Analysis of Innovative Design of Energy Efficient Hydraulic Actuators

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ABSTRACT

Hydraulic cylinder actuators are used extensively in industrial, construction and agricultural works. The small sized outlet ports of the cylinders resist the flow of discharged oil; and as a result the piston motion is slowed down. This causes a lot of heat generation and energy loss within the actuators. The study investigates and analyzes the possibilities of reducing the hydraulic resistance and increasing efficiency of the hydraulic actuator. Conventional hydraulic cylinders are simulated in FLUENT. Results show that the small outlet ports are the sources of energy loss in hydraulic cylinders. A new hydraulic system was proposed as a solution to relieve the hydraulic resistance in the actuators. The proposed system is a four ports hydraulic cylinder fitted with a novel flow control valve. The proposed four ports cylinder was simulated and parameters such as ports sizes, loads and pressures are varied during the simulation. The hydraulic resisting forces, piston speed and mass flow rates are computed. Results show that the hydraulic resistance is significantly reduced in the proposed four ports actuators; and the proposed cylinders run faster than the conventional cylinders and a considerable amount of energyis saved as well.

Keywords - Computational Hydraulic, Energy Efficient Actuators, Energy Saving in Hydraulic, Hydraulic Control

I INTRODUCTION

Energy efficiency of hydraulic power systems has been particularly important in heavy work applications. Hydraulic power technologies have been used in industries and all kinds of mobile machineries such as construction, agricultural and forestry machines. The common thing to all these applications is the high power required to perform the desired job, such as material handling and harvesting. Industrial hydraulic systems often work continuously around the clock, handling large amounts of power. Even little improvement in efficiency, therefore, will have a significant economic impact on the overall life-cycle cost of the hydraulic system. On the other hand, the total life-cycle cost of energy consumption in the mobile sector is much less compared to industrial sector. However, in the last few years increased fuel prices and stricter environmental regulations regarding engines emissions, are pushing forward the improvement of energy efficient solutions in the field of mobile hydraulics. A double acting differential hydraulic cylinder has two ports having small areas. When the cylinder is actuated the oil pressure forces the piston to move in the flow direction. The discharge oil from the hydraulic cylinder is highly restricted by the small area of the outlet port. Piston motion, therefore, is resisted and energy is lost. The energy lost in this operation is converted to heat within the cylinder and overloads the pump. Unnecessary additional work of the pump is required to overcome this hydraulic resistance every stroke during its operation. Energy saving possibilities of the existing hydraulic cylinder is investigate and analyzed in this study. FLUENT CODE makes it easy to obtain a better solution for energy loss in cylinder actuators. Computational simulation provides essential solutions for hydraulic losses with minimum cost compared to experimental analysis. CFD makes it possible to examine the cylinder actuator characteristics. It also helps in optimizing the cylinder and port sizes before the manufacturing processes start.

Many studies have been carried out to improve the performance and the energy efficiency of individual components of hydraulic system, such as pumps, motors and valves. Most of these studies focus on improving the performance of the actuators by developing and improving the control algorithms rather than improving the actuator hardware structure. Krus (1988) studied valve controlled systems (VCS), where flow and pressure are regulated by operating hydraulic orifices. He showed that VCS have better energy efficient than many other solutions. High cost and instability tendencies due to its dynamic properties are their main weakness [1]. Raymond and Chenoweth (1993) introduce a symmetrical actuator in the conventional electro-hydraulic actuator systems (EHA) [2]. EHA has no throttling losses show better overall energy efficiency than valve controlled and displacement controlled hydraulic systems. But Habibi and Goldenberg (1999) shows that using a fixed displacement variable speed pump in EHA decreases the volumetric efficiency specially at low speeds [3]. S. R. Habibi and G. Singh (2000) in their studies the linking of system requirements to design parameters for EHA. They has prototyped, demonstrated and reviewed the mathematical model of EHA and used it for linking its performance to its design parameters through a set of mathematical functions. [4]. Separate controls of meter-in and meter-out orifices are recently introduced to hydraulic system. These applications provide a higher degree of freedom in control as all the orifices can be controlled individually. A lot of work has been done on such ideas by Jansson and Palmberg, (1990) [5] and Elfving and Palmberg (1996). Achten et al., (1997) developed another hydraulic transformer model (IHT transformer) to increase efficiency. Werndin and Palmberg (2003) introduce a hydraulic transformer that converts an input flow to a different output flow at the expense of a pressure level. Since no valves are used in the transformer, the throttling

losses can be totally eliminated but with a decreased overall efficiency [6]. Many studies have been conducted to improve the hydraulic transformer system, such as Vael et al., (2003) [7], Vael et al., (2004) [8]. All of them implied that additional valves will improve the efficiency of the original transformer. In recent studies a greater emphasis is laid on the efficiency aspects of separate metering valve controlled systems, such as (Liu and Yao, 2002) [9]. Rydberg (2005) proposes valve-less hydraulic system, known as secondary control system, to eliminate throttling losses. All actuators in the secondary control system are connected to a common and semi-constant pressure rail fitted with a pressure compensated pump.

Eriksson (2007) uses in his study asymmetrical cylinders as a discrete transformer to control loads in order to minimize the losses. [10]. He presents a solution enabling lower losses in hydraulic actuator systems. His proposed controller is capable of recuperating energy by letting the overrunning actuator provide any simultaneously operated actuator with flow and pressure. Linjama et al., (2008) [11] and [12] developed digital solutions to energy losses hydraulic system. Their approaches showed a considerable amount energy saving potential. Another solution has been introduced and widely utilized in hydraulic systems to eliminate these metering losses. The solution based on introducing a separate pump for each hydraulic actuator. This solution will add additional cost, but higher system efficiency can compensate for it in some applications.

A lot of studies have been carried out in developing control strategies for the purpose of improving performance and energy efficiency in hydraulic cylinders.

Q. Xiao et al., (2008) examined the control strategies of hybrid system used in hydraulic excavators. They proposed a control strategy named "the engine constant-work-point" and studied it in a simulative experimental system. A dynamic-work-point control strategy, which regulates the engine's working point dynamically, was developed to make the system work more efficient [13]. G.S. Beard and D.P. Stoten (1996) applied the Minimal Controller Synthesis adaptive controller to the problem of energy efficient digital control of a hydraulic system. Experimental studies show that despite inherent non-linearity in the system, the MCS algorithm performs well following major plant parameter changes [14].

J. Mattila and T. Virvalo (2000) proposed, designed and implemented a novel hydraulic closed-loop motion control system on a heavy-duty 2- DOF hydraulic manipulator. They initiated a new unconventional hydraulic drive to remove the complex non-linear interconnection between cylinder pressure levels, supply pressure and load force. A new hardware combined with their controller design was able to improve the controllability of the load with lower supply pressure values than conventional controllers. That leads to improved energy efficiency [15]. S. Liu and B. Yao (2008) studied the energy saving in the hydraulic system from the control point of view. They proposed a "Coordinate Control of Energy Saving Programmable Valves". High precision control performance and significant energy saving was achieved [16]. B. Yao and S. Liu (2002) conduct a research on "Energy Saving Control of Hydraulic Systems with Novel Programmable Valves". Results show an improved energy efficient system [17]. B. Yao and C. DeBoer (2002) studied "Energy-Saving Adaptive Robust Motion Control of Single-Rod Hydraulic Cylinders with Programmable Valves," [18].

M. Osman, Nagarajan T. and F. M. Hashim (2010/2012) investigated numerically the pressure drop in hydraulic spool valve. They showed in their study the outlet geometry of the outlet port has a significant effect on the pressure drop and energy loss [19] and [20]. They also showed that small outlet ports participate significantly on the energy loss in hydraulic components. M. Osman, T. Nagarajan and F. M. Hashim (2011) showed the same results in their study "Numerical study of flow field and energy loss in hydraulic proportional control valve." [21].

II MODELING OF THE HYDRAULICCYLINDER

The intention of the study presented in this research article is to identify the major power losses in linear power hydraulic cylinders and to find alternative solutions to improve performance and energy efficiency. A specific aim of the study is to develop a new energy efficient hydraulic cylinder. To improve the energy efficiency of the cylinder actuators a CFD is utilized for examining the cylinder characteristics. CFD helps in optimizing the hydraulic cylinder and port sizes before the manufacturing stage. In this study cylinder actuators are simulated on FLUENT CODE using 3D meshed models prepared in Gambit. The flow and pressure patterns obtained from simulation of different cylinders models is discussed and analyzed.

The flow-rate"ṁ" through any port or orifice can be found from (1):

$$\dot{m} = \rho Q = C_f A_o \sqrt{2\rho.\Delta p} \qquad (1)$$

Where:

Q is the flow rate, m^3; A_o is the orifice area, m^2; ρ is the fluid density, kg/m^3; C_f is flow coefficient; and Δp is the different between upstream and downstream pressures, Pa.

The flow coefficient C_f can be found from reference books or experimentally. Flow coefficient depends on the orifice and main pipe diameters as well as on Reynolds Number. Its value ranges from 0.6 to 0.9 for most orifices.

2.1 Equilibrium of Cylinder Actuator

Hydraulic cylinders are normally subjected to both internal and external forces. Fig. (1) shows a simple conventional hydraulic cylinder actuator connected to a load, F_L.

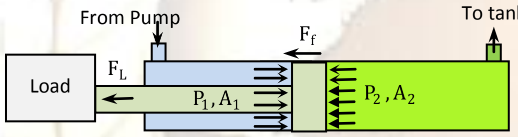

Figure 1: a loaded cylinder actuator.

When the cylinder is supplied with pump pressure, P_1, neglecting the small frictional force F_f and solving the equilibrium equation for the unknown tank side pressure (back pressure), P_2, it gives the relation as in (2):

$$P_2 = \frac{P_1 A_1 - F_L}{A_2} \qquad (2)$$

A_1 and A_2 are piston and rod side areas and are constant for any cylinder. For a given supply pressure "P_1" the load "F_L" will determines the resisting pressure "P_2" for each cylinder. In extension stroke the tank side pressure "P_2"frequently becomes greater than the pump pressure "P_1" if $F_L \leq P_1(A_1 - A_2)$. But still the force on the pump side is always greater than the force on tank side. That's why the regeneration is possible. Since the fluid in use is incompressible the speed and acceleration of the cylinder actuator depend on the flow rates allowed by the outlet port. The fluid zone at tank side of the cylinder actuator was simulated in Fluent and equation (2) was used to determine the inlet pressure to this fluid-zone of the actuator.

2.2 CFD Modeling

In this study Fluent software was utilized as a tool for simulation of the oil flow inside the hydraulic cylinder. A steady state 3D model was defined as a solver in Fluent. The k-epsilon 2-equations viscous model was used in the solver. Second order equations are selected for the solution control. A no slip velocity at the walls, pressure-inlet at inlet zone and pressure-outlet at outlet zones were applied as boundary conditions for all models. The fluid used in simulation was standard hydraulic oil having density of 870 kg/m^3 and viscosity of 46 cSt. at 40°. Density and viscosity of the oil were all assumed to be constant, i.e. the oil was assumed Newtonian and incompressible.

Hydraulic cylinders actuators were simulated in order to compute the flow variables such as pressures, mass flow rate, and piston speed. Cylinders having wide range of port diameters varying from 5mm up to 15mm were simulated in this study for various measurements. The pressure input is set at the left of the cylinder as in Fig. (2) and Fig. (3). Inlet pressure (back pressure) exerted by the piston on the tank-side fluid zone is kept constant during simulation of each model. This input pressure corresponds to "P_2" of equation (2). The outlet ports are open, through connector pipes and valves, into oil reservoir having atmosphere pressure. Each model used in the simulation contain two symmetrical outlet ports; the lower ports are assigned as walls (closed) in the Fluent boundary conditions panel when the conventional cylinder with single outlet port is the case; and assigned as outlet (open) when the flow is needed through double outlet ports as in the proposed four ports cylinder.

III SIMULATION OFTHE CLASSIC CYLINDER

The classic single outlet cylinders with various outlet diameters are simulated under the same resisting pressures; mass flow rates and piston speeds are computed. Contours of static pressure for a 7mm port cylinder are shown as in Fig. (2). Pressure gradient is noticed to be very high at the exit port. Pressure and energy losses are high at this location. The oil in main chamber in front of the piston is highly pressurized which means that the piston motion suffers high hydraulic resistance (back pressure). The piston has to overcome this resisting pressure in order to move. Contour of velocity magnitude for the same 7mm port cylinder is shown as in Fig. (3). The velocity in main chamber is noticed to be low while the velocity at outlet port is very high and turbulent.

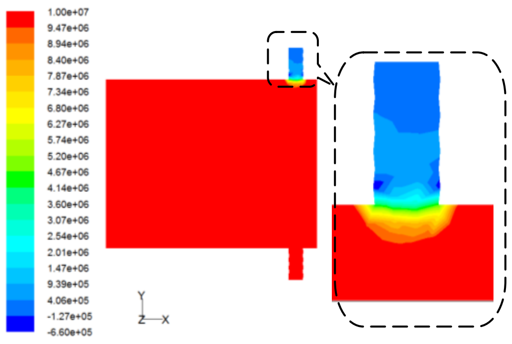

Figure 2: static pressure contours for single outlet port.

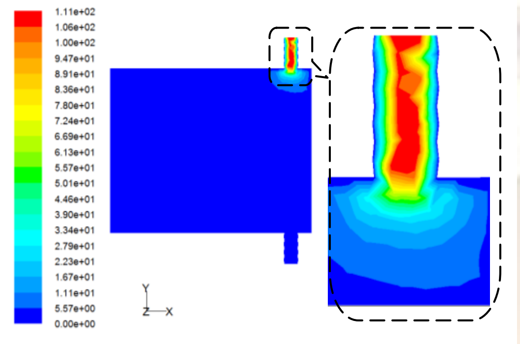

Figure 3: velocity contours for single outlet port.

Mass flow rates for the various simulated cylinders,under the inlet pressureof 100bar,are recorded as in Table (1). Results shown in Table (1) agreed with (1) of the flow rate with $C_f \approx 0.7$

Results show that if the pump supply is sufficient enough the mass flow rate increases rapidly as the outlet diameter increases. It has been shown that if other things remain the same, the larger the outlet diameter the higher the mass flow rate and the faster the cylinder actuator will be.

Table 1 – Mass Flow Rate on Hydraulic Actuators.

Outlet Diameter (mm)	Mass-flow Rate (kg/s)
5	1.48
6	2.36
7	3.40
8	4.51
9	5.84
10	7.40
11	9.11
12	11.05
13	13.15
14	15.04
15	17.23

The mass flow rate vs. ports diameters are plotted as in Fig. (4).

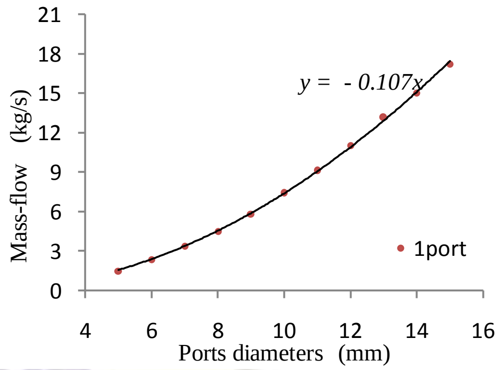

Figure 4: mass rate vs. ports diameters

The flow rate can be expressed in term of the outlet diameter as in the polynomial (3):

$$\dot{m} = 0.0847d^2 - 0.1073d \qquad (3)$$

A conventional cylinder having single outlet port of 7mm diameters is simulated under varied load conditions. The tank-side zone pressure was varied from 10bar (highly loaded cylinder) to 100bar (unloaded cylinder). The mass flow rate was computed and plotted as in Fig. 5.

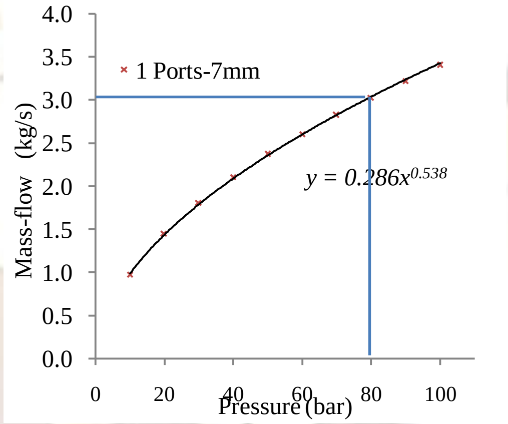

Figure 5: mass rate vs. load pressure.

It can be said that mass flow rate increases as the load decreases. The relation is excellent described by the power law as in (4):

$$\dot{m} = 0.2863p^{0.5389} \qquad (4)$$

It's also noticeable that the resisting pressure in the cylinder depends on the flow rate. The higher the speed the higher is the resisting pressure. To overcome this resisting pressure a lot of hydraulic energy is consumed.Cylinder of single outlet port having 5mm port diameter is simulated against external loads. Actuating velocities are computed and plotted against the loads as in Fig. 6. It was shown that the cylinder reaches its maximum force when it is stationary (overloaded) as no back pressure in the cylinderand no pressure losses at the port due to throttling, which is agreed with [22].

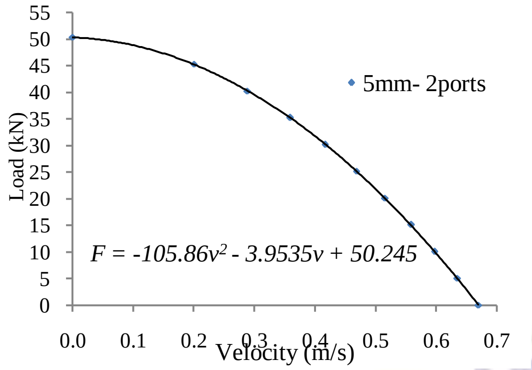

Figure 6: load vs. velocity.

When the load is reduced the piston moves and the forces are reduced by the amount used to accelerate the load and the amount lost in throttling as a pressure drop. In an unloaded cylinder travelling at maximum speed almost all the energy provided at the valve in the form of throttling losses is converted into heat.

3.1 The Proposed Cylinder Actuator

Hydraulic cylinder with four ports is proposed in order to improve energy efficiency. The proposed cylinder presented in this study is based on adding two new ports to the traditional two ports linear hydraulic cylinder as shown in Fig. 7.

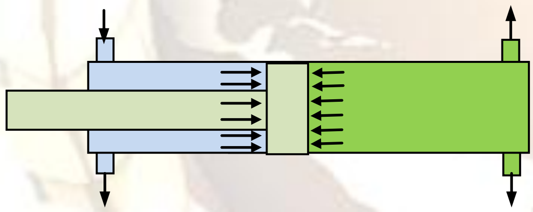

Figure 7: the proposed four ports hydraulic cylinder actuator.

The new two ports work as outlet ports only and they function alternately, i.e. they are connected to the tank. The proposed cylinder, therefore, has only one inlet port and two outlet ports functioning at a time. Flow through the two new additional ports is controlled by a separate novel flow control valve as in Fig. 8. This flow control valve permits the discharge flow from the tank side of the cylinder and blocks the flow from the pump side of the cylinder.

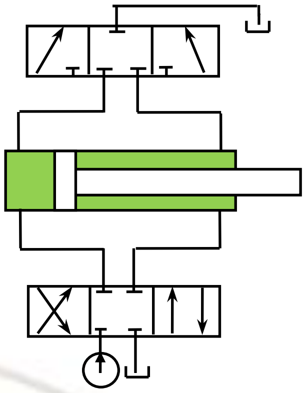

Figure 8: the proposed hydraulic circuit.

The inlet flow to the cylinder in the proposed system remains as it was in the conventional cylinder.

IV SIMULATION OF THE PROPOSED CYLINDER

Double outlet ports cylinders with various outlet diameters are simulated under 100bar. Mass flow rate are recorded and plotted in Fig. (9). Theplot shows second order polynomials as in (5):

$$\dot{m} = 0.1548d^2 + 0.0914d - 1.4622 \qquad (5)$$

With referenceto the results in Fig (4) and Fig (9), it can be said that adding a port of the same size of the existing one to the conventional cylinder actuatordoubles the flow rate for all ports size. The cylinder speed is also doubled as a result.

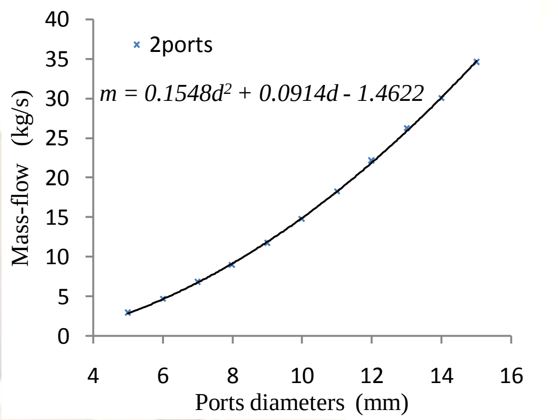

Figure 9: mass rate vs. ports diameters.

Cylinder with double outlet ports, 7mm diameters each, is simulated against varied load conditions. Again the pressure is varied from 10bar to 100bar. Mass flow rates were computed and plotted as in Fig. (10).

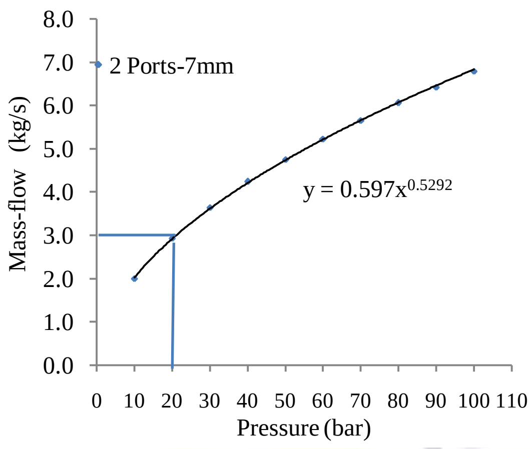

Figure 10: mass rate vs. outlet port size.

Referring to results in Fig. (5) it is clear that mass flow rates are doubled as the outlet ports are doubled. The pressure-mass rate relationship is best fit to power law as in (6):

$$\dot{m} = 0.597p^{0.5292} \qquad (6)$$

On the other hand, it can be said that for the same flow rate (the same speed), the proposed cylinder suffer low resisting pressure compared with the standard cylinder. This clearly illustrated as in Fig (5) and Fig (10). For example, at 3kg/s the standard cylinder suffers pressure resistance of 80bar as shown in Fig (5);while,at the same flow rate, the proposed cylinder suffers hydraulic resistance as low as 20bar as depicted in Fig (10).This improvement participates in energy saving, since low energy is dissipated to overcome the low resisting pressure in the proposed cylinder.

Two outlet ports cylinders of 5, 7 and 9mm diameter are simulated on the same loads conditions. Mass flow rates are computed and plotted versus the resisting pressure as in Fig. (11).

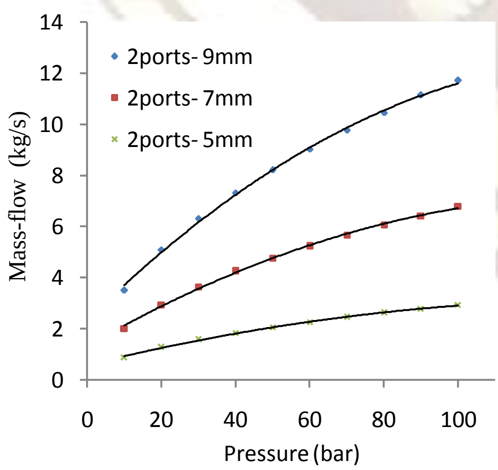

Figure 11: mass rate vs. load pressure.

It could be noticed that for the same loads condition, cylinder actuators with large ports run at higher actuation speed than those of small ports. It's also noticed that mass flow rate depends on the number of ports and on the back pressure. To increase the port size need to increase the whole pipelines of the system, as well as to increase the size of all the control valves. This is practically uneconomical comparing to add-new-ports solution.

Single and double outlet ports cylinders of 7mm port diameters are simulated against the same external loads. Actuation velocities are computed and plotted against the loads as shown in Fig. (12).

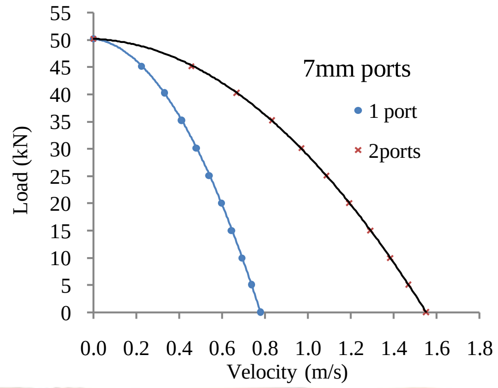

Figure 12: load vs. velocity in hydraulic cylinder.

When the outlet port is doubled the cylinder speed is also doubled for each load and supply pressure. Hence, the output power is also doubled.

V CONCLUSION

The conventional cylinder actuators were simulated in Fluent for the purpose of speed and energy optimization. Four ports cylinder actuator was proposed and simulated as well. The resisting forces, piston speed and mass flow rates are computed. Results showed that the outlet ports are the source of energy losses due to throttling effect, and the source of the induced resisting pressure. It has been found that the resisting pressure increases as the piston speed increase. The addition of new ports to the standard cylinder reduce the re resistance pressure significantly, especially at high speeds. The proposed four-port actuators give better performance regarding the piston speed and energy savings. The proposed hydraulic system can be used in all industrial and mobile applications.

VI ACKNOWLEDGEMENT

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