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DEVELOPMENT OF OILY HIGH BULK MODULUS FLUID

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ABSTRACT

The most important role of a hydraulic fluid is transmission of power among various roles. A bulk modulus of the fluid is crucial for hydraulic systems, particularly for high-pressure hydraulics. In theory, compression energy losses are in diverse proportional to the effective bulk modulus of the fluid, and response speed and stability depend directly on the square root of it. Conventional mineral oils have pretty low bulk modulus, compared to water-based hydraulic fluid. On the other hand, the water-based fluids are disadvantageous in lubricity and evaporation. Under the circumstances, we've searched for available oily high bulk modulus fluid, and found organic compounds with water-level bulk modulus.

KEY WORDS

bulk modulus, hydraulic fluid, compression energy, response speed, stability

NOMENCLATURE

d   : Pipe inside diameter

D   : Damping coefficient

K   : Bulk modulus

K_{oil} : Bulk modulus of pure oil

K_{pipe} : Bulk modulus of pipe wall material

s   : Pipe wall thickness

ΔP : Pressure change

ω_0 : Natural angular frequency

INTRODUCTION

Through the development of traction fluid for cars, we have realized great influence of the molecular structure of base oil on the machine performance, that is, the power of the "Fluid Power", and have been cultivated a molecular design and novel synthetic lubricant developing technology [1]. This time we have paid attention to the hydraulic fluid, and studied its possibility of evolution into a vital machine element.

In recent years, stationary hydraulic drive systems have been changed to electric drives in various uses owing to response speed, control stability, design flexibility and cleanliness. Since hydraulic drives have an advantage of power density, electro-hydraulic drives increase in high performance area such as injection molding machine. So improvement of disadvantages of hydraulic fluid, i.e. response speed and stability, could strengthen its competitiveness (Figure 1).

The most important role of the hydraulic fluid is transmission of the power among various roles, such as lubrication in pumps, seals, and rust prevention. The performance of power transmission depends on bulk modulus and air bubbles release ability of the

fluids. And base fluids have important roles in both properties. On the other hand, corresponding to energy saving in recent years, hydraulic fluids tend to be lower viscosity and higher viscosity index in order to decrease flow resistance. In general, lowering base fluid viscosity means lowering bulk modulus of the fluid, which means spoiling the primary performance of the hydraulic fluid (Figure 2).
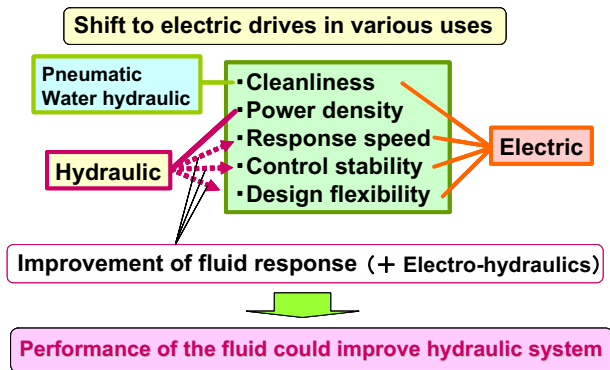

Figure 1 Present circumstances of stationary hydraulics

Figure 2 Primary performance of hydraulic fluid

In this paper effects of hydraulic fluids' bulk modulus upon less compression energy loss, rapid response and precise controllability in hydraulic systems were reviewed, and developmental possibility of a practical oily high bulk modulus fluid which contributes to them was investigated.

BULK MODULUS OF CONVENTIONAL LUBRICANTS

Klaus et al. measured isothermal secant bulk modulus

of various lubricants [2]. Read values from the literature at 37.8℃ and 50MPa are 2.68GPa of polyphenyl ether (5P4E) and 2.48GPa of water, compared to 1.65GPa of mineral oil, on the other hand silicone oil has low value of 1.15GPa. Goldman et al. measured isothermal tangential bulk modulus of several kinds of synthetic fluids and mineral oils, and revealed that polyglycol, diester, and tributyl phosphate have lower bulk modulus than that of mineral oil has [3].

5P4E has disadvantages in too high viscosity and poor low temperature fluidity, and water based fluids have disadvantages in poor lubricity and easy evaporation to use for practical hydraulic system. In this way, any available high bulk modulus fluids have not been developed yet.

EFFECTS OF BULK MODULUS ON HYDRAULIC PERFORMANCE [4]

Summaries of the report about theoretical calculation on effects of a high bulk modulus fluid upon improving hydraulic system performances are as follows.
1)   In low pressure hydraulics less than about 20MPa, advantages in using high bulk modulus fluid are small. Because effective bulk modulus of the fluid is largely decreased by great influence of extrinsic factors (air bubbles and pipe wall expansion). However, enough pipe wall thickness and less air bubbles make it advantageous.
2)   On the other hand, in high pressure hydraulics more than about 20MPa, advantages in using high bulk modulus fluid are great. Because the influence of extrinsic factors becomes less due to thick pipe wall and small air bubble size.
Table 1 shows effective bulk modulus ratio calculated from pipe wall thickness ratio s/d. It says that the lower available pressure is, namely thinner pipe wall, the larger decline of effective bulk modulus ratio with increasing of oil bulk modulus is.

Table 1 Effective bulk modulus ratio calculated from pipe wall thickness ratio

	s/d	0.01	0.05	0.10	0.15	0.20	0.25
	Pmax [MPa]	2.8	14.0	28.0	42.0	56.0	70.0
Koil [MPa]							
1,400		0.60	0.88	0.94	0.96	0.97	0.97
1,600		0.57	0.87	0.93	0.95	0.96	0.97
1,800		0.54	0.85	0.92	0.95	0.96	0.97
2,000		0.51	0.84	0.91	0.94	0.95	0.96

Kpipe = 210,000 MPa for St 35.4 steel pipe
SigmaMax = 140 MPa for St 35.4 steel pipe

A volumetric shrinkage rate of oil by compression is expressed with $\Delta P/K$ and a compression energy loss of oil by volumetric shrinkage is expressed with $\Delta P/(2K)$. For instance, when the mineral oil having bulk modulus of 1.4GPa is used under pressure of 28MPa, it is compressed by 2% and consequently elastic energy of 1% is preserved in oil, but the energy becomes loss without recovery.

Practically the loss is larger than that, in case of axial piston pumps with hollow pistons to reduce inertial weight, which often have the same dead volume as volume of the displacement has, their energy loss becomes 2%. Many pumps with adjustable stroke, especially when controlled in a constant pressure or constant power configuration, operate most of the time at high pressure and low stroke. In this case, the displacement volume is reduced, while the dead volume even increases. That means the compression energy losses easily reach levels of several times of the maximum input power rating. Theoretically compression energy contained in the dead volume in pumps can be recovered. In design practice, however, this can only be achieved to a very minor degree, as output pressures vary in a wide range, making exact fine-tuning is impossible.

In servo-hydraulic control circuits, performance is largely determined by two parameters: speed and stability. The technical equivalents for these are natural angular frequency ω_0 of a system's open control loop, and the damping factor D. For most applications, higher values of both are an advantage. As both ω_0 and D depend directly on the square root of the effective bulk modulus, increasing the bulk modulus of a fluid also increases servo performance, but three times faster servo valve is required. For instance, when the mineral oil having bulk modulus of 1.4GPa is replaced with the synthetic fluid having bulk modulus of 2.0GPa, speed and stability of the system are improved by 20% respectively.

As mentioned above, in theory, it is confirmed that favorable usage for high bulk modulus fluid can bring various improvement of hydraulic system performance in terms of energy saving, high response speed and precise controllability.

RESEARCH INTO HIGH BULK MODULUS FLUID

Measurement of bulk modulus [5]

Bulk modulus was calculated from measured high-pressure density data, as an isothermal tangential bulk modulus at 10, 20, 35 and 50MPa. A high-pressure density was measured by means of the plunger type high-pressure dilatometer (Figure 3), the fluid was gradually pressurized from ambient pressure to 200MPa at 40℃. The outer cylinder, with an outer diameter of 80.0mm and inner diameter of 30.0mm, is made of Ni-Cr-Mo steel. The plunger and plug are made of Cr-Mo steel. The plunger and plug each have a high pressure seal. It is comprised of an O ring, a back up ring and an anti-extrusion ring made of beryllium copper. The volume of the tested fluid at ambient pressure was 2ml. The volume of fluid in the chamber correspondent to the pressure is determined from the displacement of the plunger by using a linear gauge.
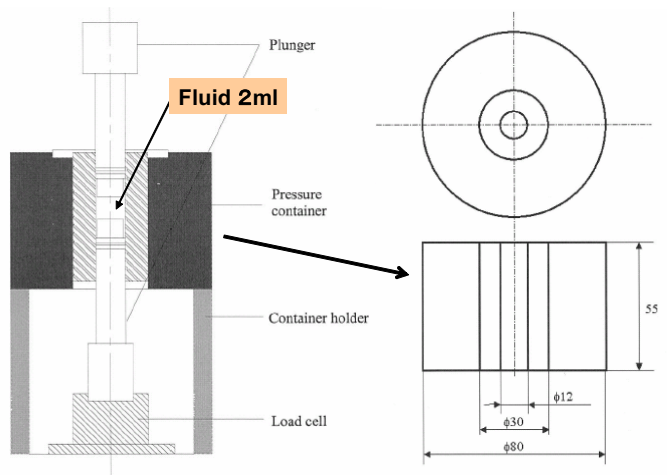

Figure 3 Apparatus for the measurement of fluid's bulk modulus

Figure 4, 5, 6 and 7 show bulk modulus of the conventional base oil (poly butene, mineral oil, 5P4E, and water-glycol type hydraulic fluid) measured by this method at 10, 20, 35 and 50MPa versus kinematic viscosity at 40℃ respectively. They agree with preceding literature data.

Candidate fluids synthesis

Before synthesizing the candidate fluids, following interim criteria which were bare requirements for base fluids were fixed.

Kinematic viscosity at 40℃ : less than 100mm^2/s
Pour point : less than -20℃
Flash point : more than 200℃
Elements in molecule : C, H, O, N
(Containing no harmful elements)

Figure 4, 5, 6 and 7 show bulk modulus at 10, 20, 35 and 50 MPa versus kinematic viscosity at 40℃ of newly synthesized candidate fluids together with conventional oils respectively. It is proved that organic compounds having high bulk modulus as water level and also low viscosity do exist. We also have confirmed that fluids with high bulk modulus can be endowed with biodegradability.
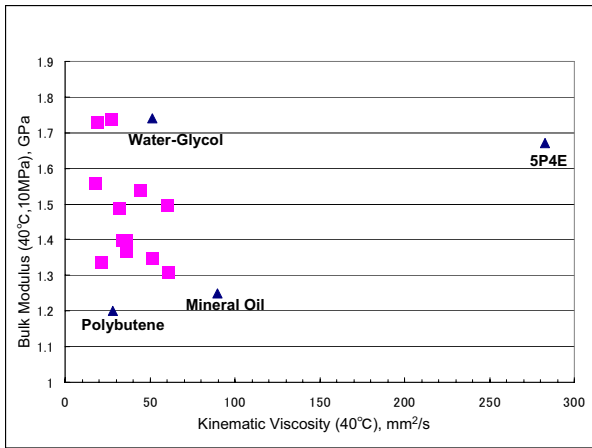
Figure 4 Bulk modulus at 10MPa
versus kinematic viscosity of conventional oil
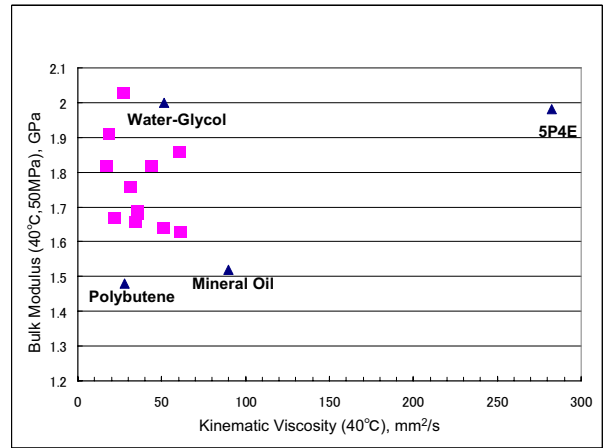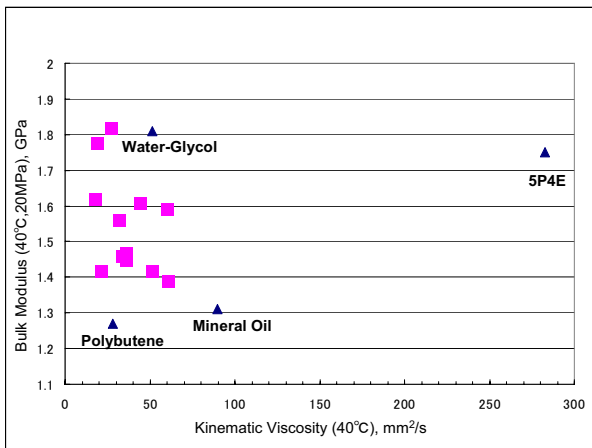and newly synthesized fluid

Figure 5 Bulk modulus at 20MPa
versus kinematic viscosity of conventional oil
and newly synthesized fluid

Figure 6 Bulk modulus at 35MPa
versus kinematic viscosity of conventional oil
and newly synthesized fluid

Figure 7 Bulk modulus at 50MPa
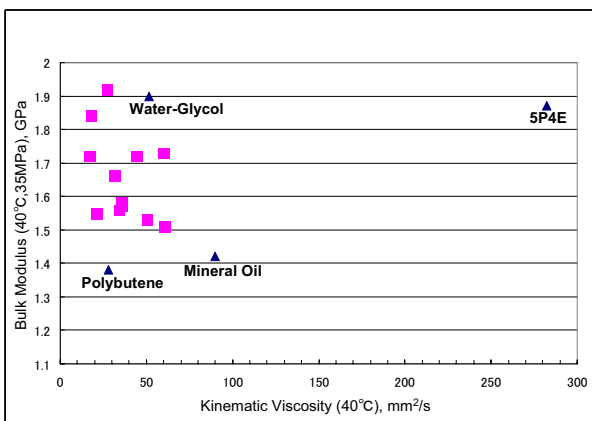versus kinematic viscosity of conventional oil
and newly synthesized fluid

GAS SOLUBILITY OF HIGH BULK MODULUS FLUID

Measurement of gas solubility

As high bulk modulus fluids have small free volume of the molecules, gas solubility is expected to be low, and so nitrogen gas solubility was measured by means of the diffusion type gas-solubility apparatus at 23.5℃ (Figure 8) [6] [7].
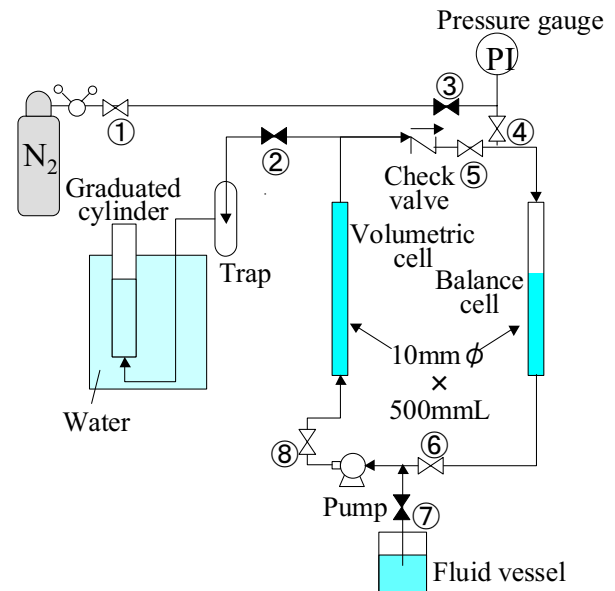

Figure 8 Diffusion type gas-solubility apparatus

After full volume of volumetric cell and half volume of balance cell were filled with test fluid by pump, nitrogen gas was introduced into the balance cell up to

2.5MPa or 4.5MPa. Then fluid was circulated through volumetric cell and balance cell until pressure became stable. After valve⑤ and valve⑧ were closed, valve② was opened gradually, and diffused gas volume was measured with graduated cylinder. Figure 9 shows measured nitrogen gas solubility of high bulk modulus fluids and mineral oil versus pressure.
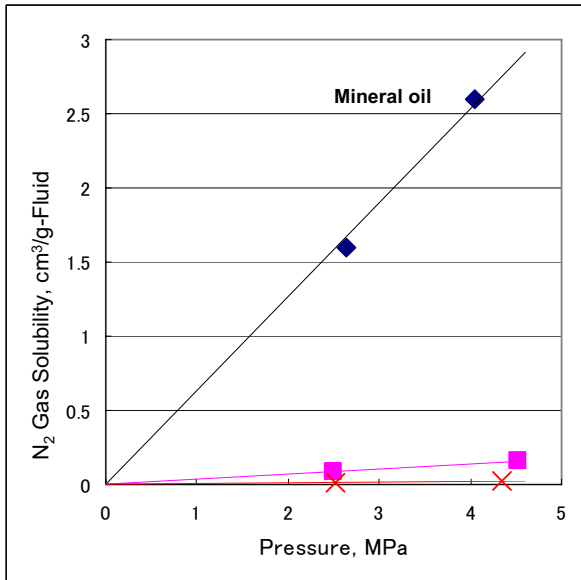

Figure 9 N_2 gas solubility versus pressure

Figure 10 shows bulk modulus at 50MPa of the fluids versus N_2 gas solubility at 0.1MPa, 20MPa and 50MPa calculated under the Henry's law.
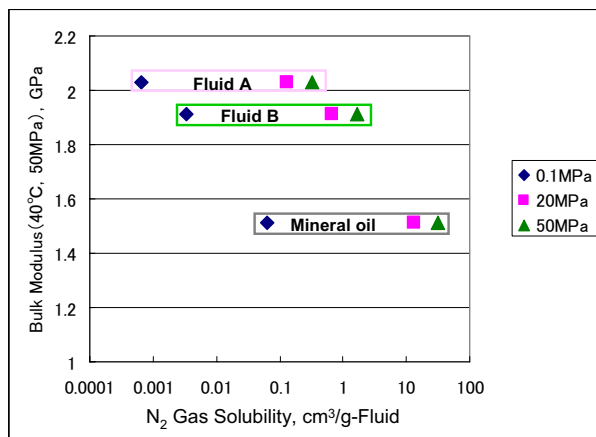

Figure 10 Bulk modulus versus N_2 gas solubility

As shown in Figure 10, high bulk modulus fluids have extremely lower gas solubility than that of mineral oil has.

That is to say, high bulk modulus fluids tend not to generate cavitation and tend not to generate air bubbles caused by gas solubility difference under high pressure and ambient pressure. In addition, generated air bubbles tend to separate from the fluids easily due to high density of the fluids.

High bulk modulus fluids are expected to have an excellent hydraulic performance under low pressure as well.

EXPERIMENTALLY FORMULATED FLUID

Table 2 shows an example of test result of experimentally formulated fluids which consist of two of candidates shown in Figure 4-7. Although there is room for improvements, it has enough performance compared to conventional biodegradable hydraulic fluid.

SUMMARY

1) There is a possibility that energy saving, response speed and precise controllability of the hydraulic system can be improved by using the high bulk modulus hydraulic fluid.
2) The organic compounds having high bulk modulus as nearly water level and also low viscosity with no harmful elements have been found.
3) Biodegradability and high bulk modulus can be compatible.
4) As high bulk modulus fluids have very low gas solubility and high density, they are expected to have an excellent hydraulic performance under low pressure as well.
5) Newly synthesized oily high bulk modulus fluids are expected to be base oils of new concept hydraulic fluids.

PLANS FOR THE NEXT STAGE

1) Optimization of base fluid compound
2) Verification of the effects on energy saving, response speed and precise controllability.
3) Study of possible applications which make the most of oily high bulk modulus fluids.

We sincerely hope that the development contributes toward upgrade of hydraulic systems.

REFERENCES

1. T.Tsubouchi, H.Hata, Y.Yoshida, "Optimization of Molecular Structure for Traction Fluid", Lubrication Science, 16(4), 393-403(2004)
2. E.E.Klaus,J.A.O'brien, "Precise Measurement and Prediction of Bulk-Modulus Values for Fluids and Lubricants", Transactions of the ASME, ser,D,86,469-474(1964)
3. I.B.Goldman, N.Ahmed, P.S.Venkatesan, J.S.Cartwright, "The compressibility of selected fluids at pressures up to 230,000 PSI", Lubrication Engineering, 27(10), 334-341(1971)
4. H.Theissen, H.Murrenhoff, "Determination of Effects of a High Bulk Modulus Fluid", IFAS/RWTH Aachen undisclosed report (2006)
5. N.Ohno,R.Mukai,M.Z.Rahman,K.Shibata, "Bulk Modulus and Poisson's Ratio of Traction Fluids", Proceedings of the 2001 International Symposium on the Tribology of Vehicle Transmissions, 9-12(2001)
6. Erwin Brunner, "Solubility of Hydrogen in Organic Solvents at 298.15, 323.15 and 373.15 K", J. Chem. Eng. Data, 30(3), 269-273(1985)
7. K.Kumanaga, S.Miyamoto, "Method for gas solubility measurement", Idemitsu Technical Report, 45(2), 182-189(2002)   (in Japanese)

Table 2 Test results of experimentally formulated fluid

General Properties	Unit	Test Fluid A	Test Fluid B (Biodegradable)	Conventional Biodegradable Fluid
Kinematic Viscosity(40℃)	mm^2/s	47.26	29.83	45.69
Kinematic Viscosity(100℃)	mm^2/s	7.128	7.208	8.767
Viscosity Index		109	220	175
Acid Number (Indicator Method	mgKOH/g	0.03	0.22	0.84
Base Number (HCl Method)	mgKOH/g	–	0.29	0.06
Density(15℃)	g/cm3	1.0596	1.0594	0.932
Flash Point(COC)	℃	254	272	312
Pour Point	℃	−47.5	−50.0>	−50.0>
Foaming Test （1）	ml−ml	0−0	–	0−0
Foaming Test （2）	ml−ml	0−0	–	0−0
Foaming Test （3）	ml−ml	0−0	–	0−0
Copper Corrosion Test 100℃×3h		1(1b)	1(1b)	1(1b)
Tone		Brown	Yellow	Yellow
Form		Transparent Liquid	Transparent Liquid	Transparent Liquid
Color(ASTM)		–	–	L1.0
RBOT(1.75kg/cm2)	min	927	1030	123
Rust Preventing Test (Distilled Water) 60℃,24hr		No Rust	–	No Rust
ISOT 165.5℃×72h Properties After 72hrs				
Kinematic Viscosity(40℃)	mm^2/s	47.43	—	99.19
Acid Number	mgKOH/g	3.02	—	10.9
Viscosity Change Ratio	%	0.36	—	117.09
Increase of Acid Number	mgKOH/g	2.99	—	10.06