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# EXPERIMENTAL STUDY ON THE PERFORMANCE ESTIMATION EFFICIENCY MODEL OF A HYDRAULIC AXIAL PISTON MOTORS

Dong-Soo JUNG*, Hyoung-Eui KIM*, Heon-Sul JEONG**, Bo-Sik KANG*
Yong-Bum LEE*, Jong-Ki KIM* and E-Sok KANG***

* Mechanical System Reliability Research Group,
Korea Institute of Machinery and Materials
Yusung P.O Box 101, 171 Jang Dong, Yu Sung Gu, Taejun, Korea, 305-600
(E-mail: jds667@kimm.re.kr, khe660@kimm.re.kr, kbs668@kimm.re.kr, lyb662@kimm.re.kr, bellflag@kimm.re.kr)
** School of Mechanical Engineering,
Kunsan National University
Miryong-dong #68, Kunsan, Chonbuk, Korea 573-701
(E-mail: hsjeong@kunsan.ac.kr)
***Department of Mechanical Design Engineering,
Chungnam University
220 Kung-dong, Yuseong-gu, Daejeon, Korea 305-764
(E-mail: eskang@cnu.ac.kr)

## ABSTRACT

Performance of a hydraulic piston motor is very difficult to estimate in advance before experiment. But it is highly required because, if an efficiency model for performance estimation is already in hands, the model enables one to design a hydraulic motor with good efficiency at a designated operating point. Recently such a performance estimation model is developed by H.S. Jeong. In this paper, validity and accuracy of the performance model is studied by comparison with experimental efficiency test data.

## KEY WORDS

Hydraulic Axial Piston Machine, Performance Estimation Model, Volumetric Efficiency, Mechanical Efficiency, Leak Flow Rate

## NOMENCLATURE

$C_{DVN}$ : discharge coefficient of valve notches

$C_{DPP}$ : discharge coefficient of piston ports

$C_{wSP}$ : discharge coefficient of shoe and pistons

$f_P$ : equivalent friction coefficient of a piston

$f_{pBr}$ $f_{vBr}$ : friction coefficient of bearings

$h_P$ : gap height between piston and cylinder

$h_S$ : gap height of slipper and swash plate

$h_V$ : gap height of valve plate and cylinder block

$Q_L$ : leak flow rates of each parts

$M_L$ : loss moments of each parts

$n$ : rotational speed of a motor in rev/min

$V_g$ : geometrical displacement of a hyd. motor

$\mu$ : viscosity of hydraulic oil

$\eta_v$ $\eta_{hm}$ : volumetric, hydro-mechanical efficiency

## INTRODUCTION

The hydraulic system is used variously for construction heavy equipment, vehicle, ship, aircraft and so on. Because it has a great amount of power per load by unit and is easy to transfer the large amount of power and it is good to realize linear and rotational motion easily. The system consists of hydraulic pump generating hydraulic power and hydraulic motor converting hydraulic energy into mechanical power. These 2 components are the core element determining the efficiency of whole system.

These hydraulic components are usually operated under the unique condition, rotating speed and torque or pressure. Therefore, it is very important to select or build hydraulic pump and motor which have a high efficiency for organizing hydraulic system in the view point of energy consumption.

However, unique efficiency character and maximum efficiency point are determined for the model presented from manufacturers. Normally, it needs high cost and long time to develop new hydraulic pump and motor which have the maximum efficiency in the working point required for the object system.

But the requirement of hydraulic power representing the high efficiency is still unchanged in the each using area. For solving this problem, the research of estimation of efficiency characteristics for hydraulic system has been progressed in the design stage of hydraulic pump and motor by Europe and Korea.

This paper tries to analyze propriety, accuracy and effectiveness of efficiency estimation model from the result data of 36cc/rev hydraulic motor for the new efficiency estimation model of hydraulic piston motor.

The preceding studies for the subject are as follows.

1) ‘Preliminary design of a hydraulic piston motor for achieving an user-defined optimal efficiency point (by Heon-Sul Jeong)

2) ‘On the Instantaneous and Average Piston Friction of Swash Plate Type Hydraulic Axial Piston Machines (by Heon Sul Jeong and Hyoung Eui Kim).

## 1. MEASURE OF LOSS AND EFFICIENCY OF HYDRAULIC MOTOR

### 1.1 VOLUMETRIC LOSS AND MECHANICAL LOSS

Various kinds of losses occur on each element of hydraulic piston motor during rotating and going-returning movement and interaction with flow. These losses could be divided into loss of working oil and the loss of hydro-mechanic. At first, loss of volumetric flow is described as below.

There are three contacting point between piston and cylinder, slipper and slope and cylinder block and valve plate in hydraulic piston motor.

Poiseulli flow leakage which is proportional to the pressure and to the cube of interval is generated through the interval between the movement contacting point

If there is a notch to relieve the pressure variation which is occurred when the piston moves between two ports of valve plate, then internal leakage is generated and this is one of losses. Meanwhile, there is 1% loss of volume in the working oil when the 150 bar of pressure is increased. This compression of fluid has same effect as the reduction of output flow. If the pump is operated with high speed, cavitations could be generated and then it is corresponded to the loss of volumetric flow

On the other hand, the examples of hydro-mechanical losses are as follows. Fluid lubrication film is formed at the contacting point and it has relative movement so that Newtonian flow is generated which is in proportional to speed and inverse proportional to the interval. The loss between piston and cylinder has Coulumb friction characteristics in proportional to the pressure variation. The slight loss of pressure is one of hydro-mechanical losses occurred when the piston moves to piston chamber through the two ports on the valve plate. Also churning loss generated because cylinder block and slipper in the housing filled with working oil rotates at high-speed and losses came out from the bearing installed at front and rear on input and output axis. They are also hydro-mechanical losses.

### 1.2 MEASUREMENT OF EFFICIENCY

For the measurement of efficiency of hydraulic motor, after realizing working area with wide range, rotating speed $n$ and pressure variation $\Delta p$, in accordance with the definition of volumetric efficiency and mechanical efficiency, we shall measure 6 physical quantities like $M, n, Q_1, Q_2, p_1, p_2$ in each working condition.

But, there are some considerations and problems for measuring and analyzing the subject motor by using this method. First, we need to calculate displacement $V_i$ from the measured data. We can get displacement $V_i$ as inclination of output flow when the speed is increased under the $\Delta p = 0$ condition. But we can also derive it from the efficiency measurement data. If the displacement $V_i$ is miscalculated, the efficiency could be over 100%. Secondly, external leakage flow $Q_{Le}$ is correlatively small so that flow meter with small capacity is needed. Simply, we can suppose $Q_{Le} = Q_1 - Q_2$ but it is difficult to use $Q_1 - Q_2$ as a leakage flow due to the limitation of resolution of flow sensor. Third, in the case of calculating the volumetric efficiency, it is one of trifle things to decide if $Q_1$ or $Q_2 + Q_{Le}$ or $n \cdot V_i + Q_{Le}$ as input flow. This is a problem related to the accuracy of flow meter used in

Table 1 Models of leakage flow and torque loss of hydraulic pump

| | |
|---|---|
| Wilson | $Q_P = \varepsilon_P V_P n_P - C_s \frac{V_P \Delta p}{2\pi\mu} - Q_R$ <br> $M_P = \varepsilon_P \frac{V_P \Delta p}{2\pi} + C_f \frac{V_P \Delta p}{2\pi} + C_d \mu V_P n_P + M_c$ |
| Schlosser | $Q_P = \varepsilon_P V_P n_P - C_s \frac{V_P \Delta p}{2\pi\mu} - Cst V_P^{2/3} \sqrt{\frac{2\Delta p_P}{\rho}}$ <br> $M_P = \varepsilon_P \frac{V_P \Delta p}{2\pi} + C_f \frac{V_P \Delta p}{2\pi} + C_d \mu V_P n_P + C_h \frac{\rho V_P^{5/3} n_P^2}{4\pi}$ |
| Thoma | $Q_P = \varepsilon_P V_P n_P - C_s \frac{V_P \Delta p}{2\pi\mu}$ <br> $M_P = \varepsilon_P \frac{V_P \Delta p}{2\pi} + C_f \frac{V_P \Delta p}{2\pi} + C_d \mu V_P n_P + Ch \frac{\rho V_P^{5/3} n_P^2}{4\pi} + \frac{V_P p_c}{2\pi}$ |
| Zarotti & Nevegna | $Q_P = \varepsilon_P V_P n_P - C_1 p_P - C_2 p_P^2 - C_3 p_P^2 n_P^{1.5} - C_4 p_P n_P (C_5 + \varepsilon V_P)$ <br> $M_P = \varepsilon_P p_P V_P + n_P (C_1 + c_2 \varepsilon_P n_P) + C_3 p_P (1 + \frac{C_4 \varepsilon_P^2}{\sqrt{p_P}} + \frac{C_5 (\varepsilon_P + C_6)}{n_P + C_7}) + \frac{C_8}{(n_P + C_9)}$ |
| Dorey | $Q_P = \varepsilon_P V_P n_P - C_s^* \frac{V_P \Delta p}{2\pi\mu} - \frac{p_P n_P V_P}{\beta} (V_r + \frac{1 + \varepsilon_P}{2})$ <br> $M_P = \varepsilon_P p_P V_P + C_v^* \mu n_P V_P + C_f^* p_P V_P$ |
| Ryberg | $Q_P = \varepsilon_P V_P n_P - C_s^* \frac{V_P \Delta p}{2\pi\mu} - a_0 \varepsilon_P V_P n_P - (a_1 + a_2 \varepsilon_P) \frac{V_P n_P \Delta p_P}{\beta} - a_4 V_P \Delta_P^2$ <br> $M_P = \varepsilon_P \frac{V_P \Delta p}{2\pi} + (b_0 + b_1 \varepsilon_P) \frac{V_P \Delta p}{2\pi} + (b_2 + b_3 \varepsilon_P) \frac{V_P p_L}{2\pi} + b_4 \frac{\lvert p_h + \delta p_L \rvert}{1 + (n_0 / n_{P0})^\gamma} \frac{V_P}{2\pi}$ |

Meanwhile, it is easy to realize $n - \Delta p$ condition as lattice type of regular space for understanding the efficiency characteristics according to the working area. However, this way needs much efforts to realize the working area which has exactly equal space. Therefore, it is good alternative plan to treat the measurement data by 3-dimension curve fitting method.

## 2. EFFICIENCY MODEL OF HYDRAULIC MOTOR

### 2.1 EXISTED EFFICIENCY MODEL

Mathematical model of hydraulic pump and motor is recognized as one of important fields in hydraulic engineering. Because, it is important to simulate the dynamic characteristics of hydraulic system and it is essential to perform the most suitable design of system function.

The model describing the efficiency in the working area $n - \Delta p$ is divided into polynomial model and performance coefficient model. Polynomial model is often used for representing the efficiency test data of the existed pump and motor mathematically. It expresses the efficiency by polynominal equations with speed.

$n$ and pressure difference $\Delta p$ as an independent variable. In case of variable volume type, volumetric ratio $\varepsilon = V / V_{\max}$ is selected as an additional factor.

Polynomial model is determined by the test data but performance coefficient model is the model that characteristics coefficient is achieved from the test data in mathematical formula based on the physical law. A number of efforts has been progressed to make the exact efficiency model from the wide-range working area since Wilson established the model for leakage flow and moment loss in 1948. Huhtala has read that unfortunately he couldn't find any sufficient efficiency coefficient model after comparison of accuracy and merits and demerits of each model in the range of speed 500~3000 rpm and pressure 20~210 bar in the existed efficiency coefficient model shown as table 1.[5)]

### 2.2 NECESSITY OF EFFICIENCY MODEL FOR PERFORMANCE ESTIMATION

The efficiency model for performance estimation is the model that can estimate the working condition of given pump and motor, that is, efficiency in the speed and pressure. It should satisfy two conditions to be a useful efficiency estimation model. At first, the accuracy of efficiency estimation must be guaranteed in the working area. And moreover, the efficiency coefficient should be expressed as measurable dimensions of pump and motor.

The secure of guaranteed efficiency estimation model means that the efficiency characteristics can be estimated from the origin of pump and motor, so that it also means that we can estimate the efficiency of pump and motor in the designing stage without test. Finally, it has an important point that we can design the pump and motor which have a good efficiency at the point of working condition of object system.

### 2.3 NEW DEVELOPED EFFICIENCY MODEL FOR PERFORMANCE ESTIMATION

Under this condition, it can be summarized as follows.[6)] After analyzing the physical law and the construction of piston motor, derived leakage flow and friction loss torque are as follows.

$$\begin{aligned} Q_L &= Q_{L\mu} + Q_{L\rho VN} + Q_{L\rho PP} + Q_{Lc} + Q_{Lo} \\ &= C_\mu \Delta p / \mu + C_{\rho VN}\sqrt{\Delta p / \rho} + C_{\rho PP}\rho n^3 / \Delta p \\ &\quad + zC_c n \Delta p / \beta + Q_{L0} \end{aligned} \quad (1)$$

$$\begin{aligned} M_L &= M_{L\mu} + M_{L\rho VN} + M_{L\rho PSP} + M_{Lp} + M_{Lo} \\ &= K_\mu \mu n + \frac{C_{\rho VN}}{2\pi}\Delta p \sqrt{\frac{\Delta p}{\rho}} / n + K_{\rho PSP}\rho n^2 \\ &\quad + K_p \Delta p + K_{p2}\Delta p^2 + M_{L0} \end{aligned} \quad (2)$$

Meanwhile, the definition of volumetric efficiency and mechanical efficiency of general hydraulic motor is like this,

$$\begin{aligned} \eta_v &= \frac{Q_{th}}{Q_{th} + Q_L} \\ &= \frac{V_g n}{V_g n + (Q_{L\mu} + Q_{L\rho VN} + Q_{L\rho PP} + Q_{Lc} + Q_{L0})} \end{aligned} \quad (3)$$

$$\eta_{km} = \frac{V_g \Delta p / 2\pi - (M_{L\mu} + M_{L\rho VN} + M_{L\rho PSP} + M_{Lp} + M_{L0})}{V_g \Delta p / 2\pi}$$

Therefore, the revised efficiency estimation model can be summarized as following two equations

$$\eta_v = \frac{V_g n}{V_g n + C_l \Delta p + C_{tN}\sqrt{\Delta p} + C_{tP} n^3 / \Delta p + C_c n \Delta p + Q_{L0}} \quad (4)$$

$$\eta_{km} = \frac{\begin{array}{c} V_g \Delta p / 2\pi - K_{tP} n^2 - K_{tN}\Delta p \sqrt{\Delta p} / n \\ - K_v n - K_p \Delta p - k_{p2}\Delta p^2 - M_{L0} \end{array}}{V_g \Delta p / 2\pi} \quad (5)$$

According to the efficiency estimation model as mentioned above, characteristics coefficient of leakage flow like $C_\mu, C_{\rho VN}, C_{\rho PP}, zV_c, Q_{L0}$ and characteristics coefficient of loss torque like $K_\mu, K_{\rho VN}, K_{\rho PSP}$, $K_p, K_{p2}, M_{L0}$ are expressed by 11 efficiency characteristics coefficients.

### 2.4 FACTORS DETERMINING EFFICIENCY

11 characteristic coefficients of the equation (5) ~ (6) in the efficiency model are not be indicated because of the paper's limitation. However, with the standard dimensions, the efficiency characteristics are dominated by the following 14 efficiency determination factors.

Table 2 Factors determining efficiency

| Factors Category | Factors Symbol |
|---|---|
| Interval of movement contacting point | $h_P$ $h_S$ $h_V$ |
| Friction coefficient | $f_{Pi}$ $f_{P0}$ $f_{pBr}$ $f_{vBr}$ |
| Flow coefficient | $C_{DVN}$ $C_{DPP}$ $C_{wSP}$ |
| Etc. | $V_{P\max}$ $K_{p2}$ $Q_{L0}$ $M_{L0}$ |

Meanwhile, viscosity and density of hydraulic oil and volumetric elasticity coefficient can be changed into equations expressed by 7 characteristic coefficients as follows.

$$\mu = \mu_0 e^{\gamma_P p} e^{-\gamma_T (T - T_0)} \qquad (6)$$

$$\rho = \rho_0 \{1 + \kappa_P p - \kappa_T (T - 4_0)\} \qquad (7)$$

$$\frac{\beta}{\beta_0} = \frac{1 + (p_0 / p)^{1/\kappa} (V_a / V_F)(\beta / \kappa p)}{1 + (V_a / V_F)} \qquad (8)$$

At last, the efficiency of hydraulic motor, that is the volumetric efficiency and the mechanical efficiency are determined by total 14 factors and 7 sub-factors which indicate the characteristics of hydraulic oil.

## 3. TEST ANALYSIS OF PERFORMANCE ESTIMATION EFFICIENCY MODEL

We compared and analyzed that the estimation data by efficiency test data and performance estimation efficiency model for Jeil Hydraulic JMF 36 piston motor which has 36cc/rev volume.
Comparatively, the density of hydraulic oil and bulk modulus are less effective and the viscosity has a great effect to the efficiency of hydraulic motor. This paper supposes that the efficiency determining sub-factors as characteristic hydraulic oil are foreknown from the proper references related to hydraulic oil.

### 3.1 RESULT OF EFFICIENCY ESTIMATION

From comparison between the efficiency test data and the efficiency model of equation (5) and (6), supposed 14 efficiency determining factors and the efficiency characteristic coefficients calculated from the factors can be arranged like the following table.

Table 3 Estimated efficiency determining factors and efficiency characteristic coefficient

| | | | | | | |
|---|---|---|---|---|---|---|
| Efficiency determining factors | $h_P$ $[\mu m]$ | $h_S$ $[\mu m]$ | $h_V$ $[\mu m]$ | $f_P$ $10^{-5}$ | $f_{P\,Br}$ | $f_{v\,Br}$ |
| | 8.3 | 4.0 | 10.2 | 9.20 | 5.5 | 0.5 |
| $C_{DVN}$ | $C_{DPP}$ | $C_{wSP}$ | $V_{p\max}$ $[cc]$ | $Kp2$ $10^{-16}$ | $Q_{L0}$ $[LPM]$ | $M_{L0}$ $[Nm]$ |
| 2.2592 | 0.5265 | 0.2647 | 0.1091 | 0.0139 | -0.258 | 4.3359 |
| Volumetric efficiency characteristic coefficient | $C_\mu$ $10^{-14}$ | $C_{\rho VN}$ $10^{-8}$ | $C_{\rho PP}$ $10^{-7}$ | $zV_c$ $10^{-6}$ | $Q_{L0}$ $[LPM]$ | |
| | 0.9718 | 1.7735 | 3.4461 | 0.9821 | -4.300 | |
| Mechanical Efficiency Characteristic coefficient | $K_\mu$ | $K\rho VN$ $10^{9}$ | $K\rho PSP$ $10^{-6}$ | $K\rho$ $10^{-7}$ | $Kp2$ $10^{-16}$ | $M_{L0}$ $[Nm]$ |
| | 3.9140 | 2.8226 | 1.8906 | 1.5721 | 0.0139 | 4.3359 |

The error distribution graph which shows the relationship between the measured efficiency and efficiency estimation factors in the table 3 is shown in the Figure 1 and the average and the maximum error also shows very satisfying results like table 4.

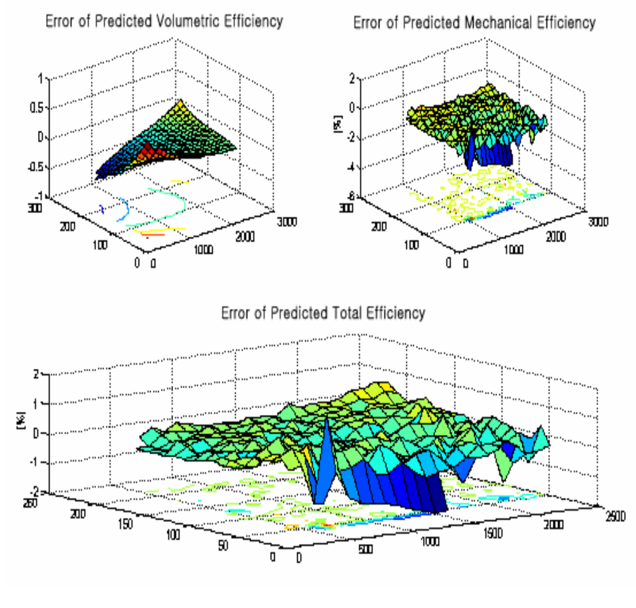


Figure 1 Error percentages of the model on efficiencies

Table 4 Statistics on performance estimation efficiency error

| | | |
|---|---|---|
| Total efficiency Estimation Average error | Volumetric Estimation Average error | Mechanical Estimation Average error |
| 0.248% | 0.291% | 0.417% |
| Total efficiency Estimation Max. error | Volumetric Estimation Max. error | Mechanical Estimation Max. error |
| 2.371% | 1.776% | 2.880% |

### 3.2 COMPARISON BETWEEN TESTED AND ESTIMATED EFFICIENCY

The comparison between measured efficiency and estimated volumetric efficiency, mechanical efficiency and total efficiency of hydraulic motor from performance estimation efficiency model is shown as Figure 2 ~ 5. We performed the efficiency test by changing pressure and speed. Colored lines indicate pressure values in ‘Total efficiency vs. speed’(fig. 2 and 3) and speed values in ‘Total efficiency vs. pressure’(fig. 4 and 5). The height of the lines varies according to their values. The lines display 250~50 $kgf/cm^2$ of pressure in fig. 2 and 3 and likewise, the lines display 2,500 ~ 300 rpm of speed in fig. 4 and 5.

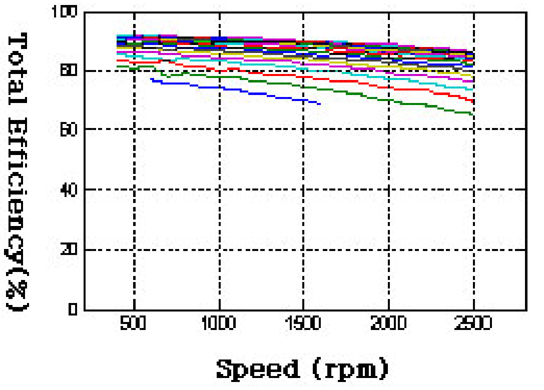


Figure 2 Total efficiency vs. speed(Experiment)

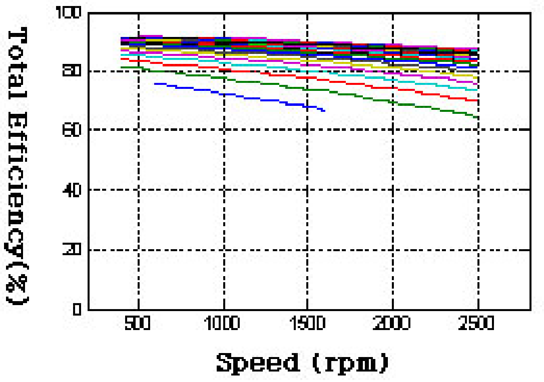


Figure 3 Total efficiency vs. speed(Calculation)

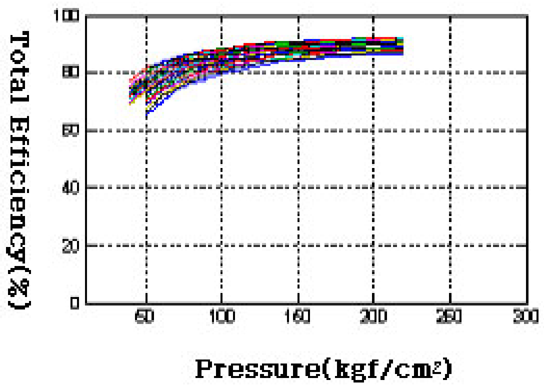


Figure 4 Total efficiency vs. pressure(Experiment)

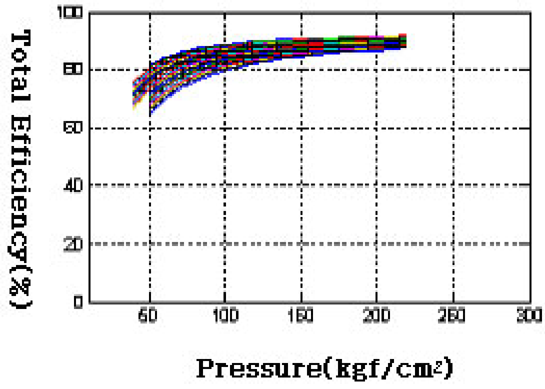


Figure 5 Total efficiency with pressure(Calculation)

As we can see the above diagrams, even though we compared in wide range like 300~2600 rpm speed and 20~270 bar pressure, the efficiency value of each point can be estimated very precisely and at the total point as well.

Meanwhile, we can get the following diagram, if we compare the leakage flow and the friction loss torque used in the working area.

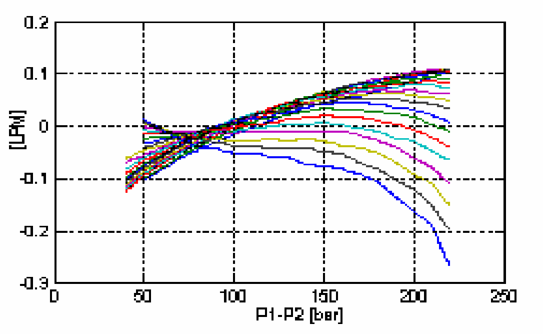


Figure 6 Predicted error of leakage flow with pressure

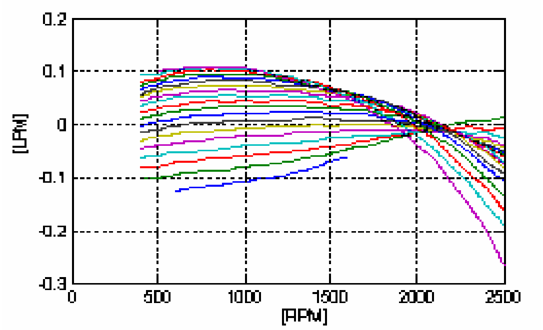


Figure 7 Predicted error of leakage flow with speed

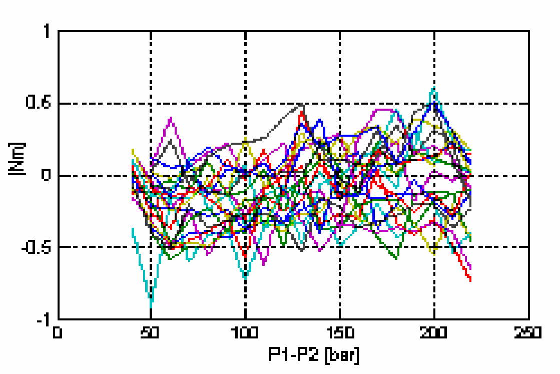


Figure 8 Predicted error of torque loss with pressure

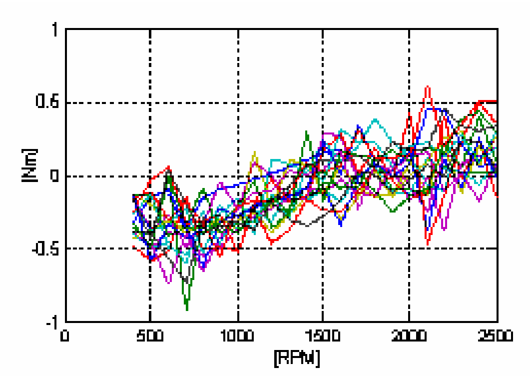


Figure 9 Predicted error of torque loss with speed

As we see in the diagram 5, the average of leakage flow and the maximum error are respectively 0.128 LPM and 0.368 LPM. And the average of losing torque and the maximum error are respectively 0.428 Nm and 2.461 Nm. They show a good result.

Seeing this, we can say that propriety and utility of performance estimation efficiency model in equation (5) and (6) are confirmed by experiments.

## CONCLUSION

It is thought that hydraulic pump and motor must pass the efficiency test because, there was no efficiency model for hydraulic pump and motor which has accuracy in the wide working range.

But for designing of hydraulic system which has a good efficiency, the necessity of the performance estimation model from the design stage has been proposed for a long time.

Under this situation, this paper analyzed the propriety and utility of performance estimation efficiency model from test data of 45 cc/rev hydraulic motor for various types of losing elements and new developed performance estimation efficiency model.

The efficiency characteristics of this new model are determined by total 14 efficiency determining factors with the basic dimensions of pump and motors. And after comparing the test data and the performance estimation model from the new developed model at the rotating speed 300~2600 rpm and pressure 20~270 bar, we got the good result of average estimation as 0.248% and the maximum error as 2.37%.

These results are just assumption of efficiency determining factors to get the nearest result to the test data for estimated efficiency so that we can anticipate that it is possible to secure the performance estimation efficiency model.

Henceforth, if we have more elaborative model and make a database of efficiency determining factors from test data, we suppose that we can estimate the efficiency of pump and motor in the near future. Furthermore, we assume that it is possible to design and manufacture the most effective piston pump and motor in the various working condition.

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