ANALYSIS OF TEMPERATURE CHARACTERISTICS OF THE PLUNGER PAIR OF THE CERAMIC PLUNGER PUMP FOR HEMODIALYSIS

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Through the design of the ceramic plunger pump for hemodialysis, the mathematical model of the water film of the plunger pair of the ceramic plunger pump was built. The distribution characteristics of the speed and pressure of the water film of the plunger pair were analyzed, and the temperature distribution characteristics of the water film surface were obtained. The effects of inlet pressure, inlet temperature, rotational speed, and chamber temperature on the water film temperature of the plunger pair were studied. Experiments and analysis show that the closer the temperature of the plunger pair is to the inlet of purified water, the smaller the temperature change. The farther the ceramic plunger rod is from the inlet of purified water, the greater the temperature change, and the main influencing points are concentrated inside the plunger pair; Therefore, maintaining a certain amount of purified water temperature, pressure, and flow rate for lubrication is crucial for the service life of ceramic piston pumps.

Key words：Hemodialysis; Ceramic plunger pump; Plunger pair; Water film; temperature characteristic

1 Introduction

Blood purification is one of the conventional treatment methods for chronic renal failure, and in the course of blood purification treatment, the usual treatment modes are hemodialysis and peritoneal dialysis. In the mode of hemodialysis treatment, treatment equipment such as hemodialysis machine will be used, because hemodialysis requires the mixing ratio of hemodialysis concentrate to enter the dialyzer with a certain flow rate and pressure for dispersion, convection, ultrafiltration and other functions[1]. In use, A certain volume of saturated concentrate A and saturated concentrate B is quantitatively extracted by a ceramic plunger pump by matching the concentrated solution of hemodialysis. At the same time, purified water is entered into the lubrication chamber of the ceramic plunger pump to lubricate the plunger pair[2]. Then in the process of extracting liquid in the plunger pump, the plunger pair is an important moving part of the ceramic plunger pump, which directly affects the temperature characteristics of the plunger pair movement, resulting in aging and wear of the plunger rod, etc., which will affect the pressure distribution and flow of the plunger pump. The high temperature will also cause the thermal deformation of the lubricating auxiliary surface for a long time, which will affect the assembly gap and cause the failure of the surface material of the moving auxiliary, resulting in the normal use of the ceramic plunger pump, so it is necessary to analyze and calculate[3].

In recent years, with the gradual development and application of polymer materials and engineering ceramic materials, various universities and research institutions have conducted development and research on ceramic plunger pumps, such as coke Juan, etc. to analyze the cavitation phenomenon and friction loss temperature of pure water pressure plunger pumps, and to study the friction characteristics of ceramic materials, stainless steel and modified polyether ether ketone under water lubrication. Moreover, relevant tests were carried out on its dynamic characteristics through design experiments [4]. Lu Yimin et al. optimized the design and strength analysis of the key structural components of the hydraulic piston pump by using basic theoretical design and combined with simulation analysis [5]. By establishing the actual output flow model of the hydraulic piston pump, Yin Fanglong optimized the structure parameters of the valve plate under the condition of considering the leakage flow of key friction pairs and the pre-lift pressure Angle, and conducted numerical analysis on the motion state and position of the pump to study the reasons for the flow pulse generated by the hydraulic axial piston pump [6]. Zhou Weihuan et al. designed the aseptic precision filling zirconia ceramic valveless pump, established the relationship model between pressure and flow, and proposed the realization method of flow control and precision fine-tuning of valveless rotary pump [7]. In summary, most researchers mainly establish a simplified motion model to optimize the design of friction characteristics and flow rate, and rarely analyze the influence of structural parameters of ceramic piston pumps on the temperature of moving pairs.

Combined with the characteristics of the analysis, in order to accurately describe the distribution characteristics and rules of the overall temperature of the water film lubrication of the plunger pair, the temperature characteristics of the purified water were fully considered in the way of combining the principles of thermodynamics and fluid mechanics, and the water film temperature and distribution rules along the axial direction of the plunger pump were analyzed and studied, especially the influence of the relevant structural parameters of the ceramic plunger pump on the entire temperature distribution[8].

2. System description

2 .1 Design of ceramic plunger pump for hemodialysis

The plunger pump mainly consists of a motor, a motor fixing bracket, a rotating shaft sleeve, a pump head connecting rod, a ceramic plunger, a cylinder, a dialysate chamber, and a purified water chamber. The motor is mounted on a fixed bracket and rotates by driving a rotating shaft sleeve [9]. The rotating shaft sleeve is connected with the link rod of the pump head, and the ceramic plunger rotates in the cylinder barrel by rotating in the Angle support bearing; a certain Angle A is formed between the central axis of the ceramic plunger and the horizontal line, so that the cylinder of the ceramic plunger moves back and forth in a straight line, and a certain volume of chamber is formed inside to realize the night discharge and suction in the ceramic plunger pump, so as to achieve the purpose of the cannery. In the process of movement, the pump head is connected with the rod part and rotates in the form of an arc [10].

In the dialysate chamber of the hemodialysis ceramic plunger pump, the ceramic plunger rod cuts the volume of length L and depth H to form the liquid storage space of the plunger pump, that is, the liquid storage chamber. When the ceramic piston pump rotates in the cylinder, the liquid is in the state to be injected when the plane of the liquid storage chamber is parallel to the inlet chamber. When the ceramic plunger rod is rotated 90°, the liquid enters the liquid reservoir and fills; When the rotation continues to 90°, a certain internal pressure is formed in the liquid storage chamber to be discharged. When the final rotation is 90°, the liquid is discharged from the drain port. At the same time, the purified water cavity continues to have liquid flowing from the inlet and the outlet, so that the plunger rod keeps moisture lubrication, because the gap between the plunger rod and the cylinder is coordinated, the precision of the coordination is very high, long-term movement makes the plunger rod heat, so it is very important to maintain the lubrication between the plunger rod and the cylinder[11].The structure of the ceramic plunger pump and the movement of the plunger pair are shown in Figure 1.

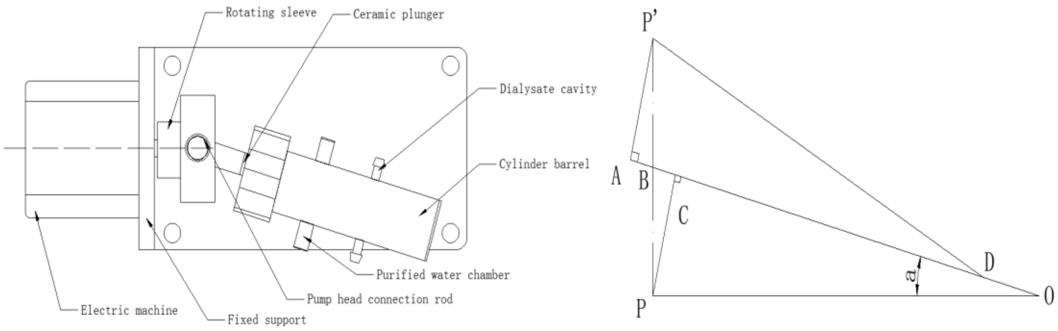


Figure 1. Ceramic plunger pump structure and plunger pair movement

2.2 Displacement of plunger movement

According to the status and characteristics of the motion of the ceramic piston pump, when the Angle support bearing of the ceramic piston pump rotates to the horizontal position of 0°, that is, point P, the plunger pair is in the shortest position point, the pump motion working state is in the pumping state, the rotating rod is represented by PC, and the corresponding plunger rod is represented by CO; When the Angle support bearing of the ceramic plunger pump is rotated to the horizontal position of 180°, that is, P' point, the plunger pair is in the longest position point, the working state is in the suction state, the rotating rod is represented by P'A, and the corresponding plunger rod is represented by AD; PC=P'A=R through the calculation of rotation 0-360°displacement OD=2R*tan(a), at the same time, it can be concluded that the greater the tilt Angle (a) of the plunger rod, the greater the suction corresponding to each suction beat, the smaller the tilt Angle (a), the smaller the displacement, the smaller the suction volume[12].

2.3 Reynolds equation of water film for plunger auxiliary inlet

According to Reynolds equation obtained from the water film of the plunger pair of the ceramic plunger pump[13], the analysis method of the water film thickness is established in the reference plane, z=0 as shown in the figure 2 . At any point $a(x, y, 0)$ is projected onto the upper and lower surfaces of the plunger pairs, denoted by $a_c(x, y, z_c)$ and $a_p(x, y, z_p)$, respectively.

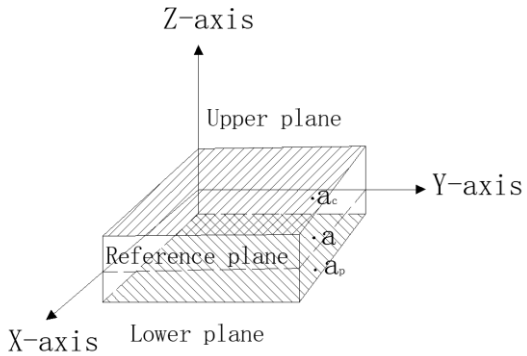


Figure. 2 Schematic diagram of the water film plane of the plunger auxiliary

Water film thickness at position point:

$$h(x,y) = z_c(x,y) - z_p(x,y) \quad (1)$$

The Naiver-Stokes formula based on viscous flow is expressed as follows:

$$\nabla * (\rho v v) + \rho \frac{\partial v}{\partial t} = \nabla \sigma - \nabla p + \rho f \quad (2)$$

In the formula,

V --Water velocity vector of the plunger pair (m/s);

ρ --Water density (kg/m3);

σ --Stress tensor of water (Pa);

p --Pressure in the flow field (Pa);

f --Volume force of water (N/m^3)。

Considering that purified water is presented as a Newtonian fluid, there is a certain relationship between the applied tensor flow rate and the velocity vector:

$$\sigma = \mu \nabla v \quad (3)$$

Since the length and width of the purified water film are greater than its own thickness during the sliding pair movement, there are corresponding assumptions for this, and the viscous internal force between the water films will be greater than the inertial force, so $\nabla * (\rho vv)$ and volume force ρf can be ignored. It is assumed that the fluid state in the water film is steady flow, expressed as $\rho \frac{\partial v}{\partial t} = 0$; The liquid pressure value of the water film does not change the direction of the thickness of the water film, so the liquid pressure of the water film is expressed as $p = p(x,y)$; The gradient of the water film liquid velocity vector in the water film thickness is greater than the gradient value of the ink length and width direction, expressed as $\frac{\partial u,v}{\partial z} \rangle\rangle \frac{\partial u,v}{\partial x}, \frac{\partial u,v}{\partial z} \rangle\rangle \frac{\partial u,v}{\partial y}$.

Based on the above hypothetical analysis, the Naiver-Stokes publicity can be simplified as follows:

$$\nabla p = \nabla * (\mu \nabla v) \quad (4)$$

3 Temperature analysis

When the purified water passes through the gap of the ceramic plunger pump, the water film is rubbed against the surface of the ceramic plunger, and the heat generated will cause the water temperature to rise. The fluid unit is selected as the analysis object, and the object flows through the gap of the ceramic piston pump to produce energy changes: First, the change of purified water pressure will cause the loss of water film energy [14]; Secondly, the friction of the viscous liquid produces the loss of energy; The final energy change of the cavity and plunger and the surrounding environment. During the process, the change of purified water pressure, viscous friction loss and environmental change affect the energy change of the analysis object, and the change of purified water energy is mainly reflected in the change of water film temperature **Δ*t*.** Therefore, a mathematical model of the secondary temperature field distribution of the ceramic piston pump can be established to analyze the temperature change during the moving process.

3.1 Pressure drop energy loss in liquid inlet chamber

The energy loss caused by pressure changes will be converted into heat energy. The pressure difference between the pressure ***P*** of the ceramic piston pump in normal operation and the research object ***P(z)*** is derived and analyzed[15].

$$\Delta p = (p_1 - p_2)\, z / L \quad (5)$$

In unit time, the energy value of the resulting pressure drop loss is

$$E_p = q_V * \Delta p \quad (6)$$

3.2 Changes in liquid friction energy loss

During the flow of purified water in the gap of the plunger, the friction loss will be converted into the heat energy entering the research object. The water film thickness ***s*** is very small, which can be determined as the velocity gradient in the thickness direction of the water film is the velocity difference between the upper and lower contact surfaces of the water film. Therefore, combined with Newton's law of internal friction [16], the shear stress of the water film can be obtained:

$$t_z = \frac{\varepsilon v}{h} - \frac{(p_1 - p_2)s}{2L} \quad (7)$$

The energy lost by liquid friction of the research object per unit time is

$$E_f = t_z v_z dx \quad (8)$$

Where ***dx*** represents the differential length of the research object.

3.3 Change of heat conduction energy loss

The flow form of purified water in the plunger pair of the ceramic plunger pump can be expressed as the flow of fluid between two parallel wall surfaces. The forms of heat transfer and exchange between purified water and the environment include heat convection, heat conduction and heat radiation. However, the value of energy exchange generated by heat conduction and heat radiation is small and can be ignored [17]. In this paper, only the influence of heat convection is considered, and the energy loss generated by the research object due to heat conduction factors in unit time can be expressed as:

$$E\varphi = \alpha\ (T - T_w)\ dx \quad (9)$$

Where, $\boldsymbol{T}$ represents the temperature of the fluid; $\boldsymbol{T_w}$ is the average surface temperature of the plunger pair; $\boldsymbol{\alpha}$ is the surface heat transfer coefficient.

3.4 Surface temperature change of water film

The energy loss caused by liquid friction enters the water film of the plunger, and the change of water film energy can be expressed as:

$$\Delta E = E_f + E_p - E_\varphi \quad (10)$$

The energy change value of the water film can be expressed as a change in temperature:

$$\boldsymbol{T} = \boldsymbol{t_0} + \frac{\Delta E}{\rho c q v} \quad (11)$$

Where, $\boldsymbol{t_0}$ is the initial state temperature of purified water; $\boldsymbol{\rho}$ is the density of purified water. $\boldsymbol{c}$ is the mass heat capacity of purified water.

In the analysis, ignoring the energy transfer between the liquid and assuming that the temperature change of each fluid unit is independent of each other, the water film of the ceramic plunger pump can be divided into a number of finite units, and the temperature field characteristic curve of the water film of the plunger can be obtained by analyzing it.

3.5 Plunger temperature field analysis

According to the loading and constraint of the ceramic plunger cavity and the data transfer of the temperature field of the fluid structure, the fluid-structure coupling of the water film of the plunger can be calculated and analyzed. The flow of the structural field solver for the calculation of cavity and plunger deformation is shown in Figure 3.

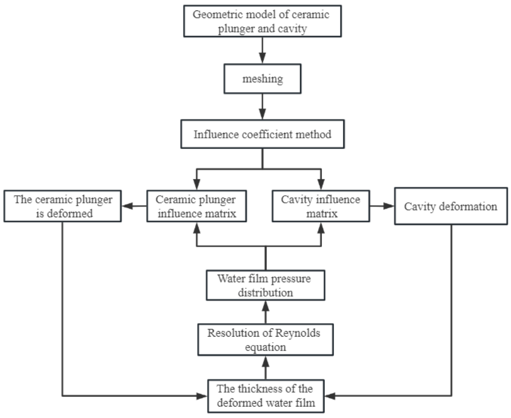


Figure. 3 Flow chart of structure field solver

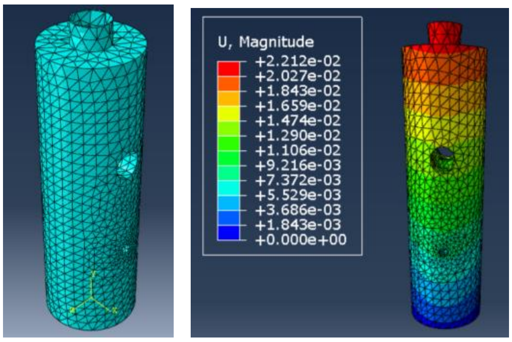
3.6 Study on thermal deformation of ceramic plunger and cavity

Due to the time-varying characteristics of the temperature distribution of the ceramic plunger and the cylinder cavity, especially when the plunger pump works steadily, the heat exchange of the plunger pump tends to be stable, and the temperature change of the ceramic plunger and the cylinder cavity is not obvious. Due to the environmental requirements of high temperature resistance and corrosion resistance, the ceramic plunger and the cylinder cavity are made of Al_2O_3 material. At the same time, the outer chamber is made of PVDF material and the cylinder chamber is installed inside. The thermal deformation of ceramic piston pump cylinder and plunger was studied by simulation software. The material properties of the ceramic plunger and cylinder cavity involved in the simulation are shown in Table 1.

Table.1 Material property parameters

mod	Materials	Modulus of elasticity(N/m^2)	Poisson's ratio	Mass density(g/cm^3)	Thermal expansion system($1*10^{-6}/°C$)	Thermal conductivity（W/m.k）	Dielectric constant
Ceramic plunger/cylinder chamber	Al_2O_3	$3.5\text{-}4*10^{11}$	0.23	3.89	7.9	30	9.7

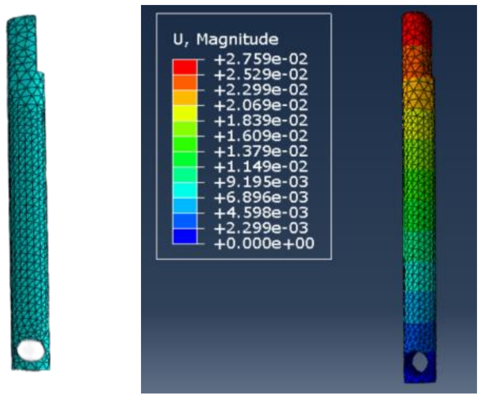
Set the initial temperature to 20℃, and calculate the deformation of the cylinder cavity and plunger when heated to 45℃ respectively. The grid and results of thermal expansion analysis of the cavity are shown in Figure 4. The two holes of the cavity are purified water inlet and outlet holes and dialysate inlet and outlet holes respectively.In Figure 4a, the cylinder cavity is divided into 22,014 tetrahedral mesh units and 33,259 nodes. Figure 4b indicates that the thermal deformation of the cylinder cavity is concentrated in the part close to the contact of the moving pair.



4a) Cavity meshing 4b) cavity thermal deformation

Figure. 4 Mesh division and thermal deformation of cavity

Figure 5 shows the grid and results of thermal expansion analysis of the plunger. Figure 5a shows that the plunger is divided into 5351 tetrahedral grid units and 8724 nodes. Figure 5b shows that the thermal deformation of the ceramic plunger is concentrated in the moving contact of the plunger drainage fluid.The missing cylinder in the figure is the volume of the plunger chamber; The bottom hole is the mounting hole for the plunger to connect the movable rod.



5a) Ceramic plunger meshing 5b) ceramic plunger thermal deformation

Figure.5 Grid division and thermal deformation of ceramic plunger

4 Experimental analysis

The water film temperature of ceramic piston pump auxiliary was studied and the whole parameter was analyzed [18]. Combined with the designed ceramic piston pump working parameters, the maximum continuous pressure ≤4bar, the maximum intermittent pressure of 6bar, the speed range: 0-1000rpm, the pump displacement: 0-195μL/ RPM (adjustable), the plunger length 50mm, the tilt Angle 0-15° (adjustable), the water film thickness of 20μm.

According to the environmental conditions, the indoor working temperature is 20 ° C. Ignore the temperature change or loss of the silicone pipe connection, and the temperature at the entrance and outside is 20 ° C. According to the motion characteristics of the ceramic piston pump, the position of the maximum speed of the piston is selected for research and analysis, and the pressure fluctuation and other changing factors of the transient ceramic piston pump are ignored in the process. When the plunger is squeezing the liquid flow and the plunger is pressing the liquid area at the bottom, the deeper the push, the more significant the temperature change of the water film on the plunger side[19].

When the ceramic piston pump moves, the moving medium into which the liquid flows is purified water. The viscosity of purified water is affected by temperature, pressure and other factors[20]. If it is assumed that purified water is A liquid that cannot be compressed, the viscosity of purified water is significantly affected by temperature, and the viscosity characteristic curve of purified water is shown as

$$\mu = u_0 e^{-a\Delta T} \quad (12)$$

Where, ***a*** represents the viscosity temperature coefficient of purified water; $\mathbf{u_0}$ is the purified hydrodynamic viscosity at temperature $\mathbf{T_0}$. $\mathbf{\Delta T}$ is the temperature increment,

$$\Delta T = T - T_0 \quad (13)$$

The viscosity, density and other related physical indexes of purified water are directly related to the ceramic piston pump[21]. The density changes with temperature as shown in the figure, the density of water itself is not affected by the change of environmental pressure, and when the temperature changes, the density has little influence. In this analysis, the influence of temperature on the density of purified water is ignored[22].

4.1 Temperature distribution of the fluid along the axial direction of the plunger

The figure 6 shows a schematic diagram of the reciprocating working area of the ceramic piston pump. The purified water flows vertically down the plunger pair, and the bottom of the liquid inlet is selected as the coordinate origin, while coordinate ***x*** represents the position of the water film of the research object.

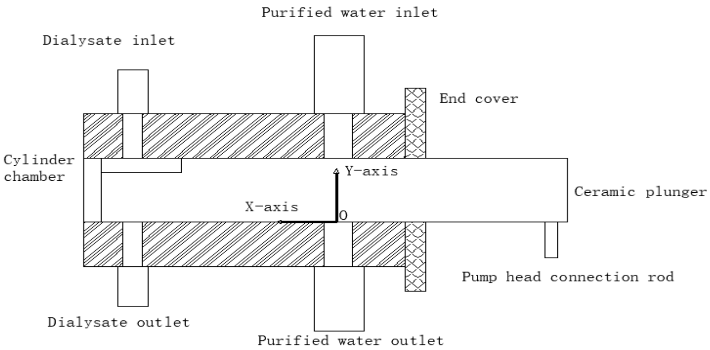


Figure.6 Working diagram of the plunger

Figure. 7 shows the axial temperature distribution of the water film of the auxiliary plunger.. When the purified water enters from the inlet and moves, the water temperature keeps rising and reaches the end, it can reach 30℃. The calorific value of purified water is related to the viscosity, and the viscosity decreases with the increase of temperature. The reduction of viscosity will also cause the corresponding shear stress to change, reducing friction, and the work generated heat is also reduced, resulting in little temperature change of the purified water. During operation, the inlet will continue to flow into new purified water, which is the heat that generated friction before and will be taken away by the new purified water, so the heat conduction on the surface of the cavity will also be reduced, thus reducing the temperature growth of the water film[23].

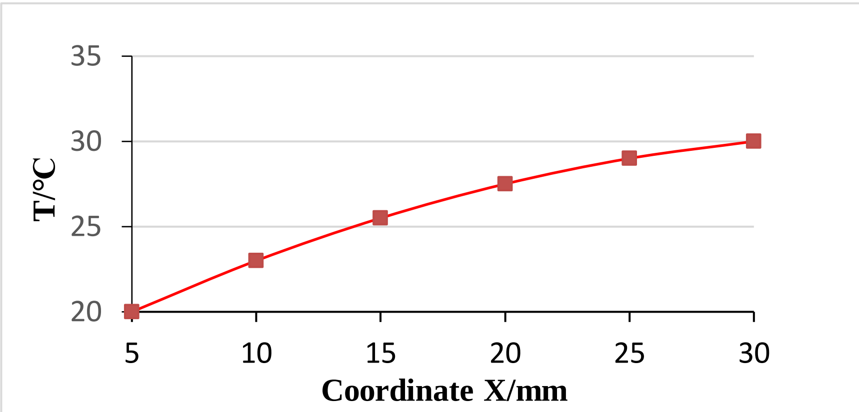


Figure.7 Axial temperature distribution of water film in ceramic piston pump

4.2 Analysis of influencing factors of water film temperature of plunger pair

The distribution of water film temperature has a direct influence on the working pressure, working speed and tilt Angle of the ceramic piston pump. The design of ceramic piston pump is studied and analyzed, and the influence of single parameter change in different categories on the temperature distribution of water film is analyzed. Speed, working water pressure and tilt Angle are tested by self-made circuit boards, motor drivers and ceramic plunger pumps，, as shown in Figure 8.

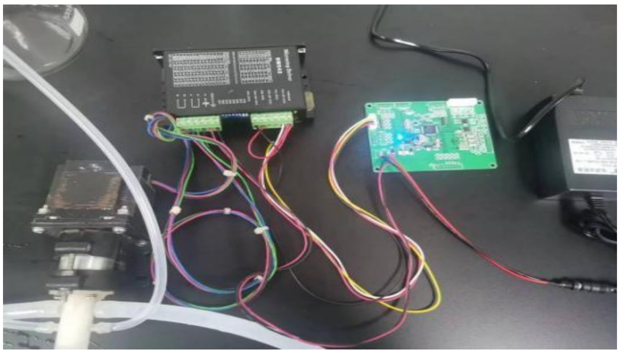


Figure.8 Working test diagram

4.2.1 Influence of rotational speed on water film temperature

For the designed ceramic piston pump, the speed is set to 300r/min, 500r/min and 800r/min respectively; The test time is 5min, it can be seen that the higher the rotational speed, the higher the outlet temperature, as shown in Figure 9.

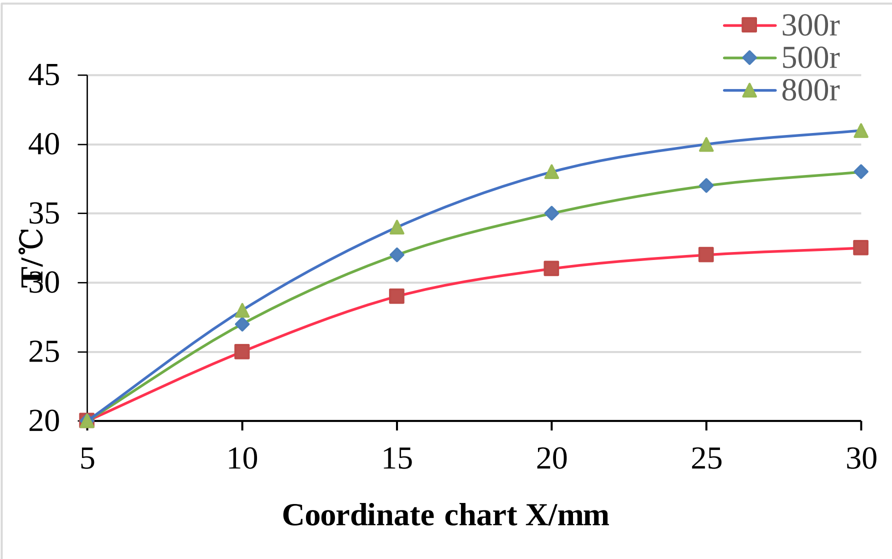


Figure.9 Temperature distribution of plunger pair at different speed states

4.2.2 Influence of working pressure on water film temperature

The normal continuous working pressure of the ceramic plunger pump is 4bar. When the pressure changes to 2bar and 6bar, the temperature distribution changes are obtained through analysis. The water temperature at the outlet of the plunger pair of the ceramic plunger pump increases with the increase of the pressure, and the temperature also decreases with the decrease of the pressure,as shown in Figure10.

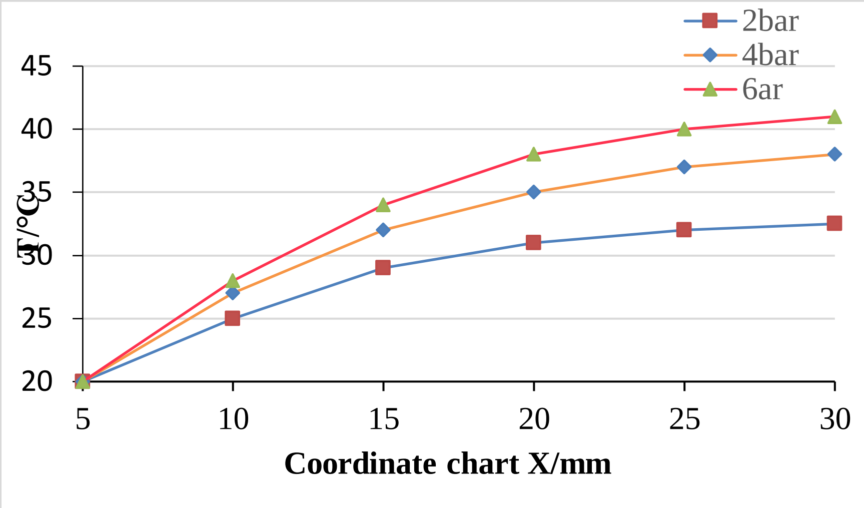


Figure. 10 Temperature distribution of plunger pair under different working pressures

4.2.3 Influence of tilt Angle on water film temperature

The tilt Angle of the ceramic piston pump ranges from 0 to 15°. Through the above analysis, it is known that the greater the tilt Angle, the greater the offset position Angle, the greater the corresponding partial friction force, the higher the water temperature, the longer the travel of the movement, and the more volume of water pumped, as shown in Figure 11.However, the dip Angle has little effect on the surface temperature of the water film and is not the main factor affecting the temperature distribution of the plunger.

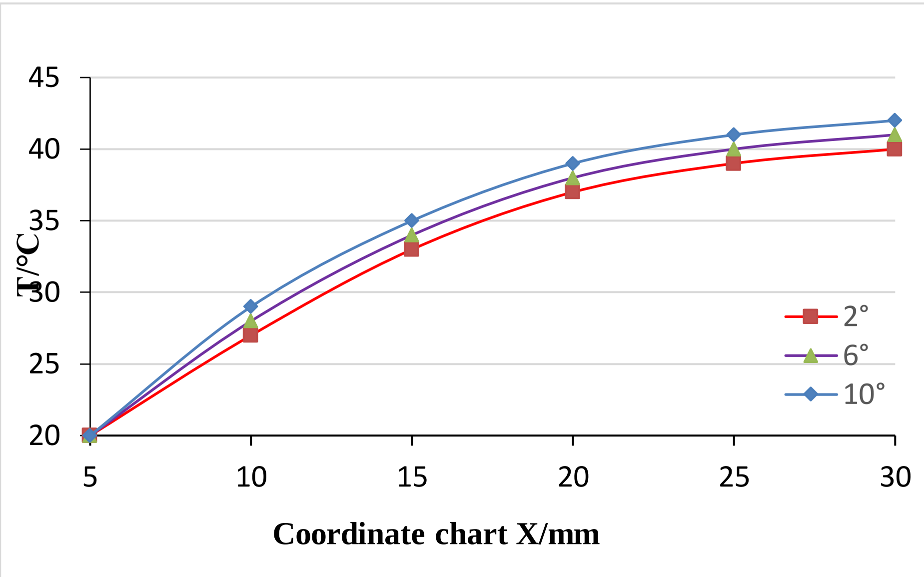


Figure. 11 Temperature distribution of plunger pair at different tilt angles

Conclusions

The speed of the ceramic piston pump directly affects the temperature of the plunger pair, the faster the speed, the higher the water film temperature; Secondly, the higher the working pressure, the higher the water film temperature of the plunger pair, and the tilt Angle of the plunger pump has no great influence on the temperature change of the plunger pair. The closer the temperature of the plunger pair is to the purified water inlet, the smaller the temperature change, the farther the distance between the ceramic plunger rod and the purified water inlet, the greater the temperature change, therefore, to maintain a certain amount of purified water temperature, pressure and flow lubrication, the service life of the ceramic plunger pump is very important.

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