Theoretical and Experimental Study of Hydraulic Actuators Synchronization by Using Flow Divider Valve

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Abstract :

A common problem in hydraulic applications is the synchronization of multi cylinders that must match each other's position. Stroke length depends on the volume of oil delivered to the cylinders, and moving them together requires equal oil flow to each cylinder as well as diameters .Oil leakages, pump slip, changing workloads, and varying friction loads could also affect oil delivery. Flow divider valve has been used to control the motion of dual actuators. To control pressure, flow rate and displacement, pressure transmitters, flow sensors and position sensors. Three values of oil operating temperatures (40, 45, 50) ^{o}C have been used to show the effect of the temperature and the compressibility also will be studied. Different weights have been used to produce different pressures (4, 10) bar. Matlab/Simulink will be used to represent the mathematical model to the system. Also schematic diagram of the hydraulic circuit has been done by Automation studio program

Keywords: flow divider value, synchronization, simulation.

دراسة نظرية وعملية لتزامن مشغلات هيدروليكية باستخدام صمام تقسيم الجريان

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الخلاصة :

حركة عدة اسطوانات هيدروليكية بصورة متزامنة من المسائل الشائعة في تطبيقات الانظمة الهيدروليكية.إن طول الشوط يعتمد على حجم الزيت المجهز الى الاسطوانات الهيدروليكية وتحريك الاسطوانات سوية يحتاج الى معدل تدفق زيت متساوي الى كل اسطوانة.إن تسرب الزيت ،انزلاق المضخة ، تغيير الاحمال وقوى الا حتكاك عوامل جميعها يمكن ان تؤثر على كميةالزيت الهيدروليكي المجهز الى الاسطوانة.قد استُخدَم صمام تقسيم الجريان للسيطرة على حركة الاسطوانات المزدوجة.للسيطرة ولمراقبة ضغط المنظومة ومعدل التدفق للزيت الهيدروليكي والازاحة للاسطونات فانه ستستخدم حساسات للضغط ،لمعدل التدفق ولقياس المسافة.ثلاث قيم لدرجات حرارة الزيت الهيدروليكي (40, 45,50)

درجة مئوية قد استخدمت في هذه الدراسة لمعرفة تأثير درجات الحرارة على المنظومة كذلك سيدرس تأثير عامل الانضغاطية. استخدمت أوزان مختلفة للحصول على ضغوط مختلفة (4,10) ضغط جوي. برنامج (Matlab/Simulink) استخدم لكي يتم تمثيل الموديل الرياضي للنظام. واستخدم برنامج (Automation studio) لرسم الدائرة الهيدروليكية.

Nomenclature

A	Area	(m^2)
β	Bulk modulus	(pa)
Cd	Discharge coefficient	(dimensionless)
D_p	Pump displacement	(m^3/rev)
Ess	Steady state error	(dimensionless)
F	Force	(N)
K	Spring constant	(N/m)
M	Mass	(Kg)
p	Pressure	(pa)
Q	Flow rate	(m3/min.)
N	Angular speed of pump shaft	(rpm)

Introduction:

Flow divider valves are designed to split input source to two output ports. They are supplied with orifices that give a 50:50 split up to a 90:10 split, generally in increases of 10%. The basic structure of a spool type divider is composed of a pair of calibrated metering orifices, two centering springs, a compensating spool, and a pair of variable orifices which are adjusted by the movement of the compensating spool, a schematic diagram of a flow divider is shown in **Figure (1).** Equally divided flow divider valve is considered in this study.

Since identical metering orifices are used, the division flows, Qa1 and Qa2 are equal. Flow enters Port 1 and exits Port 2 and 3. The key component of the flow divider, as with most valves, is the spool. This spool has a passage drilled down the center. Fluid enters the spool and splits to flow along a passage in both directions.

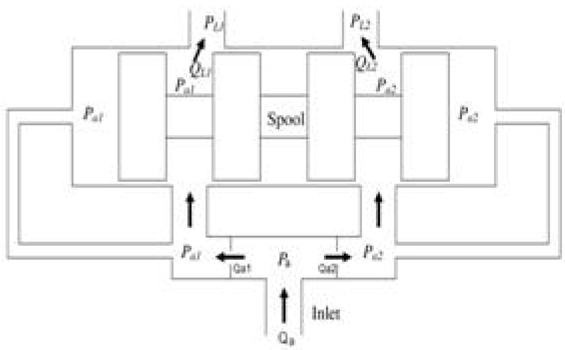

Fig .(1) Schematic diagram of flow divider valve [1].

In order to maintain synchronization of two actuators, the flow division accuracy independent of load variations is required. A literature survey shows that some of the previous work related to the experimental and theoretical works on the flow divider valve. Also, reviews and explains some of studies concerned the hydraulic synchronization motion. Kwan et al. (1979) derived a theoretical model for analyzing the accuracy of flow divider valve and proved that the flow division error was related to the external forces on the compensating spool. Chan et al. (1980): adopted Kwan's basic design concept and discovered that if a thin rim was machined into the orifice, the flow forces could be greatly reduced and this was able to reduce flow division error greatly. Zhang et al (1993). Presented an "auto-regulator", a pressure controlled pair of orifices that replaced the fixed orifices, thereby maintaining a reasonable pressure drop over a wide range of flows. Travis Kent Wiens (2004) proposed an adjustable-ratio flow divider which attempts to split one input flow into two output flows in a predetermined ratio, independent of load pressure or total flow. Minter Cheng (2009): In his study, the steady and dynamic performances of a flow divider valve are simulated numerically by solving the characteristic equations. The parameters studied in this research are centering spring constant, compensating spool mass and metering orifice area. The simulation results show that flow division error increases with increasing the load pressure differential, centering spring constant, and metering orifice area [2].

From the first researchers that deal with synchronization system are Edward and Pawel (2000). They presented an analysis of control of heavy duty machines unit with hydraulic actuator. They studied the performance for every actuator by analysis the displacement and the pressure of the hydraulic system by using flow divider valve with non uniform load. They determined the influence of constructional parameters on flow characteristic and positioning accuracy. Those parameters are: shape and dimension of throttle nozzles, spring stiffness, spool motion damping, and volumes of valve champers [3]. Hong Sun and George T.-C Chiu (2001) presented a two step design approach is applied such that it utilized linear multi input multi output (MIMO) robust control technique to design an outer loop motion synchronization controller. A nonlinear single input single output (SISO) perturbation observer based pressure/force controller is designed for each of the lift cylinder as the inner loop controller to handle the nonlinearities associated with the EH actuators[4]. Hugo Daniel Almeida (2010) discussed the development of an automatic and synchronized system. The system allows controlling pressures and movements synchronously and accompanied by position readings measured by position sensors [5]. Seong-Hoon, Jeong-Uk, Young-Won, and Myeong-Kwan (2011) presented a method to achieve a synchronous positioning objective for a dual-cylinders electro-hydraulic system with friction characteristics. The control system consists of a VSC (Variable Structure Controller) for each of the hydraulic cylinders and a PID (Proportional-Integral-Derivative) feedback controller. The simulation and experimental results show that the proposed method can effectively achieve the objective of position synchronization in the dual cylinders electro-hydraulic system [6].

There are four basic approaches to solve the synchronization of multiple Actuators which are conventional hydraulic circuit (without flow control valve), hydraulic circuit with flow control valve, flow divider valve circuit, hydraulic circuit with electro-hydraulic valve.

Synchronization by using flow divider valve that will keep the same cylinder velocity by maintaining the same flow rate on the cylinders is the simplest one but will depend on the flow divider performance. Synchronization control motion with electro-hydraulic is the most accurate one but is the most expensive and complex [7].

In the present study, dynamic and steady mathematical models have been derived for a spool type flow divider valve. Then, a computer simulation is made to simulate the synchronization system and experimentally discussing the effects of hydraulic oil operating temperature and load on the valve steady and dynamic characteristics. Two cases have been considered, the first is by conventional circuit and the second with flow divider valve.

The Experimental Apparatus

The experimental apparatus of the present work was built up to be suitable for the objective of present work as shown in **Figures (2) and (3).** It consists of the hydraulic components which include the power unit, control unit, transmission unit and output devices and measurement instruments which they are pressure sensors, flow and position sensors interfaced with analogue to digital convertor which in its rule transferred the data to the laptop **(Table 1).**

Table .(1) hydraulic components

NO.	Component designation	NO.	Component designation
1	Hydraulic reservoir	11	Hydraulic filter
2	Hydraulic pump	12	Hydraulic hoses
3	Electrical Motor	13	Pressure Transmitters
4	Pressure relief valve	14	Hydraulic Cylinders
5	Pressure gage	15	Position Sensors
6	Tee connection	16	ADC
7	Flow sensors	17	Digital multimeter
8	Check valve	18	Laptop
9	Directional control valve	19	Electrical Heater
10	Load	20	Flow divider valv

Fig .(2) Experimental apparatus

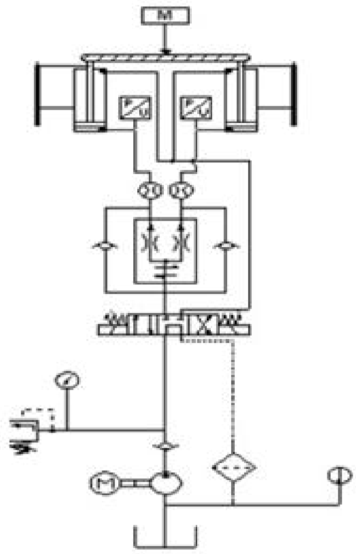

Fig .(3) Schematic diagram to the experimental apparatus

Mathematical Model

An adequate mathematical model to formulate the hydraulic system which includes the hydraulic component such as hydraulic pump, directional control vale, hydraulic cylinder and transmission lines was presented. In order to perform simulations model of the system as block diagrams in Simulink has been worked out. The following simplifying assumptions are made during the process of the system modeling [8]:-

1. The internal and external leakage of the hydraulic pump is assumed to be linear functions to the pressure difference across the pump.
2. The inlet of the pump and return line to the tank and the case drain pressure are open to atmospheric environment (i.e. their values are zero).
3. There is no slip between the electric motor and the hydraulic pump (i.e. same rotation speed).
4. The hydraulic transmission lines connecting between the system are stiff. Their expansion due to pressure changes is negligible. Consequently, the dynamics effect resulting from the pipe elasticity is neglected.
5. The pressure transmissions in the hoses are assumed to be instantaneous, and the pressure drops across the transmission lines are neglected.
6. Flow divider valve and system are in thermal equilibrium condition

Mathematical model of fixed displacement pump.

$$Q_{p\ ideal} = D_p . N \quad (1)$$

1. Mathematical model of supply hydraulic line to directional control valve

$$\frac{dPs}{dt} = \frac{\beta}{Vs}(Qp - Qs) \quad (2)$$

2. Mathematical model of directional control valve.

$$Q_L = C_d . A_1\sqrt{\frac{1}{\rho}(p_s - p_L)} - C_d . A_2\sqrt{\frac{1}{\rho}(p_s + p_L)} \quad (3)$$

$$Q_s = C_d . A_1\sqrt{\frac{1}{\rho}(p_s - p_L)} + C_d . A_2\sqrt{\frac{1}{\rho}(p_s + p_L)} \quad (4)$$

3. Mathematical model of supply hydraulic line to flow divider valve

$$\frac{dPa}{dt} = \frac{\beta}{Va}(Q_a - Q_{a1} - Q_{a2}) \quad (5)$$

4. flow through the fixed orifices

$$Q_{a1} = C_{do1} . A_{o1}\sqrt{\frac{2}{\rho}(P_a - P_{a1})} \quad (6)$$

$$Q_{a2} = C_{do2} . A_{o2}\sqrt{\frac{2}{\rho}(P_a - P_{a2})} \quad (7)$$

5. flow through the variable orifices

$$Q_{L1} = C_{dv1} . A_{v1}\sqrt{\frac{2}{\rho}(P_{a1} - P_{L1})} \quad (8)$$

$$Q_{L2} = C_{dv2} . A_{v2}\sqrt{\frac{2}{\rho}(P_{a2} - P_{L2})} \quad (9)$$

6. The intermediate pressures

$$\frac{dPa1}{dt} = \frac{\beta}{Va1}(Q_{a1} - Q_{L1}) \quad (10)$$

$$\frac{dPa2}{dt} = \frac{\beta}{Va2}(Q_{a2} - Q_{L2}) \quad (11)$$

7. Flow divider valve spool equation of motion.

$$Ms\frac{d^2xs}{dt^2} + f_s\frac{dxs}{dt} + 2kx_s = \Delta F_{hs} + \Delta F_{hd} \tag{12}$$

8. The steady state error

$$\%E_{ss} = \frac{Q_{L1}-Q_{L2}}{Q_a} \times 100\% \tag{13}$$

9. Mathematical model of supply hydraulic line to actuators.

$$\frac{dPL1}{dt} = \frac{\beta}{V_{L1}}(Q_{L1} - A_p\frac{dxp1}{dt}) \tag{14}$$

$$\frac{dPL2}{dt} = \frac{\beta}{V_{L2}}(Q_{L2} - A_p\frac{dxp2}{dt}) \tag{15}$$

10. Mathematical model of double acting single rod hydraulic cylinder.

$$M\frac{d^2x_{p1}}{dt^2} + f_p\frac{dx_{p1}}{dt} = \left(P_{L1}A_p - P_{r1}A_r\right) \tag{16}$$

$$M\frac{d^2x_{p2}}{dt^2} + f_p\frac{dx_{p2}}{dt} = \left(P_{L1}A_p - P_{r1}A_r\right) \tag{17}$$

Numerical Simulation

For simulation purposes, experimental results were used to find the necessary parameters and coefficients in addition to the other researches and data sheets to the hydraulic components. The inlet flow rate remained fixed which is 2.4 gpm; the flow rate on the outlet ports is varied according to the pressure difference across the variable orifices. The load which is used is 174.2 kg. Then, the steady state division error can be found by using equation 13.

The simulation is carried out by using a MATLAB/SIMULINK computer program. Dormand-Prince (ODE45) method with variable step was used. With permissible relative error $\varepsilon_m=10^{-3}$. Constructional parameters of the system such as area of piston, piston rod area, volumes of transmissions lines, piston stroke and mass of moving elements are shown in **Table (2)**. Initial piston rod velocity and displacement are transmitted to corresponding blocks of integrating piston rod motion equations. Output signal is cylinder piston rod displacement as shown in **(Figure 4)**

Table .(2) system parameters and coefficients

parameters	value	unit
A_p	7.07E-4	m^2
A_r	3.93E-4	m^2
l	0.123	m
Dp	1E-6	m^3/rad
N	1410	rpm
M	142.2	kg
rho	873	kg/m^3
c_d	0.61	dimensionless
M_s	0.2	kg
v_s	7E-6	m^3

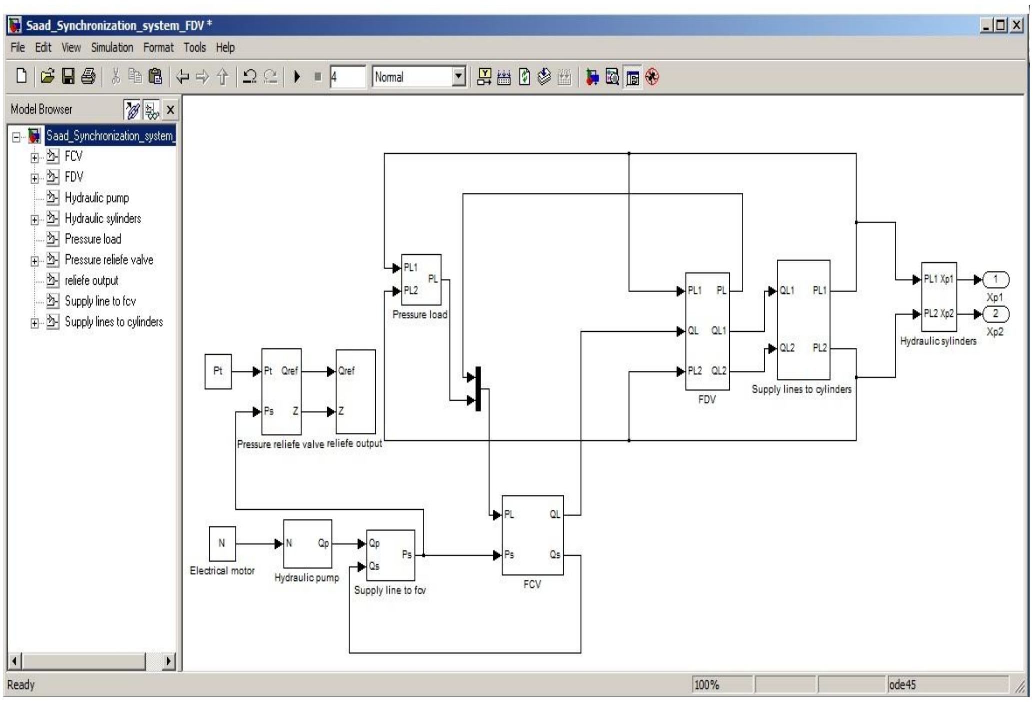

Fig .(4) Simulink model to the synchronization system

Results And Discussions

The main purpose of this study is to investigate the accuracy of flow divider valve and the effects of load and oil operating temperature on the flow division error. The load which was used was 144.2 (kg), 72.1 (kg) on each actuator, so the corresponding pressure is 10 (bar). The set pressure is 11 (bar) at ambient temperature 30 ^{o}c.

Figures (5-a) and **(5-b)** represent the Simulink results to the synchronization hydraulic system which show clearly that the displacement curves are identical.

Figures (6-a) and **(6-b)** represent the experimental behavior of the hydraulic system when tee connection was used to synchronize dual cylinders. It presented tee connection position and flow rate versus time at 40 ^{o}c operating oil temperatures with separate load. Percentage error is (13.3%) which is significant value and so the increasing linear positions curves differ corresponding to the flow rate changes. This error is properly because the friction of the cylinders or because the external and internal leakage of the hydraulic components especially in Tee connection.

Figures (7-a) to (9-b) represent the experimental behavior of the hydraulic system when flow divider valve was used to synchronize dual cylinders. They presented flow divider valve position and flow rate versus time at different operating oil temperatures (40, 45, 50) ^{o}c. the percentage error is (0.4%) which is pretty small value and so the increasing linear positions curves differ corresponding to the flow rate changes. This approval appears obviously on the displacements curves which shows them nearly identical. The result shows there was no obvious effect of the oil temperature on the synchronization motion.

Conclusions

The present experimental investigation and theoretical simulation analysis reveal many conclusions. These conclusions can be explained as the following:

1. The program was built by converting the mathematical models of the system elements to a computer program in Simulink environment.
2. Easier and cheaper way to synchronize multiple hydraulic cylinders is by using flow divider valve.
3. Best way for hydraulic cylinders synchronization except EHVS because its wide applications and accuracy.
4. Increasing or decreasing the operating hydraulic oil temperature in range of ($\pm 5^{o}$c) from the optimum temperature doesn't affect the synchronization system.
5. The compressibility factor has no effects on synchronization system because the operating system pressure is less than 1000 psi.

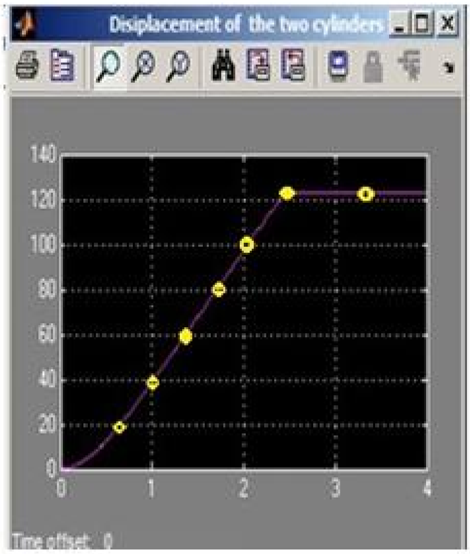

Fig .(5-a) cylinders displacement with flow divider valve.

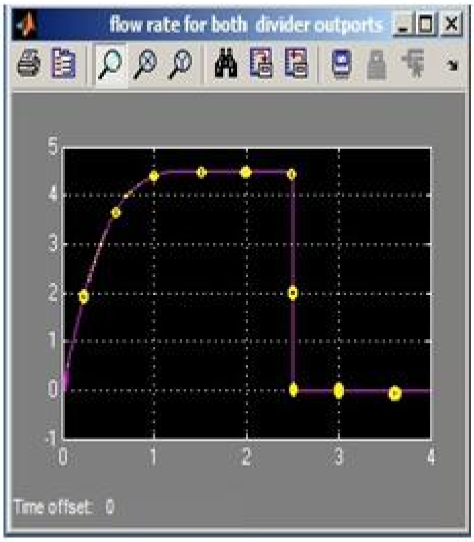

Fig .(5-b) cylinders inlet flow rate with flow divider valve.

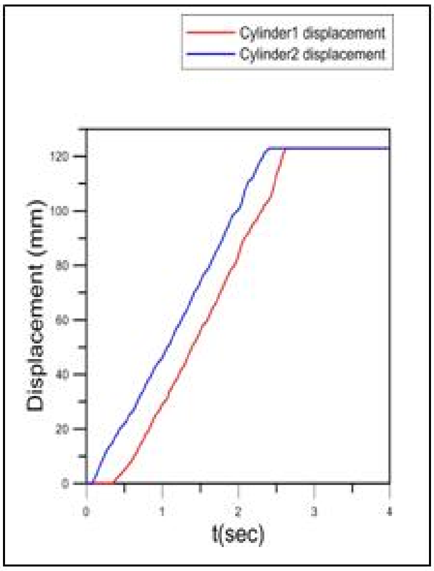

Fig . (6-a) cylinders displacement without flow divider valve.

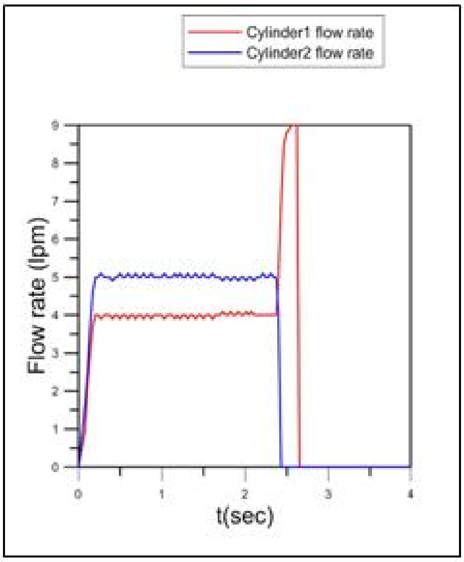

Fig .(6-b) cylinders inlet flow rate without flow divider valve

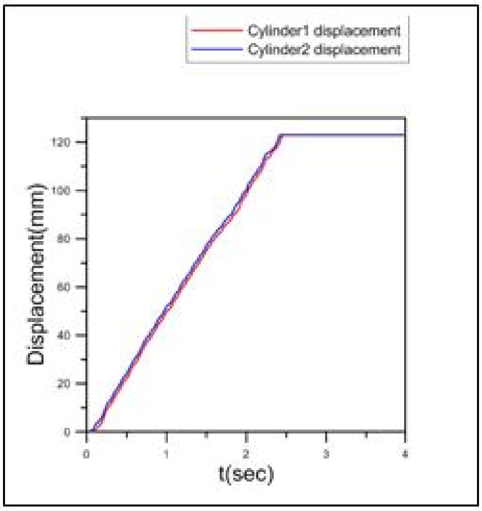

Fig .(7-a) cylinders displacement with flow divider valve at 40 ^{o}c

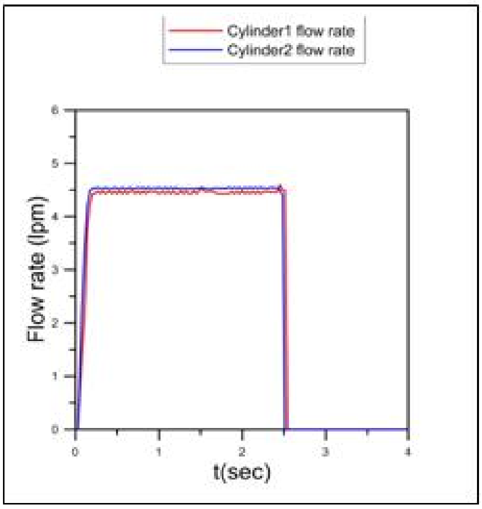

Fig .(7-b) cylinders inlet flow rate with flow divider valve at 40 ^{o}c

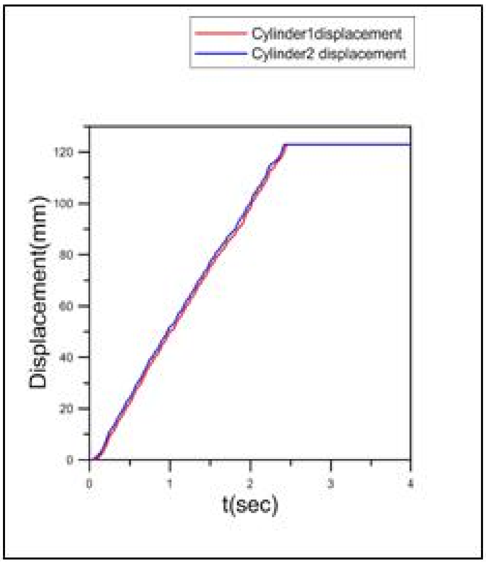

Fig. (8-a) cylinders displacement with flow divider valve at 45 ^{o}c

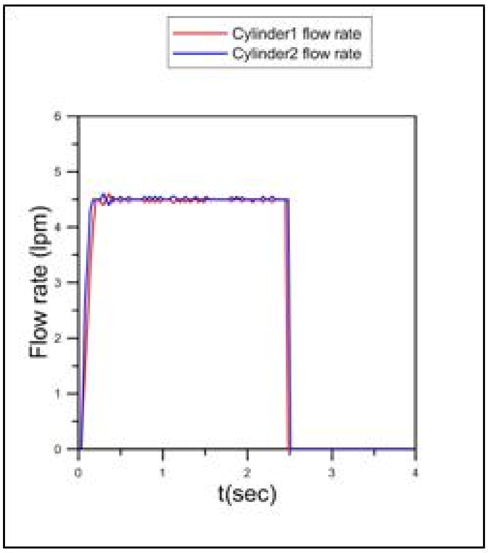

Fig .(8-b) cylinders inlet flow rate with flow divider valve at 45 ^{o}c

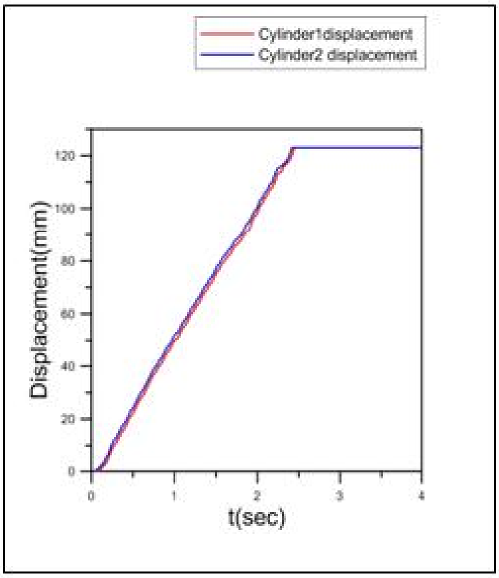

Fig .(9-a) cylinders displacement with flow divider valve at 50 °c

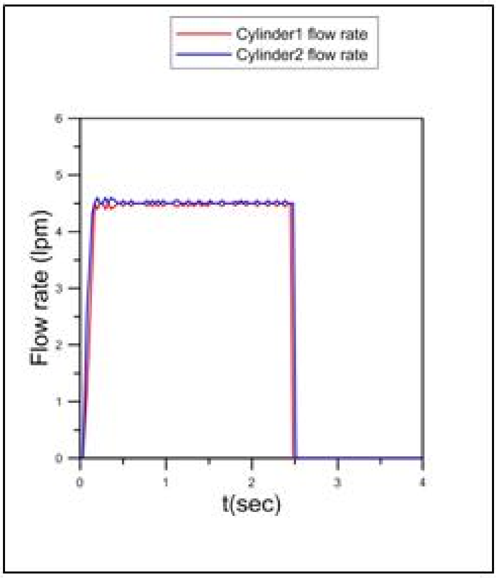

Fig .(9-b) cylinders inlet flow rate with flow divider valve at 50 °c

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