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EXPERIMENT-BASED WANKEL PUMP EFFICIENCY ANALYSIS

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ABSTRACT

In order to improve the efficiency of the existing plunger grouting pump, a new grouting pump based on Wankel engine is proposed. The structure, principle and mathematical model of the Wankel pump were proposed. The efficiency of plunger pump and Wankel pump are analyzed, and the calculation formulas of mechanical, volumetric and hydraulic efficiency of Wankel pump are proposed. The efficiency characteristics of the wankel pump were studied experimentally, and a plunger pump and a Wankel pump of the same power are selected to compare their working efficiency under different working conditions. In general, η_m and η_v increased with increasing n until the load on the shaft was too large. At the same n, The smaller the outlet, the lower the efficiency. When the outlet is *a*, *b* and *c*, the wankel pump test data at n of 190 r/min, 160 r/min and 140 r/min is optimal. When the outlet is big such as a and b, Wankel pump performs higher flow and higher efficiency. However, when the outlet is small such as outlet c, plunger pump performs higher pressure and stable flow and efficiency.

Keywords: Wankel pump, efficiency, experiment, grout pump

NOMENCLATURE

e	eccentricity
R	Radius of pitch circle of ring gear
r	Radius of pitch circle of fixed gear
η, η_M, η_V, η_H	total, mechanical, volumetric, hydraulic efficiency
Δp_m, Δp_{th}	average, theoretical pressure difference
q_m, q_0, q_{leak}	average, theoretical, leakage flow
ω	angular velocity
T_M, T	loss, measured torque
H_m, H_{th}	average, theoretical head
L_t, L_s, L_r, L_b, L_g	total, sealing friction, rotor (seals in rotor surface), bearing and gear meshing mechanical loss
v_1, v_2	flow velocity at the inlet and outlet

1. INTRODUCTION

Pump is a device that converts electrical energy into mechanical energy. In grouting engineering, grout pump is the most energy-consuming equipment [1]. At present the most commonly used is the plunger grouting pump which has high output pressure and low efficiency. The inertial load on rack of plunger pump increases by the unbalanced motion of the inertia moment and inertial force, and unstable vibration and noise are easily caused throughout the device. Further, the mechanism of the reciprocating plunger driven by the crankshaft rotation is unsuitable for high speed movement, limiting the flow and efficiency [2, 3]. In karst areas with developed underground water system, grouting engineering always consumes a lot of time, electricity and grout to control the water and mud inrush disaster of tunnel. In order to reduce energy consumption and improve engineering efficiency, a kind of pump based on Wankel engine to control water and mud inrush disaster of karst tunnel is studied.

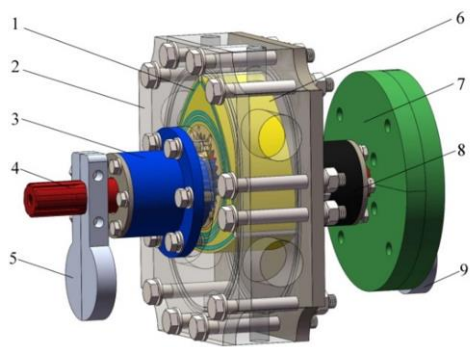
2. WANKEL PUMP

2.1 Wankel prototype

Wankel engine is a kind of internal combustion engine with an eccentric rotary tringle rotor. Like piston engine, Wankel's principle can be applied to the other systems. For instance, Wankel engine can be used to expander in the Rankine cycle [4]. Similarly to Wankel engine and Wankel expander, the Wankel pump has bigger output density and higher specific power, and prevents the unstable of inertia moment and inertial force caused by the reciprocating piston, which easily causes imbalance vibration and noise.

2.2 Wankel pump principle

Different from the original single inlet and outlet Wankel principle, Wankel pump has two inlets and two outlets (Figure 1). For single cylinder Wankel pump, there are main parts such as cylinder, rotor, crankshaft, gear seat, bearing block and cover plate. The crankshaft consists main journal and connecting journal. The centers of the main journal, the bearing block, the cylinder and the gear seat are coaxial. The center of connecting journal and rotor are coaxial. The gears from rotor and gear seat mesh with the ratio of 3:2. To



1-sealing strip, 2-cover plate, 3-gear seat, 4-crankshaft, 5-counterweight A, 6-rotor, 7-flywheel, 8-bearing block, 9-counterweight

Fig 1 Structure of Wankel pump

balance the rotational inertia force caused by the high-speed rotation of the rotor and the connecting journal,

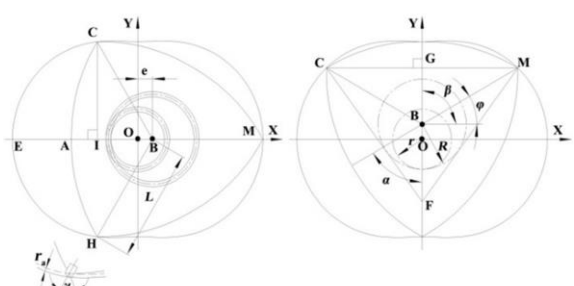


Fig 2 The geometric model of Wankel pump

counterweights are added to both ends of the crankshaft to balance the vibration caused by the eccentric motion of the rotor, as shown in Figure 1.

The envelope of motion trajectories of three apexes of the rotor, that is, the cylinder inner cavity profile, is a double arc outer trochoid [5]. In Figure 2, when the rotor movies from the left position to the right position, line OB rotaries angle of β, and line BM rotaries angle of φ. During the transfer of tangency of the pitch circle of the fixed gear and ring gear, two equal arcs appear, that is, $\alpha\cdot R$ and $\beta\cdot r$. Further, since $\alpha/\beta=r/R=2/3$ and $\beta=\alpha+\varphi$, $\beta=3\varphi$. The coordinates of one apex of the rotor in the X-Y coordinate system, that is, the cylinder inner cavity profile can be expressed as:

$$\left.\begin{aligned} \mathrm{X} &= e\cos\beta + R\cos\frac{\beta}{3} \\ \mathrm{Y} &= e\sin\beta + R\sin\frac{\beta}{3} \end{aligned}\right\} \tag{1}$$

3. EFFICIENCY

The efficiency of the pump is equal to the ratio of its output power to the shaft power:

$$\eta = \frac{\Delta p_{\mathrm{m}} q_{\mathrm{m}}}{\omega T} \tag{1}$$

With the parameters recorded by sensors, the total efficiency of plunger pump and Wankel pump can be obtained by Eq. (1). Multiply the following formula on the right side of the Formula (a):

$$\frac{(T-T_{\mathrm{M}})\omega}{(T-T_{\mathrm{M}})\omega}\cdot\frac{\Delta p_{\mathrm{th}}(q_0-q_{\mathrm{leak}})}{\Delta p_{\mathrm{m}}(q_0-q_{\mathrm{leak}})}\cdot\frac{\Delta p_{\mathrm{m}}(q_0-q_{\mathrm{leak}})}{\Delta p_{\mathrm{th}}(q_0-q_{\mathrm{leak}})} \tag{2}$$

With the parameters recorded by sensors, the total efficiency of plunger pump and Wankel pump can be obtained by upper formula. Multiply the following formula on the right side of the Eq. (1) to get:

$$\eta = \frac{T-T_{\mathrm{M}}}{\omega T}\cdot 1\cdot\frac{\Delta p_{\mathrm{m}}}{\Delta p_{\mathrm{th}}}\cdot\frac{q_{\mathrm{m}}}{q_0-q_{\mathrm{leak}}} \tag{3}$$

From the above formula, total efficiency can be expressed by mechanical (η_{M}), hydraulic (η_{H}) and volumetric (η_{V}) efficiencies:

$$\eta_{\mathrm{M}} = \frac{T-T_{\mathrm{M}}}{\omega T},\quad \eta_{\mathrm{H}} = \frac{\Delta p_{\mathrm{m}}}{\Delta p_{\mathrm{th}}} = \frac{H_{\mathrm{m}}}{H_{\mathrm{th}}},\quad \eta_{\mathrm{V}} = \frac{q_{\mathrm{m}}}{q_0} \tag{4}$$

In order to calculate η_{M}, T_{M} should be calculated as:

$$T_{\mathrm{M}} = \frac{9550L}{n} \tag{5}$$

The mechanical efficiency η_{M} reflects the friction loss of mechanical parts such as seals, shaft and bearings. The total mechanical loss (L_{t}) is divided into the loss of the sealing friction (L_s), rotor (seals in rotor surface) (L_r), bearing (L_b) and gear meshing (L_g), which are [6] :

$$\left.\begin{aligned}
&L_t = L_s + L_r + L_b + L_g \\
&L_s = \mu_N F_N\left(v_x\cos\frac{\beta}{3} + v_y\sin\frac{\beta}{3}\right) - \mu_C F_C\left(v_x\sin\frac{\beta}{3} + v_y\cos\frac{\beta}{3}\right) \\
&L_r = \frac{2\pi\mu_1\omega\omega_r\left(R_r^4 - R_e^4\right)}{\delta} \\
&L_b = \frac{2\pi\mu_1\omega_b^2 R_s^3 l_s}{c_s} + \frac{2\pi\mu_1\left(\omega-\omega_r\right)^2 R_e^3 l_e}{c_e} \\
&L_g = \frac{\mu_g z_1 l_g m e \omega^3}{2\pi\sin\theta}
\end{aligned}\right\} \tag{6}$$

The theoretical flow rate [5] (q_0) is:

$$q_0 = \left(4s\pi e^2 + 6\sqrt{3}eLs - \frac{2\pi}{3}L^2 s + 2\sqrt{3}L^2 s\right)\mathrm{n} \tag{7}$$

Based on Δp_m and the flow velocity at the inlet and outlet, v_1 and v_2, the head H_m can be obtained:

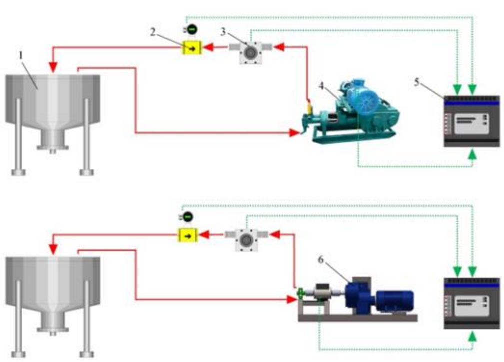
$$H_m = \frac{\Delta p_m}{\rho g} + \frac{v_2^{\,2} - v_1^{\,2}}{2g} \tag{8}$$

4. EXPERIMENT

4.1 Experiment method

To analyze the efficiency characteristics of the Wankel pump, the pump's flow, pressure, speed and shaft torque are monitored and recorded by the sensor. A plunger pump and a Wankel pump of the same power are selected to compare their working efficiency under different working conditions.

4.2 Experiment system



1-grout tank, 2-flow sensor, 3-pressure sensor, 4-plunger pump, 5-data recorder, 6-Wankel pump
Fig 3 Experiment system

The test system consists of test pump, sensors, data recorder, grout pipes and grout tank, as shown in Figure 3. The test pumps are BW50-3 (plunger pump) and WH60S (Wankel pump). The sensors involve FDDCIIIEP2M3A electromagnetic flowmeter, FD80/86 flat model pressure transmitter, and HCNJ-101 dynamic torque sensor to record the input-shaft torque (*T*) and *n*. The data is recorded e by NHR-8100/8700 color paperless recorder and stored in a computer.

Continuously variable transmission (CVT) is used to control the rotary speed of the crankshaft. The pneumatic V-type adjustment ball valve is used to control the outlet size to be *a*(7.5mm), *b*(6.5mm), and *c*(4.5mm).

4.3 Results

(1) Efficiency of Wankel pump

As shown in Figure 4, η_m increased with increasing *n* until the load on the shaft was too large. At the same *n*, $\eta_{ma} > \eta_{mb} > \eta_{mc}$. The maxima were similar, at 92.3%, 92.5% and 93,9% for η_{ma} , η_{mb} and η_{mc}, respectively.

η_{va} and η_{vb} increased slowly with increasing *n* until the load on the shaft was too large. η_{vc} decreased slowly with increasing *n* until the load on the shaft was too large. For outlet sizes *a*, *b* and *c*, the volumetric efficiencies (η_{va}, η_{vb} and η_{vc}, respectively) gradually approached 96.8%, 95.5% and 89% maximum, respectively. At the same *n*, $\eta_{va} > \eta_{vb} > \eta_{vc}$.

η_h decreased with increasing *n*. The hydraulic efficiencies at outlet sizes *a*, *b* and *c* η_{ha}, η_{hb} and η_{hc}, respectively) were similar at *n* = 100 r/min, being 94%, 92.4% and 91.4%, respectively.

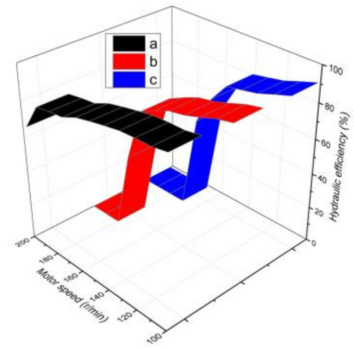
The test-pump η tended to decrease slowly with increasing *n*. Before the shaft was overloaded, η_a and η_b decreased to 72% and 65.7%, respectively. η_c began to decrease sharply at *n* = 120 r/min.

(2) Efficiency comparison of two test pumps

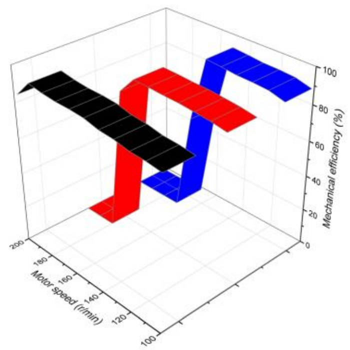
When the outlet is *a*, *b* and *c*, the wankel pump test data of 190 r/min, 160 r/min and 140 r/min is selected to be compared with the data of the corresponding outlet of BW50-3, as shown in Table 1. When the outlet

Table 1. comparison of two test pumps

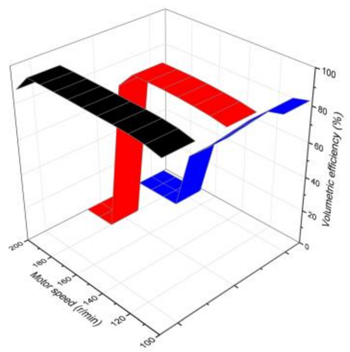
Type	outlet	*n*/(r/min)	*q*/(m^3/h)	*p*/MPa	*η*/%
WH60S	*a*	190	8.83	1.97	72
	b	160	7.34	2.3	65.7
	c	140	2.8	2.9	40
BW50-3	*a*		2.7	1.27	63.5
	b		2.7	1.88	62.8
	c		2.6	5.9	60.3



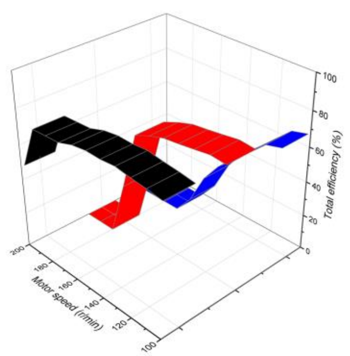
(a) Hydraulic efficiency



(b) Mechanical efficiency



(c) Volumetric efficiency



(d) Total efficiency

Fig 4 Efficiency of Wankel pump

is big such as *a* and *b*, Wankel pump performs higher flow and higher efficiency. However, when the outlet is small such as outlet c, plunger pump performs higher pressure and stable flow and efficiency.

5. CONCLUSIONS

In general, η_m and η_v increased with increasing *n* until the load on the shaft was too large. At the same *n*, The smaller the outlet, the lower the efficiency: $\eta_{ma} > \eta_{mb} > \eta_{mc}$, $\eta_{va} > \eta_{vb} > \eta_{vc}$, $\eta_{ha} > \eta_{hb} > \eta_{hc}$, and $\eta_a > \eta_b > \eta_c$. When the outlet is *a*, *b* and *c*, the wankel pump test data at *n* of 190 r/min, 160 r/min and 140 r/min is optimal. When the outlet is big such as a and b, Wankel pump performs higher flow and higher efficiency. However, when the outlet is small such as outlet c, plunger pump performs higher pressure and stable flow and efficiency.

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