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Frictional energy analysis of a vane-type air pump for assisting paper handling via air flow in offset printing machines

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Today, the technical subject for the air pump used in the offset printing machine is to reduce sliding friction and wear of vanes. If we could improve the energy efficiency, we could successfully design a smaller air pump with a longer life.

In this paper, first of all, total power consumption of the air pump was measured by axial torque and analyzed according to components of a frictional force. As a result, it was found that most of the power is consumed at the sliding face between vanes and housing cylinder in the air pump. The power increases significantly due to the sliding friction between the vanes and their guide slots of the rotor, especially when the vanes are forced to move inward. On the basis of these results, the importance of the sliding friction of the vanes was confirmed quantitatively and the arising mechanism of the sliding friction of a vane against the slot face of the rotor was investigated theoretically as well as experimentally, and finally, we proposed some counter measures to reduce the sliding friction of vanes.

1. Introduction

A Rotational moving-vane-type air pump for suction-blow (it is henceforth called an air pump for short) has a feature in operating two functions, suction and blow, by one set of pump. This air pump has a process of a suction and blow of air in a rotation of the rotor (one cycle), and this function has been utilized for handling papers in printing equipments as a source of air. For example, the air pump contributes to reducing the energy loss because the pipimg length can be shortened, also the air pump can adjust the pressure and amount of flow precisely. Therefore this air pump becomes the indispensable equipment to support the transfer and separation of papers in factories.

However the temperature of an air pump becomes 70 ～ 100 ℃ during the long running time and continuous operation and the lubricant oil becomes mist by the increase of the evaporation pressure and higher degree of vacuum. The mist of the lubricant oil becomes the source of the air pollution to damage the working environment and may produce the inferior goods by sticking to the papers. Also it has lately drawn attentions that the worn-out lubricant oil becomes the industrial waste.

In the context of the facts shown above, a non-lubricant type dry air pump has drawn attentions and started to be developed and some have been already commercialized. However there are several technical problems such as excessive generation of heat and noise, and the increase of the power consumption. Furthermore the papers tend to be polluted by the carbon powder due to abrasion in exhaust air because the vane for dry air pump is made of carbon and also the structure of dry air pumps follows that of the conventional lubricious air pump. Eventually it is necessary to install the air filter in order to remove the carbon powder in air.

Although the importance of the characteristics of friction between the vane and the housing cylinder face for dry air pumps is commonly recognized, the pronounced rational solution has not been found because it is difficult to measure and observe the vane friction inside in a sealed housing.

There are some references (1) which describe the analysis of the dynamics about the motion of vanes in the oil pump whose structure is similar to the air pump, however it is not easy to presume the motion of the air pump from phenomena of oil pumps because there are clear differences between oil and air in terms of sliding conditions, pressure , etc... Therefore the systematic investigations on the motion of a vane and the characteristics of friction for the air pump are strongly required.

2. The objectives of the present research

Although the objectives of the present study are to obtain the basic data for the development of a dry air pump, the present paper describes the conventional lubricous air pump focusing on the mechanism of the behavior of the vane.

In fact, housing temperature of a dry air pump rises significantly due to the friction at the sliding area by the action of the vanes. However, authors consider that there is basically no difference in the mechanism of the behavior of vanes between the conventional lubricous air pump and the dry air pump. Therefore, the first step should be to clarify the mechanism of behavior of vanes with the conventional lubricous-type air pump which gives less temperature affection to the experiments. The quantitative analysis of the characteristics on the friction between the vane and housing at the sliding area in the lubricous type air pump may reveal the knowledge which contributes to obtain the fundamental view to improve the performance of the dry air pump.

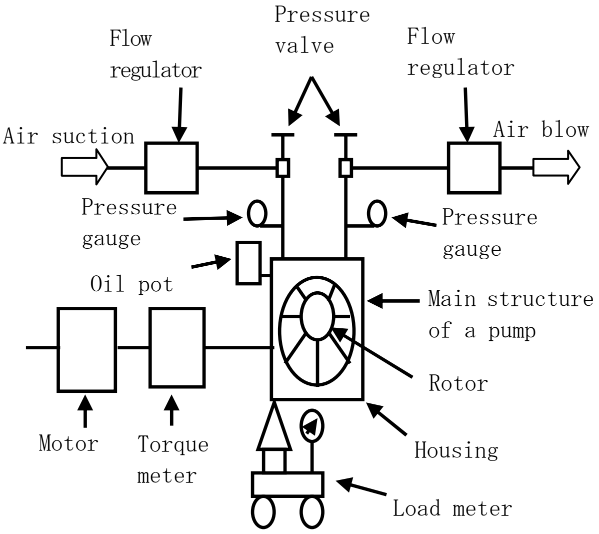

Fig.1 Constitution of the experimental system

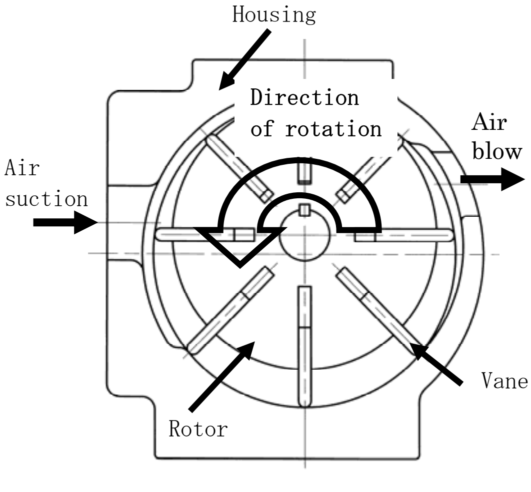

Fig. 2 Structure of a vane pump

3. Experimental arrangement

The friction force which is consumed between the vanes and housing was measured and analyzed based on the experimental data; i.e. the ratio of the friction component in the entire torque consumed, the effect on the friction of the vanes by the air pressure in the front room and the back room of the vane during the suction and exhaust, and the behavior of a vane which go in and out along the rotor slot.

Although the present study deals with the commercial air pump (Napico Ltd., suction pressure: 0.5kPa, exhaust pressure: 0.5kPa, air flow:300 l/min, total number of vanes: eight sheets), several parts have been modified in order to separate and measure the friction force at the sliding area. They are followings. First of all, the structure of a rotor and housing is rebuilt in rotating independently. A strain gauge which measures the operating torque between the motor and the main axis and also the strain gauge which measure the friction are mounted between the vane and housing at the sliding area. The sheath type

Table.1 Machine specifications and material

Specifications of air pump				
	Suction		Blow	
Pressure kPa	－60～0		0～60	
Flow rate l/min	100～260		260～240	
Rotation speed r.p.m	５５０ ～ ７５０			
Vane	Material	FC250	Hardness	HB182
	Processing method		Milling machine Lathe	
	Mass g	Plane	116.4 g	
		Grooved	116.0 g	
Housing	Material	FC250	Hardness	HB280
	Processing method		Honing	

thermocouple was mounted to the upper part of the housing for measuring the average temperature of the entire system. Fig 1 shows the experimental setup for the present study and Fig 2 show the description of the main structure of the air pump. The table 1 indicates the specifications and the materials of the pump used for the present study.

There are two kinds of the arrangement for the vanes. First of all, the number of the vanes is increased one by one following the order of the position of rotor slots. Second arrangement is that two vanes and four vanes are symmetrically mounted respectively about the axis. The number of rotation is increased by every 50rpm from 550rpm to 750 rpm and the experiments were carried out and followings were measured; ①the operation power of an air pump without the vanes.(the main power should be the friction consumed in the bearings which was about 0.7N for the present study), ②the friction between vanes and housing at the sliding area(it is measured as “the operating power of an air pump – power loss by bearings”), ③ the maximum temperature of the housing (measured by the thermocouple), ④the flow rate and pressure of the air blow and the air suction (measured by the ultra-sonic flux gauge and pressure gauge).

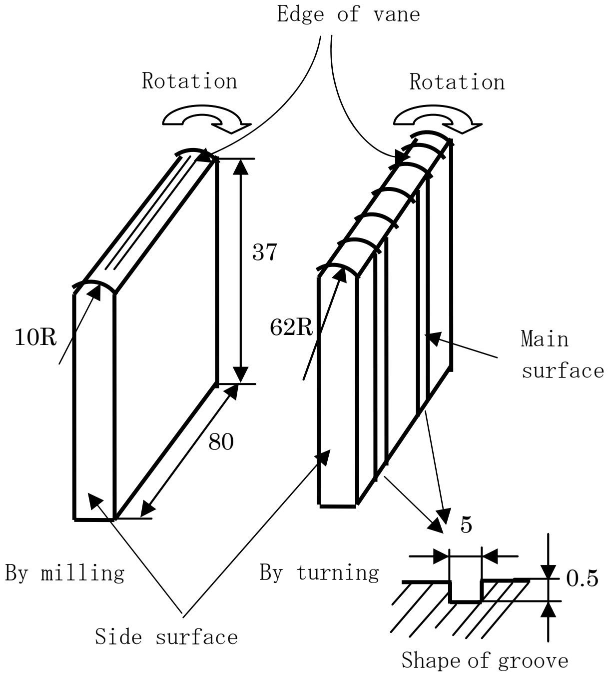

Fig. 3 Form and surface of a vane

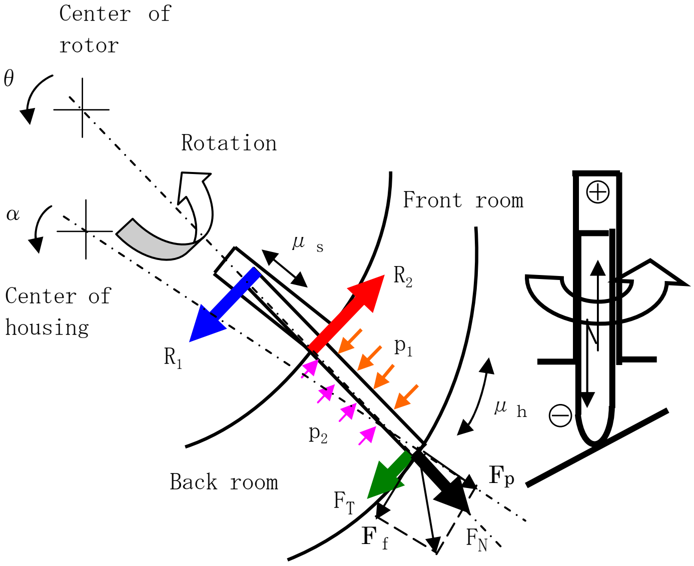

Fig. 4 Dynamic model for a vane movement

Fig 3 shows the shape of cast iron vanes. It is depicted that there are two different types of vanes; one of them has two grooves (depth 0.5mm×width 5mm) and the other has no grooves. This grooves is designed for penetrating the pressure of the bottom of the rotor slot to the vane room. The top of the vane which is the contact area was manufactured by a milling machine (curvature: 10R) and by a lathe (curvature: 62R) and the two kinds of curvatures were formed unwillingly due to the limitation of the manufacturing technique.

4. Statics analyses of a vane

The external force (Normal force F_N and Tangential force F_T to a vane main face, or Contact force F_c and Frictional force F_f to sliding surface) was expected to act to the rotating vane from the sliding surface as shown in Fig.4.

The frictional force F_f can be expressed as follows;

$$F_f = \mu \cdot m \cdot \left\{ \rho(\theta) - \frac{h}{2} \right\} \cdot \left(\frac{2\pi \cdot n}{60} \right)^2 \cdot \cos(\alpha - \theta) + \mu \cdot (\mu \cdot R_1(\theta) + \mu \cdot R_2(\theta)) \quad \cdots\cdots\cdots \ (1)$$

By solving the equations, the sliding friction F_t can be expected to be a function of the rotating angle θ of a rotor. For example Fig 6 shows the calculated value of the friction by neglecting the friction between the vane and a guide slot of a rotor, where we assumed that the sliding friction is generated only by the centrifugal force. The mass of a vane is about 0.0119 N and the centrifugal force at the number of rotation 650 r.p.m can be about 3.5N (maximum) ～ 2.3N (minimum) and up to 2.8N (the average). Here, by assuming the frictional coefficient between a vane and housing as μ= 0.2, the average sliding force (frictional force) P_{cal} becomes about 0.28N.

The fluctuation of the friction force in one rotation shows a sine curve. This is due to the eccentritity of the centre of the rotor and the accompanied change of the normal component of the force to the housing surface; in any case this fluctuation is small. On the

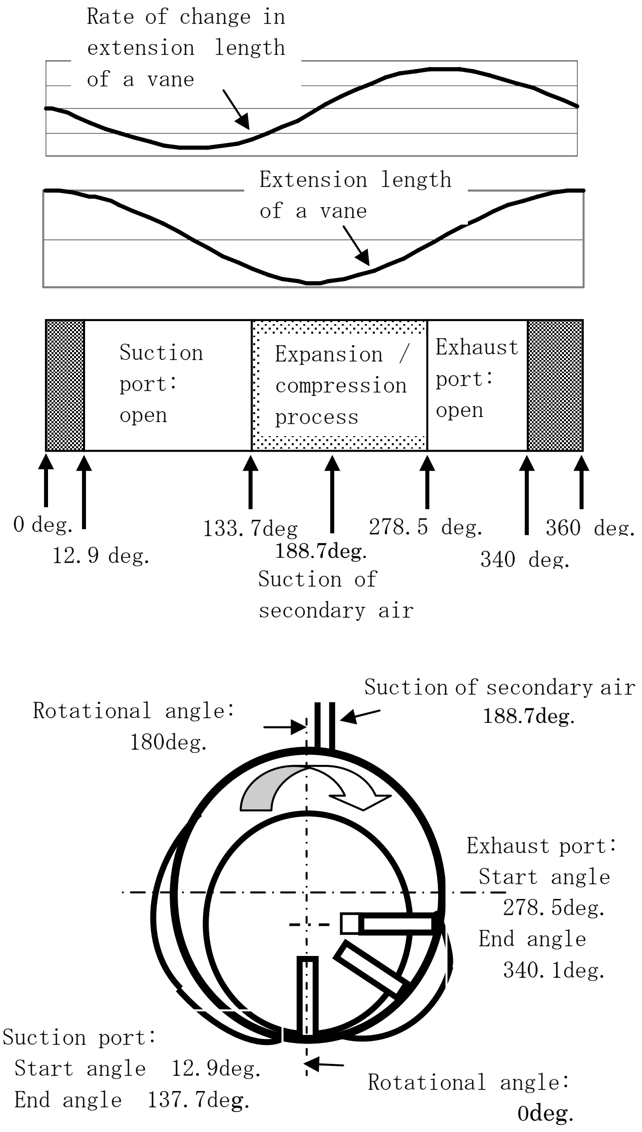

Fig. 5 Rotation angle of a rotor and pumping actions

other hand, it is confirmed that the absolute value and changing component are remarkably different from experiments as describe in the next section. It could be estimated that the friction at the clearance (μR_1, μR_2) between a vane and a rotor slot affects the sliding friction force of the vane F_t. For example, Fig 6 shows the sliding force on the housing cylinder by assuming the coefficient of the sliding friction along the guide slot of a rotor μ_s. The absolute value increases remarkably compared with the value for $\mu_s=0$ and the fluctuation curve becomes a sine wave with a rotating cycle. Also it becomes clear that the pattern of the fluctuation and phase is similar to the measured ones.

5. Result and Discussion

5.1 Performance of the air pump with one vane

Fig 5 shows the relation between the process of suction and exhaust of an air pump corresponding to the rotating angle θ to the housing. While the vane goes in and out along the sliding surface of the housing cylinder in one rotation and operates the suction and exhaust by changing the volume of the vane room, the sliding force between the vane and the housing is fluctuated. At the moment, experiments by one vane provides the crucial

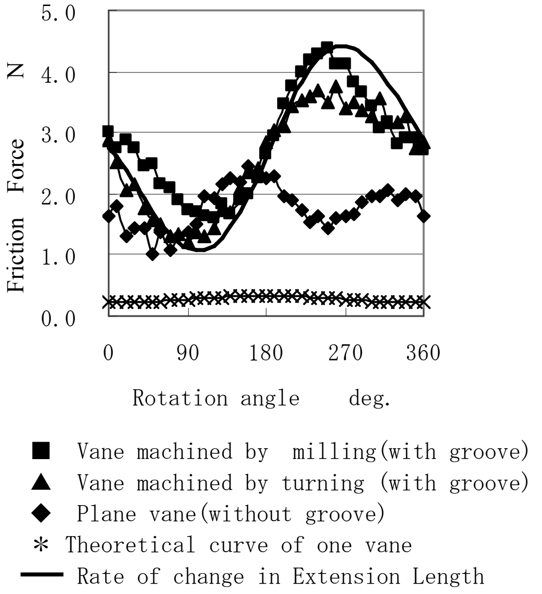

Fig. 6 Friction force for one vane which are machined by different processing methods

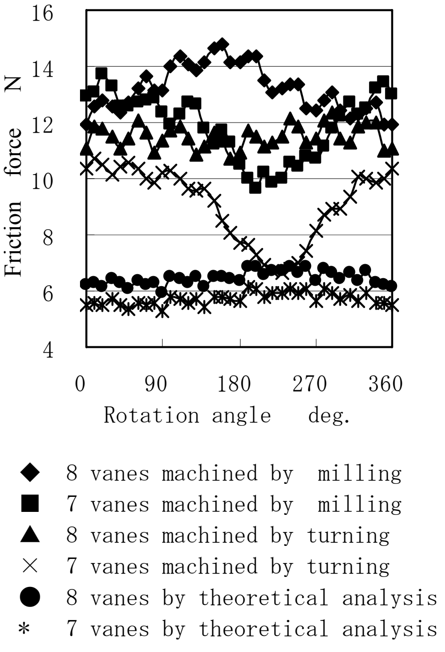

Fig.7 Comparasion of sliding power for 7 or 8 vane by different processing methods

fundamental information for analyzing the resistance of the sliding vane because the pressure in the vane room does not change for one vane. The numerical shown in the same figure indicate the rotational angle (CCW) of the rotor whose basic point is the position of the minimum clearance between the rotor and housing.

Fig 6 shows the measured friction force at the sliding area between the top of vane and the housing cylinder, and calculated friction force by centrifugal force, together with protruding length of the vane.

There are clear similarity and difference for the vanes with and without grooves. The value becomes smaller for the vane without grooves and the value becomes larger near the exit of the exhaust, also there seems no repeatability and stability in the characteristics in case of the flat (without grooves) surface. This is because the sealed space enclosed by the rotor slots and the bottom of the vane causes the change in friction force which is affected by the vane pressure against the sliding area of housing, preventing the vane motion of going in and out due to the change of the pressure in the sealed space.

The motion of the vane without grooves is difficult to follow the centrifugal force by the rotation. This might be the reason why the sliding force is nearly constant. On the other hand, the vane with grooves shows a large periodical change in the sliding force which follows the change of the protruding amount of vanes. Similarly this change shows the similar tendency which does not depend on the roughness of the machined top surface of vanes. This change of the vane with grooves shows the tendency which is similar to the change ratio of protruding length of the vane as described in the previous section. The sliding force decreases at first and then increases with the rotating angle of the rotor from 0 to 180°. This is because the sliding force decreases at first because the vane is difficult to move with the rotating angle of rotor and then it begins to increase just after it started to move. The sliding force increases at first and then decreases in the rotating angle of 180 ～ 360°. The reason of the increase of sliding resistance is that larger protruding length of a vane hookes the corner of the rotor slot and preventes insertion and eventually the force is increased. Also the reason why the sliding force is decreased is that smaller protruding length of a vane becomes difficult to hook the corner of the rotor slot with the less effect of the pressure in the vane room. In any case it can be concluded that the effect due to the sealed space enclosed by the rotor slot and the bottom of the vane plays an important role.

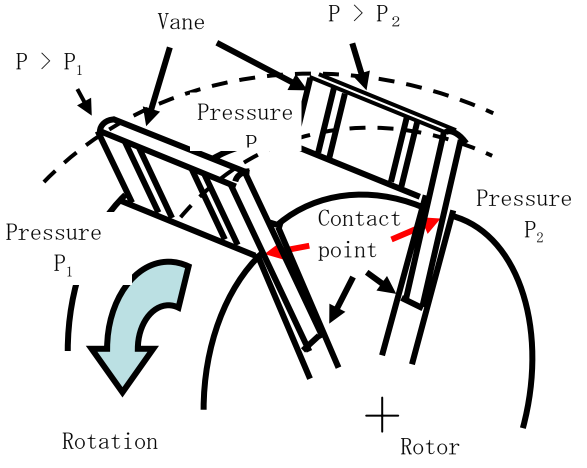

Fig. 8 Explanatory diagram of room pressure enclosed by a rotor and vanes

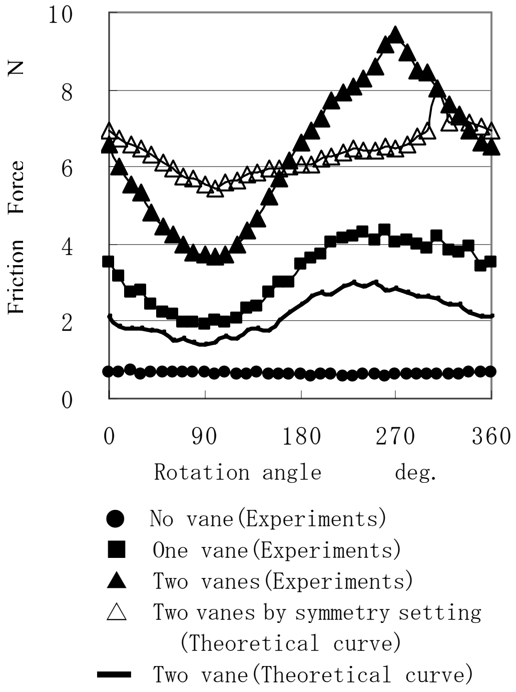

Fig.9 Relation between vane number and friction force of vanes

5.2 The performance of the air pump with two and more vanes.

Fig 6, 7 and 9 show the relation between the number of vanes and the friction force. These figures show the fact that with rotating angle of the rotor, the minimum value of the sliding power against housing cylinder becomes larger with increase of the number of the vane. The reason why the sliding power decrease near the position of the exhaust port is that there is no resistance at the top of the specified vane because the vane is added one after another backward to the rotating direction of vane. Fig 7 shows the sliding power in terms of the rotational angle for the seven and eight vanes with grooves. As shown in the figure, there is no difference between vanes machind by the milling and lathe, and the sliding power of the housing is kept constant when the number of the vane is eight. On the other hand the sliding power start to decrease when the angle of the rotor is about 180 degree. This is because the

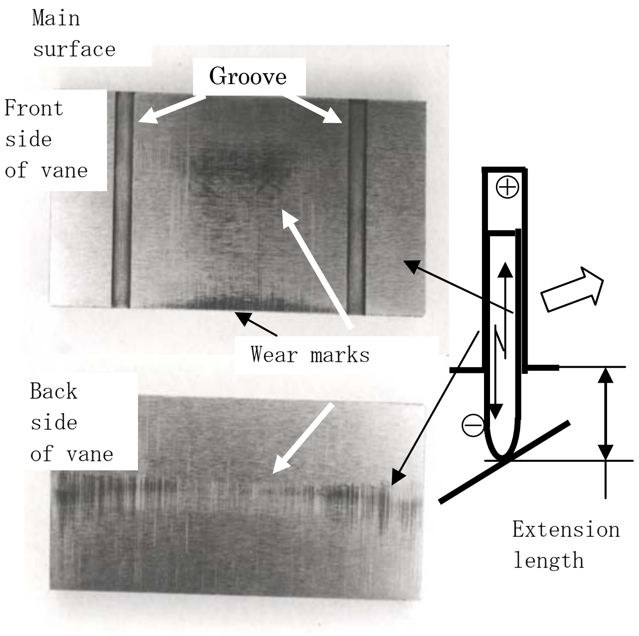

Fig. 10 Wear marks on both sides of a vane

volume of the advanced vane room is twice as large when the setting position of a vane is 0 degree. Also the sliding resistance decreases due to the decrease of the pushing power of the vane by the pressure in the vane room when the advanced vane passes the starting location of exhaust port (as shown in Fig 8).

Fig 9 shows the comparison of the sliding resistance of one and two vanes which are machined by lathe and have grooves. There are three patterns for the setting of two vanes, they are ①next to the slot of the rotor ②every other of the slot of the rotor ③ axial symmetrically. In case of the sliding power, the two vanes which are set in one every other and that which are set continuously have same tendency as that for one vane. However in case of the symmetrical two vanes, it has completely different tendency whose fluctuation is smaller and shows the constant value. This is due to the averaging effect of the sliding power when the going in and out of the vane happened in the same phase for the axial symmetrical case.

The two vanes which are located next together and one every other show the clear difference in the sliding power against the housing cylinder. This is because the action of vacuum and compression are produced in the vane room enclosed by the two vanes. It can be assumed that the resistance of inward and outward-movement of the vane increases when the sliding face of the rotor slot and the corner of the rotor slot contact together with the vane which is pushed toward the direction of the next room when the pressure difference of adjacent vane rooms and sliding resistance between the surface of the housing and the corner of the rotor slot are added. In fact, under such a operating condition, wear marks are produced within a short time elapsed as shown in Fig 10, therefore the assumption would be reasonable.

The volume of the vane room is different twice as large for the two vanes next together, compared with the vanes one every other. Therefore it can be concluded that the effect of the pressure difference is caused by the ratio of the vane room capacity.

The bottom space of the vane depends on the vanes with and without-groove of the main face. This follows the same reason as for one vane.

Also it can be considered that the depth of the protruding and insertion of the vane affects the vane motion of going in and out. It is evident as shown in equation (8) that the protrude height of $e(\theta)$ is the factor to affect the reaction R_1 and R_2. And it is also similar when the vane insert to the slot of rotor. Practically, however, it is strongly dependent on the sliding resistance rather than the height of the protruding as denoted before.

6. Conclusion

The authors discussed vane behaviors and frictional energy of a air pump experimentally as well as theoretically.

The results obtained in the paper are as follows:

(1) Most of the power of the air pump is consumed by the friction between vanes and a rotor as well as between the housing and vanes.

(2) The most important factor for the power consumption of the air pump is the friction between vanes and a rotor slit, which are influenced by reaction forces acting at the inlet corner of a rotor slit and an edge of a vane blade which contact the slit face of a rotor.

(3) Friction force between vanes and housing slide face is affected negligibly small by centrifugal force of vanes during the rotor rotation.

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