)*	*Subscripts & Superscripts*	
lpor	*Length of the porous media (m)*	*0*	*Initial condition*
m	*Mass (kg)*	*adi*	*Adiabatic condition*
p	*Pressure (Pa)*	*cy*	*cylinder*
R	*Gas constant (J/kg·K−1)*	*iso*	*Isothermal condition*
Sv	*Specific surface area (m-1)*	*liq*	*Liquid*
T	*Temperature (K)*	*por*	*Porous*
u	*Relative velocity between a fluid and a porous media (m/s)*	*seg*	*Segment*
V	*Volume (m3)*		
W	*Work (J/kg)*		

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