A Study on the Thermal Shock

in Low Speed High Torque Oil Hydraulic Motors*

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In this paper, the authors have investigated the phenomena of thermal shock in cam curve type radial piston motors which are set in the environment of low temperature, and they show the methods to analyse the variation of clearance with thermal expansion as the temperature changes in both steady and unsteady states. The experimental results are obtained that the annular clearance comes out in the hydraulic motor suddenly heated by oil of high temperature. It is made clear that the thermal shock is due to the difference of material thermal expansions between inner and outer parts of the cylinder. Thus some conclusions about prevention of thermal shock are reached.

1. Introduction

When the environment in which hydraulic equipment are set changes, the characteristics of hydraulic equipment have a great effect upon their reliability. Especially the characteristics of hydraulic equipment in the environment where temperature is very low are considered to be very important in order to assure the normal operation. Hydraulic motors are usually set in the field and is affected by the environment. In the environment where temperature is very low, there arise a lot of problems in their structures and designs.

The investigations about characteristics of low speed high torque hydraulic motors at low temperature have become very important. Up to the present it has been reported that the seizure between the rotating part and the fixed part sometimes occurred when the temperature difference between outer and inner parts in such motors is large. It, however, is explained that the seizure is caused by contamination, cavitation, material of annular clearance or its structure in the motor. But we cannot say the investigations have been made sufficiently.

In this investigation, we have used a cam curve type radial piston motor as a test motor, and have discussed the variation of annular clearance between a rotating cylinder block and a fixed circular cylinder (rotating valve) containing oil passages. The object is to obtain the theoretical and experimental data on the variation of annular clearance with the change of the environment temperature.

2. Nomenclature

\( u \) : displacement
\( u_i \) : displacement of the inner surface of a hollow cylinder
\( u_o \) : displacement of the outer surface of a hollow cylinder
\( u_p \) : displacement of the outer surface of a packed cylinder
\( \delta \) : annular clearance
\( r \) : radius
\( r_i \) : radius of the inner surface of a hollow cylinder
\( r_o \) : radius of the outer surface of a hollow cylinder
\( r_{pa} \) : radius of the outer surface of a packed cylinder
\( \rho \) : reference radius
\( \theta \) : temperature
\( \theta_i \) : temperature of the inner surface of a hollow cylinder
\( \theta_o \) : temperature of the outer surface of a hollow cylinder
\( P \) : pressure
\( P_i \) : pressure in the annular clearance
\( P_o \) : pressure on the outer surface of a hollow cylinder
\( t \) : time

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3. The theoretical analysis of the variation of the narrow annular clearance growing with the change of temperature

Considering the rotary valve and the cylinder block of the motor as a packed and a hollow cylinder, we are going to calculate the variation of the annular clearance between them when the temperature changes and the thermal expansion displacement occurs. We consider them as basic models in order to simplify the real problems and to treat them theoretically.

At first we used the usual thermal strain equation to solve it by substituting our boundary conditions, and obtain the theoretical solution. When the temperature distribution in the radial direction comes out, the displacement equation is generally shown as follows.

\[ u = Ar + \frac{B}{r} + \frac{(1+\nu)\alpha}{1-(1-\nu)\alpha} \int_{r_{0}}^{r} \theta dr \]  \hspace{1cm} (1)

The letters A and B are integration constants. In this case, boundary conditions are as follows.

(i) The force in the axial direction is zero. So

\[ \int_{r_{0}}^{r} \sigma_{0} 2\pi r dr = 0 \]  \hspace{1cm} (2)

(ii) The pressure works on the outer and inner surface in the cylinder. So

\[ (\sigma_{0})_{r_{0}} = -P_{1}, \quad (\sigma_{0})_{r} = -P_{2} \]  \hspace{1cm} (3)

From Eq. (1), we obtain the stress and substitute it into Eq. (2) and Eq. (3), so integration constants are determined as

\[ u = \frac{(1-\nu)(r_{2}^{3} P_{1} - r_{1}^{3} P_{1})}{E(r_{2}^{3} - r_{1}^{3})} \frac{1}{r} \int_{r_{0}}^{r} \theta dr \]

\[ - \frac{(1-\nu)\alpha}{1-(1-\nu)\alpha} \int_{r_{0}}^{r} \theta dr \]

\[ + \frac{r_{2}^{3} r_{1}^{3}(1+\nu)}{E(r_{2}^{3} - r_{1}^{3})} \left[ P_{1} - P_{1} \frac{1}{1-(1-\nu)r_{0}^{3}} \right] \]

\[ \times \frac{1}{r_{0}} \int_{r_{0}}^{r} \theta dr \]

\[ \int_{r_{0}}^{r} \theta dr \]

\[ \left[ \frac{1}{r} \int_{r_{0}}^{r} \theta dr \right] \]  \hspace{1cm} (4)

The temperature distribution is described as the function \( \theta = \theta(r) \), and we can assume that \( P_{1} = 0 \), because \( P_{1} \) is drain pressure. The displacement on the outer surface of the hollow cylinder is described as

\[ u_{0} = \frac{2r_{0}^{2} r_{0}}{E(r_{0}^{3} - r_{1}^{3})} P_{1} - \frac{2r_{0}^{2} r_{0}}{E(r_{0}^{3} - r_{1}^{3})} \int_{r_{0}}^{r_{1}} \theta dr \]  \hspace{1cm} (5)

The displacement on the inner surface of the hollow cylinder is described as

\[ u_{e} = \left[ \frac{r_{0}^{2} + r_{1}^{2}}{r_{0}^{2} - r_{1}^{2}} \right] \frac{P_{1}}{E} - \frac{2ar_{0}}{r_{0}^{2} - r_{1}^{2}} \int_{r_{0}}^{r_{1}} \theta dr \]  \hspace{1cm} (6)

Similarly the displacement of the surface of a packed cylinder is obtained by \( r_{e} = 0 \), \( r_{e} = r_{1} \) in the Eq. (4) and described as

\[ u_{e} = \left[ \frac{r_{0}^{2} + r_{1}^{2}}{r_{0}^{2} - r_{1}^{2}} \right] \frac{P_{1}}{E} + \frac{2a}{r_{0}^{2} - r_{1}^{2}} \int_{r_{0}}^{r_{1}} \theta dr \]  \hspace{1cm} (7)

When the temperature distributions of the packed and the hollow cylinders change from uniform state to a certain temperature, and that at the same time the pressure in the annular clearance increases, displacements of the outer and the inner surfaces are obtained from Eqs. (5),(6) and (7), and the scale change of the clearance is obtained from Eqs. (6),(7).

We have defined initial clearance as \( \delta_{0} \), and give the thermal and pressure expansion deformation of clearance as

\[ \delta = \delta_{0} + \left[ \frac{r_{0} + \nu(r_{0} - r_{1}) - r_{0}^{3} + r_{1}^{3}}{r_{0}^{3} - r_{1}^{3}} \right] \frac{P_{1}}{E} \]  \hspace{1cm} (8)

3.1 In the case of steady state temperature change

(i) In the case of uniform temperature distribution

In this case temperature distributions of the packed and the hollow cylinders have no relation to the variable \( r \), so Eq. (8) is simplified as

\[ \delta = \delta_{0} + \left[ \frac{r_{0} + \nu(r_{0} - r_{1}) - r_{0}^{3} + r_{1}^{3}}{r_{0}^{3} - r_{1}^{3}} \right] \frac{P_{1}}{E} \]  \hspace{1cm} (9)

(ii) In the case of steady state temperature distribution

In this case, temperature distribution is generally shown as

\[ \theta = \frac{1}{\ln(r_{0}/r_{1})} \left[ \theta_{e} \ln \frac{r_{1}}{r_{0}} - \theta_{e} \ln \frac{r_{0}}{r_{0}} \right] \]

So

\[ \delta = \delta_{0} + \left[ \frac{r_{0} + \nu(r_{0} - r_{1}) - r_{0}^{3} + r_{1}^{3}}{r_{0}^{3} - r_{1}^{3}} \right] \frac{P_{1}}{E} \]

\[ + \alpha \left[ \left( \frac{r_{0} + \nu(r_{0} - r_{1}) - r_{0}^{3} + r_{1}^{3}}{r_{0}^{3} - r_{1}^{3}} \right) \frac{1}{2\ln(r_{0}/r_{1})} + \frac{r_{0}^{3}}{r_{0}^{3} - r_{1}^{3}} \right] \]

\[ + \left( \frac{r_{0}^{3}}{r_{0}^{3} - r_{1}^{3}} \right) \]  \hspace{1cm} (11)
3.2 In the case of unsteady state temperature change

Considering that the oil whose temperature is different from that in the clearance suddenly flows into the clearance, the thermal expansion displacement of the clearance is obtained from Eq.(8). In this case, we have to treat the equation of heat conduction under the condition of unsteady state in the radial direction to solve this problem. The equation of this kind is usually too difficult to solve analytically, so a numerical method is often applied. In this paper, we have also taken the difference analogue method using a digital computer.

The equation of heat conduction is generally given as

\[ \frac{1}{k} \frac{\partial \theta}{\partial t} = r^2 \theta \]

(12)

Considering the case that heat conduction is only in the radial direction, we obtained

\[ \frac{1}{k} \frac{\partial \theta}{\partial t} = \frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r} \frac{\partial \theta}{\partial r} \]

(13)

We may define the following nondimensional variables

\[ \theta = \frac{\theta - \theta_0}{\theta_0}, \quad r = \frac{r}{r_0}, \quad t = \frac{k}{r_0} \]

(14)

So

\[ \frac{\partial \theta}{\partial t} = \frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r} \frac{\partial \theta}{\partial r} \]

(15)

We use forward and central differences, so

\[ \frac{\partial \theta}{\partial t} = \frac{\theta_{i+1,j} - \theta_{i,j}}{\Delta t} \]

\[ \frac{\partial^2 \theta}{\partial r^2} = \frac{\theta_{i+1,j} - 2\theta_{i,j} + \theta_{i-1,j}}{(\Delta r)^2} \]

\[ \frac{\partial \theta}{\partial r} = \frac{\theta_{i+1,j} - \theta_{i-1,j}}{2\Delta r} \]

(16)

\[ \theta_{i+1,j} = \theta_{i,j} + \frac{f(\Delta t)}{(\Delta r)^2} - \frac{(\Delta t)}{(\Delta r)^2} \]

(17)

We assume that the heat transfer through the metal and the oil complies with Newton's law of cooling. The boundary conditions are

\[ -k \frac{\partial \theta}{\partial r} = h(\theta - v) \]

(18)

We may define the following nondimensional variables

\[ h = \frac{h}{r_0}, \quad v = \frac{v}{\theta_0} \]

(19)

and use Eq.(14).

So

\[ -\frac{\partial \theta}{\partial r} = k(\theta - v + 1) \]

(20)

As the rotary valve and the cylinder block are cylindrical, we subdivide them into ten increments in the radial direction. Using Eq.(20) in the boundary increments and using Eq.(16) in the internal increments, we solve explicitly the finite difference equation from inner increment to outer ones. In the case of using the finite difference method, we have to discuss the condition for stability. In this paper, the stability criterion is given as \( \Delta t / (\Delta r)^2 \leq 0.8 \), and since we use small \( \Delta t \), the calculation is satisfied in the condition for stability. We can use small \( \Delta t \) since the total calculation time is originally short. Substituting the numerical solution of unsteady state temperature distribution by difference method into Eq.(8), the unsteady variation in the annular clearance is obtained. The data and the procedure of the calculation are shown in Fig.1.

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**Fig.1 Flowchart for the computing**

![Flowchart](image)

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**Fig.2 Hydraulic circuit of experimental apparatus**

4. Experimental apparatus

and experimental method

(1) Test 1

From the measurement of the length of the test piece at the uniform
temperature, the thermal expansion coefficient is obtained. The uniformity of the temperature is assured by the thermo couples which are buried in the test piece.

(2) Test 2

After the rotary valve was heated suddenly to an arbitrary temperature which was different from the initial temperature of rotary valve, we measured the variations of the temperature distribution and the length. Similarly we measured the variations of the temperature distribution and the radius of the inner surface of the cylinder block after the block was heated suddenly. We used a high accuracy micrometer to measure the outer diameter of the rotary valve and used a cylinder gauge to measure the inner diameter of the cylinder block.

(3) Test 3

We pay attention to the narrow annular clearance between the rotary valve and the cylinder block in the multistroke type low speed high torque hydraulic motor and measured the leakage from it. The object is to obtain the variation of annular clearance from the measurement of leakage after the motor is started and the annular clearance is heated suddenly.

Our hydraulic circuit is shown in Fig.2.

The test motor is coupled with a variable displacement pump in a closed loop hydraulic circuit. The test motor is coupled with an other motor of the same type. This motor works as a load by operating as a pump. It can give constant torque load to the test motor by regulating its pressure. As the piston pump and the motor are coupled in a closed loop, a vane pump supplies to the return line through the check valve at the constant pressure to compensate the hydraulic fluid loss by the leakage. The names of the parts and the structure in the test motor are schematically shown in Fig.3 and Fig.4.

Since the test motor is an axis rotary type, the cam and the rotary valve are fixed. In Fig.5, we show the flow passage of outer drain qo with arrows. Outer drain qo flows out of the high pressure passage through the annular clearance between the rotary valve and the cylinder block and the circular passage in the center of the rotary valve to the outside.

The rate of the charge flow supplied to main line is measured by the rotary flow meter. The leakage from the motor is measured by the absolute volume measurement. The temperature is measured in many parts by the Cu-constantan thermo couples. At the maximum 22 parts are measured in a short time by using the rotary switch box.

Fig.4 Structure of test motor

5. Experimental results and discussion

(1) The thermal expansion coefficients

Thermal expansion coefficients of the rotary valve and the cylinder block are obtained from the experimental results. They are obtained by Eqs. (9) and (10), substituting the results of measuring the length and the temperature, as follows.

The rotary valve $\alpha = 12.4 \times 10^{-6} ^\circ \text{K}^{-1}$

The cylinder block $\alpha = 14.7 \times 10^{-6} ^\circ \text{K}^{-1}$

The rotary valve is made of cast iron. The shrinkage fit was done in the cylinder block. The outer part is cast iron and the inner part is steel. Usually the steel part is affected by compression stress and the thermal expansion coefficient is considered to be large.

(2) The variation of clearance in steady state temperature distribution

Fig.5 and Fig.6 show the variations of clearance. When the temperature of the packed and the hollow cylinders change uniformly, examples of the calculations are given in Fig.5. Since the thermal expansion displacement in the radial direction is proportional to the radius at the condition of the uniform temperature distribution, the clearance changes.

Fig.5 Variation of annular clearance when the temperature of cylinder changes uniformly
with the temperature. The thermal expansion coefficient \( a \) used in Fig.5 come from our experimental results. In Fig.6, the vertical and the horizontal axes show the clearance and the temperature difference \( \Delta T \) from the initial value respectively. The calculated results are show in the case of the initial clearance at 10 \( \mu \sim 50 \mu \).

From Fig.6, we know that the clearance decreases proportionally to the temperature difference on the cylinder. At \( \Delta T = 0 \), the clearance is larger than the initial value. It is caused by the pressure in the clearance.

(3) Unsteady state temperature distribution and the measurement of the test piece

The characteristics of heat conduction and thermal expansion in the rotary valve and the cylinder block are obtained independently through the preliminary experiments. In the results, the time to reach steady state was short in the rotary valve and its thermal expansion ended quickly. See Fig.7. On the other hand, the cylinder block whose inner and outer surface are arbitrary high temperature and room temperature respectively needs more time to reach steady state.

Next, we put test results of thermal expansion displacement of inner surface of the cylinder block upon test results of the rotary valve. In the results, the clearance decreases to the minimum value after 5 - 10 minutes. The reason is considered to be in the difference in velocities of the thermal expansion displacements. We have observed that the time at which the clearance became the smallest comes after lapse of certain time from starting heat. The greater the supplied heat energy is, the larger the decreasing of the clearance is and the shorter the time in which the clearance becomes minimum is.

The experiments are made at 40°C, 50°C, 60°C, and 70°C. We show, for example, test results at 70°C in Fig.8 - Fig.11.

(4) The clearance in the hydraulic motor at room temperature

We investigated the experimental results in the case of the motor being driven with the heat supplied slowly at room temperature. In this case, the clearance is scarcely varied as shown in Fig.12.
The reason is considered as follows; A thermal edge phenomenon occurs, and the factor making the clearance large by temperature increase is cancelled by the factor making the clearance small by increase of the temperature difference in the cylinder block. But the leakage from annular clearance increases. The reason is that the temperature in the clearance increases by the heat coming from the energy loss of rotating and pressure drop caused by oil viscosity, and as the result the oil viscosity decreases.

(5) Narrow clearance in the motor heated suddenly as step input in the environment at low temperature

One of the results of the experiments and the calculations is shown in Fig.13. Its upper part shows the variation of temperature vs. time in the motor and the under part shows the variation of clearance vs. time.

When the clearance in the motor in the environment at very low temperature is heated suddenly by the oil at room temperature, it is observed that the clearance decreases temporarily. In Fig.14, the calculated results from theoretical analysis (3.2) and the experimental results are compared.

The theoretical results are in good agreement with our experimental results. Namely, the reasoning from the results of test 2 is confirmed by the theoretical calculation.

The minimum value of clearance by the theoretical calculation is smaller than that of the test results. The reason is that the input is assumed as a complete step function in the theoretical analysis but actually it is not.

\[ \bullet \text{Temperature of rotary valve} \]
\[ \bullet \text{Temperature of the entrance of the motor} \]
\[ \bullet \text{Temperature of the external leakage Q}_1 \]
\[ \bullet \text{Temperature of the external leakage Q}_2 \]

\[ \text{Rotary valve: RV2} \]
\[ \text{Pressure: 77 kg/cm}^2 \]
\[ \text{Revolutions per minute: 25 rpm} \]
\[ \text{Environment: Air cooling} \]

\[ \text{Revolutions per minute: 22 rpm} \]
\[ \text{Environment temperature: -10°C} \]

Fig.12 Variation of annular clearance and temperature of the motor at room temp.

Fig.13 Variation of annular clearance and temperature of the motor at low temp.
The average coefficient of heat transfer is obtained by using the results of test 2. The time and the clearance when the clearance becomes minimum are shown in Fig.15 and Fig.16.

6. Conclusions

Concerning the multi-stroke type low speed high torque hydraulic motor, we varied the various temperatures of the oil which flowed into the narrow annular clearance in a motor; and tested the motor under various conditions; measured the variation of the temperature in the clearance, and investigated the transient variation of the clearance theoretically and experimentally, with the following conclusions:

(1) The theoretical equation of the thermal expansion displacement in the clearance was obtained at the steady and unsteady temperature changes, using simplified models.

(2) Three kinds of tests were made, and the variation of the clearance was obtained from test results when the clearance was heated suddenly by the oil which had higher temperature than that of the motor.

(3) From the conclusion, we obtained several methods to prevent the motor from accidents which were occurred when heated suddenly under the low temperature.

(i) It is desirable to improve the heat conduction of the outer part in the motor and to avoid an unbalanced structure concerning the heat conduction of inner part in the motor.

(ii) With the help of the method presented in this paper, it will be desirable to check the narrow clearance considering the environmental conditions in the design.

(iii) When the motor must be driven at low temperature and it is impossible to widen the clearance for a certain reason of its design, it will be desirable to adopt the structure in which the outer and inner parts which make clearance are heated equally or to heat the clearance gradually by no load drive for preventing sudden heat. In our experimental regions, abnormal phenomena were not observed in more than 10 minutes from the initial drive.

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References