Lubrication Performance Improvements on Two Side Surfaces of Crescent Board of Internal Involute Gear Pump

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Abstract **— To improve the bearing capacity of oil films on both internal and external sides of the crescent board of an internal gear pump in order to get better lubricating performance and reduce abrasion effectively. The oil wedge structure having convergence can be formed by radial parallel gap existing on both sides of the crescent board by adjusting the arc contours, and could change the single static lubricating status existing in the gaps on two sides of the crescent board into the integrated static and dynamic lubricating status. Further, taking the outside gap of the crescent board as example, the optimal convergence ratio of the inside gap can be determined on the basis of maximum oil-film force, and therefore the location of the circle center and the radius of the arc contour could be calculated when the internal side of the crescent board is adjusted. The results indicate that: i) the oil-film force and the volumetric efficiency of the pump improved when the existing radial and parallel gap was adjusted as the optimal convergent gap having the oil wedge structure, ii) more specifically, the oil-film force improved to 92.4%, and the flow of the fluid taken to the pressure oil side from the intake side of the pump improved to 30.2% in the presence of the parameters of the case, iii) the effects of factors such as installation and manufacturing error, the elastic deformation and thermal deformation during working, etc. should be taken into comprehensive consideration during the actual application since the adjusted values of the arc contours on the external and internal side of the crescent board were small. We conclude that: i) the design method of the oil wedges on two sides of the crescent board is feasible, ii) the higher the revolving speed, the smaller the minimum thickness of the oil film, and iii) the lower the oil pressure were, the greater the optimal convergence ratio, the oil-film force or improvement ratio of the oil-film force, iv) for the intake flow, the hydrodynamic effect was more obvious, and the volumetric efficiency of the pump was greater.**

Keywords - Internal Gear Pump; Crescent Board; Radial Gap; Hydrodynamic Effect; Oil-Film Force

I. INTRODUCTION

The internally engaged involute gear pump (called internal gear pump for short) refers to one hydraulic element for pumping the working oil, with advantages, such as stable delivery, small noise, long service life, etc.; further, this pump is used widely [1-2] and many researches [3-8] thereof were reported. Multiple pairs of friction pairs are arranged in the internal gear pump, and the failures thereof may be associated with the integral failure of the whole pump greatly, wherein the friction pair formed between the crescent board and the internal gear and the external gear of the pump may have relatively higher [9] failure probability; the leakage loss may be increased and the volumetric efficiency may be reduced when the gap therein is great; while the so-called "Scraper" phenomenon may occur when the gap is small. Therefore, automatic compensation of the radial gaps on both sides of the crescent board becomes very necessary [10-13], and the optimum design method of the radial gap was available in the literature [14]; while the angle of the crescent board was researched in terms of the radial compensation in the literature [15].

Seen from relevant theories of friction and lubrication, abrasion of the friction pair can be reduced and the service life of the pump can be improved effectively in presence of excellent lubricating status; and the dynamic lubricating effect is one of the major forms of improving the lubricating status, more specifically, the higher the revolving speed is, the more obvious [16] the effect would be. There are many [17-19] literatures and patents for invention of improving the lubricating performance by enhancing the material; beside, the bearing capacity (called oil-film force for short) in the gap can be improved greatly by setting up the oil wedge structure having the convergence form in order to achieve excellent dynamic lubricating effect [16]. Therefore, the internal gear pump for reinforcing the lubricating effect on two sides of the crescent board was put forwards in presence of the dynamic pressure.

II. RADIAL FRICTION PAIRS ON TWO SIDES OF CRESCENT BOARD

The internal gearing theory of the gear, as show in Fig.1, is taken by the internal gear pump; the pitch circles of the internal gear 1 and the external gear 3 are close to one side, and the other side is separated by crescent board 4 on the cover of the pump. The external gear 3 is driven by the drive internal gear 1 on the drive shaft to rotate in the same direction, and the liquid can be absorbed by using the negative pressure as a result of separation of the gears at the place of the oil suction hole; while the liquid shall be output [20] during extrusion as a result of continuous embedding and meshing of the gears at the place of the pressure oil hole. In Fig.1a, o_1 and o_2 are the circle enters of the internal gear and the external gear; ω_1 and ω_2 are the rotation angular velocities: rad/s of the internal gear and the external gear. The outside surface of the crescent board is in contact with the surface of the addendum circle of the external gear by driving the internal surface thereof to contact with the surface of the addendum circle of the internal gear; therefore, the space between the internal gear and the external gear can be divided into two independent seal cavities: the oil suction cavity 2 and the pressure oil cavity 7. Further, the contact here shall not refer to the contact of zero clearance really; and certain clearance shall be necessary in view of need of rotation of the internal gear and the external gear and errors during processing and assembling, etc.

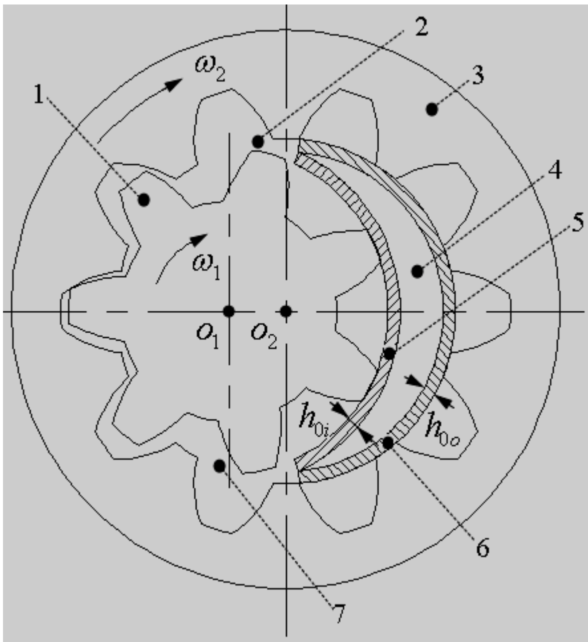

Fig.1 Oil film gaps between the internal gear pump and external side and internal side of the crescent board（Note: 1 indicates internal gear (driving gear); 2 indicates the oil suction cavity; 3 indicates external gear (driven gear); 4 indicates the crescent board; 5 indicates the inside gap of the crescent board; sign 6 indicates the internal gap of crescent board; 7 indicates the pressure oil cavity; signs o1 and o2 indicate the circle centers of the internal gear and the external gear; ω1 and ω2 indicate the rotation angular velocities: rad/s of the internal gear and the external gear; h0i indicates the radial distance m between the inside surface of crescent board and surface of the addendum circle of the internal gear; h0o m indicates the radial distance between the external surface of crescent board and the surface of the addendum circle of external gear, similarly hereinafter.）

The radial distance m between the inside surface of the crescent board and the surface of the addendum circle of the internal gear is called the inside oil film gap, as shown by h_{0i} in the Fig.1; while the radial distance m between the external surface of the crescent board and the surface of the addendum circle of the external gear is called gap of the external oil film, as shown by h_{0o} in the Fig.1. Moreover, the liquid may be trapped in leakage from the high pressure side of the pressure oil to the low pressure side of the suction oil on one hand in the gaps of the internal oil film and the external oil film, and on the other hand, a small part of the liquid may be taken to the pressure oil side from the suction oil side as a result of viscous friction caused by the peripheral velocity of the addendum circles of the internal gear and the external gear.

III. OIL WEDGE STRUCTURES ON TWO SIDES OF CRESCENT BOARD

The greater oil-film forces on two sides of the crescent boards the better [21] in order to avoid the scrapper phenomenon of the addendums of the internal gear and the external gear; in this way, lubricating effect can be improved greatly after increasing the thickness of the minimum oil film appropriately in presence of identical external force; while the oil-film force was relatively small in the equivalent gap of the existing design because the hydrodynamic effect in the oil film was not taken into account. The two sides of the crescent board may have the oil wedge structures having the convergent gap if the contours on two sides of the crescent board are adjusted, as shown in Fig.2; further, the maximum convergent gaps may be h_{2i}, h_{2o} and m on the oil suction oil side, and minimum convergent gaps may be h_{1i}, h_{1o} and m. (Note: To exaggerate the drawing is to facilitate description because the gap in the figure is very small.)

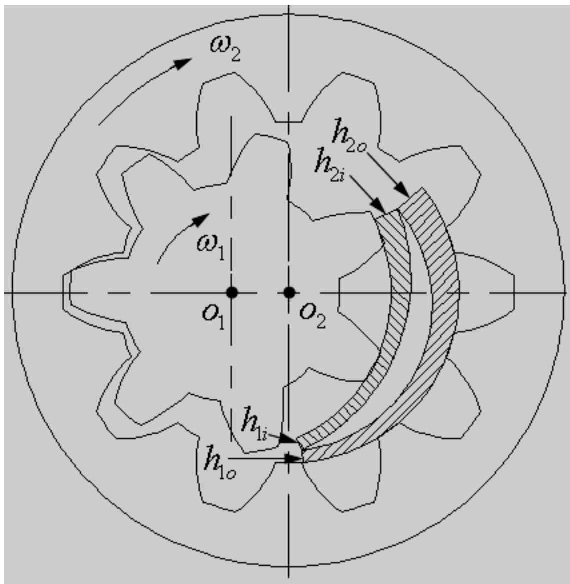

Fig.2 Convergent oil film gaps on two sides of the crescent board（Note: h1i indicates the minimum inside radial convergent gap m of the crescent board; h2i indicates the maximum inside radial convergent gap m of the crescent board; h1o indicates the minimum external radial convergent gap m of the crescent board; h2o indicates the maximum external radial convergent gap m of the crescent board, similarly hereinafter.）

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The internal oil wedge inclined plane and the external oil wedge inclined plane, as shown in Fig.3, can be formed by unfolding the inside oil wedge structure and the outside oil wedge structure required by the crescent board as shown in Fig.2 along circumferential directions respectively; and the two inclined planes are in line with relevant tribology theory [16] of the sliding block of the infinite slope.

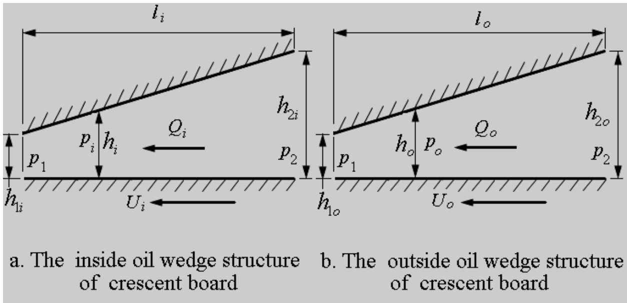

Fig.3 Inclined planes of oil wedges on two sides of the crescent board（Note: Ui and Uo indicate the movement speeds m/s of the addendums of the internal gear and the external gear; li and lo indicate the lengths m of the sealing areas formed by the internal gear wheel and the external gear with the internal side and the external side of the crescent board respectively; p1 and p2 indicate the pressures Pa of the pressure oil and the suction oil of the pump; Qi and Qo indicate the flows m3/s of the liquid taken to the pressure oil side from the suction oil side in the inside oil film gap and the outside oil film gap of the crescent board; hi and ho indicate oil film gaps m under certain locations in the inside oil film gap and the outside oil film gap of the crescent board; pi and po indicate the pressures Pa of the oil films under certain locations in the inside oil film gap and the outside oil film gap of the crescent board, similarly hereinafter.）

In Fig.3, *Ui* and *Uo* indicate the movement speeds m/s of the addendums of the internal gear and the external gear; *li* and *lo* indicate the lengths m of the sealing areas formed by the internal gear wheel and the external gear with the internal side and the external side of the crescent board respectively; *p1* and *p2* indicate the pressures Pa of the pressure oil and the suction oil of the pump; *Qi* and *Qo* indicate the flows m3/s of the liquid taken to the pressure oil side from the suction oil side in the inside oil film gap and the outside oil film gap of the crescent board, and the greater this value is, the higher the volumetric efficiency of the pump is; *hi*, *ho*, *pi* and *po* indicate the gaps and the pressures of the oil films under certain locations in the inside oil film gap and the outside oil film gap of the crescent board, and the greater the oil film pressure is, the greater the oil film force is, and the smaller [16] the minimum oil film gap required is.

IV. INSIDE OIL-FILM FORCE OF CRESCENT BOARD AND INTAKE FLOW

The inside oil wedge structure shall be taken as the example here only because the oil wedge structures on internal side and the external side of the crescent board are consistent with each other in terms of design. The expression acquired of the pressure distribution in the sliding block of the inclined plane can be in presence of initial pressure difference $\Delta p=p_1-p_2$(Pa) after derivation by combining with the literatures [22-23] according to the lubricating theory [16] of the sliding block of the infinite inclined plane:

$$p_i = \frac{6U_i \mu l_i}{h_{1i}K_i}\left[\begin{array}{l}\frac{1}{h_i}+\frac{h_{ip}}{4}\left(\frac{1}{h_{2i}^2}+\frac{1}{h_{1i}^2}\right)\\ -\frac{h_{ip}}{2h_i^2}-\frac{1}{2}\left(\frac{1}{h_{2i}}+\frac{1}{h_{1i}}\right)\end{array}\right]+\frac{p_2+p_1}{2} \tag{1}$$

In the formula, μ indicates the viscosity Pa.s of the fluid; $K_i = h_{2i}/h_{1i}-1$ indicates the convergence ratio of the inside oil wedge of the crescent board; h_{ip} indicates the thickness m of the oil film at the location having maximum pressure; and the formula (1) shall be consistent with the formula given in the literature [16] completely when $p_1=p_2= 0$.

In presence of $\mathrm{d}p_i$ / $\mathrm{d}h_i=0$ at the location of the maximum pressure in the oil film, so:

$$h_{ip} = 2h_{1i}\frac{K_i+1}{K_i+2}-\frac{h_{1i}^3(K_i+1)^2}{3U_i\mu l_i(K_i+2)}\Delta p \tag{2}$$

And the formula (2) shall be consistent with the formula given in the literature [16] completely when $p_1=p_2= 0$ and $\Delta p = 0$.

By integrating the pressure distribution function as shown in formula (1) along width direction of the crescent board, the inside oil film force W_i(N) of the crescent board can be acquired:

$$W_i = \frac{Bl_i}{h_{1i}K_i}\int_{h_{1i}}^{h_{2i}} p_i \mathrm{d}h_i \approx \frac{Bl_i}{M}\sum_{j=1}^{M} p_i(j) \tag{3}$$

In the formula, B indicates the width m of the crescent board; and M indicates the number of steps for integral iteration.

The flow (called intake flow): Q_i (m^3/s) of the fluid flowing to the pressure oil side from the suction oil side after passing through the inside oil film gap of the crescent board is:

$$Q_i = Q_{\omega 1} - Q_{\Delta p} = r_{a1}\omega_1 B h_{1i}\frac{K_i+1}{K_i+2}-\frac{Bh_{1i}^3(K_i+1)^2}{6\mu l_i(K_i+2)}\Delta p \tag{4}$$

In the formula, $Q_{\omega 1}$ indicates the shearing flow m^3/s caused by ω_1, and the greater $Q_{\omega 1}$ is, the higher the volumetric efficiency of the pump is; $Q_{\Delta p}$ indicates the pressure difference flow m^3/s caused by the pressure difference Δp, and the greater $Q_{\Delta p}$ is, the smaller the volumetric efficiency of the pump is; and r_{a1} indicates the radius m of the addendum of the internal gear.

V. OPERATION AND ANALYSIS OF CASE

If the modulus is 3mm, the number of the teeth of the internal gear is 10, the number of the teeth of the external gear is 16, the pressure angle of the pitch circle is 20°, the meshing angle of the pitch circle is 25°, the width of the tooth is 20mm, l_i=0.5πr_{a1}, h_{0i}=h_{1i}=0.03 mm, p_1=2MPa, p_2=0.1MPa, the revolving speed n_1=6000RPM, the viscosity is 0.0262Pa.s, and M=10000, the inside oil-film force of the crescent board and the intake flow shall change along changes of the convergence ratio K_i in presence of the oil wedge structures having $K_i>0$ and not having K_i=0, as shown in Fig.4,.

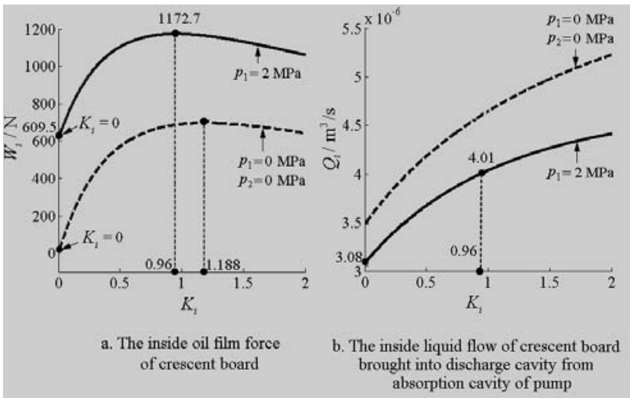

Fig.4 Inside oil-film force of crescent board and intake flow（Note: Wi indicates the inside oil film force N of the crescent board; Qi indicates the inside intake flow m3/s of the crescent board; Ki indicates the convergence ratio of inside radial convergence of the crescent board, similarly hereinafter.）

The optimal convergence ratio is 1.188≈1.2 which is consistent with the value 1.2 given by relevant literature [16] completely in the Fig.4a in absence of initial pressure difference of p_1=p_2=0, which proves the derivation accuracy of the formulae (1)~(4); the oil-film force is 1172.7 N and the intake flow is 4.01×10^{-6} m^3/s at the location having the optimal convergence ratio K_i=0.96 in presence of the initial pressure difference of the p_1=2MPa, p_2=0.1MPa is available; while the oil-film force is 609.5 N and the intake flow is 3.08×10^{-6} m^3/s at the location of K_i=0 in presence of the oil-film force in the parallel gap having identical minimum. Thus it can be seen that the oil-film force is improved for (1172.7-609.5)/609.5≈92.4%, and the internal side of the crescent board has more excellent lubricating performance by using the hydrodynamic effect; and the intake flow is improved for (4.01-3.08)/3.08≈30.2%, and therefore the pump has higher volumetric efficiency.

The dimensions of the internal contour of the crescent board can be designed and calculated once the optimal convergence ratio of the inside convergent gap of the crescent board under certain operating condition is determined on the premise [16, 24-26] that the installation and manufacturing error and the gap change as a result of flexible deformation and thermal deformation during working are not taken into account, as shown in Fig.5. Moreover, the dimensions of the inside contour of the crescent board shall refer to eccentric distance *ei* from the center o_i of the circle to the center o_1 of the circle of the internal gear and the radius r_{ai} of the arc.

In the triangle $\Delta o_i o_1 i$ and the triangle $\Delta o_i o_1 o$ as shown in Fig.5, there exist following geometrical relationships

$$r_{ai}^2 = e_i^2 + (r_{a1} + h_{2i})^2 - 2e_i(r_{a1} + h_{2i})\sin\alpha_{2i} \tag{5}$$

And

$$r_{ai}^2 = e_i^2 + (r_{a1} + h_{1i})^2 + 2e_i(r_{a1} + h_{1i})\sin\alpha_{1i} \tag{6}$$

In the formulae, α_{1i} is the included angle rad of the inside sealing area of the crescent board corresponding to the pressure oil side of the pump, α_{2i} is the included angle rad of the inside sealing area of the crescent board corresponding to the suction oil side of the pump, which are determined values on the basis of the basic parameters of the pump.

When the formulae (5)~(6) are equal, and $\alpha_{1i} = \alpha_{2i} = 45°$, it could acquire:

$$\begin{aligned} e_i &= 0.5K_i^* h_{1i} / \sin\alpha_{1i} \\ &= 0.5 \times 0.96 \times 0.03 / 0.707 \approx 0.01 \text{ mm} \end{aligned} \tag{7}$$

The corresponding radius r_{ai}≈18.53 mm of the arc can be acquired when e_i is substituted into the formula (5) or (6), while r_{a1}≈18.48 mm. e_i is very small because h_{1i} is small. It was proved that the change of gap as a result of the installation and manufacturing error and the flexible deformation and the thermal deformation during working often exceeds the thickness of the minimum oil film in designing of the convergent oil wedge structure; therefore, it is necessary to take the effect [16] of these factors into account; see the literature [27] for the processing method.

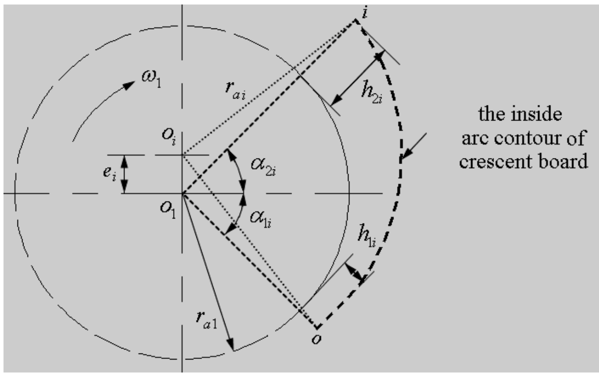

Fig.5 Design of contour of the inside convergent oil wedge of the crescent board （Note: i indicates the starting point of inside convergent gap of the crescent board; o indicates the end point of the convergent gap; ra1 indicates radius m of the addendum circle of the internal gear; rai indicates the radius m of the contour of the inside convergent oil wedge of the crescent board; oi indicates the circle center of the contour of the inside convergent oil wedge of the crescent board; ei indicates the eccentric distance m from point oi to point o1; α1i indicates the included angle rad of the inside sealing area of the crescent board corresponding to the pressure oil side of the pump; α2i indicates the included angle rad of the inside sealing area of the crescent board corresponding to the suction oil side of the pump, similarly hereinafter.）

The inside oil-film force of the crescent board and the intake flow shall change along with changes of the convergence ratio, as shown in Fig.6, when the revolving speed is 2000 RPM, 3000 RPM and 4000 RPM respectively, while other parameters are not changed. Thus it can be seen that the higher the revolving speed is, the greater the optimal convergence ratio will be; the greater the oil-film force and the intake flow are, the more excellent the lubricating performance of the internal side of the crescent board in presence of the hydrodynamic effect will be, and the higher the volumetric efficiency of the pump will be.

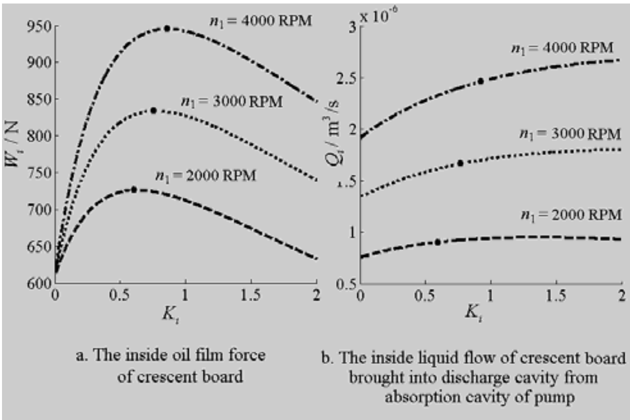

Fig.6 Oil film force and intake flow in presence of different revolving speeds （Note: n1 indicates the revolving speed of drive gear, RPM, similarly hereinafter.）

The inside oil-film force of the crescent board and the intake flow shall change along with changes of the convergence ratio, as shown in Fig.7, when the minimum oil-film gap is 0.03 mm, 0.05 mm and 0.07mm respectively, while other parameters are not changed. Thus it can be seen that the smaller the minimum oil film gap is, the greater the optimal convergence ratio should be; the greater the oil-film force and the intake flow are, the more excellent the lubricating performance of the internal side of the crescent board in presence of the hydrodynamic effect will be, and the higher the volumetric efficiency of the pump will be.

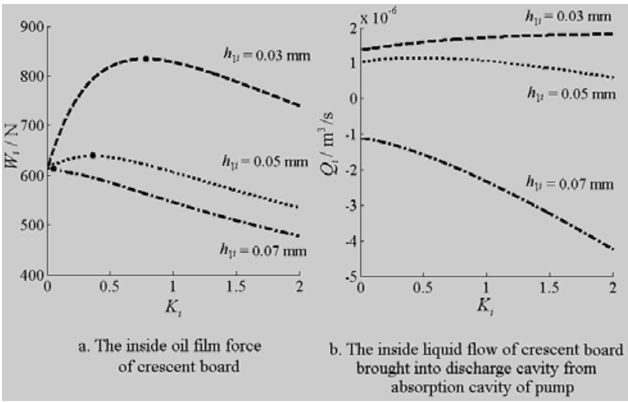

Fig.7 Oil film force and intake flow in presence of different minimum oil film gaps

The inside oil-film force of the crescent board and the intake flow shall change along with changes of the convergence ratio, as shown in Fig.8, when the pressure p_1 of the pressure oil of the pump is 1MPa, 3MPa and 5MPa respectively, while other parameters are not changed. The improvement rate of the oil film force of the optimal convergence ratio shall be (604−320)/320≈88.8% when p_1=1MPa, (1072−900)/900≈19.1% when p_1=3MPa and (1571−1480)/1480≈6.1% when p_1=5MPa. Thus it can be seen that the smaller the pressure of the pressure oil is, the greater the optimal convergence ratio will be, and the greater the improvement ratio of the oil-film force and the intake flow will be, and the more excellent the lubricating performance of the internal side of the crescent board in presence of the hydrodynamic effect will be, and the higher the volumetric efficiency of the pump will be.

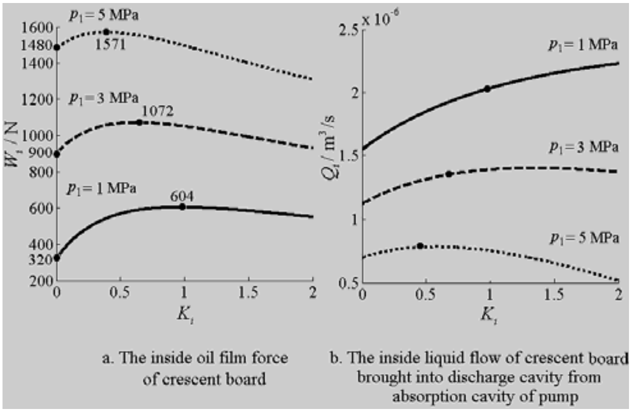

Fig.8 Oil film force and intake flow in presence of different pressures of the pressure oil

The outside oil wedge structure of the crescent board could be designed completely according to the design of the internal side, and the relevant conclusion acquired was consistent with that of the internal side completely. Furthermore, this thesis shall be applicable for the unilateral internal gear pump only because the crescent board had the oil wedge structures on both sides; and oil wedge structures on two sides of the crescent board could also be designed by using relevant contents of the thesis as for other straight-conjugate internal gear pumps having the crescent boards.

VI. CONCLUSION

1) The oil film force and the volumetric efficiency of the pump were improved when the parallel radial gaps on two sides of the crescent board was adjusted as the optimal convergent gap having the oil wedge structure. Moreover, the inside oil-film force of the crescent board was improved for 92.4%, and the flow of the fluid taken to the pressure oil side from the suction oil side was improved for 30.2% in presence of the parameters of the case.

2) The higher the revolving speed, the smaller the minimum oil film gap and the lower the pressure of the pressure oil were, the greater the optimal convergence ratio, the oil-film force or improvement ratio of the oil-film force and the intake flow, the more obvious the hydrodynamic effect, and the greater the volumetric efficiency of the pump

would be.

3) The design method of the convergent oil wedge structures on two sides of the crescent board was discussed in this thesis, and the effect of factors, such as installation and manufacturing error and the flexible deformation and the thermal deformation during working, etc. shall be taken into comprehensive account during actual application. Moreover, the thesis shall be applicable for the unilateral internal gear pump only because the crescent board had the oil wedge structures on both sides.

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