International Journal of Nanoelectronics and Materials
Volume 13 (Special Issue) May 2020 [233-246]

The Effects of Multiple Energy Storage on The Capacity and Performance of Hydro-Pneumatic Driveline

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ABSTRACT

The study is related to the effect of multiple energy storage on the capacity and performance of hydro-pneumatic driveline. The plan is to make the driveline operates on the hydro-pneumatic hybrid passenger car. The greatest challenge in developing a hydro-pneumatic hybrid passenger car is how to provide enough and optimum provision storage systems. Energy capacity affects the performance of a hybrid driveline, and it can be increased by increasing the size of the energy storage. However, the passenger car space is minimal. Therefore, one of the solutions is to use smaller storage, but more in numbers. Its small size allows it to be placed in several suitable locations in the car while the number increases the storage capacity. An experiment was carried out to see the multiple storage system behaviours to operate at the low-pressure level. Through the experiment, it was found that the multiple storages produced better power and discharged time compared to single storage. However, the torque and efficiency had an adverse effect because of the increase in motor speed and flow disturbance. The lowest efficiency recorded by the experiment was 40%, and the highest was 55%. In conclusion, the multiple storage systems are possible to be adapted to the hybrid hydro-pneumatic passenger car. However, some tweaks on component efficiency and lightweight material need to be considered.

Keywords: Hydro-Pneumatic, Hybrid Hydraulic, Energy Storage.

1. INTRODUCTION

Hybrid technology advancement has become dominant in the automotive business. The innovation demonstrates positive feedbacks which are enhancement of vehicle efficiency, economical in fuel consumption, and greener technology. One of the hybrid vehicle types is a hydro-pneumatic hybrid. The hydro-pneumatic hybrid car is a compounding of two or more types of propulsion subsystems work in a vehicle. This concept is not new because it has been practised on the heavy vehicle as a part of its hybrid system. However, using the concept of hydro-pneumatic on passenger automobiles is an innovation. The hydro-pneumatic hybrid technology uses a combination of the internal combustion engine (ICE) subsystem as the main propulsion, hydraulic subsystem as a hybrid propulsion unit, and the hydro-pneumatic accumulator as a power source as illustrated in Figure 1. During operation, the energy is stored in the accumulator, and once the energy in the accumulator is low, through braking and coasting, the regenerative braking is activated to charge the accumulator [1]. The concept utilises energy losses in braking

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and recovers into useful energy [2]. The hydro-pneumatic system usually applied by the heavy hybrid vehicle as secondary propulsion [3-5]. It is also widely used in the suspension system [6].

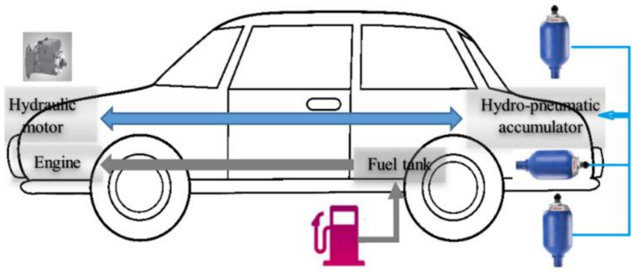

Figure 1. Configuration of the hydro-pneumatic hybrid system in passenger car.

Bosch, Eaton, and Parker are the giant company that is actively doing development to support the hydraulic hybrid technology. Bosch has produced the hydrostatic regenerative braking system and estimated fuel consumption improvement to 25% in urban refuse trucks or buses [7]. Eaton (2007) wrote that the company collaborated with the US Environmental Protection Agency (EPA) and US Parcel Service (UPS) to develop a hydraulic launch assist for a series-hybrid diesel truck system [8]. The company claimed a 60% to 70% fuel economy and a 40% reduction of carbon emission in the stop-and-go delivery. Parker was producing hydraulic hybrid drive transmission known as the RunWise to refuse truck [9]. California Water Resource Board has confirmed that the technology saves fuel economy and efficiency by up to 50%. Flaig (2013) stated that Bosch later collaborates with PSA Peugeot Citroen to produce a passenger car prototype that can reduce fuel consumption by up to 45% called Hybrid Aircar [10]. Eaton produces a hybrid system for refuse trucks and buses that operate in the stop-and-go duty cycle [11]. The company estimated a 20% to 30% improvement in fuel consumption. The actual driving shows that the lowest fuel savings are 20% while the highest is 70%.

The hydro-pneumatic hybrid technology is widely applied to heavy vehicles because of the relatively large size of its components, high force, and torque, which able to drive any commercial vehicles. However, one problem with this technology is the low energy density. Energy density is defined as the amount of energy stored in each system or region of space per unit volume or mass, which then is termed as specific energy. The low energy density of hydro-pneumatic technology makes it not suitable to be used in the full hybrid configuration [11][12]. This weakness is due to the limited capacity and low travel distance. Energy density is closely related to fluid type, compression, and the storage system. The large size of the storage system caused the energy capacity to increase. However, problems arise when it needs to be applied to the car system. While the small size more practical but its ability is limited. Materials for storage system affect the strength to store high pressure. The high pressure produces excellent torque to move the car. However, it resulted in adverse effects through the increase of weight to the system.

Most research focused on the use of a single storage system, which consists of a high-pressure accumulator and low-pressure accumulator [13][14]–[16]. This is imputable to the growth of weight that has been distinguished above. Lammert et al. (2014) conducted a lab-scale experiment on a parcel delivery truck. The truck used an 83.3 L accumulator that operate at 241 to 276 bar. He found that the configuration was able to increase 19% to 52% of fuel consumption in the diesel engine while 30% to 56% saving in the gasoline engine. Kepner (2002) had been using the bladder gas accumulator 54.5 L, operate at 172 to 345 bar at 5.4 L V8 sports utility vehicle. He found that the arrangement was likewise able to cut the emission that will affect pollution [17]. Boretti & Zanforlin (2014) take his first step to simulate the hybrid system in a passenger car application [18]. The high-pressure accumulator operates between 135 to 485 bars and the low-pressure tank 3.5 to 13.5 bars. The accumulators have low specific energy (1.8-4

Wh/Kg) but a wide range of specific power (7-4,000 W/kg). He found that the system was able to achieve a 30% better fuel economy.

Due to the low energy density and capacity faced by this technology, the authors would like to propose a new approach to overcome them. The proposed system is called multiple storage systems. The energy storage is arranged in parallel orders. This scheme delivers a smaller storage size, and it is easy to fit in the passenger car. Therefore, more storages number can be set up. The result, however, neglected the impact of extra weight at the moment since the research is still in the beginning phase. Based on the study, it is clearly shown that the technology is still in the research and development phase. Most of the research focused on simulation rather than experimental work [19][20]. Therefore, there are vast areas of research ready to be explored.

2. MATERIAL AND METHODS

2.1 Design

The procedure starts by designing the schematic diagram. Then, the functional simulation was conducted by using Automation Studio software. The purpose of the simulation is to ensure the designed schematic operate as desired. If not, the schematic diagram will be further improved until the desired operations obtained. Component's specification is determined in this process. When the design was completed, the next process is preparing the experiment setup. It involves the process of installation and fabrication based on the schematic diagram that has been drawn as shown in Figure 2 and 3. Once finished, the experiment was carried out to obtain the dependent data such as time, revolution per minute, and flow rate while the storage pressure is an independent variable. Some parameters were obtained through theoretical calculation such as power, torque, and efficiency. The obtained data was referred to as the component specification to ensure they are within the range and reasonable.

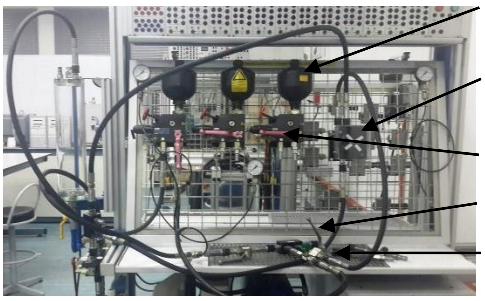

Figure 2. Experiment layout.

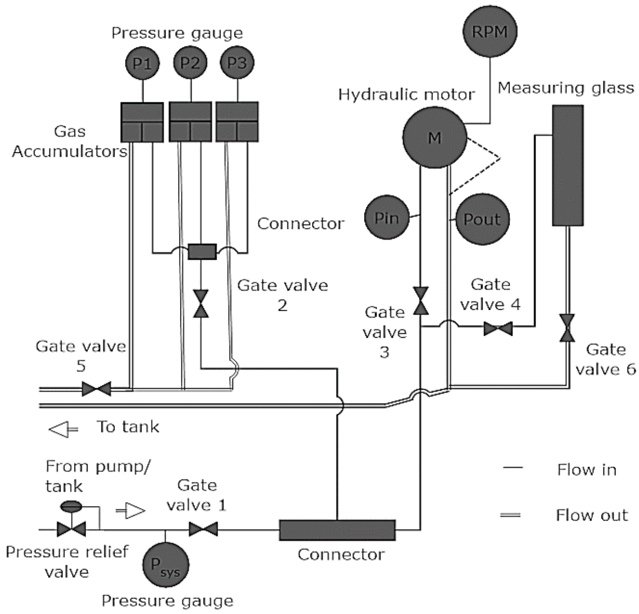

Figure 3. Schematic diagram.

The fix displacement vane pump was used to charge the accumulator with the volume displacement of 8 cm^3/revolution. The safety block was used to protect the accumulator from overpressure and embedded in the accumulator block. The experiment was conducted by using a 0.75 L accumulator with a permissible pressure ratio of 8:1, which is 30 bar, and maximum operating pressure is 210 bar. The flow rate specification for the accumulator is 95 L/min. The hydraulic motor has 8.2 cm^3 displacement and a maximum speed of 2450 rpm. The parameters involved in the experiment are as in Table 1.

Table 1 Testing parameter for the experiment

No.	Item	Variable Type
1	System pressure, p_{sys}	Independence
2	No of accumulator	Control
3	Pressure in, p_{in}	Dependence
4	Pressure out, p_{out}	Dependence
5	RPM	Dependence
6	Flow rate	Dependence

2.2 Experimental Procedure

In the experiment, the accumulator pressure p_1, p_2 and p_3 is set as 35 bar, 40 bar, 45 bar, 50 bar, and 55 bar. The pressure was selected based on the minimum range of permissible accumulator working pressure since the pre-charge is 30 bar. For the charging process, the gate valve 1 and 2 are open, and the rest are closed. When the pressure in the accumulator reaches the set limit, the gate valve 1 and 2 were closed. Then, to operate the hydraulic motor, gate valve 2 and 3 were opened. Based on the layout, the system fluid power can be calculated by using the following equation.

$$P_{fluid} = p_{1,2,3} \times Q \tag{1}$$

where P_{fluid} is power (Watt) produced by the energy storage tank. It depends on $p_{1,2,3}$ pressure in (N/m^2) and Q is the flow rate (m^3/s) in the input area.

In this study, it is assumed that the vane motor is working without losses. So, the shaft power is equal to fluid power. Therefore, power produced by the motor is calculated by using the following equation.

$$P_{motor} = \frac{2\pi NT}{60} = \Delta p \times Q \tag{2}$$

where, P_{motor} is power produced by a motor (Watt), N is motor speed (rev/min), T is theoretical torque (Nm), Δp is pressure different (N/m^2) or equivalent to $p_{in} - p_{out}$ (friction losses and minor losses has been considered) and Q is flow rate (m^3/s).

By inserting equation 2 in equation 3, the theoretical torque can be simplified as

$$T = \frac{60 P_{motor}}{2\pi N} \tag{3}$$

where, T is theoretical torque (Nm), P_{motor} is power produced by a motor (Watt) and N is motor speed (rev/min).
Another important parameter is the system efficiency that serves as how much energy converted to useful work as shown in equation 4.

$$\eta_{overall} = \frac{P_{motor}}{P_{in}} \times 100 \tag{4}$$

where, $\eta_{overall}$ is the overall efficiency of the system, P_{motor} is power produced by a motor (Watt) and P_{in} is power (Watt) generated by the energy storage.

3. RESULTS AND DISCUSSION

3.1 Charging and Discharging Time

Figure 4 shows that the higher the accumulator's pressure, the longer the time required for charging. The profile is linear and similar for the first, second, and third accumulators. In the beginning, the load time is almost the same, but once the pressure was increased, the required charging time varied. The starting is almost similar because the pressure has just surpassed the pre-charge pressure at 30 bar. At this stage, the level of compression is low, and there is much more space in the accumulator. Therefore, it filled up quickly.

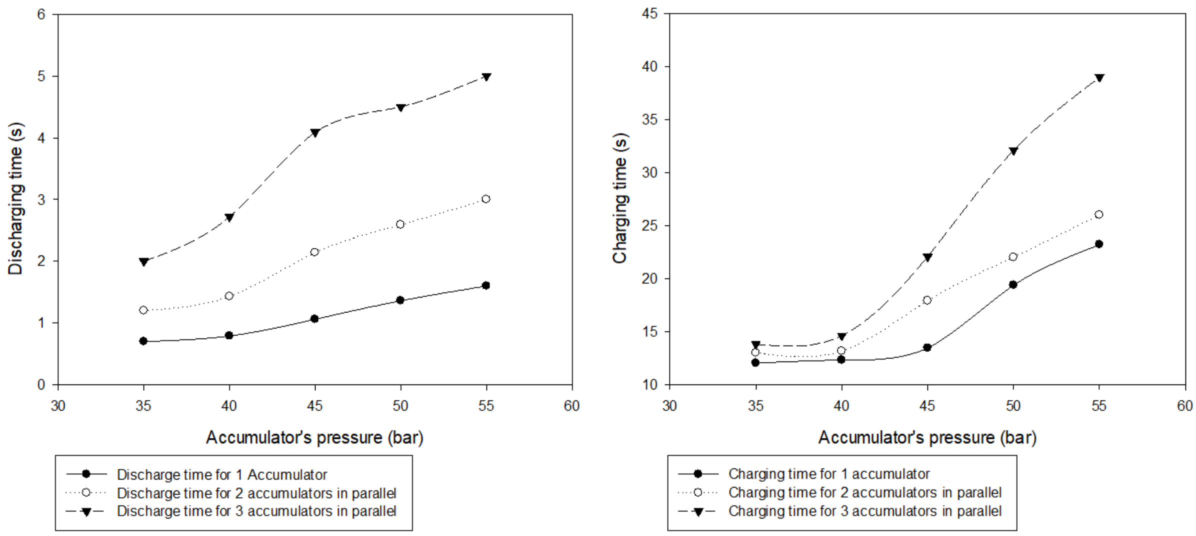

Figure 4. Effects of accumulator's pressure and charging time, discharging time.

When the pressure rises, the accumulator bladder space depleted, therefore, higher pressure is needed to push the diaphragm to compress the nitrogen gas. At a pressure of 35 bar, the charging time difference is 8% higher between 0.75 L (one accumulator) and 1.5 L (two accumulators in parallel). Meanwhile, at 45 bar and 55 bar, the charging time difference is 33% and 12%, each. For the 2.25 L (three accumulators in parallel), the charging time difference even wider about 14%, 64% and 68% at 35 bar, 45 bar, and 55 bar, respectively. During compression, there is one crucial element that should be considered and called the bulk modulus, β. The bulk modulus defined as the substance resistance to compression, $E_{\upsilon} = -V \times (\Delta p / \Delta V)$ where V is the original volume, Δp changes in pressure, and ΔV change in volume. In the beginning, the pressure is lower, and the bladder volume is high, so, based on the formula, the bulk modulus value is high. However, when the pressure was increased, the volume in the bladder will reduce. The bulk modulus becomes low. That explains the behaviour of the charging time different at low and high pressure. There are two types of fluids involved in the experiment: hydraulic oil and nitrogen gas. Bulk modulus for hydraulic oil is very low and can be neglected. Nitrogen is compressible and has high bulk modulus. It enables the compression process to store more energy. However, the bulk modulus also will result in the accumulator volume to reduce to the effective volume, which is lower than the volume of the accumulator [21]. In the case of thermodynamic relation, for an ideal gas, the isentropic bulk modulus is defined as the relationship between pressure, p and heat capacity ratio, γ. As for the discharging time, longer discharge time is better because more work will be done. The combination of three accumulators produces the longest discharge time due to the high volume flow rate and displacement.

The lowest discharge time is one accumulator with less than two seconds. Every increase in the pressure, the discharge time is increased. Therefore, it is necessary to control the volume flow rate of the accumulator. The higher volume flow rate will result in power increase but lower in discharging time. It is vice versa to the lower volume flow rate. At a pressure of 35 bar, the discharging time different between 0.75 L accumulator and the 1.5 L accumulator is 0.71 times higher. Meanwhile, at 45 bar and 55 bar, the percentage of difference are 1.0 and 0.87 times higher. For the 2.25 L, the discharge time differs even wider about 1.85, 2.85, and 2.12 times longer at 35 bar, 45 bar, and 55 bar, respectively. A proper selection of accumulator's volume flow rate is crucial, and it can be controlled by adopting a flow control valve.

3.2 Flow rate, Q and Motor Rotational Speed, RPM

Figure 5 shows the effect of accumulator's pressure on the volume flow rate. The flow rate is measured at the accumulator's output. The flow rate is proportionally increased to the increase of the accumulator's pressure. The flow rate results in the 0.75L accumulator were lower compared to the two and three accumulators. The continuity equation can prove the high value in 1.5 L and 2.25 L because $Q_t = Q_1 + Q_2 + Q_3$ where Q_t is the total flow rate, Q_1 is the first branch flow rate, Q_2 is the second branch flow rate and Q_3 is the third branch flow rate. However, the flowrate in 1.5 L and 2.25 L fluctuated. These are due to the additional volume giving the effect of disturbances at the branch connector; then, the fluid propagates at a finite velocity. The connected branch and valve limit the flow inside the components.

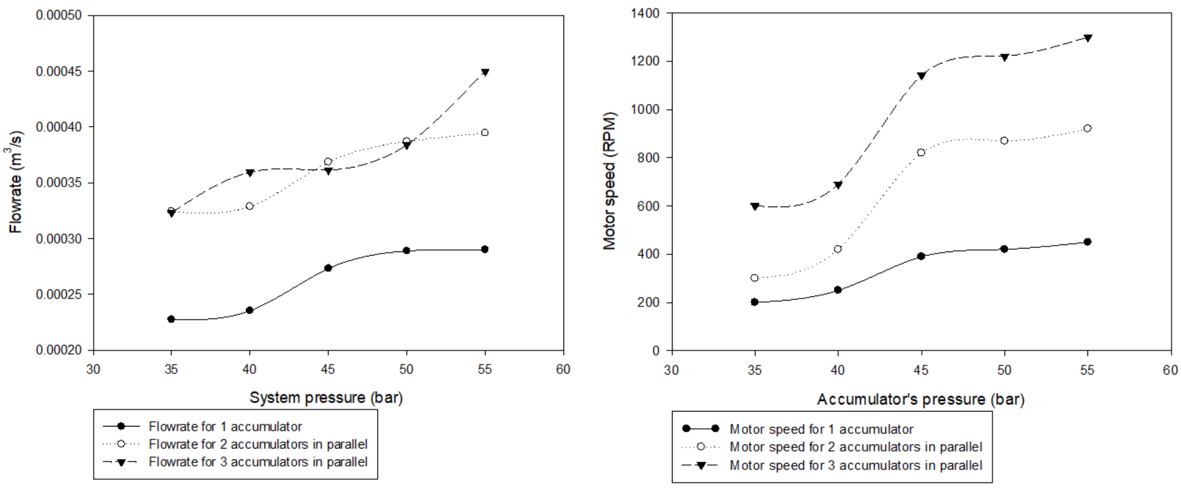

Figure 5. Effect of pressure changes to the flow rate and motor speed.

In this situation, at the orifice, the kinetic energy was increased, but pressure energy was reduced. The occurrence can be simulated by applying the energy equation as in Equation (5):

$$p_1 / \rho g + v_1^2 / 2g + z_1 = p_2 / \rho g + v_2^2 / 2g + z_2 + h \tag{5}$$

The setting with one accumulator produced RPM from 200 to 400. Meanwhile, two accumulators in parallel produced RPM from 300 to 900. The highest speed recorded by three accumulators in parallel, about 600 to 1300 RPM. The motor speed started with slight acceleration at 35 to 40 bar. Then, the acceleration increased sharply until 45 bar and then once again repeating slight acceleration until 55 bar. The profile of acceleration was similar for one, two, and three accumulators.

The disturbance inflow might be caused by the bottleneck and the occurrence of conflict flow direction between the direction of accumulator 1 and accumulator 3 as illustrated in

FigIt created a back pressure and produced a lower flow rate and some losses of pressure. In the future, the correct design and sizing of connector/branch must be properly selected to reduce such effect. Thus, further research needs to be conducted to see the effect of backpressure on the accumulator.

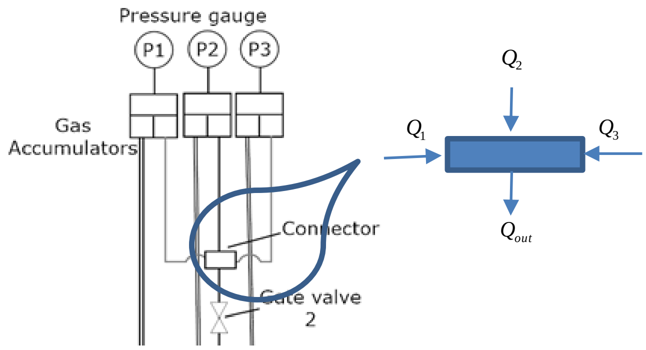

Figure 6. Disturbance to flow direction between accumulator 1, 2 and 3.

Volume displacement, V_d is used to associate the relationship between these two parameters, which have been discussed earlier. Volume displacement is the amount of liquid transferred from a pump's inlet to its outlet in one revolution or cycle. In theory, volume displacement is obtained by dividing flow by rpm. In a fixed-displacement pump, the output can be changed only by varying the drive speed. For the fix displacement pump, if the pressure value increases, the displacement volume will also change. For the volume displacement case, the relationship between flow and rpm is the opposite. Referring to Figure 6, the increase in flow rate was small, while the RPM change was significant. Therefore, the volume displacement value was reduced when the RPM increased. In another relationship, RPM increased when the system pressure increased. Thus, it can be concluded that the increase in pressure will decrease the volume displacement as shown in Figure 7.

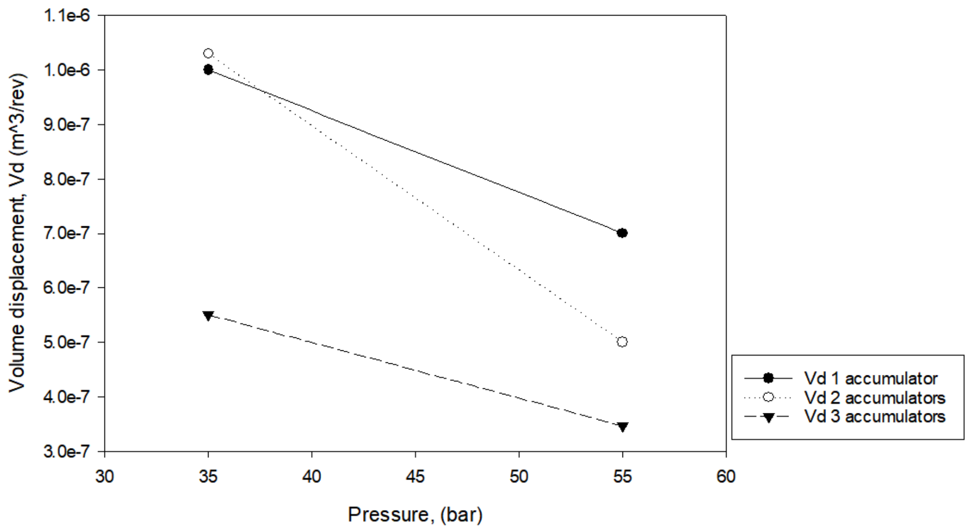

Figure 7. Volume displacement reduces when pressure is increased.

3.3 Pressure Drop, Δp

Pressure drop in fitting is a very crucial element in the fluid power system. The lower the pressure drop in the system will result in increased system efficiency. Otherwise, additional pressure is required to compensate for the pressure loss, or else, the output also decreases. The incremental in Figure 8 is proportional. However, the losses were considered to increase consistently since there are only slight changes between all accumulators. The accumulators' raise profile looks similar for each elevation of pressure. This figure has shown that the pressure loss was consistent in the system. Mostly, the pressure drops occur in the fitting and accessories due to major and minor losses. Significant losses also called friction losses, and minor losses happen when there is a disturbance in flow and effect of geometry. In the experiment, the effect of pressure losses cannot be neglected since the pressure changes have caused the pressure drop to increase too. This indicates that the pressure losses are significant. However, there are cases when the pressure is dominant, and the diameter increased; the losses in fitting become small.

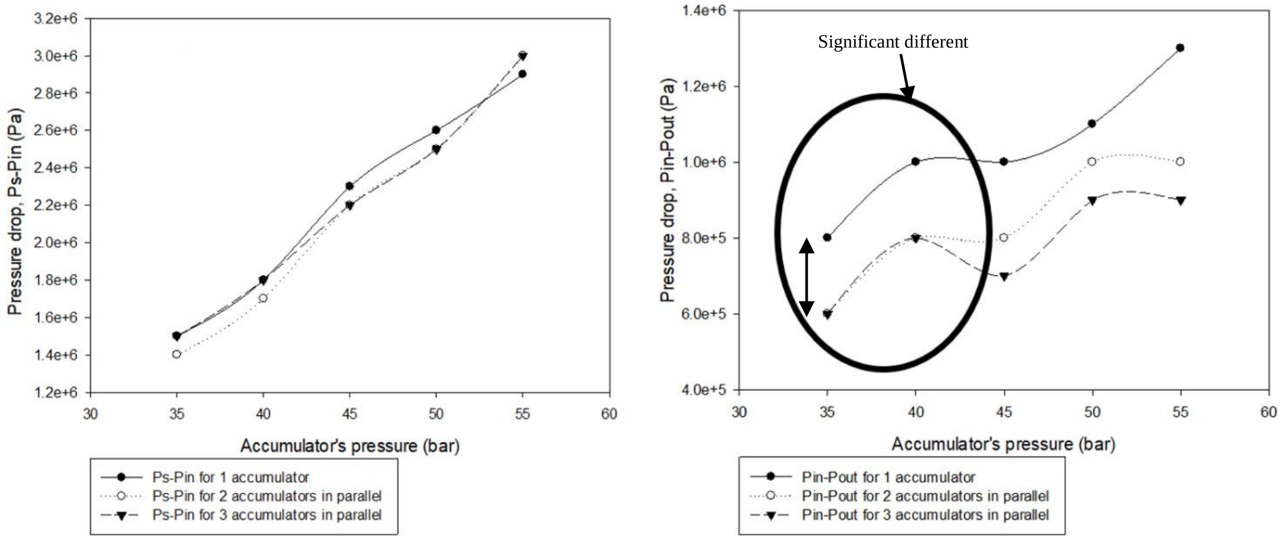

Figure 8. Effect of pressure change to the fitting's pressure drop and pressure drop in motor.

Another pressure loss that is considered as consequential is losses in the motor. By determining the input and output, the hydraulic motor efficiency can be calculated. Motor efficiency is closely related to cost-effective. It also indicates the time for maintenance. The maintenance will ensure the components return to the optimal level of operation. Pressure losses are higher at a single accumulator's motor. High losses in motor suggest that more energy has been converted to work, which resulted in high power. The lowest pressure losses are in the three accumulators. For the two and three accumulators, the profile was similar at 35 and 40 bars. However, when the pressure was increased, the different of the two accumulators start to increase higher than the three accumulators. The profile was related to the change of flow in the system, as previously shown in

Fig.

3.4 Calculated Power and Torque

The power generated by hydraulic motor and torque were proportional to the pressure difference shown in Figure 9. The highest power generated is at 55 bar by the three accumulators in parallel. Meanwhile, the lowest power is generated at 35 bar by the one accumulator. This suggests that power correlates with the capacity of the accumulator. Higher accumulator capacity and flow produced more power in return. The only restriction for the two and three accumulators is the flow limitation. This was confirmed by the similarity of the power generated and flow profile in the system, as illustrated in the previous Figure 5 and Figure 8

Figure . Up to one point, the flow has been fully developed and reached maximum flow which caused the profile of flow and power generated saturated. Since the branch orifice and flow conflict disrupted the flowrate, thus it affects the power generated. The profile also has shown that the power keeps increasing from 35 to 55 bar. There is a tendency that the profile will remain increase if higher pressure is given. The effect of high-pressure experiments should be considered in the future for the investigation of the limitation of the system.

For torque, the relationship between them is proportional. The higher the system pressure value, the higher the torque value. Nevertheless, results from the analysis shown that the torque effect caused by the pressure losses on the motor is inversely proportional. This comparison refers to the graph profile. Overall, although they are inversely proportional, the values of the torque change from one pressure to another in their respective categories. The highest torque value recorded was 18 Nm generated by 1 accumulator at 55 bar pressure. Whereas the smallest torque value is around 6.5 Nm produced by 3 accumulators at 45 bar pressure.

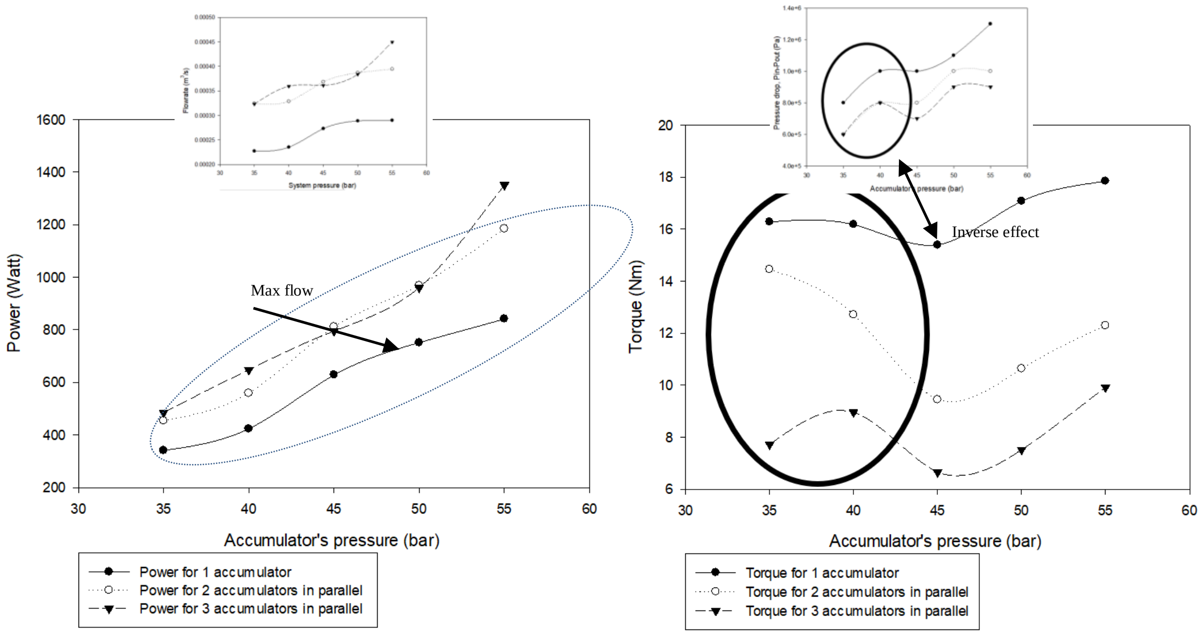

Figure 9. Effect of pressure change to the power and torque.

In overall, the torque value is high, and it is very practical to be applied in a vehicle application. However, there is something worthwhile to raise that is related to the initial pressure spiking issue. When the valve is open, the discharge pressure is extremely high and forming pressure spike causing the torque to increase. These usually happen at the low speed because lower speed swept more volume displacement per revolution. The "intermediate" small accumulator can be used to dampen the high pressure and avoid spiking [22]. The single accumulator produced the highest torque. It clearly shows that the more accumulators added to the system, the lower the torque it may produce due to higher flowrate and rpm.

3.5 Efficiency

The higher the value of effectiveness means the less energy is needed to move the propulsion unit. Figure 10 shows that effectiveness increased when the accumulator pressure is increased for all cases. However, since the flow rate influences the power, it also affects efficiency. Single accumulator produced the highest efficiency of about 52%, and it still considers low due to losses in the system and operating at lower operational pressure. There are too many losses caused by mechanical, flow, volumetric, and minor leakage. So, higher input pressure is required to compensate for the losses. The single accumulator has resulted in higher efficiency compared to two accumulators and three accumulators. This indicates that the more accumulators are added, the systems become more complex and decrease efficiency. Therefore, more advanced system control and higher efficiency components are needed to reduce the effect. The turning point of the efficiency profile is at 53 bar. The two and three accumulators had been intercepted and are higher than one accumulator.

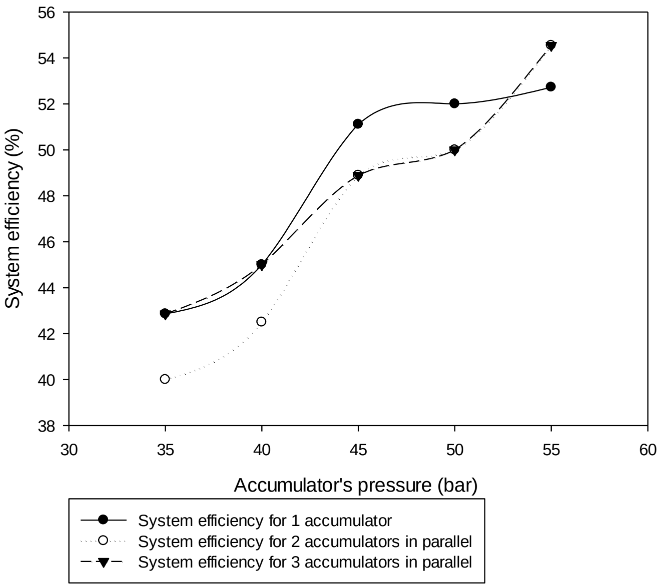

Figure 10. The overall efficiency of the system.

In some cases, the efficiency generated is the opposite of the above profile. The efficiency value decreases as pressure increases [23]. This scenario is dependent on the increased input and output values of the system. If the output increased is dominant for each pressure increase, then it produces an increase in the value of efficiency. However, if pressure and flow values are dominant in input, then they will produce less efficiency value. This relationship is illustrated through the equation $\eta_{sys} = P_{out}/P_{in} = 2\pi nT/pQ$. So, it can be said that each case has two possibilities as above. It depends on the value of pressure change, pressure loss, flow, rpm and torque. In the end, all that is required is an increased value of efficiency.

4. CONCLUSION

In conclusion, the study has shown that by adding more accumulators to the driveline of the hydro-pneumatic system does not increase the whole system performance. It is only valid for the power and discharges time, but for torque and efficiency at a certain pressure, it shows the opposite results. The high number of accumulator source in the system causes disturbance and orifice effect to the flowrate and has resulted in torque and efficiency to drop. Meanwhile, in terms of pressure, losses in two and three accumulators are less affected compared to the single accumulator. The lowest efficiency recorded by the experiment is 40%, and the highest is 55%. The efficiency is still lower and not optimum. The operating pressure is higher than the 55 bar. In the future, research should focus on finding the optimum operating pressure, improve the orifice effect, and reduce the leaking in the motor to improve efficiency.

ACKNOWLEDGEMENT

This paper was made possible by a scholarship from the Ministry of Higher Education and Universiti Teknikal Malaysia Melaka. Authors also would like to take this opportunity to thank Universiti Malaysia Pahang for the opportunities and the facilities provided to complete this study.

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