Simulation of Stirling driven desalination power system

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Abstract. This paper presents a new power system for reverse osmosis desalination, which is composed of a Stirling engine driven booster pump and a reciprocating piston pump rigidly connected. Firstly, the physical model is established by SolidWorks, and then the frequency of reciprocating motion of piston is calculated through the principle of piston component motion. Then, the UDF file of piston motion is compiled. Then, CFD analysis is carried out by FLUENT software to select the standard for temperature field, velocity field and pressure field in the pump chamber of Stirling engine are simulated by coupled method, and the output work of the engine is studied. The results show that the gas movement in Stirling engine is stable, the pressure at the discharge port of reciprocating pump is greater than the required osmotic pressure, and the whole power system can operate normally.

Key words: Free piston Stirling engine; reciprocating piston pump; CFD analysis; motion frequency.

1. Introduction
The energy needed to alleviate seawater desalination has become the focus of current research [1]. Reverse osmosis is a high-pressure pump as the power source, continuous delivery of seawater for it, but with the increase of seawater salinity, the working pressure of high-pressure pump will continue to increase, so additional driving device is needed to overcome the corresponding resistance. However, the power consumption of general work is very large, so the development of renewable energy, such as solar energy, biomass energy and so on, has attracted more and more attention.

Stirling engine, as a piston type power machine with external heating, has strong adaptability to heat source. It can use renewable energy such as solar energy, biomass energy, industrial waste heat and exhaust gas [2]. Jian m studied and tested three types of Stirling engine according to the conditions that the work of expansion chamber and compression chamber of Stirling engine is positive and the work of gas to piston and displacer is also positive. It is found that the free piston Stirling engine can not be started because the gas body does negative work to the piston. The premise of this study is that under the condition of no external force, the engine of this model can also be started and run under certain external force [3], Jian m established a new research thermodynamics, taking into account non isothermal effect, regenerator efficiency, main heat loss and thermal resistance between heater and cooler [4]. The output work and efficiency obtained by this thermodynamic model are close to the reality first than those obtained by isothermal model and ideal adiabatic model. At present, Stirling engines are
mostly used for power generation. Chen Xi [5] et al. Studied the dynamic characteristics of free piston Stirling generator, established the mass spring damping system, and analyzed the dynamic characteristics of power piston and valve piston by force polygon method.

Reciprocating pump is an important device in hydraulic system. It has the advantages of high rated pressure, compact structure and high efficiency. Xu Wei [6] simulated the reciprocating piston pump with CFD software, obtained the pressure distribution and velocity distribution of the flow field in the pump, intuitively reflected the pressure impact and vibration phenomenon in the pump cavity and the flow backflow phenomenon at the oil inlet and outlet, and obtained the central angle structure of the oil suction chamber and the oil discharge cavity which is more conducive to the stability of flow pulsation and reduce the pressure impact.

In this paper, a new Stirling driven reverse osmosis desalination power system is proposed. The Stirling engine is used as the power source to drive the reciprocating pump with the same motion form to pressurize the seawater. The CFD analysis is carried out based on FLUENT software. In order to further improve the utilization of energy and reduce the energy cost of seawater desalination, the internal changes of flow field are explored.

2. Structure and principle of power system

2.1. Overall structure

![Figure 1. Power system structure diagram](image)

1. Expansion chamber 2. Heater 3. Regenerator 4. Compression chamber 5. Compression chamber 6. Spring 7. Pump piston 8. Power piston 9. Air distribution piston plate spring 10. Air distribution piston 11. Pump cavity 12. Compression accumulator 13. Reverse osmosis components

2.2. working principle

At the beginning of the movement, the pump piston is located at the top dead center of the pump chamber, and the pump chamber is filled with seawater. The free piston Stirling engine heater is heated. When the working fluid in the expansion chamber is heated to a certain temperature, the valve distribution piston begins to move down the dead center. The heated working fluid enters the compression chamber after passing through the regenerator and cooler. At this time, the power piston moves from the top dead center to the bottom dead center. Because the piston in pump chamber and power piston are rigidly connected by piston rod, the motion law of pump piston is the same as that of power piston. This process is a drainage process. Part of seawater enters the reverse osmosis component through the drainage pipe in the pump chamber, and part enters the compression accumulator to store energy to prepare for the water absorption process. After the completion of drainage, under the action of compression accumulator, the power piston drives the pump piston to start reverse movement, that is to say, the water absorption process begins. In the free piston Stirling engine, after isothermal compression, isovolumetric heat absorption and isothermal expansion, the power piston and valve piston return to their original position, and the water absorption process is completed in the pump chamber. So far, Stirling driven booster pump completed a suction and drainage process. When the pump is in normal operation, this process does reciprocating circulation movement.
3. Establishment of model

3.1. Establishment of physical model

![Figure 2. Physical model of power system](image)

3.2. governing equation

Mass conservation equation:

\[
\frac{\partial \rho}{\partial t} + \nabla \rho \vec{V} = 0
\]  

Among, \( \vec{V} = \frac{\partial}{\partial x} \vec{i} + \frac{\partial}{\partial y} \vec{j} + \frac{\partial}{\partial z} \vec{k}, \ \vec{V} = u\vec{i} + v\vec{j} + w\vec{k} \)

Momentum conservation equation:

\[
\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho u^2 + p)}{\partial y} + \frac{\partial (\rho u v)}{\partial z} = \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + \frac{\partial (-\mu'u')}{\partial x} + \frac{\partial (-\mu'v')}{\partial y} + \frac{\partial (-\mu'w')}{\partial z}
\]  

Energy conservation equation:

\[
\frac{\partial (\rho e)}{\partial t} + \frac{\partial (\rho e u)}{\partial x} + \frac{\partial (\rho e v)}{\partial y} + \frac{\partial (\rho e w)}{\partial z} = \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} 
\left[ \left( \lambda + \frac{c_p u}{\rho} \right) \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} 
\left[ \left( \lambda + \frac{c_p u}{\rho} \right) \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} 
\left[ \left( \lambda + \frac{c_p u}{\rho} \right) \frac{\partial T}{\partial z} \right]
\]  

Among, \( \frac{D}{Dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z} \)

\( \rho \) - Density; \( u, v, w \)-component of velocity vector in \( x, y, z \) directions; \( P \)-pressure on fluid microelement; \( C_p \) - specific heat capacity; \( \lambda \) - thermal conductivity; \( \mu \) - viscosity.

4. Boundary conditions and initial conditions

Stirling engine is a very complex process in operation, and many factors will affect the thermal cycle of Stirling engine. Therefore, some simplifications should be made in the simulation:

(1) It is assumed that the model is absolutely sealed and the working medium is ideal gas;
(2) The heat exchange between the model and the outside and the friction between piston and cylinder are ignored;
(3) The temperature in the model is the same as that in the porous medium;
(4) Suppose that the piston is a simple harmonic motion.

The moving mesh model in fluent is used to simulate the piston motion by writing UDF file.

\[ v_d = -\pi f \cdot A_d \cdot \cos \left( 2\pi ft + \frac{\pi}{2} \right) \]  

\[ v_p = v_z = -\pi f \cdot A_p \cdot \cos \left( 2\pi ft \right) \]

The required parameters and initial values of Stirling engine are shown in Table 1. The required parameters of reciprocating pump are shown in Table 2.
Table 1. Setting of engine parameters and initial conditions

| Gas working medium | Frequency / Hz | Heater wall temperature / K | Cooler wall temperature / K | Diameter of power piston / mm | Length of power piston / mm |
|---------------------|----------------|----------------------------|-----------------------------|-------------------------------|----------------------------|
| helium              | 12             | 959                        | 300                         | 72                            | 90                         |

| Power piston stroke / mm | Valve piston diameter / mm | Valve piston length / mm | Valve piston stroke / mm | Initial pressure / MPa | Porosity of regenerator |
|--------------------------|---------------------------|-------------------------|-------------------------|-----------------------|-------------------------|
| 45                       | 90                        | 135                     | 41                      | 1.95                  | 0.668                   |

Table 2. Setting of parameters and initial conditions of reciprocating pump

| Plunger diameter / mm | Plunger length / mm | Diameter of suction pipe / mm | Diameter of drain pipe / mm |
|-----------------------|---------------------|-------------------------------|----------------------------|
| 45                    | 170                 | 25                            | 25                         |

| Length of suction pipe / mm | Length of drain pipe / mm | Suction port pressure / MPa | Outlet pressure / MPa |
|-----------------------------|---------------------------|-----------------------------|-----------------------|
| 300                         | 500                       | 0.09                        | 5                     |

In order to verify the reliability of the model, it is necessary to obtain the output power of the engine through the P-V diagram of the expansion chamber and the compression chamber:

\[ W = \int_0^T p \, dV = \int_0^T p \, dV \]  \hspace{1cm} (6)

\[ P_{out} = \int p_c \, dV_e + \int p_i \, dV_e \]  \hspace{1cm} (7)

5. Results and analysis

As shown in Fig. 3 is the volume change diagram of expansion chamber and compression chamber of free piston Stirling engine. At the beginning of the movement, the valve distribution piston moves to the outer dead center, and the volume of the expansion chamber decreases until all the working fluids enter the compression chamber. At this time, the expansion chamber volume becomes zero. At the same time, the cooler cools the gas working medium in the compression chamber, and the gas is compressed. The valve distribution piston moves towards the inner dead center again, and the expansion chamber volume increases gradually.

Figure 4 shows the pressure versus volume curve of expansion chamber and compression chamber. Positive work is done in the expansion chamber and negative work is done in the compression chamber. The sum of the work done by the two chambers is positive, so the engine as a whole does positive work.

Fig. 5 shows the temperature and speed variation field in Stirling engine during the whole cycle. During the drainage process, the power piston moves from the balance position to the outer dead center,
thus driving the plunger to move to the dead center in the pump chamber. The temperature in the compression chamber is 726k. Due to the continuous high-speed gas flow into the compression chamber, the gas collides continuously in the compression chamber, so that a large amount of gas velocity reaches very fast, reaching 5.53m/s. When the power piston reaches the outer dead center to complete a drainage process, under the action of the spring reverse force and the cooler, the gas temperature in the compression chamber begins to drop sharply, the gas is compressed, the power piston starts to move from the outer dead center to the inner dead center at a higher speed, and the power piston reaches the balance position to complete the water absorption process.

Fig. 5 Cloud chart of temperature field and velocity field

Fig. 6 shows the pressure field and velocity field nephogram in the pump chamber. It can be seen that during the drainage process, the seawater pressure in the pump chamber is very high, and the speed at the drainage pipe is very fast. This is because during the drainage process, the piston pushes the seawater out of the drainage pipe at high speed, and even vortex appears. In the process of water absorption, due to the piston moving to the left, the pressure in the cavity becomes smaller, which is lower than atmospheric pressure. The water enters the pump cavity at high speed from the suction tank, and has a great impact on the upper wall of the pump chamber, and the pressure is greater than other parts.

Fig. 6 Cloud chart of pressure field and velocity field in pump chamber
6. Conclusion
1) The power system of free piston Stirling driven booster pump for seawater desalination can operate normally.

2) The pressure in Stirling engine changes according to the sine law, and the positive work done by the expansion chamber is far greater than the negative work done by the compression chamber.

3) The results of the steady-state model are taken as the initial values of the transient model, and the temperature and velocity nephogram of the transient dynamic mesh model at different times are obtained, and the gas variation in each chamber is stable.

4) Through the simulation data, it provides a theoretical basis for future experiments.

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