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An Experimental Study Into The Effect Of Temperature And Pressure on The Hydraulic System

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Abstract

The present work is conducted in order to study the effect of oil temperature and pressure variation on the hydraulic system performance at various ranges of temperature and pressure. The oil is the first component which will be influenced by the changes in the surrounding conditions and all its properties will be changed. The most important property of the oil that will be studied is the viscosity. The viscosity is measured experimentally at different temperatures (20 → 100) °C and atmospheric pressure and by using correlations taken from literature of other researchers in order to evaluate the viscosity at different temperatures and pressures. The hydraulic test bench existing at the Fluid Mechanic Laboratory/University of Technology has been developed to meet the requirements of the experimental work. The effect of the temperature and pressure will be studied by evaluating the work of two loading actuators (hydraulic cylinder and motor). It was found that, the oil viscosity depends mainly on the temperature and the effect of pressure on the viscosity can be noticed clearly at low temperature. The temperature rising in the closed hydraulic circuit is faster and higher than that in the open hydraulic circuit and the work of the system depends mainly on the temperature and the working period.

Keywords: Hydraulic system, oil viscosity, temperature effect.

الدراسة العملية في تأثير درجة الحرارة والضغط على المنظومة الهيدروليكية

الخلاصة

الغاية الأساسية من هذا البحث هو دراسة تأثير درجة الحرارة وتغير الضغط على اداء المنظومة الهيدروليكية لمدى متغير من درجات الحرارة والضغط . أول تأثير تم تناوله في هـذه الدراسة هو تأثير تغيير درجات الحرارة والـضغط علـى الزيـت المـستخدم فـي المنظومـة الهيدروليكية , حيث إن الزيت هو أول من يتأثر بالمتغيرات المحيطية وتتغير جميع خواصه. من أهم الخواص التي تم التطرق إليها في هذا البحث المتعلقة بالزيـت المـستخدم هـي اللزوجـة (Viscosity) . تم قياس اللزوجة عمليا لمدى متغير من درجات الحرارة°C(100 → 20) وعنـد الضغط الجوي , وتم حساب قيم اللزوجة لدرجات حرارة وضغوط مختلفة باستخدام العلاقات من البحوث السابقة. تم تطوير منصة الفحص الهيدروليكي الموجودة في مختبـر الموائـع/الجامعـة التكنولوجية لإجراء مجموعة من التجارب للغرض أعلاه . تم دراسة شغل المنظومة الهيدروليكية بتقييم أداء نوعين من المشغلات (Actuators) (اسطوانة ومحرك هيدروليكي) . لقد تم التوصـل إلى إن اللزوجة تعتمد بشكل كبير على درجة الحرارة وان تأثير الضغط على اللزوجـة يكـون واضحا عند درجات الحرارة الواطئة . إن ارتفاع درجة الحرارة في الدائرة الهيدروليكية المغلقـة

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يكون أسرع وأعلى من الدائرة الهيدروليكيــة المفتوحـــة (Closed Hydraulic Circuit) (Open Hydraulic Circuit) وإن شغل المنظومة يعتمد بشكل كبير على درجة الحرارة وفترة العمل .

Introduction

Hydraulic systems utilize the process of energy conversion and transmission. The process of energy conversion and transmission involve losses in which mechanical and hydraulic energy is converted into heat. The operating temperature is one of the factors governing the efficiency of a hydraulic system. Where the temperature of the hydraulic fluid depends on:

- The power losses
- The place of installation
- The surface area of heat-radiating components (such as tank)

and the maximum permitted fluid temperature depends on:

- The type of fluid
- The requirements of the system

If the temperature is too low, the flow resistance is increased and difficulties are experienced with the suction of the pump. If the temperature is too high, there are more fluid leaks so losses and wear are greater [1]. A hydraulic system that could operate at constant temperature, including start-up, would function at optimum efficiency at all times if the proper fluid viscosity had been selected. Unfortunately, such a hydraulic system is purely theoretical because a typical hydraulic system converts about 20% of its input horsepower into heat [2]. Heat in the hydraulic system may be caused by two things- friction and external temperature. A large volume of high-pressure oil spilling through the relief valve or passing through long lengths of piping is bound to create excessive heat. Very high external temperatures will transfer considerable heat into a hydraulic system. For example, a hydraulic system which is used for feeding and controlling the opening and closing of furnace doors is subjected to extensive heat. Various methods have been devised to reduce the temperature of the hydraulic oil. Where it is generally agreed that the operating temperature (temperature of oil in the reservoir) should not exceed 60 °C . One of this method is to provide larger oil reservoirs for the power unit with or without heat exchanger depending of its application [3]. **Vern Hopkins, and Benzing R. J. (1963)** [4] developed a simulated hydraulic circuit in order to evaluate fluids subjected to high shear rates at pressure up to 207 bar and at temperature up to 370 °C. On resuming the test, the pumping rate had usually increased a small amount. However, after the last test interruption the pumping rate decreased, probably because of increased internal pump leakage. Like the pumping rate, the pressure drop across the filter is also higher on restarting after a test is interrupted. This greater pressure drop across the filter is probably caused by disrupting an established flow pattern through the filter disks. **Drexler P. (1988)** [5] presented the change in viscosity with temperature which was expressed by the viscosity index specified in DIN ISO 2909. The viscosity-pressure behavior of hydraulic fluid was also presented which is more important when the operating pressures are higher. **Love L. J. et al (1997)** [6] showed that the hydraulic drives are sensitive to temperature variation. Figure (1) illustrates the variation, supply and reservoir oil temperature over 5 hours of continuous operation. The ripple in the supply temperature is due to the dissipation of heat in the oil through the rubber hoses during high-frequency operation. They found that when the fluid temperature rises, the effective bulk modulus of the fluid decreases, this decreases in the bulk modulus directly reduces the effective stiffness of the fluid. **Knežević D. and Savić V. (2006)** [7] presented a mathematical model "*Modulus Equation*" for calculating dynamic viscosity. "*Modulus Equation*" is based on the ***Barus equation*** ($\mu = \mu_o e^{\alpha P}$). The model compromise pressure ***P*** (bar) and temperature *T* (°C), as shown below:

$$\mu = \mu_o\, e^{\left[\frac{P}{a_1 + a_2 T + (b_1 + b_2 T) P}\right]} \quad \ldots(1)$$

and by using ***Vogel equation*** to determined the viscosity at the atmospheric pressure ($\mu_o = a e^{\left(\frac{b}{T_A - c}\right)}$) as follows:

$$\mu = a e^{\left[\frac{b}{(T+273.15)-c}\right]} e^{\left[\frac{P}{a_1 + a_2 T + (b_1 + b_2 T) P}\right]} \quad \ldots\ldots(2)$$

Parameters a_1, a_2, b_1 and b_2 represent the oil behavior and have to be calculated from the experimental data, table (1). It can be seen that neglecting the influence of working pressure can lead to significant mistakes at calculating of value of dynamic viscosity of hydraulic oils. The error value increases with the growth of pressure and decreases of temperature.

In this paper a verification of the oil viscosity change and its effect on the hydraulic system at low temperatures and pressures will be studied experimentally.

2- Experimental System

The hydraulic system device used in this work consists of the following parts as shown in figures (2) and (3):

1) AC motor
   - Power = 3 kW
   - Speed = 1500 rpm
2) Pump (Gear pump)
   - Flow rate = 14 L/min
   - Max. Pressure=120 bar
3) Directional control valve
   - Size 10
4) Relief valve
   - Size 6
5) Flow control valve
   - Size 10
6) Check valve
   - Type S
   - Size 10
7) Hydraulic cylinder
   - Unsymmetrical
8) Hydraulic motor (Gear type)
9) DC generator
10) Variable resistance
11) Spring load
12) Manual directional valve
13) Digital multimeter

14) Pressure gauge (Borden gauge and Transducer)
15) Digital thermometer
16) Heaters (Two Heaters)
    For each heater:
    - Length = 180 cm
    - Diameter = 1 cm
    - Power = 1000 W
17) Pressure transducer
    - Rang (0-40) bar
    - Output (4-20) mA
    - Input (24V DC)
18) Selector switch
19) Pressure display
20) Power supply
21) Temperature controller
22) Tank
23) Coupling
24) Directional control valve switch
25) AC motor switch

And the viscosity measuring device is consisted of the following parts as shown in figures (4):

a) Water reservoir, where the water is used as a heating medium
b) Mixing device
c) Electrical heater
d) Temperature controller
e) Capillary viscometer
f) Iron catcher, to fixed the viscometer inside the water reservoir

In this work, there are several practical tests to evaluate the effect of temperature on the system, where the viscosity of the system's oil (**HL22**) is measured experimentally under the atmospheric pressure in the temperature range (20→100) °C, and these experimental data for the dynamic viscosity at three temperatures (20, 40 and 100) °C are used in the ***Vogel equation*** (where , three equations can be determined to evaluate the three constants a, b and c of ***Vogel equation*** and by solving these three equations one can get three constants as follows for a, b and c were 0.000031083 Pa.s, 1132.5833 K and 147.4466 K respectively) and the last equation is used in a two correlations of ***Barus equation***, eq. (2) and the following equation in order to evaluate the oil viscosity at different temperatures and pressures and for comparing the results of the two correlations [8].

$$\mu = a\, e^{\left[\frac{b}{(T_K - c)}\right] + \left[\frac{\left(0.6 + 0.965 \log_{10}\left(a\, e^{\frac{b}{(T_K - c)}} \times 10^{3}\right)\right) \times 10^{-8}}{0.980665}\right] P} \quad \ldots(3)$$

The effect of the neutral and loading (open and closed) circuits, figures (5) and (6), on the system temperature and pressure is observed by making the system work at 40 bar for the two cases during 240 min of the continues work, and taking the pressure and temperature reading every 5 min for comparing purpose between the two cases.

The effect of temperature on the hydraulic cylinder displacement and the hydraulic motor rotational speed is observed as follows:

For cylinder test, figure (7), the system is working and raising its temperature by the two heaters that located in the tank and measuring the piston displacement by an electronic digital caliber that was fixed on the cylinder, figure (8), every 5 °C of temperature raising from (25→70) °C at constant pressure (10, 20, 30 and 40) bar.

For the hydraulic motor test, and to evaluate the change in the motor rotational speed, the hydraulic motor is loaded by DC generator (These types of DC generators have linear relationship with rotational speed, if the rotational speed is affected by the temperature; the output (voltage) of this DC generator will be influenced too) that was loaded by variable resistance to generate a sufficient obstruction in order to make the pressure grown up. The system is working and raising the system temperature by the two heaters during 256 min of continues working at constant pressure (20, 30 and 40) bar and taking the pressure, temperature, generated voltage and the rotational speed of the hydraulic motor every two minutes (where a digital tachometer type (DM-2264) is used to measure the rotational speed of the hydraulic motor).

3- Results and Discussion

3.1 Verification of Viscosity Measurement

The comparison between the decreasing in the experimental data and the correlated dynamic viscosity (***Vogel equation***) with the temperature raise at atmospheric pressure is shown in figure (9). A great agreement between the two curves can be noticed except at temperatures 25 °C and 30 °C and the deviation between the two curves at these points are 1.7% and 2.11% respectively.

The effect of pressure-viscosity coefficient (α) on the variation of the viscosity as a function of temperature and pressure by using two correlations (equations (2) and (3)) is shown in figure (10). The difference between the two correlations at high pressures and low temperature (300, 400 and 500) bar at 0 °C are 1.63%, 3.04% and 4.85% respectively but at temperatures above 20 °C the results are too close.

Figure (11) shows the dynamic viscosity gradient with temperature raise at different pressures according to equation (2) and that at the range of our working temperatures and pressures. There are small differences in the dynamic viscosity at these working pressures. This difference being smallest whenever temperature raises, and the ratios between the maximum pressure (40 bar) and the minimum pressure (1 bar) at temperatures 20, 30, 40, 50, 60, 70, and 80 °C are 9.28%, 8.62%, 8.04%, 7.53%, 7.09%, 6.69% and 6.35% respectively.

3.2 The Effect of the Neutral and Loading Circuits on the System Temperature

Figures (12) and (13) present the temperatures raising history during run time at the tank, pump body, pump outlet and relief valve body, and the pressure drop with time to the neutral case (closed circuit) and the loading case (open circuit) tests without heating.

Figure (14) presents the comparison between pressure drops with time for the previous cases. The fluctuations of the pressure drop in the loading case is higher than that of the neutral case due to the pulsating flow, where in the neutral case the flow is accumulated and this will prevent the pulsating flow. The range of pressure drop in the loading case is higher than that of the neutral case, where in the neutral case, the pressure drops approximately to 4 bar but in the loading case the pressure drops approximately to 4.7 bar and the ratio of the pressure losses of the neutral and loading circuits were 10.2% and 11.65% respectively, and this because, in the neutral case the pressure drop is due to the losses in the relief valve only, but in the loading case there are many losses added to that of the relief valve such as the losses during the flowing of the oil in the flow control valve and two manual directional valves and last and not least the losses due to the continual load of the hydraulic motor.

3.3 Temperature Effect on the Hydraulic Cylinder Displacement

The effect of the oil temperature rising at the pump outlet on the system pressure and the hydraulic cylinder displacement is shown in figure (15) and (16) for pressures (10, 20, 30 and 40) bar. The gradient of pressures and displacements increase as pressure increase as shown in table (2) and one can notice the similarity between the pressure drop curves and that of the displacement drop. The losses ratios for the pressures (10, 20, 30 and 40) bar were 22.36%, 17.36%, 13.09% and 9.95% respectively. There are constant pressure regions at temperatures ranging between 45 °C to 50 °C for pressure 10 bar, 50 °C to 55 °C at pressure 30 bar and 45 °C to 55 °C at pressure 40 bar. This means that, for temperature ranging from 45 °C to 55 °C are the best working conditions for our hydraulic system due to constant pressure.

3.4 Temperature Effect on the Hydraulic Motor Rotational Speed

Figures (17), (18) and (19) show the pressure drop and temperatures raise in the system with time for all test pressures. The ratios between the final tank's oil temperature and the other final system temperatures are shown in table (3) for all pressures, and one can notice the fluctuation in the pressure drop curve due to the pulsating flow.

The compatibility between the fluctuation (that due to the pulsating flow) in the pressure drop and that of the generated voltage drop with time are shown in figures (20), (21) and (22), and from this compatibility one can notice that, the pressure is affected by temperature and that reversed on the generated voltage from the hydraulic motor.

Figures (23), (24) and (25) show the drop of the voltage and the rotational speed with time for all test pressures, where the compatibility between the two curves is more clear, and that means, the rotational speed is influenced by the temperature raising and that would affect the generated voltage .

Figure (26) shows the comparison between the pressure drops with time at all test pressures, where the pressure drops approximately 4.61bar at 20 bar, 7.21 bar at 30 bar and 7.74 bar at 40 bar.

The comparison between the voltage drop curves is shown in figure (27), where one can notice that the generated voltage is decreased when the pressure increased due to the obstruction increasing.

4- Conclusions

The present work has reached to the following conclusions:

1- The oil viscosity is a large dependence on the temperature but the degradation of the oil viscosity with high temperature (above 60) will be small than that at low temperature.
2- At high temperature (above 60 °C), the effect of pressure on the oil viscosity can be neglected, where the effect of pressure is present clearly at low temperature.
3- The position of the maximum temperature in the system can be in the tank if the tank's cooling system was insufficient.
4- The temperature raising in the neutral circuit is faster and higher than that in the loading circuit, where at a pressure of 40 bar and at the same period of (240 min), the temperature of the oil at the tank reaches to (59.1 °C) for the neutral circuit and (52.4 °C) for the loading circuit, i.e. the ratio was 11.33%.
5- The ratio of the pressure losses in the tests of the neutral and loading circuits for a pressure of 40 bar at the same period of (240 min) were 10.2% and 11.65% respectively, due to more losses in the loading circuit.
6- The system performance dependence mostly on the temperature and the working period.

5- References

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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), Mechanical Engineering, Vol. 4, No. 1, p27-p34, 2006.

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List of Symbols

Symbol	***Definition***	***Unit***
a	*Vogel equation constants*	*Pa.s*
b		*K*
c		*K*
a_1	*Constants of pressure-viscosity coefficient*	*bar*
a_2		*bar/* °C
b_1		.....
b_2		*1/* °C
$\boldsymbol{P}$	*Pressure*	*bar*
T	*Temperature*	*℃*
T_A	*Absolute temperature*	*K*

Greeks Letter

Symbol	***Definition***	***Unit***
α	*Pressure-viscosity coefficient*	*1/bar*
μ	*Dynamic viscosity*	*Pa.s*
μ_o	*Dynamic viscosity at atmospheric pressure*	*Pa.s*

Abbreviations

Abbreviation	***Definition***
AC	*Alternating Current*
DC	*Direct Current*
$Pump_{Body}$	*Pump Body Temperature ℃*
$Pump_{outlet}$	*Pump Outlet Temperature ℃*
$Re.Va._{Body}$	*Relief Valve Body Temperature ℃*

Table 1: Parameters Value for Pressure-Viscosity Coefficient, α [7]

Hydraulic oil of paraffinic base structure	a_1 (bar)	a_2 (bar/ °C)	b_1	b_2 (1/ °C)
	334	3.2557	0.026266	0.000315

Table 2: Pressure Drop and Displacement

Pressure (bar)	Pressure Drop (bar)	Displacement Drop (mm)
10	2.24	2.45
20	3.47	4.65
30	3.93	4.91
40	3.98	5.14

Table 3: Ratios of Tank's Oil Temperature with Other System Temperatures

Pressure (bar)	Pump Body Temperature	Oil at Pump Outlet Temperature	Relief Valve Body Temperature
20	7.41%	3.05%	51.11%
30	9.24%	4.43%	52.86%
40	9.64%	4.45%	53.40%

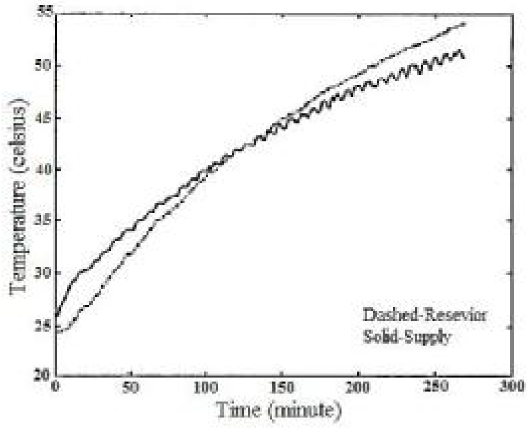

Figure (1) Temperature Variation vs Time [6]

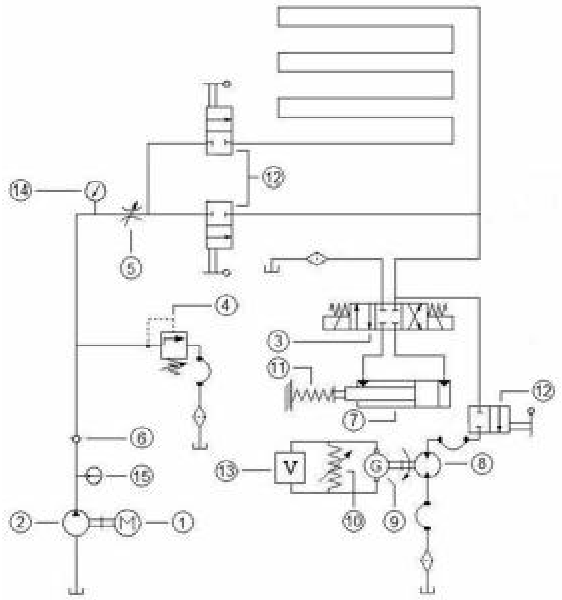

Figure (2) Schematic Diagram of the Hydraulic Circuit

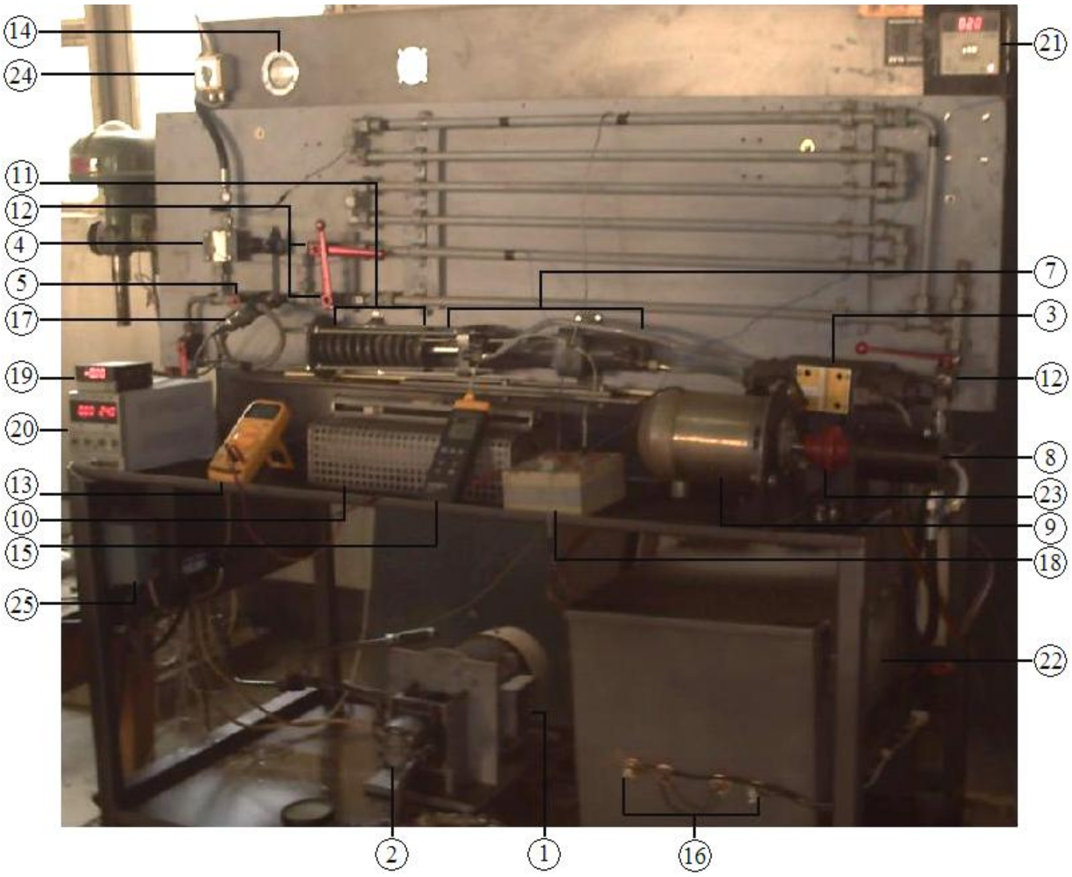

Figure (3) The Test Bench of Hydraulic System

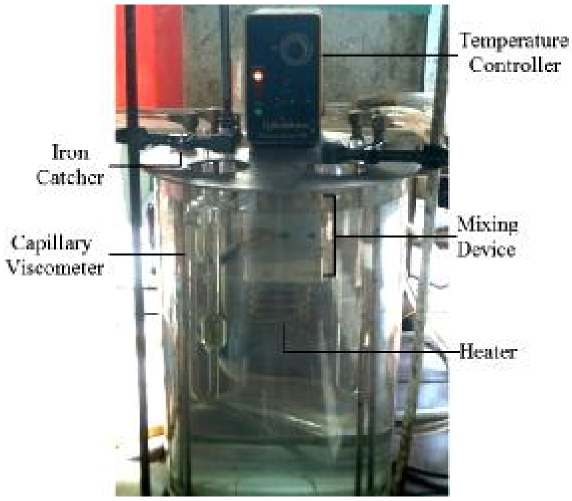

Figure (4) The Viscosity Measuring Device

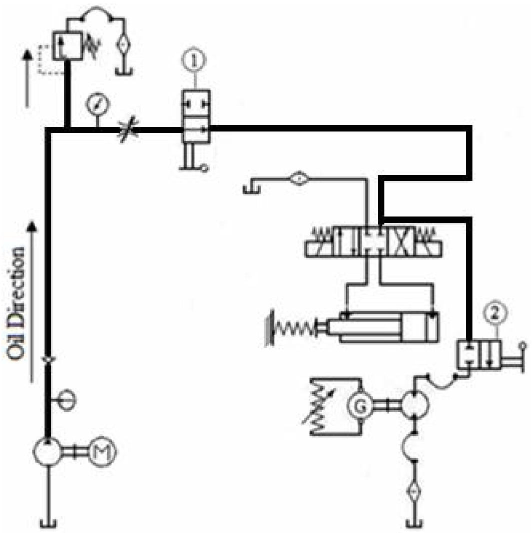

Figure (5) The Schematic Diagram of the Neutral Circuit

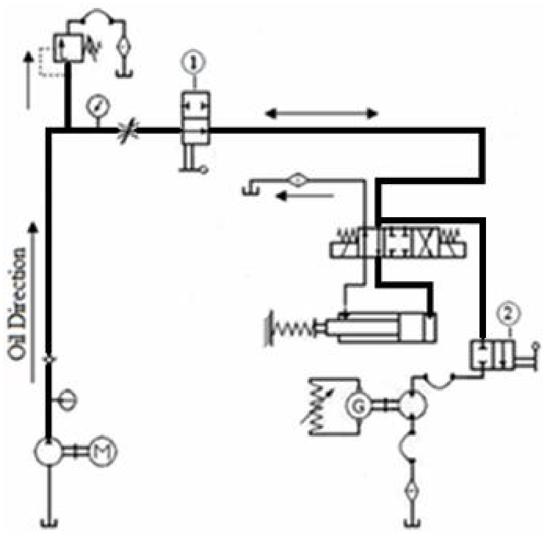

Figure (7) The schematic diagram of the Extending Circuit

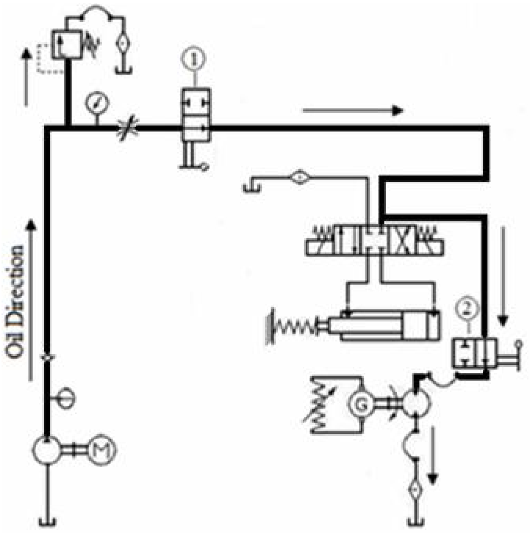

Figure (6) The Schematic Diagram of the Loading Circuit

Figure (8) The Electronic Digital Caliper

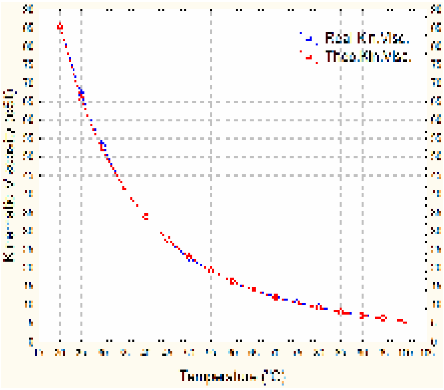

Figure (9) Measured and Correlated Dynamic Viscosity With Temperature

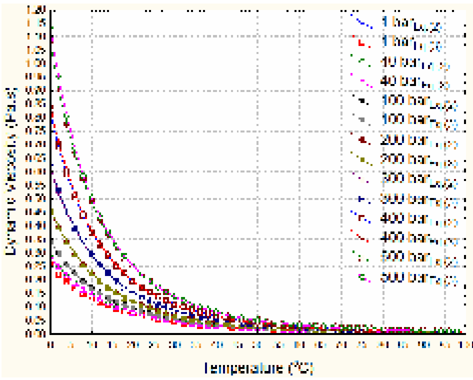

Figure (10) Two Correlated Dynamic Viscosity at Different Temperatures and Pressures

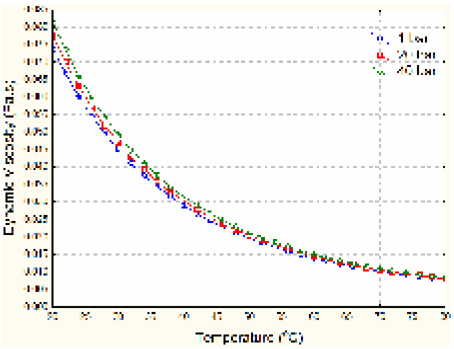

Figure (11) Correlated Dynamic Viscosity at Our Working Temperatures and Pressures

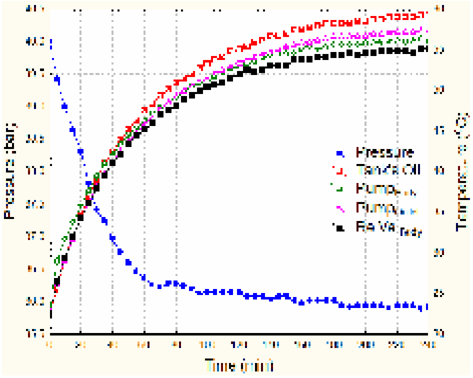

Figure (12) The Pressure Drop and Temperatures Raising With Time (Neutral Case)

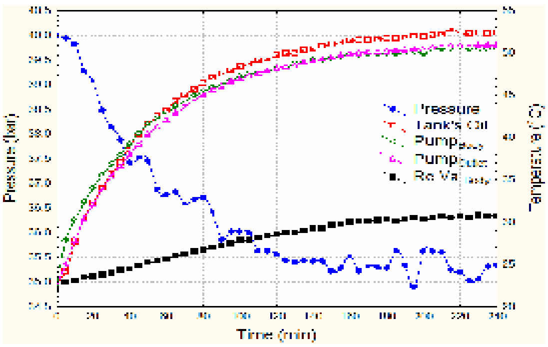

Figure (13) The Pressure Drop and Temperatures Raising With Time (Loading Case)

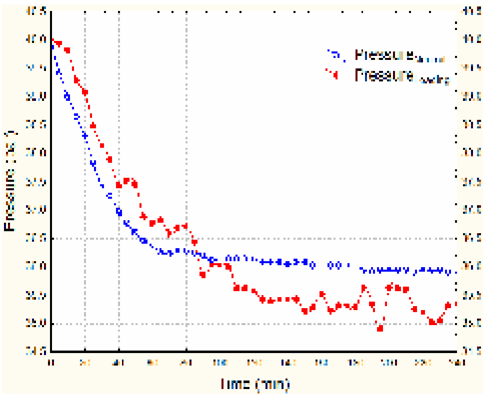

Figure (14) Comparison of Pressure Drop with Time for the Two Cases

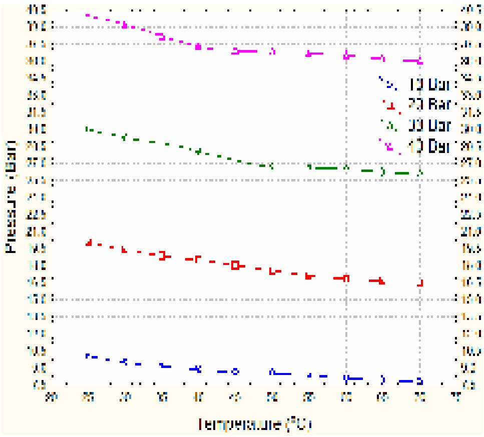

Figure (15) **All Pressures Drop with Temperature Raising**

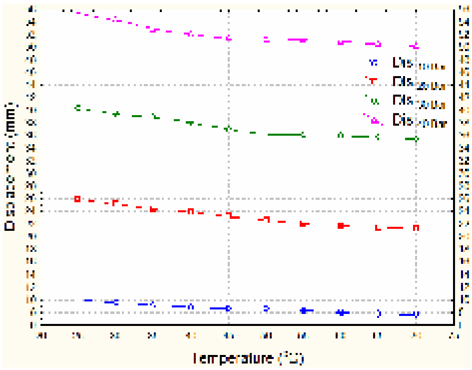

Figure (16) **All Displacements Drop with Temperature Raising**

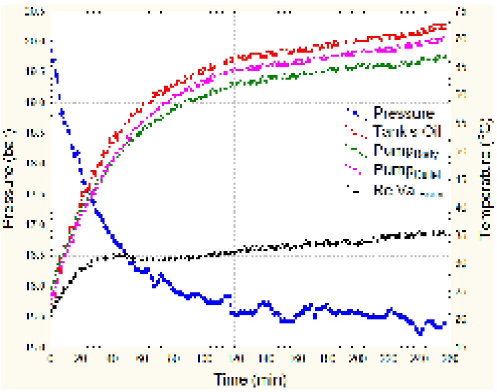

Figure (17) **Pressure Drop and Temperatures Raising with Time at 20 bar**

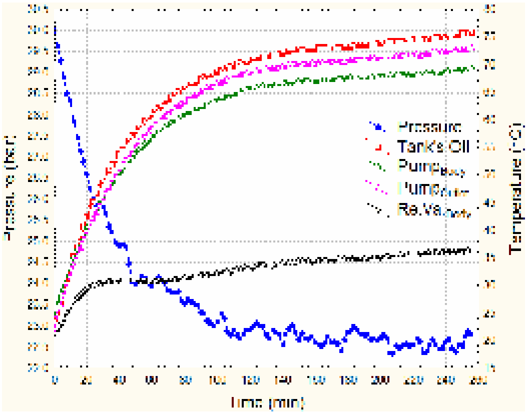

Figure (18) Pressure Drop and Temperatures Raising with Time at 30 bar

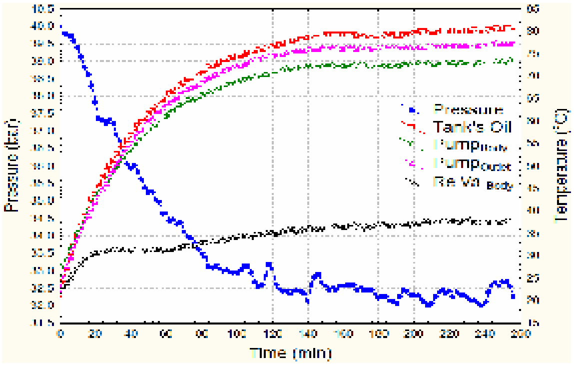

Figure (19) **Pressure Drop and Temperatures Raising with Time at 40 bar**

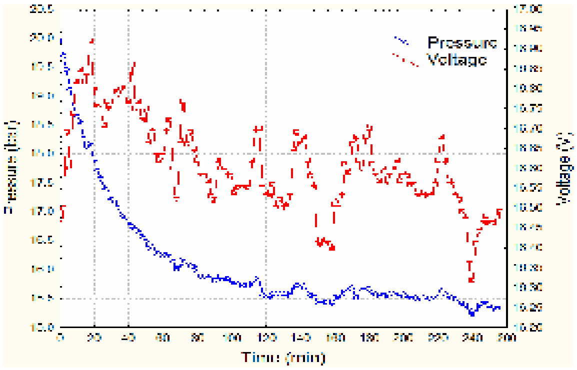

Figure (20) **Pressure and Voltage Drop with Time at 20 bar**

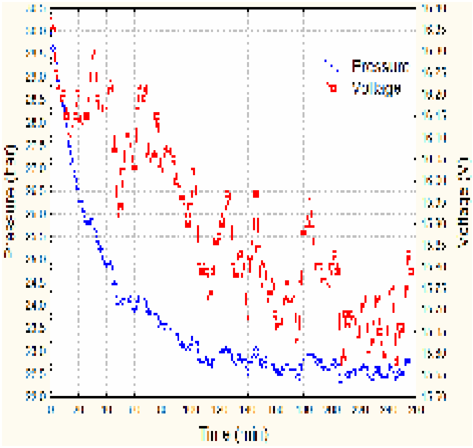

Figure (21) Pressure and Voltage Drop with Time at 30 bar

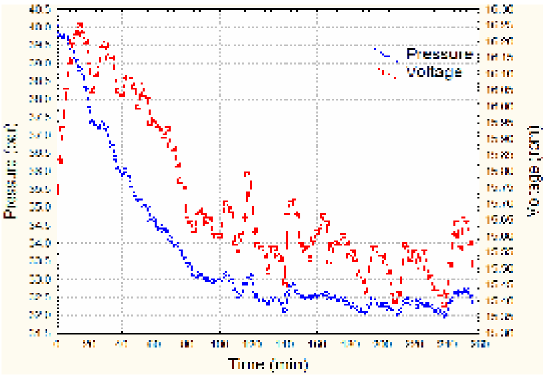

Figure (22) Pressure and Voltage Drop with Time at 40 bar

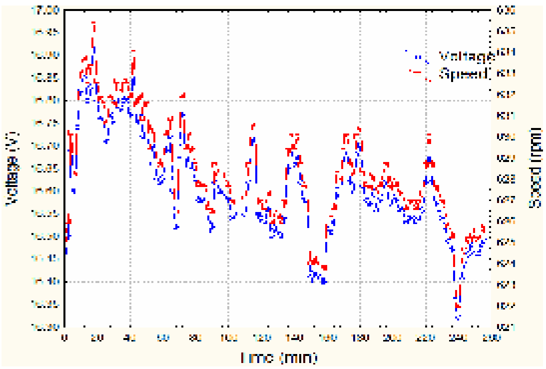

Figure (23) Voltage and Speed Variation with Time at 20 bar

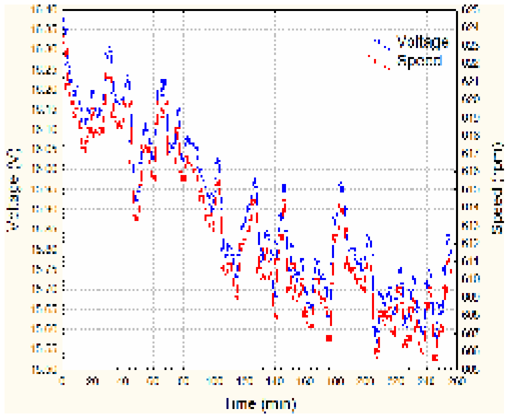

Figure (24) Voltage and Speed Variation with Time at 30 bar

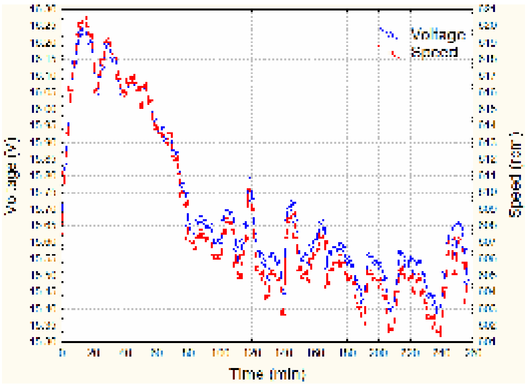

Figure (25) Voltage and Speed Variation with Time at 40 bar

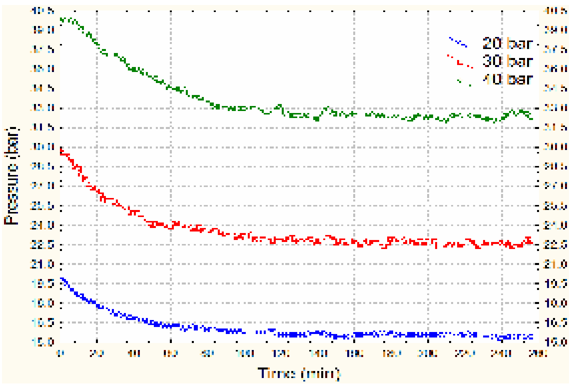

Figure (26) All Pressure Drops with Time

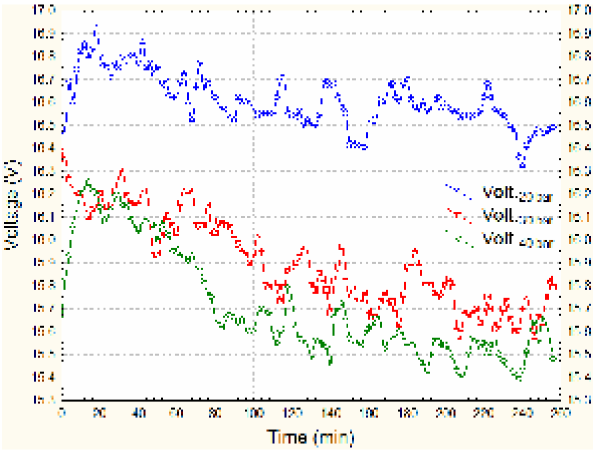

Figure (27) Voltages Drops at All Pressures