Effects of temperature on the properties of HL32 oil in the conventional hydraulic actuators

Walaa M. Hashim *, Huda A. Al-Salihi, Faten N. Al Zubaidi

Department of Electromechanical Engineering, University of Technology, Baghdad, Iraq

ARTICLE INFO

Keywords:
HL32 oil
Kinematic and dynamic viscosity
Stroke displacement
Accurate position
Conventional hydraulic actuators

ABSTRACT

Present study pays more attention to optimize the performance of the hydraulic system by selecting the accurate position of the traditional hydraulic actuators. It was used HL32 as working oil, due to its ability to withstand high temperatures (15–200) °C as well as having the best mechanical properties, since the density and viscosity are the most important factors that are extremely affected on the hydraulic system. Hence, this work examined the effect of the variation kinematic, dynamic viscosity, and the density of HL32 oil on the accurate position of conventional hydraulic actuators. The kinematic and dynamic viscosity was obtained theoretically and experimentally over a wide range of temperatures ranged (20–80) °C. It was found that the percentage error between the theoretical and experimental results ranged (21*10 ^0.028), respectively. Whereas, the deviation of the results in the actuator stroke displacement were observed 4.8%, 6%, 6.5% and 4.8% for pressure supply of 20, 30, 40 and 50 bar separately.

1. Introduction

It is well known that the hydraulic fluid is normally utilized as a power transmission medium, lubricant, heat transfer medium, and sealer, since the volume hydraulic fluid is directly affected by the kinematic viscosity, density, boiling point, freezing point, and specific heat [1, 2]. In fact, hydraulic fluid characterized as having anti-wear and anti-corrosion properties, as well as resistance to oxidation and thermal degradation [3].

The viscosity of the hydraulic oil H32 is the most essential physical parameter for determining the efficiency of the hydraulic components and systems since viscosity is defined as the internal resistance of a fluid to shear or flow at a specific temperature and pressure [4]. The ideal dynamic viscosity of the hydraulic oil H32 is a balance between lubricating needs and environmental concerns efficiency, both mechanical and volumetric.

Operating temperature is another factor that affects on the hydraulic system performance. In fact, operating temperature depends on the various parameters such as loss in energy and fluid type. In fact, fluids volume increase as heated up to a certain temperature. While, these fluid volumes are shrinking when they are cooled. Consequently, fluid density varies with this change when they subjected to the temperature fluctuation. It is worth to mention that the variable values of the viscosity and density of the fluid in the hydraulic system bearing in mind high pressure and temperature, since this variation extremely affects on the capability and the precise placement of the actuator [5, 6].

The instrumentation in which a dynamic pump stands at a high temperature hydraulic fluid circuit was modelled by Hopkins and Benzinger [7]. The fluids that were exposed to higher shear rates at pressures over 207 bar and temperature 370 °C were examined. It was revealed that the rate of the pumping was dropped as the internal pump leakage increased, according to the numerical data.

Belov et al. [8], highlighted the porous metals hydraulic resilience at low temperatures, allowing them to be used as filters in cryogenic engineering. The hydraulic properties of porous metals were examined during liquid or gas filtration at 15 → 20 °C. It was revealed that there was a significant temperature difference between the filtered fluid and the porous metal at this point, resulting in the pressure decrease.

Rydberg [9], investigated the performance of the hydraulic unit which was extremely dependent on the oil viscosity. The results showed that the conventional mineral oil, produced ester fluids offer lower friction losses. In compared to mineral oil and unsaturated esters. Also, the saturated esters' shear stability was much improved.

Neveu et al. [10], examined the percentage of the pump sets that can operate between a given start-up and the maximum operating temperature as a function of the oil grad and viscosity index (VI). The results showed that combination and the selection of fluid with high viscosity index can reduce fluid.

On the other hand, Kefas et al. [11], determined the impact of the temperature, pressure, and time on the viscosities for lubricant types. An
analysis of variance procedure was made to establish the extent effect of the process variables. The results revealed that many samples were not affected by the process variables. Whereas, the variation of the temperature showed as significant effect on the viscosities and the performance of the system.  

Jaffer [12], studied the influence of heating on the kinematic viscosity of the engine oil and the mean slope of the kinematic viscosity curve with temperature. It was found that the viscosity decrease as the heating time increase, during the range of minimum temperatures. Further, the rate of (viscosity-temperature curve) descent decreased with an increase in the heating period.  

Knezević and Savić [13], established a mathematical model of the Modulus Equation to predict the viscosity at atmospheric pressure by using a Vogel equation. It was found that neglecting working pressure can lead a significant mistake in the dynamic oil viscosity value. Rostocki et al. [14], evaluated the variation in the viscosity of castor oil, due to the pressure change up to (0.9 G Pa) at room temperature by using the ultrasonic method. From the previous research, it can be concluded the viscosity rises exponentially with pressure till reach the phase transition (0.6 G Pa) according to the Barus’ formula. During phase transition, however, there is a significant increase in viscosity at constant pressure.  

Previous studies focused on the controlling the accurate position of conventional hydraulic actuators by using known control systems [15, 16, 17, 18, 19, 20].  

Present work concern to identify the most important reasons for unobtainable the accurate position of the hydraulic system, due to the change in the properties of the operating oil as a result of the high oil temperature and pressure.

2. Theoretical analysis

Numerous scientists have contemplated and enhanced the impacts of the viscosity which is extremely reliant on the pressure and temperature. There are several viscosities-temperature relationships have been used. Several studies are totally based on the empirical work to establish the relationship, whereas other relationships were derived from theoretical models such as Vogel’s equation. Three measurements of the viscosity at different temperatures are required to obtain the equation constants [21].  

The oil density at a certain temperature and atmospheric pressure can be determined by applying the experimental measurement value of the density at the temperature $15^\circ C$ and thermal expansion coefficient (Figure 1).

$$\rho = \rho_{15\circ C} [1 - 0.0007(T - 15)]$$ (1)

The variation of the density can be expressed by the following equation:

$$\rho_{t_2} = \rho_{t_1} [1 - \alpha_{vol} (T_2 - T_1)]$$ (2)

where: $\alpha_{vol}$ is the volume-temperature expansion coefficient ($1/\circ C$), and for mineral oil-based hydraulic fluids is $0.0007/\circ C$.

Vogel’s Equation was successfully employed to obtain the numerical value of dynamic viscosity at a certain temperature, as shown in Eq. (3):

$$\mu = \alpha e^{b(T - c)}$$ (3)

On the other hand, Barus equation describes the behavior of the viscosity-pressure of hydraulic fluids [22]:

$$\mu = \mu_0 e^{-\alpha P}$$ (4)

By Substituting Vogel equation in the Barus equation gets [22]:

$$\mu = \alpha e^{\frac{b}{(T_A - c)}}$$ (5)

where: $a$, $b$, $c$ – constants, $\nu_0$ – kinematic viscosity at the atmospheric pressure [m²/s], $\mu_0$ – dynamic viscosity at atmospheric pressure [Pa.s], $\mu$ – dynamic viscosity at the pressure $'p'$ [Pas], $\alpha$ – pressure-viscosity coefficient that depends on pressure and temperature [1/Pas], $T_A$ – absolute temperature [K], $P$ – absolute pressure [Pa].

The value of the dynamic viscosity as follows [22]:

| $\mu_{20^\circ C}$ (Pa.s) | $7.3856 * 10^{-2}$ |
| $\mu_{40^\circ C}$ (Pa.s) | $2.8900 * 10^{-2}$ |
| $\mu_{100^\circ C}$ (Pa.s) | $0.4697 * 10^{-2}$ |

The three constants of the Vogel’s equation, $a$, $b$, and $c$, may be calculated using the following equations:
1. \( a = e^{\frac{2.605646}{C_2}} \)

2. \( b = 4306.66943 - 28.44374 c + 0.04691 c^2 \)

3. \( c = \frac{440.77305 \pm \sqrt{440.77305^2 - (4 \times 43250.08901)^2}}{2} \)

By solving the above equations, the three constants will be:

- \( a = 0.000031083 \) (Pa.s)
• b = 1132.5833 (K)
• c = 147.4466 (K)

It was used the equation of Modulus, which was based on Barus’ equation, to incorporate the experimental data into the mathematical model. The pressure, p [bar], temperature T [°C], and the dynamic viscosity’s dependency were included in this model [23].

\[ \mu(T,p) = \mu_0 e^{\gamma (\frac{p}{p_0} - 1)} \]  

(6)

and

\[ \mu = a e^{\gamma (\frac{1}{T-T_a}) + \left[ \left( a_1 - a_2 T_{T_a} + (b_1 + b_2 T_{T_a}) \right) \right]} \]  

(7)

Eq. (8) gives the coefficient of pressure-viscosity, as a function of pressure and temperature [23]:

\[ \frac{a(T,p)}{p - p_0} = \frac{1}{a_1 + a_2 T + (b_1 + b_2 T)} \]  

(8)

where a1, a2, b1, b2 is the oil characteristics, which can be obtained from the experimental results.

The kinematic viscosity (\( \nu \)) was obtained by measuring the required time for the oil to reach the checked off line. The computed time was used in the following equation [23]:

\[ \nu = k \ast t \]  

(9)

where t is the calculated time and k is a constant consisted of many variables, as follows [23]:

\[ k = \frac{\pi d^4 \cdot g \cdot \Delta h}{128 \cdot l \cdot q} \]  

(10)

where: d – experimentally of the capillary tube; g – gravitational acceleration; \( \Delta h \) – change in the oil height level through the capillary tube; l – length of the capillary tube; q – volume of the oil in the capillary tube.

3. Experimental procedures

The experimental rig was designed and built in the laboratories of the University of Technology-Iraq; the total time between designing and building the rig and taking the required data was about 16 months. The experimental work is divided into two parts: mechanical and electrical. The mechanical portion includes the parts of the hydraulic system, while the electrical part includes a system for controlling and other attachments.

3.1. Mechanical parts (hydraulic system)

The hydraulic system equipment depicted in Figures 2 and 3 includes an atmospheric reservoir type ELF3 with an 80 L full capacity of hydraulic oil (type HL32). To swiftly elevate the hydraulic oil temperature to the wanted temperature. Two oil heat generators have been installed in the oil container. The heat generator was constructed to be 180 cm length 1 cm and diameter. The heating supply power of each heat generator has been adjusted at 1000 W. The controller of the temperature was set to a temperature range of (0–400) °C. It should be mentioned that the pump was used as a gear type G2 (Rexroth Company Production) that was powered by an electrical motor and has a speed of 1500 rpm. This pump was used flow rate 14 l/min and 120 bar hydraulic pressure. A 4/3 directional control valve (Rexroth Company Production) with a size 10 solenoid 24v and spring return to a neutral state that was latched was employed efficiently to regulate the flow direction in the hydraulic system. In actuality, a DBD size 6 alleviation made the fluid pressure flexible at the required pressure. This valve can be used an oil with a viscosity (2.8 → 380) cSt and oil temperatures ranging from (−20 → 100) °C with a high pressure 350 bar.

A check valve type size 10 was employed to protect the pump switch pressure. As an actuator, a double acting, single rod was employed. The cylinder stroke length was 250 mm, while the piston and rod diameters were 50 mm and 25 mm, respectively. In addition, the flow control valve (size 10) was used as an instant mounting on the pressure line in the present system (DV (10i)/OP350). This valve was designed to work with oil with a viscosity of (2.8→380) Pa.s, oil temperatures of (−20 → 100) °C, and a maximum pressure of 350 bar. For calculating the viscosity adjustment of the fluid capillary viscometer, a site sensor has been used to manage the precise situation of a hydraulic cylinder with a higher stroke length of 300 mm.

It’s a glass tube that is used to measure the kinematic viscosity (\( \nu \)) by measuring the amount of time it takes for oil to flow from the checked offline with the word (start) to the checked offline with the word (finish) (stop). This sort of the viscometer comes in a variety of sizes, each of which covers a certain viscosity range. In this study, two distinct sizes of the viscometer (sizes 3 and 4) were employed to cover viscosity ranges ranging from 6 cSt to 100 cSt, Figures 4 and 5 show the thermocouple and pressure transducer calibration.

3.2. Hydraulic HL32

As noted in Table 1, Hydraulic oil HL32 is a mineral oil-based hydraulic oil with great protection corrosion, wear and be fully grown.
Hydraulic HL32 is mentioned for high performance hydraulic systems with high pressure and speed vane pumps, gear pumps and axial piston pumps. Since of the better compatibility with bronze and steel, control valves as well as servo pumps are well worked here. These products are utilized in a wide range of the hydraulics of machine tools, in case that hydraulic oils with wear protection are desired. It is worth to mention that the most important characteristics of the hydraulic oil HL32 are high corrosion protection, wear protection, prevents filter clogging, high oxidation resistance, optimal air release properties, ability of water separation, and long period service life [25].

### 3.3. Electrical and control parts

To control the required set oil temperature in the tank, directional control valve operation, set oil pressure in the high pressure line and the position of stroke actuator displacement an Arduino with Lab-view program was used.

As indicated in Table 2 and Figure 6, digital I/O 14, six pins with analog input a microcontroller was attached on the board to regulate and send the signal from the system to a computer that had been efficiently programmed using the Arduino programming language and Arduino's integrated evolution environment.

Arduino has been connected to the sensors (thermostat, pressure transducer, and solenoid and position sensor) and electronic components so that it could interface with PC programs like handling and max MSP, as well as lab software. In the experiment, five computerized signals were employed. The thermostat sends one digital signal, and the directional control valve solenoid sends two digital signals for extend and retract stoke. While, there were two analog signals of the pressure transducer and position sensor, Figure 4 shows a flow chart of the experimental part. Figure 7 displays the flow chart of the experimental procedure.

### 4. Results and discussion

It is well known that both density and viscosity of the oil have a profound impact on the performance efficiency of the hydraulic systems. Accordingly, the paper’s goal was to show the impact of increasing oil temperature in the conventional hydraulic system and simultaneously their influence on the pressure and actuator displacement was presented.

Present work examined seven oil temperatures starts from 20 °C and ends with 80 °C for four different pressures (20, 30, 40 and 50) bar. The temperature of the oil was raised using a proper heater, which was located in the principle tank of the system. To assess the variability of the change in the viscosity of the liquid capillary, it was used viscometer which has a glass tube to measure the kinematic viscosity (ν) In order to store the information (digital and analog) on the Personal Computer, an Arduino with Lab View Program was applied. According to Eqs. (1) and (2), it can be seen that the oil density decreases linearly with temperature. Figure 8 illustrates the reduction in the working oil density (HL32) at temperatures ranged (20–80 °C), since the maximum and minimum values at 20 °C and 80 °C were observed 0.8655 and 0.831 gm/m³, respectively. It is well known that the viscosity of Newtonian fluids is a function of the temperature and pressure, which makes the added loads between the molecules extremely essential. Depending on this fact the additional contribution to the shear stress although the precise mechanics of this remain controversial. Accordingly, the viscosity is not dependent of the pressure (excluding at exceptionally high pressure), however, it will in general drop as the temperature rises.

Figures 9 and 10 illustrate the actual values of the kinematic and dynamic viscosity gradient at a temperature rise in the atmospheric pressure. It was found that the kinematic viscosity decreased from 85.19 cSt at 20 °C to 5.74 cSt at 100 °C. While, the dynamic viscosity decreased from 0.074 Pa s at temperature of 20 °C to 0.0047 Pa s at 100 °C. The decreasing in the viscosity was attributed to the decreasing in the intermolecular forces as a result of the increasing in the molecules move and the distance between them. It seems to be that the average speed of the particles in the liquid surges with increasing temperature. While, the required time to contact with their closest particles increases. Therefore, as the temperature goes up, the average intermolecular loads goes down.

#### Table 2. Specifications of Arduino.

| Specification            | Value   |
|--------------------------|---------|
| Working voltage          | 5 V     |
| Input voltage values     | 6–20 V  |
| Desired voltage          | 7–12 V  |
| I/O outlet               | 40 mA   |
| Size of Memory           | 32 kB   |
| Speed                    | 16 MHz  |

#### Table 1. Oil type HL32 specifications.

| Specification            | Value   |
|--------------------------|---------|
| ISO Grad                 | 32      |
| Sp. gr @ 15 °C           | 0.87    |
| Kin. Viscosity (cSt) @ 40 °C | 29 – 35 |
| Kin. Viscosity (cSt) @ 100 °C | 5 – 5.5 |
| Viscosity Index (min)    | 95      |
| Flash Point °C (min)     | 200     |
| Pour Point °C (max)      | -15     |

**Figure 6.** Arduino interface.

**Figure 7.** Flow chart of the experimental part.
In reality, the two quantities differ in the nonlinear way and change suddenly when the liquid phase is changed. In fact, there’s a molecular interchange in the liquid, but also there are additional substantial cohesive forces between the liquid molecules. Both cohesion and molecular interchange identify the liquid viscosity. It should be noted that the increase of the pressure for a specific liquid was resulted in the reduction of the cohesive forces and increasing the rate of molecular interchange. The first effect was caused a decrease in the shear stress, while the latter effect results in an increase in the shear stress. Accordingly, it could be said that the liquids exhibited a reduction in the viscosity with increasing pressure [26].

Figure 11 and Table 3 show a reasonable comparison between the experimental data and the correlated kinematic viscosity. At rising
temperature and air pressure, Figure 12 depicts the contrast between the diminishing experimental data and the corresponding dynamic viscosity (Vogel equation). Also, there is a satisfactory understanding between the two curves, excluding at temperatures of 25 °C and 30 °C. It was observed that the deviation between these two curves about 1.7% and 2.11%.

It is clearly seen that the increase in oil temperature and pressure lead to decrease the density, hence in both kinematic and dynamic viscosity. High temperature leads to an increase in the external leakage by the evaporating oil and thus losses in the supply pressure. It seems that the low density leads to an increase in the internal leakage of the hydraulic moving parts, which caused an increase in the low pressure and decreased high pressure. Further, low viscosity of the oil reduced the lubrication efficiency of the moving parts, subsequently this could be required a higher pressure to overcome. The accurate position of the linear actuator displacement considered to be a significant hydraulic application (heavy earth moving machineries, robotics, elevators, etc.) for remote location along machine tool applications. In the position control of the actuator, the main role is to control the pressurized fluid flow rate, according to the position demand of the actuator. Therefore, there is an essential need to find out the best control strategy of the linear actuator. It can be seen from Figure 13 that the actuator displacement decreases with increasing the temperature for all pressures used. The greatest drop in the displacement values was found at 60 °C with (3.7, 5.8, 6.5 and 6) mm at different pressures (20, 30, 40 and 50) bar.

In comparison with Beak [27] study, it can be noticed that the present work seeks to examine the effect of increasing the temperatures of the working oil on the properties of the oil (density and viscosity) and subsequently on the performance of the conventional hydraulic actuator displacement. While, Baek [27] studied the effect of increasing the hydraulic load of the servo hydraulic actuators on the accuracy required position and controlling it using a tracking control system.

### Table 3. Errors between measured and calculated data.

| Temperature (°C) | Real Kin. Vis. (cSt) | Theoretical Kin. Vis. (cSt) | Error% | Real Dyn. Vis. (Pa.s) | Theoretical Dyn. Vis. (Pa.s) | Error% |
|-----------------|----------------------|-----------------------------|--------|-----------------------|----------------------------|--------|
| 20              | 85.19                | 85.1909                     | -0.009 | 0.073856              | 0.07385979                  | 2.1E-06|
| 25              | 67.2                 | 66.05621                    | 114.379| 0.058055              | 0.05706661                  | 0.998834|
| 30              | 53.2                 | 52.07592                    | 112.408| 0.045798              | 0.044830334                 | 0.0967666|
| 35              | 41.65                | 41.67615                    | -2.615 | 0.035728              | 0.035750638                 | -0.0022638|
| 40              | 33.81                | 33.81235                    | -0.235 | 0.0289                | 0.028901952                 | -0.001952|
| 45              | 27.72                | 27.77659                    | -5.659 | 0.02361               | 0.023658158                 | -0.0048158|
| 50              | 22.83                | 23.08004                    | -25.004| 0.019375              | 0.019587686                 | -0.0212666|
| 55              | 19.28                | 19.37928                    | -9.928 | 0.016304              | 0.016387891                 | -0.0083991|
| 60              | 16.39                | 16.42916                    | -3.916 | 0.01381               | 0.013843125                 | -0.0033125|
| 65              | 14.02                | 14.05212                    | -3.212 | 0.01177               | 0.011797454                 | -0.0027454|
| 70              | 12.37                | 12.11776                    | 25.224 | 0.010348              | 0.010136569                 | 0.0211431|
| 75              | 10.67                | 10.52912                    | 14.088 | 0.008893              | 0.008775604                 | 0.0117396|
| 80              | 9.5                  | 9.213226                    | 28.6774| 0.007889              | 0.007650801                 | 0.0238199|

**Figure 12.** Comparison between the theoretical and real of dynamic viscosity with temperature.

**Figure 13.** Variation of the linear actuator displacement with temperature and pressure supply.
5. Conclusions

Current study used oil type HL32 as working oil to optimize the performance of the hydraulic system, since the properties of the working oil have a crucial impact on the performance of the hydraulic system. Accordingly, it was obtained the kinematic, dynamic viscosity and density of the HL32 oil gradient over a wide range of temperature ranged (20–80 °C). Experimental results revealed that the efficiency of the hydraulic system depends primarily upon the oil temperature which showed an improvement in the operating time. A closed cycle control hydraulic system (servo-hydraulic system) is preferable to the open cycle control hydraulic system for precise applications.

Also, it was found that the position error was reduced when the oil HL32 at a specified pressure of 70 bar and a temperature of 40 °C. The oil HL32 exhibited undesirable properties at 20 bar pressure and temperature over 30 °C, owing to the significant reduction in the displacement position. Whereas, these properties of the HL32 oil were enhanced significantly at all possible oil temperatures with pressure 70 bar.

Present work suggest to improve the hydraulic system efficiency by using a control system to increase the pressure supplied when the oil temperature is increased. On the other hand, the properties of the oil could be enhanced by adding nanomaterials in order to increase the density at higher temperatures. Utilizing the heat exchangers also is recommended to obtain the suitable oil temperatures, especially for the hydraulic systems with large loads. Finally, present study proposes to use an accumulator, since the capacity of this accumulator is directly proportional with the density and viscosity and resulting the change in the temperature.

Declarations

Author contribution statement

Walaa. M. Hashim: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data.
Huda A. Al-Salihli: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Faten N. Al Zubaiedi: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest’s statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The authors are greatly indebted to the University of Technology, in particular, the Electromechanical Engineering Department for providing significant support during the experimental work.

References

[1] Joanna Wilezierska, Ewa Kulisi, Marcin Łukasiwicz, Łukasz Fornal, Natalia Blahunovych, The assessment of the impact of the chosen expolational conditions of hydraulic arrangement on the working liquid condition, in: MATEC Web of Conferences 182, EDP Sciences, 2018, 01026.
[2] Yutaka Tanaka, Ryushi Suzuki, Bubble elimination from working oil for environmentally friendly hydraulic system design, Int. J. Autom. Technol. 6 (4) (2012) 488–493.
[3] Artur Olzak, Karol Osowski, Ireneusz Musialek, Elżbieta Rogos, Andrzej Key, Zbigniew Key, Application of plant oils as ecologically friendly hydraulic fluids, Appl. Sci. 10 (24) (2020).
[4] H. Stewart, Hydraulic and Pneumatic Power for Production, fourth ed., First Printing, Industrial Press Inc., New York, 1977.
[5] V. Savić, L. Zirojević, Oil Hydraulics 3, first ed., Mala knjiga Press, Serbian, Novi Sad, 2003.
[6] K. Hodges, Hydraulic Fluids, Arnold, first ed., Elsevier Press, London, Great Britain, 1996.
[7] V. Hopkirie, R. Benzing, Dynamic Evaluation of High Temperature Hydraulic Fluids, Midwest Research Institute, Kansas City 10, Mo. and Wright-Patterson Air Force Base, Ohio, 1963.
[8] S. Belov, E. Lebedov, O. Kartusov, A. Popov, Investigation of Hydraulic Properties of Porous Metals at Low Temperatures, Division of Plenum Corporation, 227 West 17th Street, New York, 1972.
[9] K. Rydberg, Hydraulic Fluid Properties and Their Impact on Energy Efficiency the 13th Scandinavian International Conference on Fluid Power, SIIFP, 2013.
[10] C. Neveu, S. Herzog, D. Placek, March, Selecting the Optimum Hydraulic Oil to Meet the Viscosity Requirements of Major Pump Manufacturers, Presented at the 10th Annual Fuels and Lubes Asia Conference, Portman Ritz Carlton, Shanghai, 2004.
[11] H. Kefas, M. Edoga, A. Kovo, Testing and modeling of petroleum based lubricants oils by an improvised system, Leonardo Electron. J. Pract. Technol. 7 (2005) 23–30.
[12] O. Jaaffer, The Effect of Heating and Contamination on the Oil Viscosity in I. C. Engine, University of Technology, Department of Mechanical Engineering, 2006.
[13] D. Knetevič, V. Savić, Mathematical modeling of changing of dynamic viscosity, as a function of temperature and pressure, of mineral oils for hydraulic systems (University of Banja Luka, RS-B&H and University of Novi Sad, Serbia), Mech. Eng. 4 (1) (2006) 27–34.
[14] A. Rostocki, R. Siegoczyński, P. Ketzczynski, M. Szalewski, High Pressure Changes of the Castor Oil Viscosity by Ultrasonic Method, Warsaw University of Technology and Polish Academy of Science, Warszawa, J. Phys. (2008).
[15] Manuel Pencelli, Renzo Villa, Alfredo Agiolas and Andrea Maria Zanchettin Accurate Position Control for Hydraulic Svernomechanisms, 36th International Symposium on Automation and Robotics in Construction Conference, 2019.
[16] Andreas Plockinger, Christoph Gradl and Rudolf Scheidl high accuracy Sensorsless hydraulic Stepping actuator, in: The Eighth Workshop on Digital Fluid Power (DFP), Tampere, Finland, 2016.
[17] Manuel Pencelli, Renzo Villa, Alfredo Agiolas, Gianni Ferreretti, Marta Niccolini, Matteo Ragaglia, Paolo Rocco, and Andrea Maria Zanchettin Accurate Dynamic Modelling of Hydraulic Svernomechanisms in Design, Automation and Test in Europe (DATE), 2019.
[18] Zulfatman Has, Mohd Fauad’Rahmat, Abdul Rashid Husain, Mohd Noor Ahmad, Robust precision control for a class of electro-hydraulic actuator system based on disturbance observer springer, Int. J. Precis. Eng. Manuf. 16 (8) (2015) 1753–1760.
[19] H. Zeng, N. Sepehri, Tracking control of hydraulic actuators using LuGre friction model compensation, J. Dyn. Syst., Measure., Control - Trans. ASME 130 (1) (2008) 1–7.
[20] M. Rahmat, A. Zulfatman, K. Husain, Y. Sam, R. Ghazali, Modeling and controller design of an industrial hydraulic actuator system in the presence of friction and internal leakage, Int. J. Phys. Sci. 6 (4) (2011) 3502–3517.
[21] G. Stachowiak, A. Batchelor, Engineering Tribology, University of Western Australia, 2001.
[22] JUGOMA-Group of authors, Lubricants and Lubrication, Association of Yugoslav Societies for the Application of Fuels and Lubricants, Zagreb, 1986.
[23] A. Schmidt, Viscosity-Pressure-Temperature Behaviour of Mineral and Syntetic Oils, 12th International Colloquium Tribology, Stuttgart, Germany, 2000.
[24] Walaa.M. Hashim, Huda.A. Al-Salihi, Aws.F. Hassan, Investigation the variation of bulk modulus of elasticity on the performance of conventional electrohydraulic system, J. Univ. Babylon Eng. Sci. 27 (3) (2019).
[25] Oil & natural gas company, ADDINOL Lube Oil GmbH – High-Performance Lubricants Am Haupts, D-06237 Leuna, Germany.
[26] E. Ike, The study of viscosity-temperature dependence and activation energy for palm oil and soybean oil, Global J. Pure Appl. Sci. 25 (2) (2019) 209–217.
[27] Seung Guk Baek, Sanghoon Ji, Ja Choon Koo, Experimental study of electro-hydraulic actuator with payload for precision motion control, Microsyst. Technol. (2016) 1347–1357.