

## Experimental measurements of bulk modulus for two types of hydraulic oil at pressures to 140MPa and temperatures to 180°C

**Professor YANG Shudong<sup>1</sup>**

1. School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China, email: yangsd@mail.hust.edu.cn

**TAO Aihua<sup>2</sup>, LUO Yulin<sup>2</sup>, ZHANG Junxiang<sup>1</sup>, ZHOU Peng<sup>1</sup>, ZHOU Lin<sup>1</sup>**

2. Well-Tech R&D Institute, China Oilfield Services Limited, Sanhe 065201, Hebei, China

### Abstract

Bulk modulus of hydraulic oil represents the resistance of hydraulic oil to compression and is the reciprocal of compressibility. The bulk modulus is a basic thermodynamic property of hydraulic oil that has a very important influence on work efficiency and dynamic characteristics of hydraulic systems, especially for the hydraulic systems at ultra-high pressure or ultra-high temperature. In this study, a bulk modulus experimental equipment for hydraulic oil was designed and manufactured, two types of hydraulic oil were selected and its isothermal secant bulk modulus were measured at pressures to 140MPa and temperatures of 20~180°C. Compared the experimental results with the calculated results from the prediction equations of liquid bulk modulus that proposed by Klaus, Hayward, and Song, it is found that the experimental results are not completely identical with the calculated results.

**KEYWORDS:** Bulk modulus of hydraulic oil, Experimental equipment, Ultra-high pressure, Ultra-high temperature, Prediction equations of bulk modulus

### 1. Introduction

For a conventional hydraulic system, when the working pressure is less than 40MPa and temperature is less than 80°C, the hydraulic oil is usually considered as incompressible. Although this is only an approximation to the truth, it is near enough to satisfy the needs of design for most conventional hydraulic systems. When the working pressure or temperature is much higher than that described above, the change in volume of hydraulic oil due to compressibility amounts to several per cent, which can not be ignored and needs to be allowed for design calculations. The compressibility of hydraulic oil working at high pressure or high temperature will significantly affect the

characteristics of hydraulic systems, such as the response time, the control accuracy of the hydraulic system, the efficiency of pumps and motors, and so on /1/. According to the definitions of the compressibility and bulk modulus of fluids, the bulk modulus is the reciprocal of compressibility. It represents the resistance of a fluid to compression, and the greater its numerical value is, the stronger its ability to resist compression is. So the bulk modulus becomes a basic thermodynamic property of hydraulic oil for the design calculations and characteristics analyses of hydraulic components and systems in recent years.

There are admittedly four definitions about bulk modulus, they are respectively called as isothermal secant bulk modulus, isothermal tangent bulk modulus, isentropic secant bulk modulus and isentropic tangent bulk modulus. For one hydraulic oil, at the same pressure and temperature, the bulk modulus values of four definitions are different, but they are very relevant with each other /2/. In this study, the isothermal secant bulk modulus of hydraulic oil is adopted and discussed, its definition is as following:

$$K_T = \left[ \frac{V_0(P-P_0)}{V_0-V} \right]_{T=const} \quad (1)$$

Our project team has come up against a challenge in developing a hydraulic system that will work in wellbore detecting instruments, such as in the Ultrasonic Borehole Imager. The pressure of mud in wellhole should be up to 140MPa and the temperature of mud in wellhole will be up to 180°C /3/. Which is very typical working condition of ultra-high pressure and ultra-temperature. That is to say, the hydraulic system in wellbore detecting instruments must reliably work under the condition of pressure of up to 140MPa and temperature of up to 180°C. Two types of hydraulic oil, Mobil Jet Oil II and UNIVIS HVI 26 supplied by Exxon Mobil Corporation were selected, they have good viscosity-pressure characteristics and viscosity-temperature characteristics, and can work at ultra-high pressure and ultra-high temperature. But there are no bulk modulus data of the two types of hydraulic oil for the wide range of pressure and temperature mentioned above. Which makes it hard to do design calculations and characteristics analyses of the hydraulic system.

Exhilaratingly, there have some empirical prediction equations which can be used to predict the bulk modulus of hydraulic fluids with the changes of pressure and temperature. In 1964, after measuring the bulk modulus of some hydraulic fluids and lubricants at pressures of 0~70MPa and temperatures of 0~176°C, Klaus found that the slope of the isothermal secant bulk modulus versus pressure curve is constant, and the bulk modulus decreases logarithmically with the increase of temperature, then Klaus proposed his prediction equations /4/. In 1971, based on a mass of experimental

measurements for the compressibility of hydraulic fluids at pressures of 0~70MPa and temperature of 20°C, Hayward thought that the isothermal secant bulk modulus of any normal mineral hydraulic oil is related with its kinematic viscosity at atmospheric pressure and 20°C, with it Hayward also proposed his prediction equations /5/. In 1991, base on the previous experiment data of bulk modulus for hydraulic fluids at pressures of 0~210MPa and temperatures of 0~100°C, Song developed the equations that the isothermal secant bulk modulus of mineral oils and non-polymeric pure hydrocarbons at atmospheric pressure is related with its viscosity, and the slope of bulk modulus versus pressure curve has a linear relationship at a certain temperature /6/. Unfortunately, the hydraulic system, which is designed and calculated with the bulk modulus derived by above prediction equations, is still with troubles. Perhaps the application coverage of the prediction equations proposed by Klaus, Hayward, and Song is not suitable for the condition in wellbore. So we have attempted to measure the bulk modulus of the two types of hydraulic oil selected by means of much more close to its working conditions.

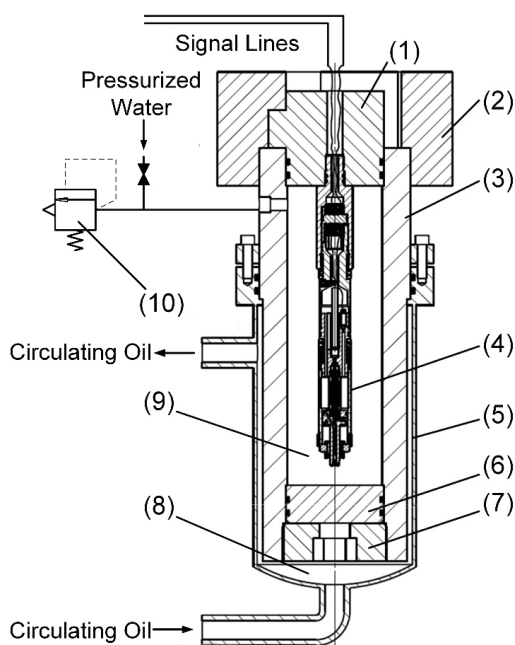
In this paper, an experimental equipment for measuring the bulk modulus of hydraulic oil under ultra-high pressure and ultra-high temperature is introduced. The bulk modulus of two types of hydraulic oil at pressures to 140MPa and temperatures of 20~180°C are measured by experiment, and then the experimental results are showed and compared with the calculated results from the prediction equations by Klaus, Hayward, and Song. It is expected that it can effectually solve the difficulty about the design calculations and characteristics analyses of hydraulic systems in the wellbore detecting instruments, and provides a chance to discuss some academic questions with savants in hydraulics.

## 2. Experiment

### 2.1. Experimental equipment

**Figure 1** is the schematic diagram of the experimental equipment, which consists of the working condition simulator and the experimental device. The working condition simulator includes an upper sealing block (1), a screw cover (2), a pressure vessel (3), a sleeve (5), a lower sealing block (6), a screw plug (7), a relief valve (10), a water pressurizing system and a circulating oil system. There are two full separate chambers: the circulating oil chamber (8) and the water chamber (9), and the water chamber is enveloped in the circulating oil chamber. The water chamber is a pressure vessel, which can withstand ultra-high pressure and ultra-high temperature, and fills with filtrated fresh water. The pressure of the water chamber can be adjusted by the water

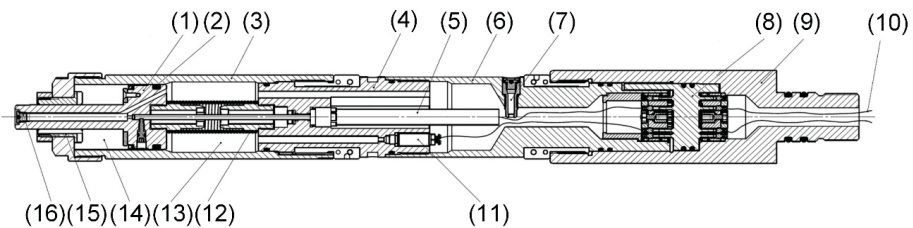
pressurizing system and the relief valve from 0 to 200MPa, and the temperature of the water chamber can be adjusted by the circulating oil system from ambient temperature to 240°C. The circulating oil system includes a heater and a cooler that can regulate the temperature of the circulating oil. Therefore the adjustable ranges of pressure and temperature in the water chamber of the working condition simulator can meet the experiment needs.



**Figure 1:** The schematic diagram of experimental equipment  
 (1) upper sealing block, (2) screw cover, (3) pressure vessel,  
 (4) experimental device, (5) sleeve, (6) lower sealing block, (7) screw plug,  
 (8) circulating oil chamber, (9) water chamber, (10) relief valve

The structure diagram of the experimental device is shown in **Figure 2**. The experimental device includes a piston (1), a seal ring (2), a cylinder (3), a sensor holder (4), a body (6), an oil filler plug (7), a multicore connector (8), a screw sealing block (9), a spring (12), a guide sleeve (15), a plug (16), and so on. A displacement sensor (5) and a pressure & temperature sensor (11) are attached to the sensor holder. By the screw sealing block of the experimental device screwing in the upper sealing block of the working condition simulator, the experimental device can be installed in the water chamber of the working condition simulator. There is a multicore connector that can not only seal the test hydraulic oil with ultra-high pressure in the test hydraulic oil chamber

(13), but also elicit the sensor signal lines (10), so as to output signals of the piston displacement, the pressure and temperature in the test hydraulic oil chamber to instruments or computer outside the experiment equipment. The telescopic rod of the displacement sensor (Subminiature Instruments Corporation, Model 100-1060) is connected with the piston, it detects the displacement of the piston that can infer the volume change of the test hydraulic oil. The pressure & temperature sensor (Paine Corporation, Model 310-38-520-06, 0-172MPa, 23-176°C) is directly installed in the test hydraulic oil chamber.



**Figure 2:** The structure diagram of experimental device

- (1) piston, (2) seal ring, (3) cylinder, (4) sensor holder, (5) displacement sensor,  
 (6) body, (7) oil filler plug, (8) multicore connector, (9) screw sealing block,  
 (10) sensor signal lines, (11) pressure & temperature sensor, (12) spring,  
 (13) test hydraulic oil chamber, (14) water chamber, (15) guide sleeve, (16) plug

The main advantages of this experimental equipment are followings:

Because the experimental device fully submerges into the water in the working condition simulator, and the force to the piston from the side of the test hydraulic oil is nearly equal to that from the side of the water, so the pressure and temperature of the test hydraulic oil is almost equal to that of the water. That is to say, both the pressure and the temperature of the test hydraulic oil can be adjusted, and the isothermal secant bulk modulus of the test hydraulic oil at the pressure of 0~140MPa and temperature of 20~180°C may be obtained by experiment.

The pressure & temperature sensor is installed in the test hydraulic oil chamber, which directly detects the pressure and temperature of the test hydraulic oil. The pressure inside the experimental device is almost equal to that outside, so the deformations of the cylinder and body can be ignored and has no effect on the volume of the test hydraulic oil. And the test hydraulic oil chamber designed can fill with test hydraulic oil about 2.8 litres, which means that the changes in volume of the test hydraulic oil with the changes of pressure and temperature will be more obvious. That all will make for improving the measurement accuracy.

Of course, there are also disadvantages with this experimental equipment, for example, the experimental equipment is big and expensive, and it is time-consuming for experiment, so it is difficult for commercial use.

## 2.2. Experimental procedure

Before experiment, on the condition of atmospheric pressure and ambient temperature, the test hydraulic oil selected is filled into the test hydraulic oil chamber of the experimental device using an evacuation circulation device, the undissolved air in the test hydraulic oil should be eliminated as far as possible. By weighing the experimental device that is empty and filled, the original volume of the test hydraulic oil will be derived.

The experimental procedure is designed as followings:

- (a) Keeping the temperature of the water in the working condition simulator as ambient temperature, then adjusting the pressure of the water in the working condition simulator up gradually from atmospheric pressure to 140MPa in accordance with a step of 20MPa, and then adjusting the pressure of the water down gradually from 140MPa to atmospheric pressure also in accordance with a step of 20MPa. Keeping each pressure of the water steady about 20 minutes, and recording the data of the pressure and temperature of the test hydraulic oil and the displacement of the piston from sensors, and the pressure and temperature of the water.
- (b) Adjusting the temperature of the water up gradually to 40°C and making it remain constant, then adjusting the pressure of the water up and down according to the procedure described above, and recording the data for each pressure and the temperature of 40°C.
- (c) Adjusting the temperature of the water up gradually from 40°C to 180°C in accordance with a step of 20°C, and keeping each temperature of the water steady for enough time, then adjusting the pressure of the water up and down according to the procedure described above, and recording the data for each pressure and each temperature.

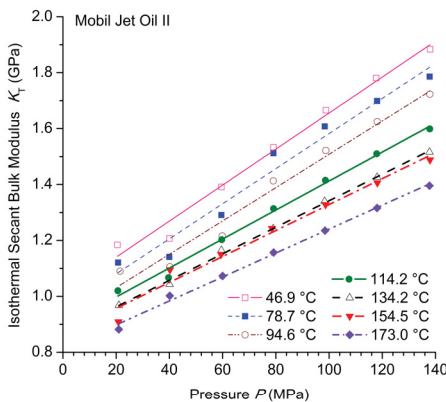
According to this procedure, there are at least 126 adjusting steps or test points for the experiment of one test hydraulic oil.

### 3. Experimental results

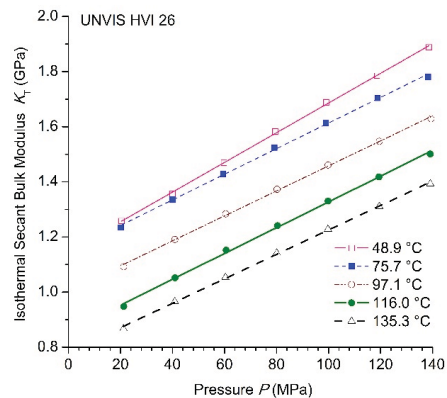
#### 3.1. Results

By adjusting the pressure and temperature of the water in the working condition simulator, the pressure, the temperature and the volume of the test hydraulic oil for each test point will be obtained. Because it is difficult to precisely control the pressure, especially the temperature of the water during experiment, there are a slight difference between the experimental data of the test hydraulic oil and that designed in experimental procedure. By data processing, there are 7 actually measured temperature points of 46.9°C, 78.7°C, 94.6°C, 114.2°C, 134.2°C, 154.5°C and 173.0°C for Mobil Jet Oil II, and 5 actually measured temperature points of 48.9°C, 75.7°C, 97.1°C, 116.0°C, and 135.3°C for UNIVIS HVI 26. Eventually the isothermal secant bulk modulus of Mobil Jet Oil II and UNIVIS HVI 26 can be derived from the experimental data by formula (2) that from the standard ASTM D6793-02 [7], the dots of isothermal secant bulk modulus versus pressure at different temperatures for the two test hydraulic oils are separately plotted and shown in **Figure 3** and **Figure 4**, the curves of isothermal secant bulk modulus versus pressure at the corresponding temperature points through least square fitting method are synchronously plotted.

$$K_{Tij} = \frac{V_{i0}(P_j - P_0)}{V_{i0} - V_{ij}} \quad (2)$$



**Figure 3:** The graph of  $K_T$  vs  $P$  for Mobil Jet Oil II



**Figure 4:** The graph of  $K_T$  vs  $P$  for UNIVIS HVI 26

From Figure 3 and Figure 4, it can be summarized as followings:

- (a) The isothermal secant bulk modulus increases as the pressure rising or the temperature falling, and when the temperature is constant, there is nearly a linear

relationship between the isothermal secant bulk modulus and the pressure. This trend coincides with the known laws of bulk modulus for liquids.

- (b) The isothermal secant bulk modulus curves of Mobil Jet Oil II are very similar to that of UNIVIS HVI 26. Within the scope of experimental data, the maximal value of the isothermal secant bulk modulus of Mobil Jet Oil II is about 1.88GPa at the pressure of 140MPa and temperature of 46.9°C, the minimal value is about 0.88GPa at the pressure of 20MPa and temperature of 173°C. For UNIVIS HVI 26, the maximal value is about 1.88GPa at the pressure of 140MPa and temperature of 48.9°C, the minimal value is about 0.87GPa at the pressure of 20MPa and temperature of 135.3°C.
- (c) At the pressure of 20~140MPa and temperature of 46.9~173°C, the maximal value of the isothermal secant bulk modulus is more than 2 times of the minimal value, this change is very big. So the changes of the bulk modulus of hydraulic oil that varies with the pressure and temperature must be carefully considered when the hydraulic systems are designed for applications in wellbores, as well as in the fields with ultra-high pressure or ultra-high temperature.
- (d) With the experimental values, the isothermal secant bulk modulus of Mobil Jet Oil II and UNIVIS HVI 26 at any pressure of 20~140MPa and any temperature of 46.9~173°C (for Mobil Jet Oil II, and 48.9~135.3°C for UNIVIS HVI 26) can be derived through interpolation method.

### 3.2. Comparisons

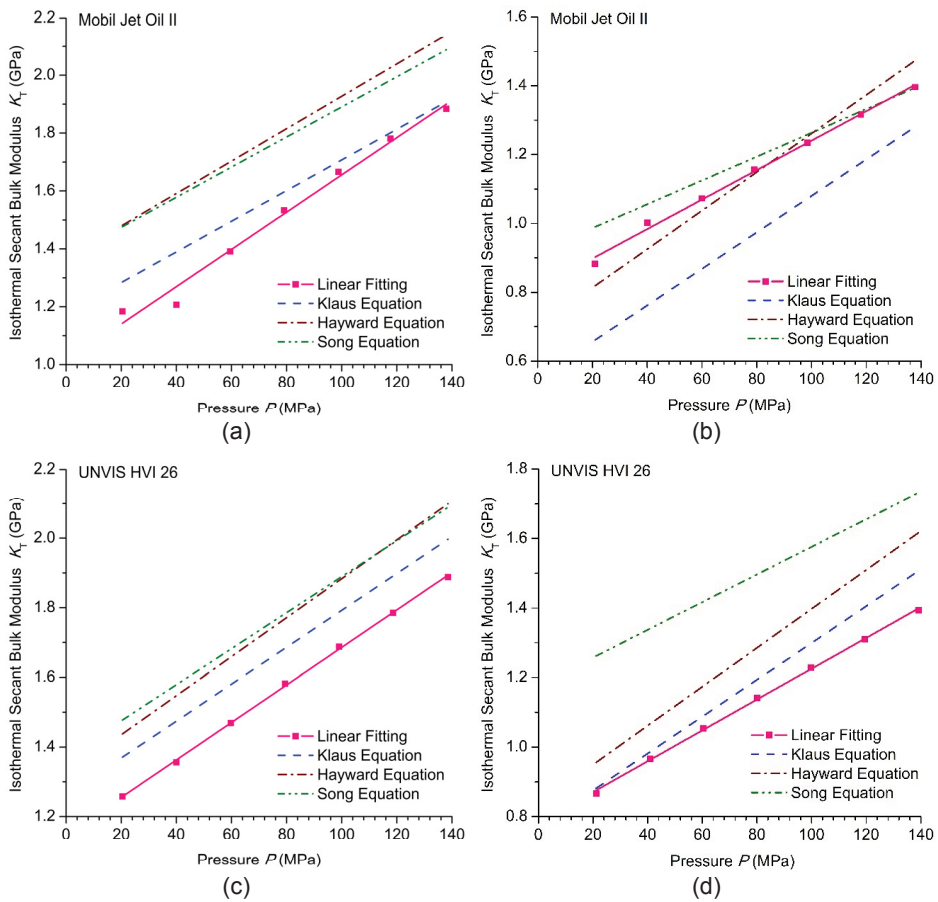
For comparison, the isothermal secant bulk modulus of Mobil Jet Oil II and UNIVIS HVI 26 at the experimental range of pressure and temperature are calculated according to the three group prediction equations that proposed respectively by Klaus, Hayward, and Song. The calculated results are shown in **Figure 5** with the relevant experimental results, only two temperature points are selected to plot for each test hydraulic oils, so as to clearly show the results and also save the length of the paper.

The Figure 5(a) shows the experimental results and the three kinds of calculated results at the temperature of 46.9°C for Mobil Jet Oil II. The slope of the four lines of  $K_T$  is very close with each other, and the experimental results are near to the calculated results from the prediction equations of Klaus, but it has a visible difference with that of Hayward and Song, and the values of experimental results are less than that of Hayward about 24%.



The Figure 5(b) shows the experimental results and the three kinds of calculated results at the temperature of 173°C for Mobil Jet Oil II. The slope of the four lines of  $K_T$  is a little different with each other, and the experimental results are near to the calculated results from the prediction equations of Hayward and Song, but it has a visible difference with that of Klaus, and the values of experimental results are more than that of Klaus about 26%.

Combining Figure 5(a) and (b), the experimental results of Mobil Jet Oil II do not go beyond the scope of all calculated results.



**Figure5:** Comparisons of prediction results with experimental results

The Figure 5(c) shows the experimental results and the three kinds of calculated results at the temperature of 48.9°C for UNVIS HVI 26. The slope of the four lines of  $K_T$  is very close with each other, but the values of experimental results are less than

the calculated results from the prediction equations of Klaus about 8.8%, and less than that of Hayward and Song about 17.6%.

The Figure 5(d) shows the experimental results and the three kinds of calculated results at the temperature of 135.3°C for UNIVIS HVI 26. The slope of the experimental  $K_T$  line is equal to that of Song, but is a little less than that of Klaus and Hayward. The values of experimental results are a little less than the calculated results from the prediction equations of Klaus, but less than that of Hayward about 17% and less than that of Song about 45%.

Combining Figure 5(c) and (d), the experimental values of  $K_T$  for UNIVIS HVI 26 are less than that of all calculated results.

On the whole, the experimental results are not completely identical with the calculated results, maybe it is because the different experimental conditions or hypotheses bring those differences.

#### 4. Conclusions

- (a) An experimental equipment for measuring the isothermal secant bulk modulus of hydraulic oil has been developed, and its experimental pressure can be controlled from 0 to 140MPa, its experimental temperature can be controlled from ambient temperature to 180°C.
- (b) The isothermal secant bulk modulus of Mobil Jet Oil II and UNIVIS HVI 26 from Exxon Mobil Corporation are measured at the pressure of 0~140MPa and temperature of 20~180°C, and the experimental results are shown with graphs.
- (c) By comparison, it is found that the experimental results are not completely identical with the calculated results that from the prediction equations by Klaus, Hayward, and Song. The causes of differences between the experimental results and the calculated results need to be investigated later.

Although this experimental equipment is big and expensive, the experiment is time-consuming, attempting to obtain the experimental data of bulk modulus of hydraulic oils at ultra-high pressure or ultra-high temperature is considered as very valuable. So the further experimental studies are being arranged.

#### Acknowledgements

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## References

- /1/ Hayward, A. T. J. 1963. Research on Lubricants and Hydraulic Fluids at National Engineering Laboratory. *Scientific Lubrication*, 15(3), pp. 112–124.
- /2/ Gholizadeh, H & Burton, R & Schoenau, G. 2011. Fluid Bulk Modulus: A Literature Survey, *International Journal of Fluid Power*, 12(3), pp. 5–16.
- /3/ TIAN Zhi-bin & OUYANG Jian. 2008. The Design and Reseach of Hydraulic System in the High Temperature and High Pressure Condition, *Chinese Hydraulics & Pneumatics*, (7), pp. 4–6.
- /4/ Klaus, E. E & O'brien, J. A. 1964. Precise Measurement and Prediction of Bulk Modulus Values for Fluids and Lubricants, *ASME Journal of Fluids Engineering*, 86(D-3), pp. 469–473.
- /5/ Hayward, A. T. J. 1970. How to Estimate the Bulk Modulus of Hydraulic Fluids, *Hydraulic Pneumatic Power*, 16(181), pp. 28–40.
- /6/ Song, H. S & Klaus, E. E & Duda, J. L. 1991. Prediction of Bulk Moduli for Mineral Oil Based Lubricants, Polymer Solutions, and Several Classes of Synthetic Fluids, *Journal of Tribology*, 113(4), pp. 675–680.
- /7/ ASTM D6793-02. 2012. Standard Test Method for Determination of Isothermal Secant and Tangent Bulk Modulus, ASTM Internation, West Conshohocken, PA.

## Nomenclature

$i$	The sequence number of experimental temperature	
$j$	The sequence number of experimental pressure	
$K_T$	The isothermal secant bulk modulus of hydraulic oil at the pressure of $P$ and temperature of $T$	MPa
$K_{Tij}$	The isothermal secant bulk modulus of the test hydraulic oil at the pressure of $P_j$ and temperature of $T_i$	MPa
$P$	The pressure of hydraulic oil	MPa
$P_0$	The atmospheric pressure	MPa

$P_j$	The pressure of the test hydraulic oil to the experimental pressure sequence number $j$	MPa
$T$	The temperature of hydraulic oil	°C
$T_i$	The temperature of the test hydraulic oil to the experimental temperature sequence number $i$	°C
$V$	The volume of hydraulic oil at the pressure of $P$ and temperature of $T$	mm <sup>3</sup>
$V_0$	The original volume of hydraulic oil at the atmospheric pressure and the ambient temperature	mm <sup>3</sup>
$V_{i0}$	The original volume of the test hydraulic oil at the pressure of $P_0$ and temperature of $T_j$	mm <sup>3</sup>
$V_{ij}$	The volume of the test hydraulic oil at the pressure of $P_j$ and temperature of $T_j$	mm <sup>3</sup>