Faculty of Mechanical Engineering

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REGENERATIVE BRAKING EFFECTS ON ISOTHERMAL AND ADIABATIC ENERGY STORAGE OF HYDRO-PNEUMATIC DRIVELINE

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Bachelor Degree of Mechanical Engineering with Honor

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REGENERATIVE BRAKING EFFECTS ON ISOTHERMAL AND ADIABATIC ENERGY STORAGE OF HYDRO-PNEUMATIC DRIVELINE

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A thesis submitted

in fulfillment of the requirements for the degree of Mechanical Engineering

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SUPERVISOR'S DECLARATION

I declare that this thesis entitled "Regenerative Braking Effects On Isothermal And Adiabatic Energy Storage Of Hydro-Pneumatic Driveline" is the result of my research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in the candidature of any other degree.

Signature :..

Name of Supervisor: FAIZIL BIN WASBARI

Date :..

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APPROVAL

I hereby declare that I have read this dissertation/report and in my opinion, this dissertation/report is sufficient regarding scope and quality as partial fulfillment of Bachelor Degree of Mechanical Engineering with Honor.

Signature : ....

Name : ....

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DEDICATION

To my beloved mother and father

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ABSTRACT

The regenerative braking system is a process whereby the motor is reversed during the deceleration or stopping of a vehicle. Nowadays, there are various types of storage used to capture energy such as electrical, hydraulic, compress and kinetic. Hydrostatic regenerative braking system (HRB) was first retrofitted on a refuse truck. In order to apply HRB in the vehicle, research towards hydraulic energy storage performance will be needed. The hydraulic energy storage also known as an accumulator and the selection of the accumulator is based on their performance. The performance of each process will produce a different result. Thus, this research seeks to simulate regenerative breaking performance for adiabatic and isothermal processes**.** The result of regenerative braking performance for adiabatic and isothermal processes was obtained from simulation and needed to be compared based on the efficiency. The software used to conduct the simulation is Automation Studio. The result shows that isothermal process gives higher volume effectiveness and energy efficiency which is 13.55% and 17% compared to adiabatic process. However, when it comes to charging process (filling time), the adiabatic process gives higher result which is 18.31% compared to isothermal process. Adiabatic process only takes 112.37 s to reach 200 bar while isothermal process took 126.27 s to reach 200 bar. For the best case, a combination of both processes will be suitable to apply to the accumulator.

ABSTRAK

Sistem brek jenaan semula adalah satu proses di mana motor diundurkan semasa kenderaan bergerak perlahan atau kenderaan berhenti. Pada masa kini, Terdapat pelbagai jenis storan yang digunakan untuk menyimpan tenaga seperti elektrik, hidraulik, mampat dan kinetik. Permulaan sistem brek regeneratif hidrostatik (HRB) telah digunakan oleh lori sampah. Untuk menggunakan HRB dalam kenderaan, kajian terhadap prestasi simpanan tenaga hidraulik akan diperlukan. Storan tenaga hidraulik juga dikenali sebagai pemumpuk dan pemilihan pemumpuk tersebut adalah berdasarkan prestasi mereka. Prestasi setiap proses akan menghasilkan keputusan yang berbeza. Oleh itu, kajian ini bertujuan untuk melihat prestasi adibatik proses dan proses sesuhu di dalam storan tenaga di pemumpuk. Hasil daripada prestasi brek rjenaan semula proses adibatik dan proses sesuhu telah diperolehi daripada simulasi dan perlu dibandingkan berdasarkan efisyen masing-masing. Perisian yang digunakan untuk menjalankan simulasi ini adalah Automasi Studio. Hasil menunjukkan bahawa sesuhu proses memberikan lebih tinggi isipadu keberkesanan iaitu 13.55% dan keberkesanan tenaga iaitu 17% berbanding adibatik proses. Tetapi apabila ia disabitkan dengan mengecas p proses adibatik (penuhi masa) memberikan hasil yang lebih tinggi berbanding dengan sesuhu proses iaitu dengan 18.31% . Bagi kes terbaik, gabungan kedua-dua proses akan sesuai dipakai di pemumpuk itu.

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LIST OF ABBREVIATIONS

HRB	Hydrostatic Regenerative Braking
CVT	Continuous Variable Transmission
EPS	Expended Polystyrene
XPS	Extruded polystyrene
PUR	Polyurethane
VIP	Vacuum Insulation Panel
GFP	Gas Filled Panel
PCM	Phase Change Material
ICE	Internal Combustion Engine
DCV	Directional Control Valve
FCV	Flow Control Valve
HEV	Hydraulic Electric Vehicle
HHV	Hydraulic Hybrid Vehicle
ICE	Internal Combustion Engine
MIG	Metal Inert Gases

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CH_4	Methane
MG	Motor Generator
N_2	Nitrogen
PHEV	Parallel Hybrid Electric Vehicle
PHHV	Parallel Hydraulic Hybrid Vehicle
PRV	Pressure Relieve Valve
SHHV	Series Hydraulic Hybrid Vehicle
SUV	Sports Utility Vehicle
SOP	Standard Operating Procedure

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LIST OF SYMBOLS

C = Displacement (m^3/rad)

E = energy storage of the accumulator (Joule)

K_i = Correction factor

η_M = Mechanical efficiency

$\eta_{overall}$ = Overall efficiency

η_v = Volumetric efficiency

Δp = Pressure different (N/m^2)

P_{gh} = Gas pressure (Pascal)

P_{op} = Pressure of the oil (Pascal)

p_{in} = Pump input pressure (N/m^2)

p_{out} = Pump output pressure (N/m^2)

P_P = Pump power (Watt)

P_S = Shaft power (Watt)

Q_i = Flow rate (m^3/s)

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$\mathrm{Q}_{\mathrm{out}}$ = Pump output flow rate (m^3/s)

Q_{out} = Pump output flow rate (m^3/s)

t_{i} = Filling time (s)

T = Torque (Nm)

V_1 = Volume before compression (liter)

V_2 = Volume after compression (liter)

V_{gh} = Gas volume (m^3)

$\Delta\mathrm{V}_{\mathrm{ideal}}$ = Effective volume (liter)

$\Delta\mathrm{V}_{\mathrm{ideal}}$ = Ideal volume under isothermal (liter)

ω = Nominal speed (rad/s)

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CHAPTER 1

INTRODUCTION

1.1 Background

The regenerative braking system is a process whereby the motor is reversed during the deceleration or stopping of a vehicle. The regenerative braking system functions by capturing kinetic energy which it will later store and reuse the energy during the acceleration of the vehicle. There are various types of storage used to capture energy such as electrical, hydraulic, compress and kinetic. For example, in an electric hybrid vehicle, the energy of a moving car is captured and stored in the battery or an ultra-capacitor. If the energy is to be stored in a battery, it will be stored chemically. On the other hand, in ultra-capacitor energy is stored through charge separation. While, in a kinetic hybrid, energy is stored by transferring energy to and from the flywheel and the drivetrain in the form of kinetic energy. Alternatively, hydraulic hybrids store energy in accumulators in the form of compressed gas where the gas and fluid are usually separated by a piston or a bladder (Midgley and Cebon, 2012).

Hydrostatic regenerative braking system (HRB) was first retrofitted on a refuse truck made by a company named Bosch Rexroth in January 2011 to ensure that the trucks are environmentally friendly as it can reduce the consumption of fuel. As it is a fact that the Fairfax

Truck stops and start almost 800 times a day to collect trash. Currently, this is the type of braking system has only been retrofitted in heavy load vehicles such as a Refuse Truck (Paul Heney,2011).

The increase of the use of the regenerative braking system has become famous for several reasons such as environmentally friendly, reduce fuel consumption, avert the loss of useful energy and increase work efficiency. Currently, many types of research concentrate more on the simulation consumption of fuel in hybrid-system rather than the subsystem itself (Wasbari *et al.*, 2014).

However, there is a limited study which focuses on the performance of energy storage under different thermal process mainly for passenger automotive hybrid section. The importance of this study is to examine the temperature effect on the performance of energy storage and come up with the most suitable solution to control the compression process in the system. This is because when a pedal break in a vehicle is pressed on, due to the process of compression, the temperature of the system will consequently increase. The increase in temperature of the system will affect the volume change accordingly as a result of the thermal expansion. Therefore, to obtain the optimal operation energy storage, the compression process must be controlled. As such, the isothermal and adiabatic process will be used for this research to achieve the optimal energy storage (Wasbari *et al.*, 2017).

1.2 Objective

The primary objectives of this project are: -

1) To design the charging system of regenerative breaking.
2) To simulate regenerative breaking performance for adiabatic and isothermal processes.
3) To validate the result of simulation.

1.3 Scope

The central subject matter of this research is the hydro-pneumatic driveline sub-system which is a form of a regenerative braking system. This type of braking system will be able to convert kinetic energy into compression energy. This research will be simulated using a software known as Automation Studio tools. Basically, the typical process assumed in the accumulator is isothermal, adiabatic and polytropic. Unfortunately, this research will only cover the effect of the isothermal and adiabatic process in the accumulator and focus on fluid power performance such as flow rate, Q, velocity, V, power, P, and efficiency.

1.4 Problem Statement

In a standard internal combustion engine, the peak efficiency of a vehicle would be around 30% to 40% (Fyffe, 2014). The loss of work efficiency is due to several reasons as the vehicle operates in a wide range of condition such as idling, acceleration, deceleration, stopping and cruising. In other words, the loss is due to combustion loss, heat loss, exhaust loss and mechanical loss. This reason causes the engine to operate away from its efficiency point. Thus, the work efficiency of the car is only 20% due to these losses (Fyffe, 2014). Unlike Hybrid vehicles, the electric power motor helps to accelerate the vehicle when a car requires more power than the internal combustion could produce and in contrary generate the electric motor in reverse to optimize the work efficiency when too much power is available during maximum efficiency point. Furthermore, in the automotive industry, no one researches the adiabatic and isothermal effect on energy storage which is an accumulator. Therefore, this research seeks to know which

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effect is the best performance adiabatic or isothermal in energy storage which is in the accumulator.

Withal, to set up the energy stored in a car, the size and the specific pressure must be counted on to make it compatible and convenient for a auto. As this type of system has only been installed in heavy load vehicles because the heavy vehicle has adequate blank to put in such a scheme as compared to cars with limited space.

1.5 Hypothesis

This research is expected to get a higher work efficiency than an average car. Other than that, regarding volume and capacity in the energy storage which is an accumulator, this research will be expected that isothermal process is better than adiabatic process.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

For the literature review, the structuring of the chapter includes the regenerative braking which covers the literature regarding electrical, hydraulic and mechanical hybrid system and its energy storage. Other than that, this chapter also includes regenerative braking background which describes the history of the regenerative braking. Next, it also includes the regenerative braking in a vehicle which describes the application of regenerative braking in the vehicle. Besides, the efficiency of regenerative braking, component and its energy storage also will be included in this chapter.

2.2 Hybrid System

Hybrid can be defined as having two components. While automobile is a vehicle which gains its energy from two or more different sources for propulsion. In previous years electric hybrid cars are known to be most efficient in fuel consumption compared to other types of hybrid technologies. However recently the production of a prototype of air hybrid car produced by PSA Peugeot-Citroen is proven to have lower consumption of fuels than electric hybrid vehicles (Wasbari, Bakar, Gan, Tahir, *et al.*, 2017). This shows the potential of air hybrid vehicles in decreasing fuel consumption. There are various types of hybrid system such as electrical, kinetic and hydraulic hybrid system. While other hybrid systems are still in the process of development, only hybrid electric has been widely used.

The first type of hybrid system is the electric hybrid system. In electric hybrid vehicle system, energy will be stored in a battery or layer capacitor also known as (ultra-capacitor). Commonly battery will store energy by electrical and for ultra-capacitor energy will be stored through charge separation. In a battery, there has particular high energy while in capacitor there have nearly high specific power and lower specific energy. Battery and capacitor are utilized to stored energy from regenerative braking and any additional power produced by vehicle power plant. From regenerative braking, the electric generator will be utilized as a transformer between rotational motion and the electrical energy. This technology has already been used in Volvo and for the hybrid heavy vehicle.

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In the kinetic hybrid system, energy will be stored in the form of kinetic energy using the flywheel and continuous variable transmission (CVT). This function is to transfer energy between flywheel and drivetrain. Moreover, energy is stored in flywheel instead of battery and ultra-capacitor. This method is commonly known as “flywheel battery” (Midgley and Cebon, 2012).

$$E = \frac{1}{2} J\omega^2 \quad (1)$$

Where E_f = flywheel stores the energy

ω= rotational speed

J=rotational inertia

The hybrid system is a vehicle consisting of two sources of propulsion mainly. Internal combustion engine (ICE) and energy storage device. In Hydraulic hybrids, a hydraulic accumulator stores energy in the form of compressed nitrogen gas by hydraulic fluid. A diaphragm separates gas and fluid. After the gas and fluid are separated in the accumulator, fluid is pumped to one side of the accumulator and gas is compressed. Hydraulic hybrid vehicles mainly consist of two accumulators. One of the accumulators is at high pressure while the other is at low pressure. The turning force of a wheel is used by the hydraulic pump-motor to pump fluid from the low-pressure accumulator to the high-pressure accumulator during regenerative braking and vice versa to remove energy. This means that fluid is transferred from high-pressure accumulator to low-pressure accumulator to remove the energy from the system and create a torque (Midgley and Cebon, 2012). Adiabatic compression and isothermal compression is a standard process that involves in the accumulator. Usually, the adiabatic compression process is related to the process that occurs inside an accumulator while isothermal compression process is related to the temperature of working fluid. During the compression process, the temperature will increase and can lead to heat losses through the walls of the accumulator. This heat loss can be prevented by thermal insulation along the gas side. This technique has been proven in previous research (Pourmovahed and Otis, 1990).

Assuming energy stored in the accumulator is adiabatic: -

$$E_{acc} = \left\{ Pcomp \ \frac{1 - r_v \,\hat{}\, 1 - \gamma}{\gamma - 1} - Patm(r_v - 1) \right\} v_{comp} \qquad (2)$$

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Where $Pcomp$= pressure of gas athe nd its compressed air

r_v= volumetric compression ratio

γ= adiabatic index

$Patm$= pressure of atmospheric

Figure 1 shows that the accumulator installed in a vehicle which is in the red is a high-pressure tank and the blue color is a low-pressure tank.

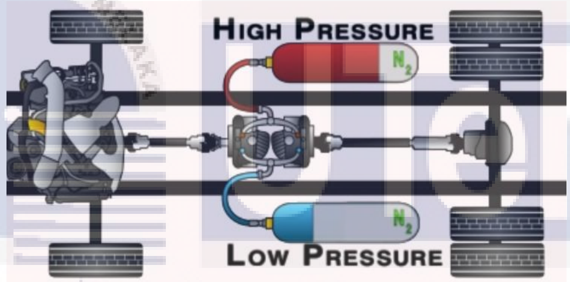

Figure 1: Accumulator in Vehicle

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2.3 Regenerative Braking Background

It is undeniable in this 21st century the demand for fossil fuels is high all around the world. The world's natural resources such as gasoline, oil, and coal are rapidly falling and because these are non-renewable resources extracted through "low-hanging fruit" principle results in depletion of resources. As fossil fuels are depleting, fuel price also tends to increase due to high demand. Thus, people are resorting towards other forms of energy sources and optimizing the use of existing energy.

Regenerative braking is system is a system introduced to reduce consumption of fuel by increasing work efficiency of a vehicle and reduce the emission of carbon dioxide (Sizing *et al.*, 2014). Regenerative braking was introduced by Frenchman M.A. Darracq in the year 1987. This technique allows recovering kinetic energy while braking and recharging the battery. It is one of the significant contributions for electric and HEV (hybrid electric vehicle) technology as it can increase energy efficiency (Ehsani *et al*. ,2009).

The regenerative braking system is a process where the kinetic energy of a vehicle can be temporarily stored by a storage system. The stored energy is converted to kinetic energy when the vehicle requires it for acceleration. Thus, reduces wastage of energy which usually dissipates when the brake is applied. Without the regenerative braking system, the more frequent the brake is applied, the more energy is lost. Therefore, the regenerative braking system improves the efficiency of a vehicle as there is an increase in energy output which also reduces the initial energy required to propel the vehicle (Rose, 2009).

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2.4 Regenerative Braking in Vehicle

In the early 70's, many researchers have studied about the implementation of a hybrid powertrain including regenerative braking which can give a benefit or save to the fuel economy of the vehicle that is operating under urban driving condition (Rose, 2009). Moreover, the increase in petroleum price is the major things that can contribute to the study and development efforts for energy conversation. Much consideration has been made by the researchers to develop this regenerative braking system such as it can reduce the fuel consumption, reduced operating cost and reduced gaseous emission including primarily carbon dioxide.

Regenerative braking only guarantees significant gains in the local area driving since 62.5% energy dissipated in the Metropolitan cycle due to frequent braking. Fuel consumption can be improved by 33% if all braking energy can regenerate without having a loss in the regenerative system (Rose, 2009). Besides that, by installing regenerative energy storage system in a vehicle, it can slightly improve fuel saving, theoretically up to 23% in a 1600 kg vehicle on a level road of public driving schedule. If the weight of the vehicle reduces the fuel-saving also decrease. In 1000 kg vehicle theoretically, the fuel saving is only up to 15% (Rose, 2009). Research by Volkswagen has shown that if the hybrid using both systems which is electrical drive and internal combustion engine that can give more fuel saving of over 20% compared with just 5-6% from only one system which is purely electric (Rose, 2009).

Most of the American vehicle manufactures believe that hybrid vehicle is a way to achieve more flexibility and range out of the electrical vehicle until better batteries are available. While most European believes that hybrid vehicle is a way to achieve high fuel efficiency and very low emission from the liquid fueled vehicle. This difference is because in LA air contamination issue stretches out finished a large region requiring a vehicle with a vast range and zero emission capability. While in Europe, it’s a quick different fact which is in Europe the pollution tends to be a localized event concentrated in urban areas, this fact also combine with the fact most of the Europe families or citizen have two or more car meaning that manufacturers need to provide a car that can deal with a local air quality (Rose, 2009).

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2.5 Advantages and Disadvantages Of Regenerative Braking

There have a lot of advantages and disadvantages of the regenerative braking system. The main advantages of regenerative braking are (Rose, 2009): -

- Improved fuel economy

  Its depend on duty cycle, powertrain design, control strategy and the efficiency of the individual component.

- Emission reduction

  Engine emissions will be reduced by engine decoupling, reducing total engine revolutions and total time off engine operation.

- Improved performance

  By using regenerative braking, the performance of the car can be increase by restoring the energy again.

- Reduction in engine wear

  This can be done by the engine on/off strategy

- Reduction in break wear

  Reduction in break wear will be reduced by reducing the cost of replacement brake lining, cost of labor to install down and vehicle downtime.

- Smaller accessories

  In hybrid Powertrain will offers downsizing or eliminating some accessories, thus partially offsetting the increased vehicle weight and cost due to the hybrid hardware addition.

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While the disadvantages are: -

- Added weight

  Extra components can increase weight and also increases fuel consumption, offset by smaller engine operating at its best efficiency.

- Complexity

  Its depends on control necessary for the operation of the regenerative braking system

- Cost

  Costing will be expensive due to of components, engineering, manufacturing, and installation. However, mass production can reduce the cost to a reasonable level

- Noise

  Its dependent on the system. Some system is noisier than usual.

- Added maintenance requirement

  Its depend on the complexity of the design. If the invention is more complicated, thus, there requires a frequent maintenance

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2.6 The efficiency of Regenerative Braking

Hybrid vehicles are considered to be more environmentally friendly and energy efficient as it can store and reuse energy efficiently. Even though Hybrid electric vehicles are more environmentally friendly and energy efficient, but the cost for such a system is expensive. On the other hand, pure electric vehicles would have the short driving range and expensive battery. As for hydraulic vehicles, it uses a hydraulic system accumulator which when it depletes, conventional engine reengages. At the same time, when the brake pedal is pressed, brake energy is recycled using the hydraulic motor-pump which circulates back the energy. In a research studying energy efficiency comparison between parallel and series of hydraulic and electric hybrid and also hydraulic-electric hybrid vehicle using the New European Driving Cycle (NEDC), the result shows that series hydraulic hybrid vehicle consumed fuel 21.8% lower as compared to series electric hybrid vehicle. Furthermore, the result also shows that parallel hybrid electric vehicle has lower fuel consumption by 3.80% than the parallel hydraulic hybrid. Also, hydraulic-electric hybrid vehicle consumed 11.4% less electricity compared too pure electric vehicle proving that hydraulic-electric hybrid able to provide the best energy cost compared to the other configurations (Chen, 2015).

Table 1 shows that percentage improvement in economic savings between electrical and hydraulic hybrid vehicle.

Table 1: Percentage Improvement in Economic Savings (Chen, 2015)

Configuration	Percentage Improvement (%)
MT vehicle used in this study	— (Baseline)
SHEV	15.4
SHHV	33.8
PHEV	38.2
PHHV	35.9
EV	72.6
HEHV	75.7

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2.7 Regenerative Braking: Hydraulic Component

Figure 2 shows that the component in regenerative braking in the hydraulic hybrid system.

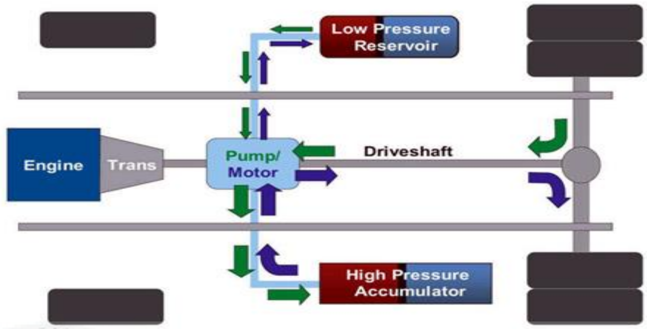


Figure 2: Component of Regenerative Braking in Hydraulic Hybrid System

There have 4 main components in regenerative braking in a vehicle which are: -

- High-pressure accumulator

  The high-pressure accumulator will store the energy by using nitrogen to pressurize the hydraulic fluid and used the pump motor to make the wheels turn.

- Low-pressure reservoir

  The function of the low-pressure reservoir is to store low-pressure hydraulic fluid. This will be stored after pressurizing that used to drive the wheel

- Engine pump/motor

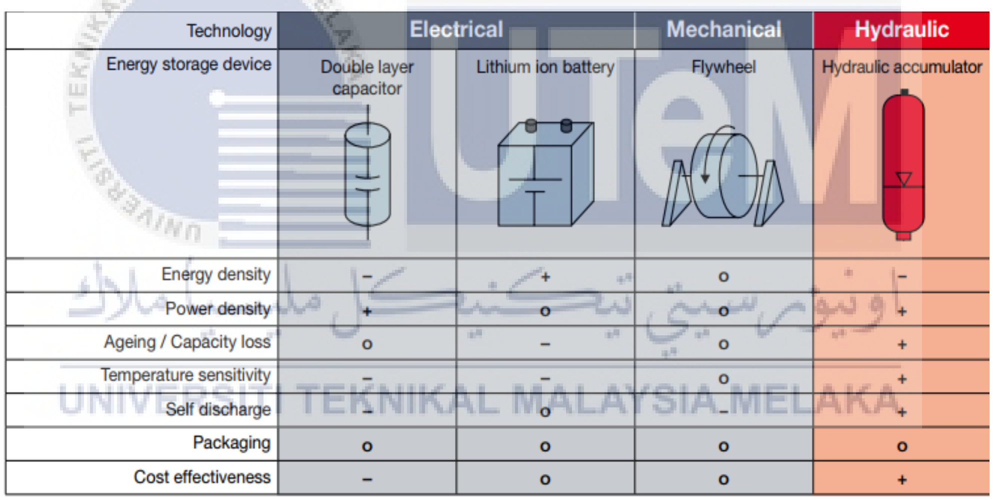
  Engine pump/motor is used to stars the engine. The pump will be used to generate fluid pressure as needed.

➢ Drive pump motor

Drives pump motor will function as tow function which is it will react as a motor when driving and it also will react to a pump during regenerative braking.

2.8 Regenerative Braking: Energy Storage

Figure 3 shows that comparison between different types of energy storage which are electrical, mechanical and hydraulic.



Technology	Electrical		Mechanical	Hydraulic
Energy storage device	Double layer capacitor	Lithium ion battery	Flywheel	Hydraulic accumulator
Energy density	–	+	o	–
Power density	+	o	o	+
Ageing / Capacity loss	o	–	o	+
Temperature sensitivity	–	–	o	+
Self discharge	–	o	–	+
Packaging	o	o	o	o
Cost effectiveness	–	o	o	+

Figure 3 : Different Types of Energy Storage (Zhang, 2010)

The primary source of energy in a vehicle comes from the internal combustion engine (ICE). While the secondary sources of energy in a hybrid system may come from double layer capacitors, flywheel system and hydraulic accumulators which acts as temporary energy storage.

2.8.1 Hydraulic Energy Storage

Energy storage systems offer a full array of technical approaches to managing our power supply to produce a more resilient energy infrastructure and bring cost savings to utilities and consumers. In Hydraulic Hybrid system the type of energy storage used is known as a Hydraulic accumulator. Though there are many types of hydraulic accumulators, the two main types of hydraulic accumulators are bladder and piston.

In gas bladder accumulator, it consists of a flexible bladder which separates the compressible gas and the fluid. The gas contained inside the bladder is squeezed by the fluid for it to compress the gas. The benefit of using a bladder accumulator is that it can be used in any orientation as long as the bladder does not rub against the wall. However, it is preferable to be installed in a vertical position. On the other hand, the disadvantage of a bladder accumulator is that over time the gas diffuses through the bladder which causes a change in pressure and compressibility.

On the other hand, in a piston type accumulator, the gas and fluid are separated by a piston. Even though a piston accumulator is much cheaper and almost maintenance free as compared to a bladder accumulator, the piston accumulator can only be placed in a vertical position. This is to prevent the building up of debris or solid contaminants which can affect or ruin the seal (Zhang, 2010).

Figure 4 below shows that, a component of the accumulator which is bladder, gas relief valve, hydraulic outlet/inlet valve and nitrogen.

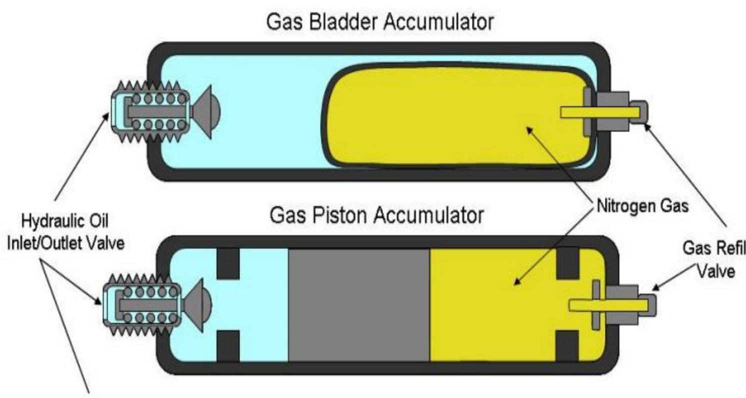


Figure 4 : Bladder and Piston Accumulator.

2.8.2 Kinetic Energy Storage

The flywheel is energy storage used in kinetic hybrids. The flywheel energy storage system has been introduced thousands of years ago and considered one of the earliest energy storage developed. (Amiryar and Pullen,2017), claimed that the flywheel system is affected by a rotating mass principle rotating in an axis. It converts the electrical energy into kinetic or mechanical energy. The energy is stored in the form of rotational kinetic energy. The flywheel speeds up when storing energy and subsequently slows down when energy is discharged to transfer the accumulated energy. The rotation of the flywheel is affected by the motor-generator which controls the interchange of energy from electric to kinetic and kinetic to electric energy. Mechanical inertia is the basis of this storage method (Amiryar and Pullen, 2017).

FESS consist of a spinning rotor, MG, bearings, a power electronics interface, and containment or housing, which are discussed in detail in the following subsections. A typical flywheel system suitable for ground-based power is schematically shown in Figure 5.

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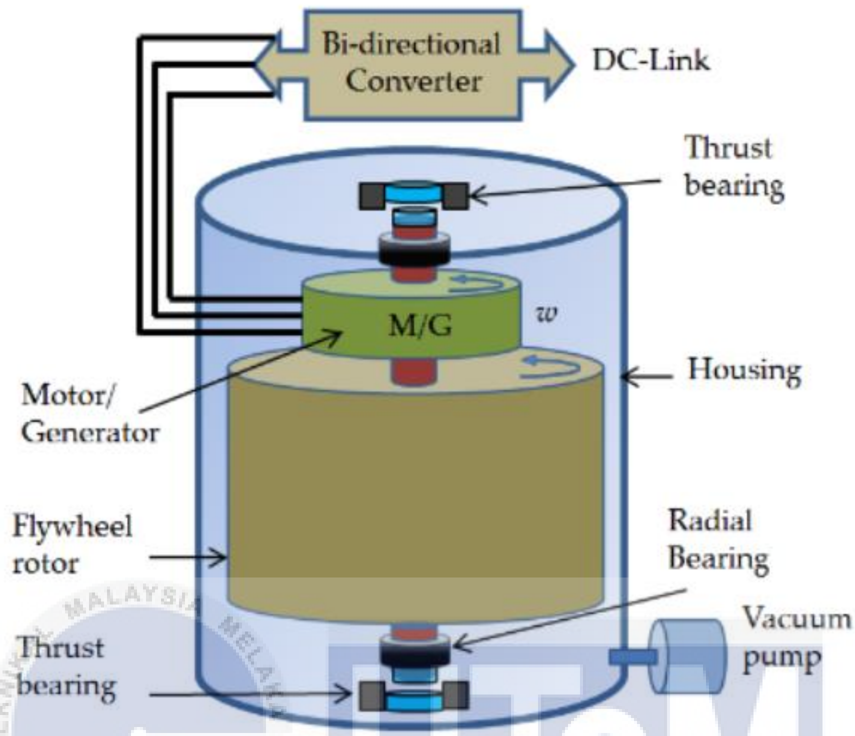

Figure 5 : Structure and Components of a Flywheel (Amiryar and Pullen, 2017)

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In the flywheel, the stored of energy is determined by the material and the shape of the rotor. It is directly proportional to the moment of the inertia and the square of its angular velocity, as shown in Equation below:

$$E = \frac{1}{2} J\omega^2 \tag{3}$$

Where E= flywheel stores the energy

ω= rotational speed

J= rotational inertia.

The useful energy of a flywheel within energy of a flywheel within a speed range of minimum speed (ω_{min}) and maximum speed (ω_{max}) can be obtained by

$$E = \frac{1}{2} I(\omega_{max^2} - \omega_{min^2}) = \frac{1}{2} I\omega_{max^2}(1 - \frac{\omega_{min^2}}{\omega_{max^2}}) \tag{4}$$

Flywheels are often built as solid or hollow cylinders, ranging from short and disc-type, to long and drum-type. For a solid cylinder or disc-type flywheel, the moment of inertia is *given by:*

$$I = \frac{1}{2} mr^2 \tag{5}$$

Where *m* is the rotor mass, and *r* is the outer radius. For a hollow cylinder flywheel of outer radius *b* and inner radius *a*, as shown in Figure 6 , the moment of inertia is

$$I = \frac{1}{2} m(b^2 - a^2) \tag{6}$$

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Figure 6 : Hollow Cylinder Flywheel (Amiryar and Pullen, 2017)

2.8.3 Electric Energy Storage

Commonly double layer capacitor and battery lithium ion are energy storage that uses in an electric hybrid. The double layer capacitor or called supercapacitor has been known for 60 years (IEC, 2011). Compared to classical energy storage which is a general battery, this double layer capacitor will fill the gaps between classical capacitor because there have extensive cycle capability, high power capability and many order of magnitude higher energy storage capability when contrasted to the traditional capacitor. This technology has two primary highlights which are high capacitance value of order many thousands farad and possibility of very fast charges and discharges regarding to extraordinarily low inner resistance. This feature is not available on the classical capacitor. This technology also delivers many advantages which no maintenance are needed, extended lifetime period and can be utilized in a broad temperature range (hot, cold and moist). Ordinarily, the lifetime period for this double layer capacitor is approximately one million cycle or 10 years of employment. They are also environmentally friendly and can be easily recycled. The efficiency of this storage reaches 90% and can simulate very high and possess a good value for efficiency (IEC, 2011). This technology is widely used mainly to applications with a large number of short charge/discharge cycles. In an electrical hybrid, this technology can be used as a buffer system for the acceleration process and regenerative braking. Figure 7 below shows the diagram of electrical double capacitor in vehicle.

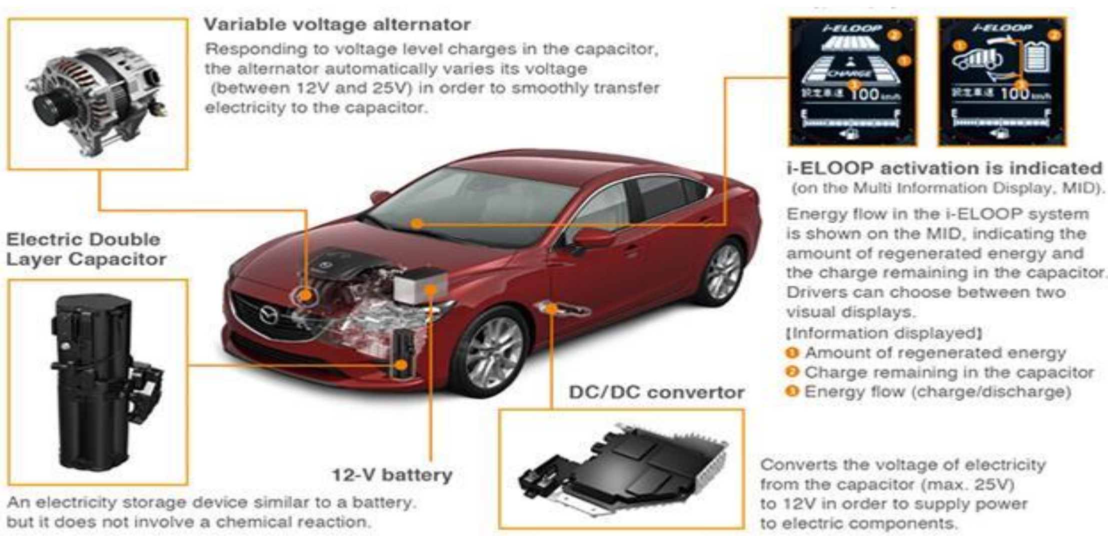

Figure 7 : Electric Double Layer Capacitor in Vehicle (Mazda, n.d)

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2.9 Thermal Processes

2.9.1 Isothermal Process

One of the processes in an accumulator is known as an isothermal process. The isothermal process is affected by the compression of gas in the accumulator. The rate of compression of gas will allow the gas to attain a constant temperature of the gas. This is because the heat produced during the process of compression of gas will dissipate through the walls of the accumulator thus allows the temperature of the gas to be maintained. While during expansion, heat will draw in and maintain the gas temperature (Flippo, 2003).

2.9.2 Adiabatic Process

The second process within the accumulator is known as an adiabatic process. This process is the opposite of the isothermal process as the temperature of the gas in this process does not remain constant. Due to the rapid compression of the gas within the accumulator, the temperature will rapidly increase or decrease. Unlike the isothermal process, the heat will not be able to dissipate through the wall of the accumulator fast enough. Thus, the heat will cause the pressure to increase. Similarly, during expansion, constant temperature also cannot be maintained as heat cannot be drawn in to maintain the gas temperature which causes the temperature and pressure to drop.

This process needs to be insulated to make sure heat is not a loss to the surrounding. Unfortunately, the way to choose suitable insulation material is to look previous research about the application of insulation such as in a refrigerant, building, and others. There have many types of insulation; for example, in building application, there has a traditional, state-of-the-art and others technology of insulation material.

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These are an example of traditional insulation material and description of it (Jelle, 2011).

1) Mineral oil

   Mineral oil insulation material is made of glass wool and rock wool the typical thermal conductivity of this is material is 30 and 40mW/mK. This material is readily perforated and cut and adjustable without any loss of thermal resistance this type material of insulation may also be used as a filler material.

2) Expended Polystyrene (EPS)

   Expended polystyrene is made of from small sphere of melted polystyrene containing an expansion gas agent such as pentane which expands by heating with water vapor. The typical thermal conductivity of EPS is between 30 and 40mW/(mK). EPS material may be perforated, and also cut and adjustable without any loses of thermal resistance.

3) Extruded polystyrene (XPS)

   Extruded polystyrene is made of from melted polystyrene (from crude oil) by adding an expansion gas HFC, CO_2 or C_6H_{12}, where the polystyrene mass is extruded through a nozzle with pressure discharge causing the mass to expand. XPS typical thermal conductivity is between 30 and 40mW/(mK). XPS material may also be perforated, and also cut and adjustable without any loss of thermal resistance.

4) Cellulose

   Cellulose insulation material is made from recycling paper of wood fiber mass. Its typical thermal conductivity is between 40 and 50mW/(mK) higher than mineral oil, EPS, and XPS. Cellulose material may also be perforated, and cut and adjustable without any loss of thermal resistance.

5) Cork

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Cork insulation material is made off from the cork oak. Its typical thermal conductivity is between 40 to50mW/(mK). Cork insulation material also can be produced as a filter material or as boards. Cork insulation may also be perforated, and cut and adjustable without any loss of thermal resistance.

6) Polyurethane (PUR)

Polyurethane (PUR) is made off from a reaction between isocyanates and alcohols containing multiple hydroxyl groups (polyols). In the expansion process, the closed pores are filled with an expansion gas which is HFC, CO_2 or C_6H_{12}. PUR typical thermal conductivity is between 20 and 30mW/(mK). Unfortunately, the disadvantages of this material are PUR rises a severe health concern and hazard in case of fire, PUR when burning will release HCN (hydrogen cyanide) and isocyanates which is very poisonous.

Below are the examples of state of the art thermal building insulation material and solution of today. These are a few examples of state of the art thermal building insulation.

1) Vacuum Insulation Panel (VIP)

Vacuum insulation panel (VIP) exists of an open porous-core of fumed silica enveloped in several metalized polymer laminate layers. The thermal conductivity of VIP ranging between 3 and 4mW/(mK) in a fresh condition. Typically, after 25 age the thermal conductivity will be 8MW/(mK). This is due to water vapor and diffusion of air through the VIP envelope and into VIP core material which has an open structure. Unfortunately, the VIP insulation material cannot be cut for adjustment at the building site or perforated without losing a large part of their thermal insulation performance. Its also cost high compared to traditional insulation material.

2) Gas Filled Panel (GFP)

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The GFPs apply a gas less thermal conductive than air, e.g. argon (Ar), krypton (Kr) and xenon (Xe), instead of a vacuum as in the VIPs. To keep the low-conductivity gas concentration inside the GFPs and avoid air and moisture penetration into the GFPs are crucial to the thermal performance of these panels. Vacuum is a better thermal insulator than the various gases used in the GFPs. On the other hand, the GFP grid structure does not cause to withstand an inner vacuum as the VIPs. Low emissivity surfaces inside the GFPs decreases the radiative heat transport. Thermal conductivities for prototype GFPs are quite high, e.g. 40 MW/(MK), although much lower theoretical value has been forecast. Hence, the GFPs hold many of the VIPs advantages and disadvantages. However, the future of GFPs as thermal building insulation may be interviewed or even doubtful, as compared to them the VIPs seem to be a better choice both for today and tomorrow.

3) Aerogels

Aerogels represent a state-of-the-art thermal insulation solution, and may be the most promising with the highest potential of them all at the moment. Using carbon black to suppress the radiative transfer, thermal conductivities as low as 4mW/(MK) may be contacted at a pressure of 50 bar. Nevertheless, commercially available state-of-the-art allergies have been described to have thermal conductivities between 13 and 14mW/(MK) at ambient pressure. The production costs of aerogels are still really high. Aerogels have a relatively high compression strength but is very thin due to its meager tensile force. The tensile strength may be increased by the incorporation of a carbon fiber matrix. A fascinating aspect of allergies is that they can be built as either opaque, translucent or sheer material, thus enabling a broad reach of possible building applications. For aerogels to become a widespread thermal insulation material for opaque applications, the costs have to be brought down substantially.

4) Phase Change Material

Phase change materials (PCM) are not thermal insulation fabrics, but since they are interesting for thermal building applications, they are mentioned in this context. PCM change phase from a solid state to a liquid when stirred up, so taking up energy in the endothermic process. When the ambient temperature drops again, the liquid PCM will turn into solid-state materials again while giving away the earlier absorbed heat in the exothermic process. Such a phase change cycle stabilizes the indoor building temperature and decreases the heating and cooling loads. Various paraffin is typical examples of PCMs, but a low thermal conductivity and a massive volume change during phase transition (Hasnain, 1998) limit their building application. An overview of the main PCM has been given by (Fatih, 2006). A suitable phase change temperature range, depending on climatic conditions and desired comfort temperatures, as well as an ability to absorb and release large amounts of heat, are essential properties for the selection of a specific PCM for building applications. Corresponding melting enthalpies and melting temperatures are depicted for various groups of PCMs.

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CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter is divided into several parts, where all the details of the construction methods show that used in a discipline or set of processes to identify in more detail towards the project objectives. Details of explanation on how the project will be carried out start with literature review, schematic, diagram, model/equation, simulation, simulation data, experiment setup, experiment and it ends with the discussion and finding.

3.2 Flow Chart

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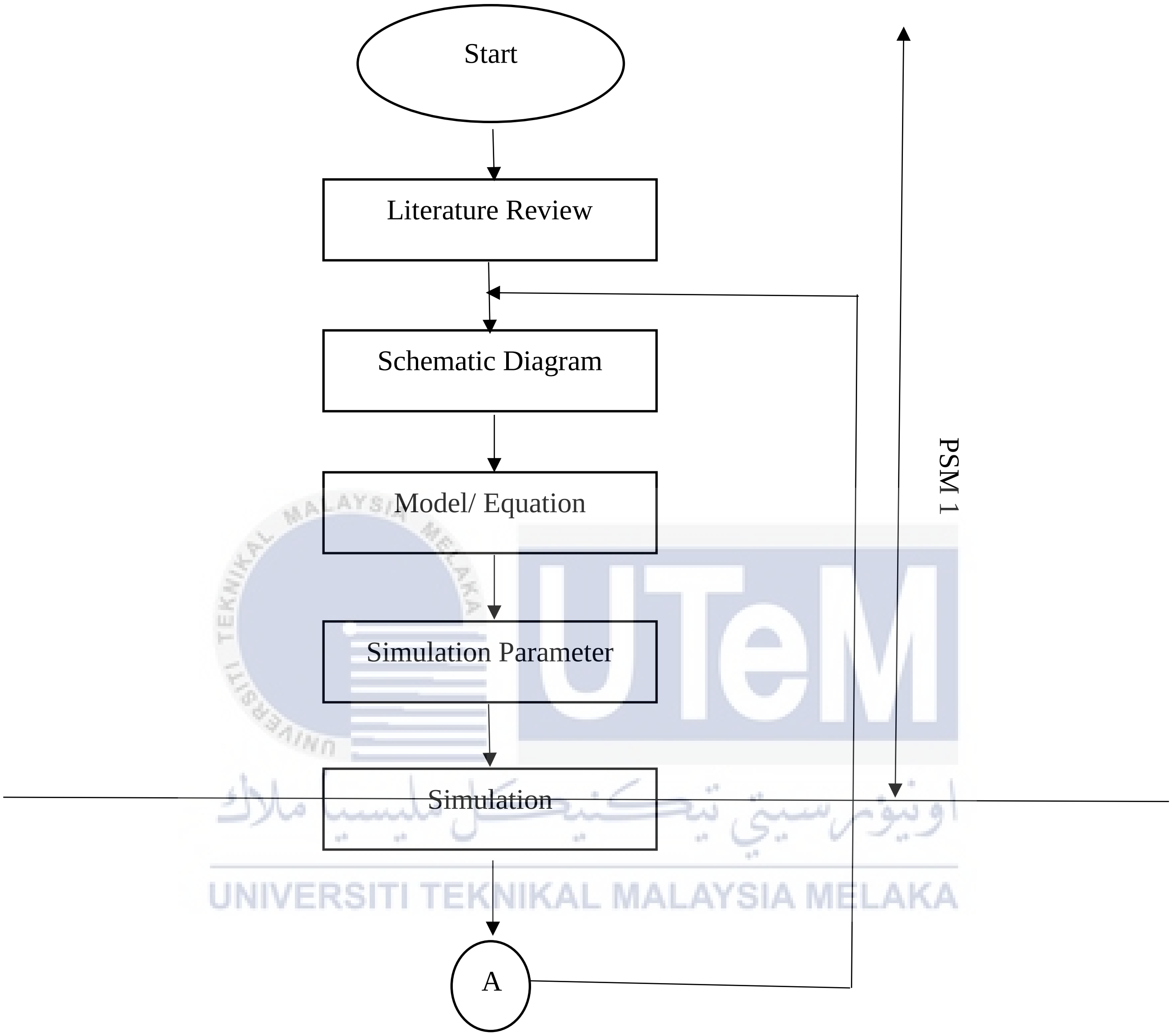
The actions that need to be carried out to achieve the objectives in this project are listed below



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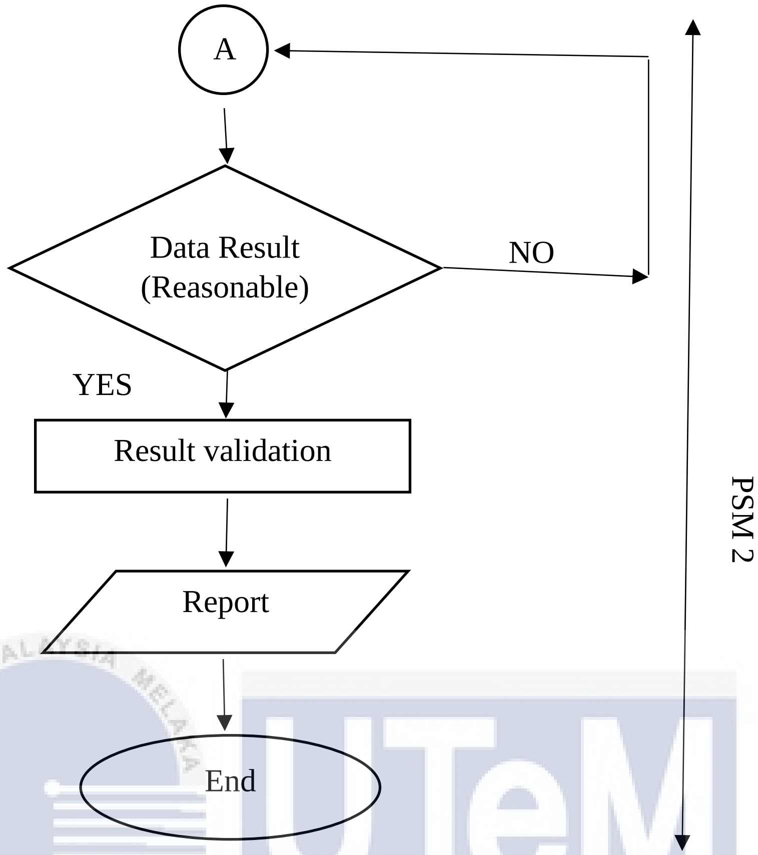

Figure 8: The process of flow chart

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Figure 8 shows the flow chart of the project. It has been done from the beginning until finishing. This is to make sure that the work has been done smoothly by following the systematic and the right path.

3.3 Literature Review

A literature review is a previous study research or paper that includes the current knowledge including substantive findings as well as thermotical and methodological contributions to this project. Examples of books, journals, article and all another alternative reference.

3.4 Schematic Diagram

This schematic diagram shows that the representation of elements by graphics or abstract of the regenerative braking system. These schematic diagrams divided into three (3) parts which are a pictorial schematic diagram, functional schematic, and fluid schematic diagram.

3.4.1 Pictorial Schematic Diagram

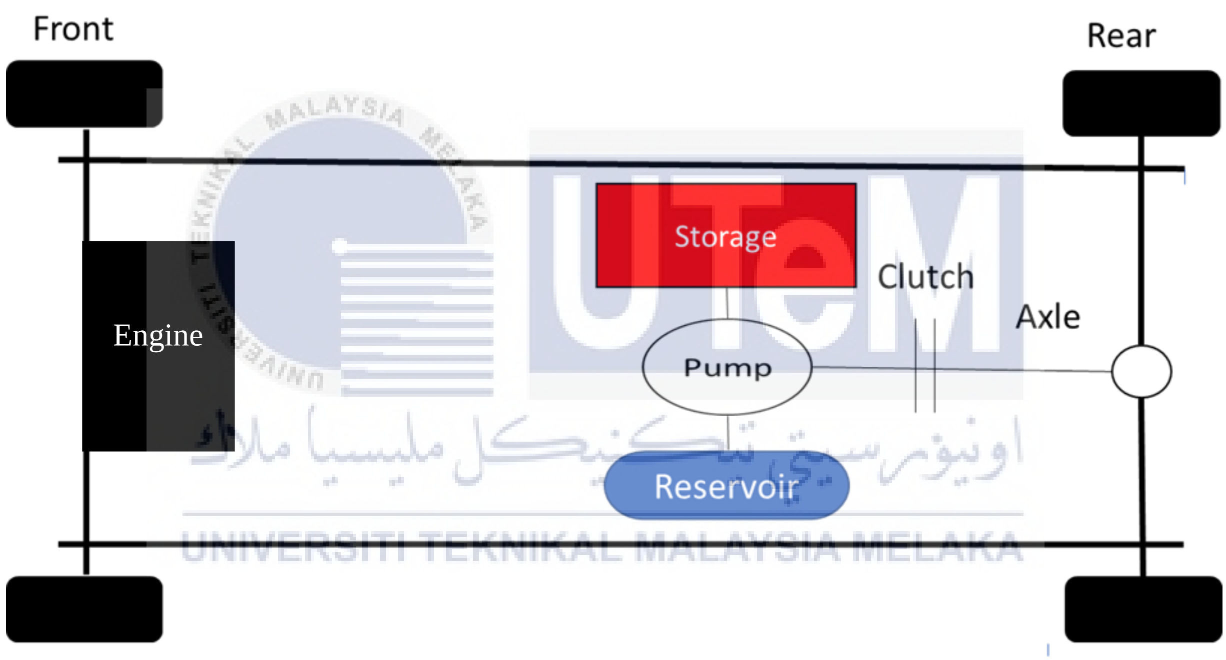

Figure 9 : Regenerative Braking System Diagram in Vehicle

Figure 9, shows that a simplified diagram represents regenerative braking system in the vehicle. The regenerative braking system in the vehicle consists of several components that are connected. One of the components is a clutch. Clutch is located at rear tire between axle and pump. Other than that, reservoir and storage are act as low-pressure storage accumulator and high-pressure storage accumulator respectively. All these systems are located and install at rear tire instead of the front tire.

3.4.2 Fluid Schematics

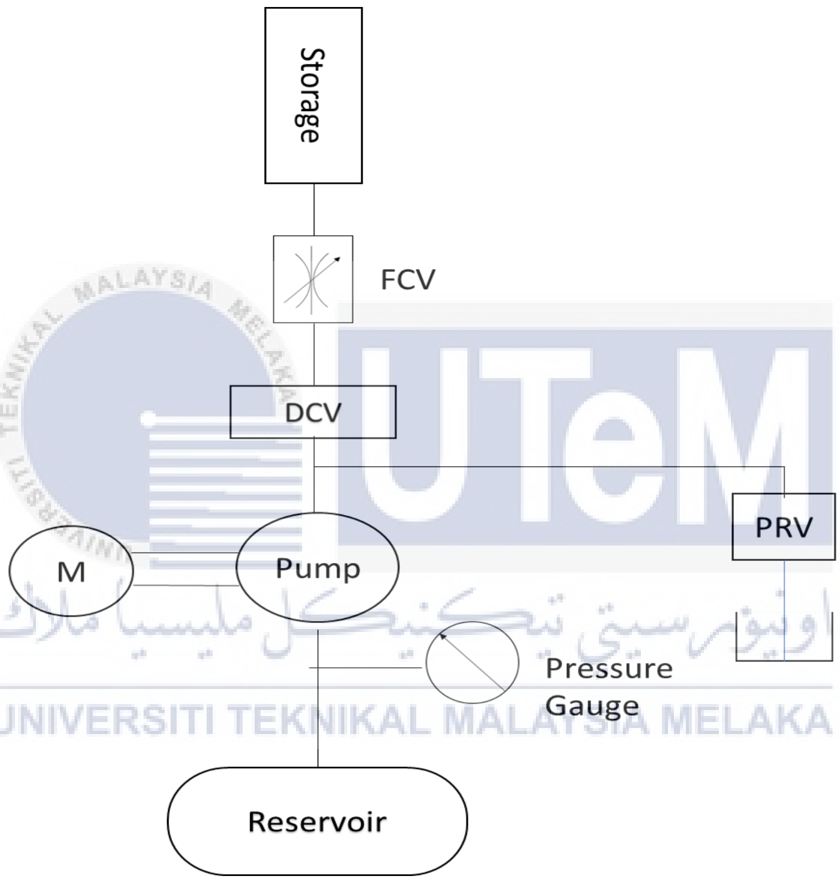

Figure 10 : Diagram Regenerative Braking

Figure 10 shows that the fluid schematic diagram of the regenerative braking system. This diagram consists of several components which are storage, fluid control valve (FCV), direct control valve (DCV), pump, hydraulic motor (M), pressure gauge; pressure relife valve (PRV) and lastly reservoir.

3.4.3 Test Rig Diagram

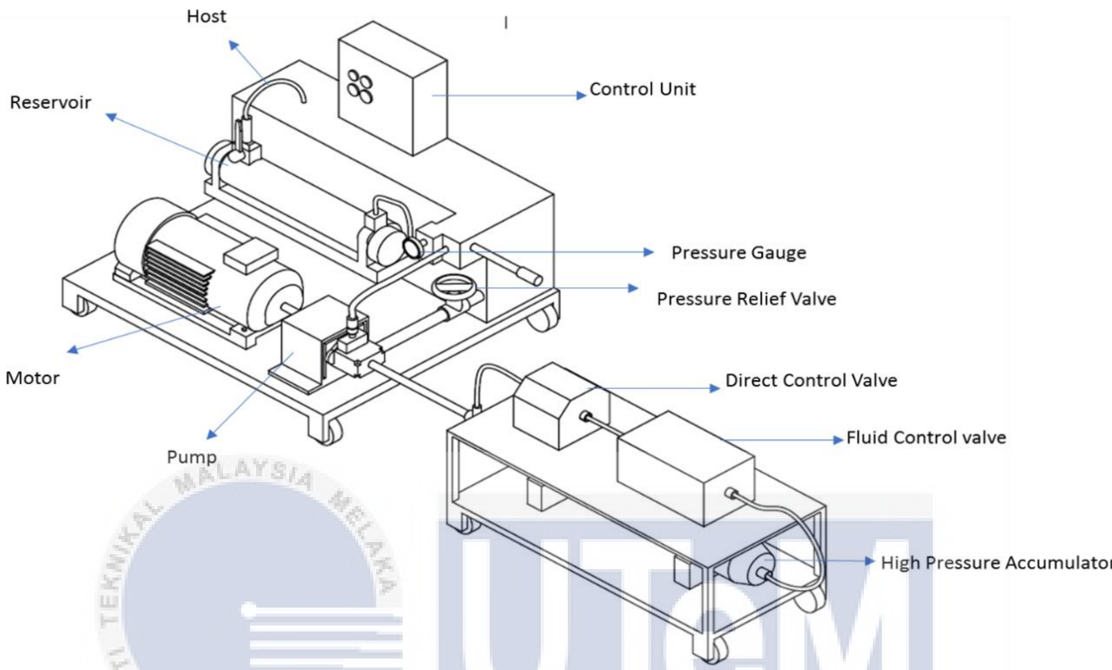

Figure 11 : Isometric View of Test Rig

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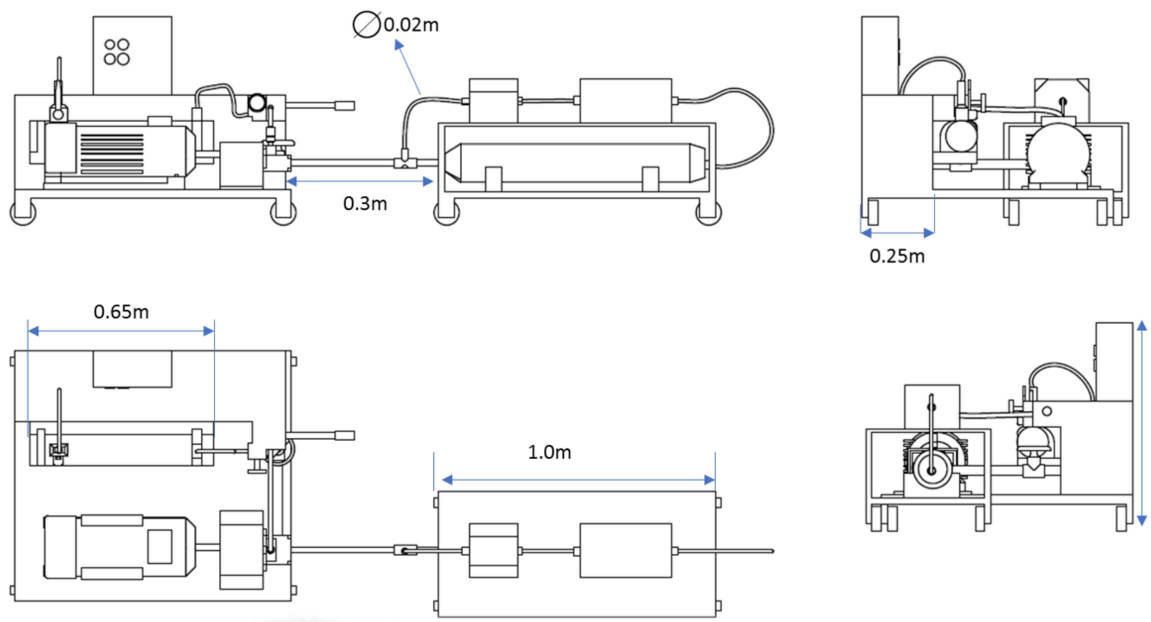

Figure 12 : Orthographic View of Test Rig

Figure 11 shows that the 3D (isometric) view of full test rig diagram. This drawing is conducted using Fusion software. Meanwhile, Figure 12 shows that the orthographic (top, front, side) view of the test rig. The test rig divided into 2 parts, which are power unit and test rig. The power unit is a component that consists of pump, motor, pressure gauge, reservoir, and control unit. While test rig consists of the high-pressure accumulator, fluid control valve, and direct control valve.

3.5 Model/ Equation

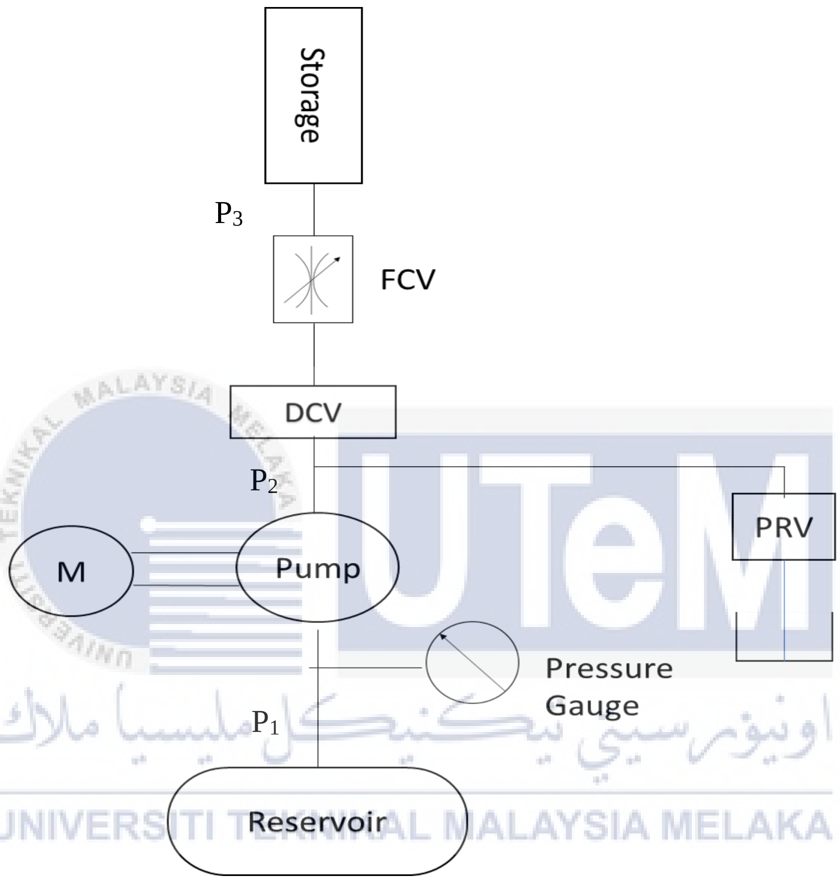

Figure 13 : Schematic Diagram Model

Figure 13 shows that the schematic diagram that will be used to stimulate the process of regenerative braking. The equation that related to this schematic diagram is fluid power, the torque required by the pump, shaft power and lastly energy in the accumulator. The details of the equation are listed below.

The fluid power required for the system can be expressed as,

$$P_P = Q_{out} \cdot \Delta p \cdot \eta_{overall} \tag{7}$$

Where P_P = Pump power (Watt)

Q_{out} = Pump output flow rate (m^3/s)

Δp = Pressure different through the pump

$\eta_{overall}$ = Overall efficiency

Meanwhile, to find the torque required by the pump, the equation can be expressed as

$$T = \frac{C \times \Delta p}{\eta_M} \tag{8}$$

Where T = Torque (Nm)

C = Displacement (m^3/rad)

Δp = Pressure different through the pump

η_M = Mechanical efficiency

Then the shaft power can be calculated through,

$$P_S = T_A \cdot \omega \cdot \eta_{overall} \tag{9}$$

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Where P_S = Shaft power (Watt)

T_A = Torque (Nm)

ω = (rad/s)

$\eta_{overall}$ = Overall efficiency

Lastly energy storage can be expressed as,

$$E = P_{gh} V_{gh} \ln \frac{P_{op}}{P_{gh}} \tag{10}$$

Where E = energy storage of the accumulator (Joule)

P_{gh} = Gas pressure (Pascal)

V_{gh} = Gas volume (m^3)

P_{op} = Pressure of the oil (Pascal)

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3.6 Simulation Parameter

Simulation parameter will be taken into consideration to obtain correct result of the experiment. In simulation parameter, there is three variable that needs to consider such as control, constant, dependent and independent variables.

Case 1: Find volume effectiveness of the accumulator, v_{eff}

Table 2: Volume effectiveness of the accumulator

No.	Parameter	Parameter type
1.	Volume effectiveness	Dependent parameter
2.	Flow rate	Dependent parameter
3.	Filling time	Independent parameter

Case 2: Find the filling time required by the accumulator,

Table 3: Filling time by the accumulator

No.	Parameter	Parameter type
1.	Pressure	Dependent parameter
2.	Time (t)	Independent parameter
3.	Volume effectiveness	Dependent parameter

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Case 3: Find energy of the system, E

Table 4: Energy of the system

No.	Parameter	Parameter type
1.	Gas pressure	Independent parameter
2.	Gas volume	Constant parameter
3.	The pressure of the oil	Constant parameter
4.	Pressure gauge	Dependent parameter

These three-simulation parameters which are volume effectiveness, the power required and energy of the system is important so that it can determine the performance of the regenerative braking system.

3.7 Simulation

Simulation of regenerative braking system will be using one of the hydraulic tools which are Automation Studio software instead of MATLAB software. This is because Automation Studio is a tool for design, functional simulation of complex automation, documentation, and preparation. It has also provided technical and commercial data for simulation. Undoubtedly that software such as MATLAB has high flexibility to play a simulation that is linked to the case study, but the Automation Studio has the advantage regarding circuit plan, functional simulation, fluid power component sizing, system design, validation and virtual simulation. Other than that, Automation Studio has improved one step ahead by connecting some applications with Simulink, MATLAB. The simulation has been conducted as shown in Figure 14 below.

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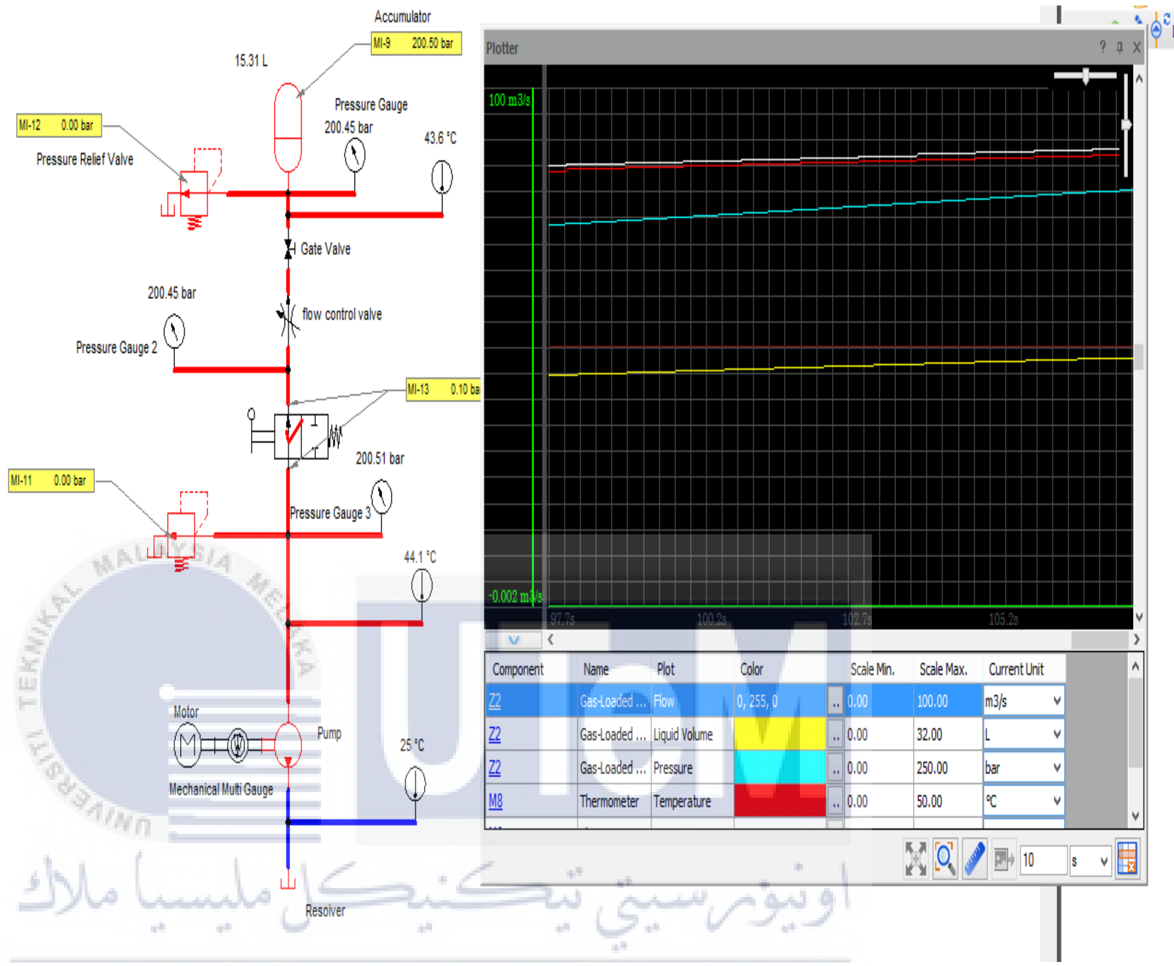

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Figure 14: Automation Studio software simulation

3.8 Report

The last footprint of this project is writing a report. This report will consist everything from the beginning until the end of the experiment. This includes result design, the result of the simulation and result of the experiment.

CHAPTER 4

RESULT AND ANALYSIS

4.1 Simulation Result

During this research, simulation has been conducted to observe and study the effect of isothermal and adiabatic compression on the performance of energy storage accumulator for hydro pneumatic driveline. With this method, we can identify all the characteristics of each process and can easily consider the process of designing energy storage and also, can optimize the process. The pre-charge pressure for the whole system was set 80 bar, and the cracking pressure was set 200 bar. If the cracking pressure exceeds 200 bar, the pressure will be relieved by using pressure relief valve (PRV) to ensure that the system is safe.

4.2 Effect of the isothermal and adiabatic process to volume effectiveness

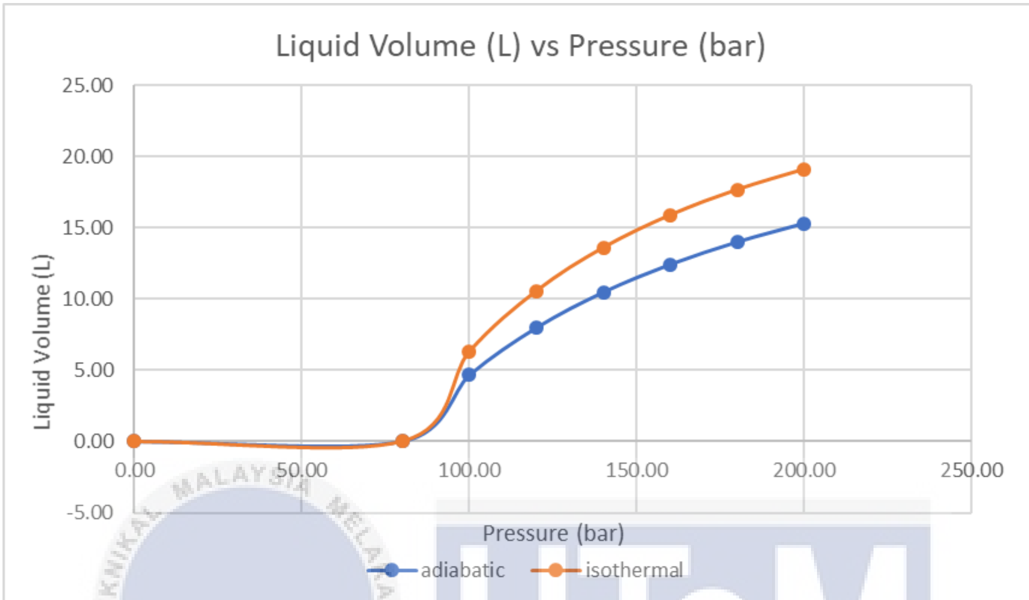

Figure 15: Effect on effective volume

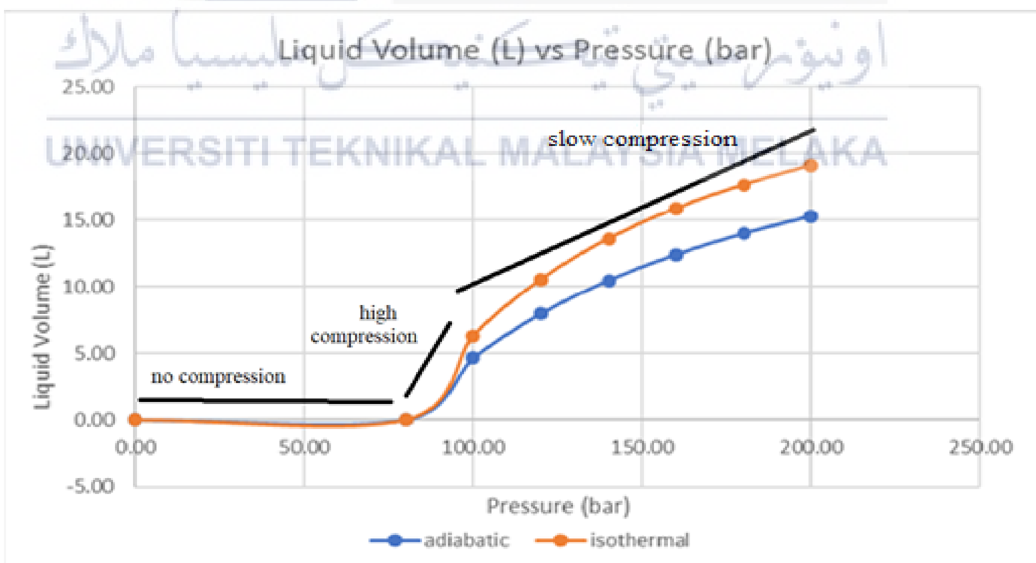

Figure 16: Annotation diagram

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As we can see in Figure 15 above, the isothermal process gives better output than the adiabatic process in term of effective volume. The maximum output for isothermal is 17.68 liter at 200 bar and for the adiabatic process is 15.28 liter at 200 bar. In the early stage of the graph for both isothermal and adiabatic, the volume is 0 liter until it reaches the pressure of 80 bar. This is due to hydraulic oil pressure is lesser than pre-charge pressure that was set at 80 bar. At this stage, there is nothing happening even with a little compression. At pressure 80 bar to 100 bar, both isothermal and adiabatic process have drastically increased from 0 litre to 6.34 liter for isothermal process and 0 litre to 4.67 litre for an adiabatic process. This is because the pressure of the hydraulic oil is exceeding the pre-charge pressure and the filling process will begin. Other than that, the low higher level of compression adjustability due to the nitrogen gas buck is another factor that will produce the drastically increase in the graph at 80 bar to 100 bar.

In term of efficiency, at 200 bar, the isothermal process at same pre-charge pressure of 80 bar shows 13.55% higher volume than the adiabatic process. Therefore, the founding clearly shows that the isothermal process is more effective than the adiabatic process regarding volume effectiveness due to the effect of temperature change and heat exchange. The result of this simulation on effective volume is the same as a previous study which isothermal give greater output than adiabatic (Wasbari, *et al.*, 2017). In overall efficiency, the percentage difference between isothermal process and the adiabatic process is 24.9% which isothermal is higher than adiabatic process.

4.3 Effect of the isothermal and adiabatic process to filling time.

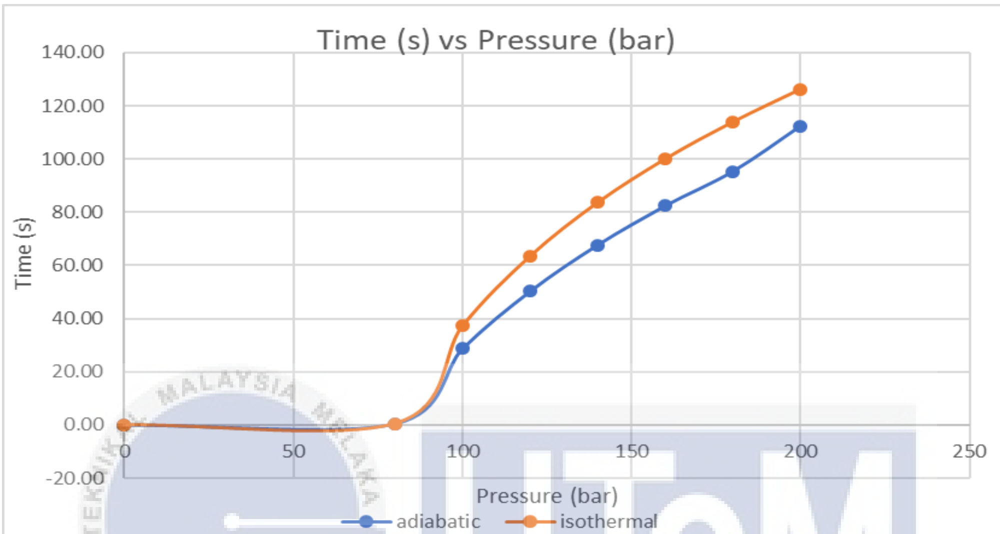

Figure 17: Effect on filling time

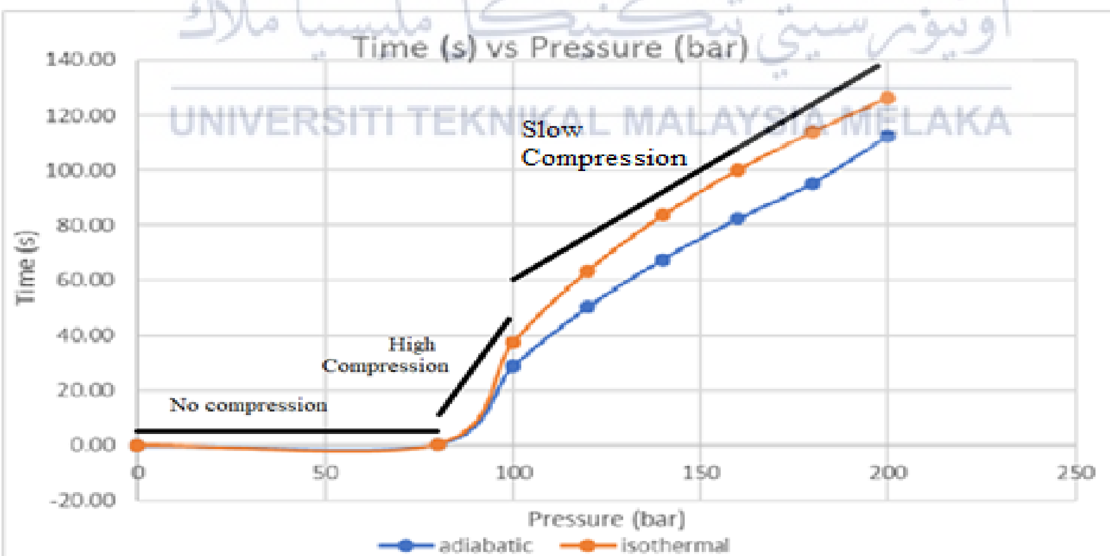

Figure 18: Annotation diagram for filling time

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Figure 17 shows the graph of effect isothermal and adiabatic prosses on filling time with fixed pressure system which is 200 bar. Regarding filling time, the adiabatic process gives a higher output than isothermal process. For an adiabatic process, it only takes 112.37 s to reach 200 bar while for isothermal it takes 126.27 s to reach 200 bar. This result shows that regarding filling time, the adiabatic process takes lesser time compared to isothermal process.

The adiabatic process raises pressure faster than isothermal starting from beginning to the cracking pre-charge pressure and straight away to the final system pressure which is 200 bar. At the early stage, the line of the graph for both processes are negative and zero. This is due to hydraulic oil pressure is lesser than pre-charge pressure that was set at 80 bar. At this stage, there is nothing happening even with a little compression. Then, the graph started to increase drastically from 80 bar to 100 bar due to high compression that occurred. At 100 bar until 200 bar, the graph slightly increases due to normal compression as shown in Figure 4.

According to previous research (Wasbari, Bakar, *et al.*, 2017), the result collected is the same as an adiabatic process. This is because it gives less filling time than isothermal process. In overall efficiency, the difference between adiabatic process and the isothermal process is 18.31% where the adiabatic process is faster than isothermal process. This filling time is also related to the volume effectiveness, which means that adiabatic process gives lesser time to fill the accumulator but also give lesser volume effectiveness compared to isothermal process.

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4.4 Effect of the isothermal and adiabatic process to energy.

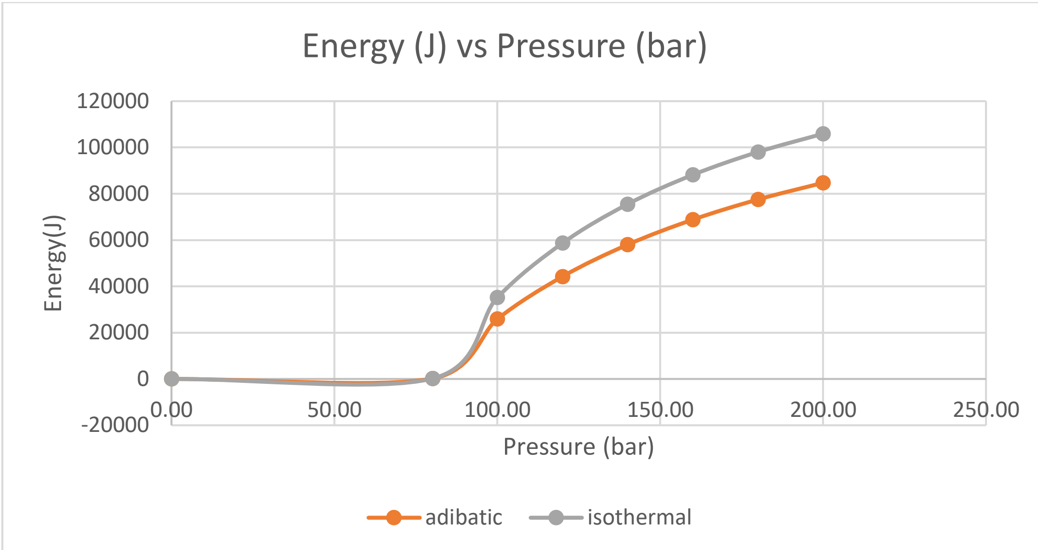

Figure 19: Effect on energy

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Figure 19 shows the effect of both processes on energy produce. The maximum energy produced at 200 bar by the adiabatic process and isothermal process are 84726.76 J and 105931.90 J respectively. At 80 bar (pre-charge pressure) the energy produce for adiabatic process and isothermal process are 181.0 J and 191.0 J respectively. Starting from 80 bar until 100 bar, there has been a drastic increase in both processes. The reason for this occurrence is due to hydraulic oil pressure being lesser than the pre-charge pressure that was set at 80 bar. At 100 bar until 200 bar the graph slightly increases due to normal compression that had occurred. The energy is calculated using energy formula. The reason isothermal process produces higher energy than the adiabatic process is that isothermal process produces a high volume of effectiveness and it will affect the energy produce. The volume of effectiveness is proportional to energy produce.

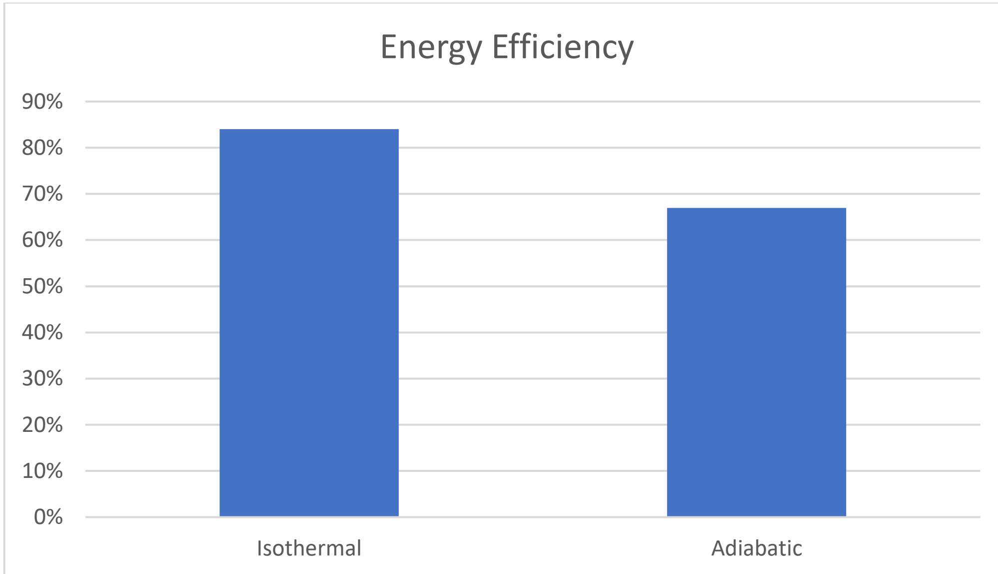

Figure 20: Energy Efficiency for isothermal process and adiabatic process

Figure 20 shows the percentage of energy efficiency for isothermal process and adiabatic process. The isothermal process gives higher efficiency which is 84% and adiabatic give less efficiency which is 67%. The efficiency has been calculated using energy produce from the accumulator divided by energy produce by the system.

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4.5 Result validation

In this subtopic, result validation will be discussed in every parameter which are volume effectiveness, filling time and energy.

4.5.1 Result validation for volume effectiveness

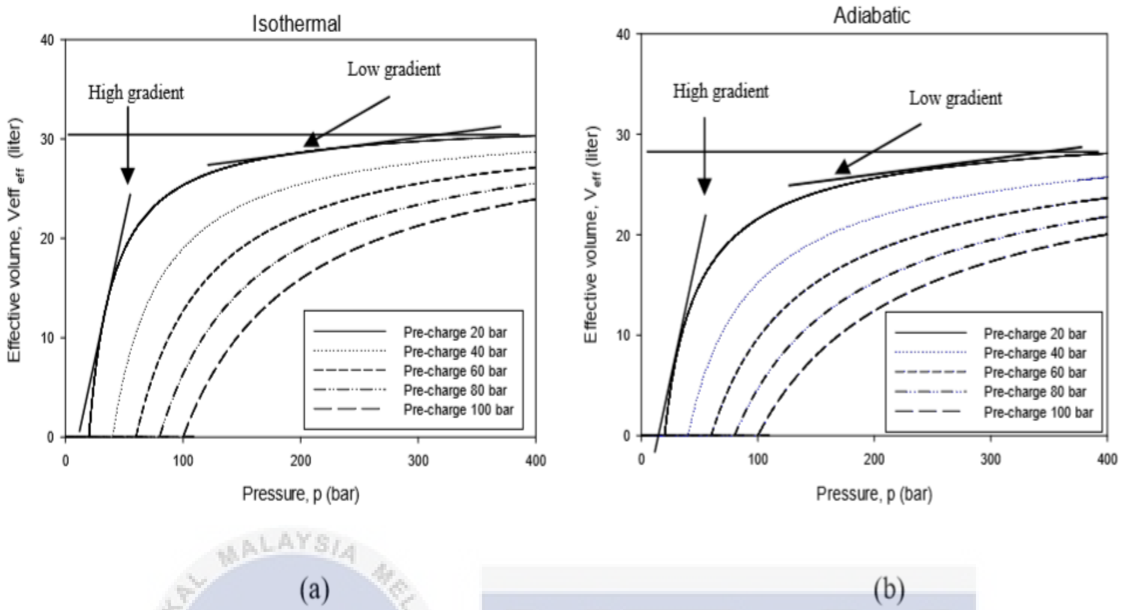

Figure 21: Effect of effective volume

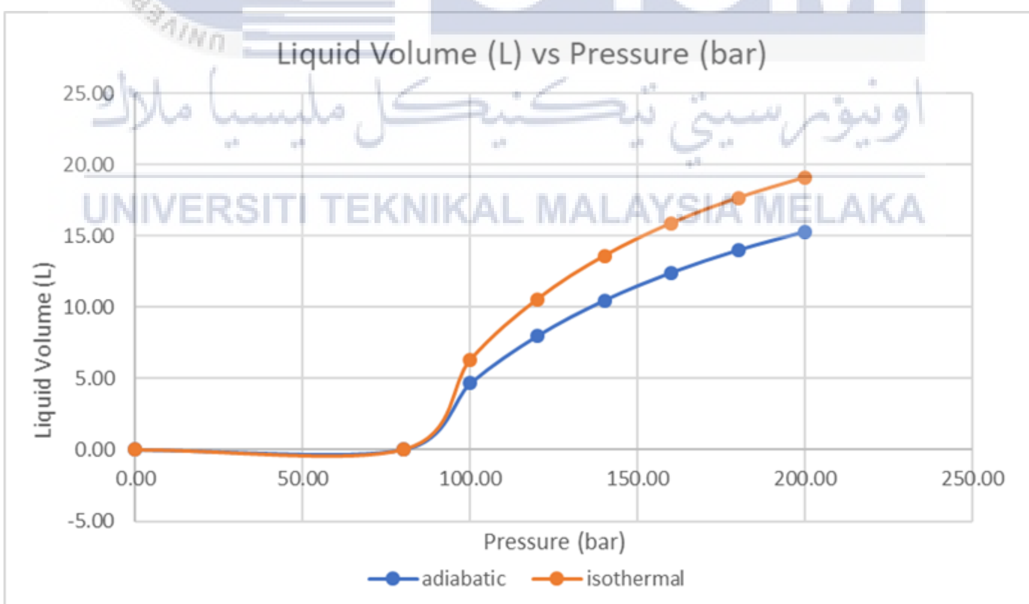

Figure 22: Effect on effective volume

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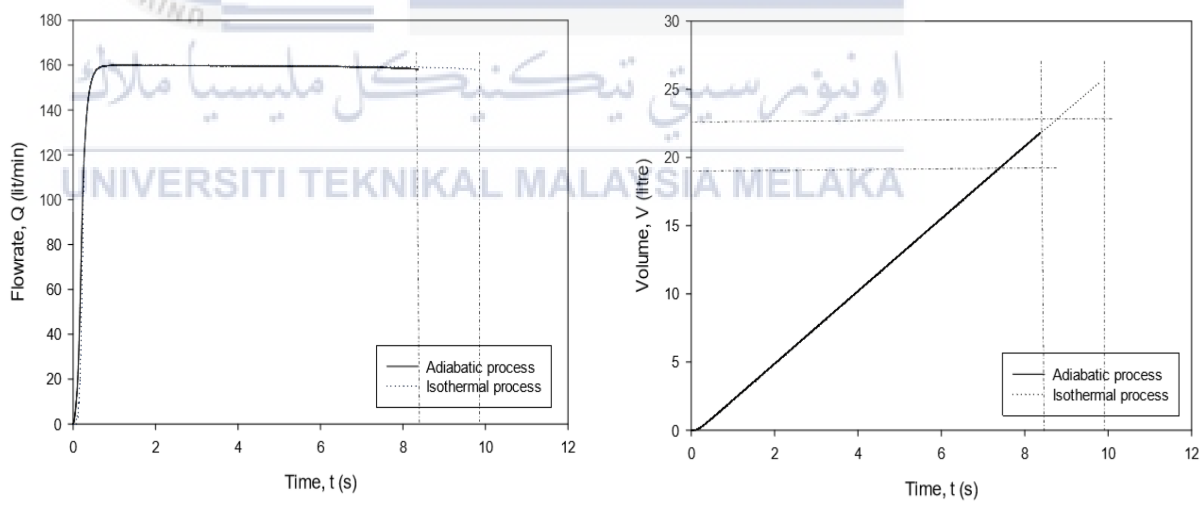
Figure 21 shows the result of the effect of effective volume from previous research. The result has been compared with the finding results to validate the result. The isothermal process gives higher volume effectiveness compare to adiabatic process. By looking at the previous research result that has been shown in Figure 21, the simulation compared both processes and also change the pre-charge pressure. However, the compared result is not one point to one-point. The comparison has been made by looking at the profile of isothermal process and adiabatic process at pre-charge pressure 80 bar only. The profile for both processes is similar to the previous research (Wasbari, *et al.*, 2017) which results in isothermal process to be higher than adiabatic process. Therefore, this result of volume effectiveness is accepted due to the comparison that has been made. Although the validation of this result has been compared with previous paper, the experiment needs to be done to check whether the result is still the same in a real situation or not.

4.5.2 Result validation for filling time



(a) (b)

Figure 23: Filling time-based on flow rate (a) and from empty to full (b) (Wasbari, *et al.*, 2017)

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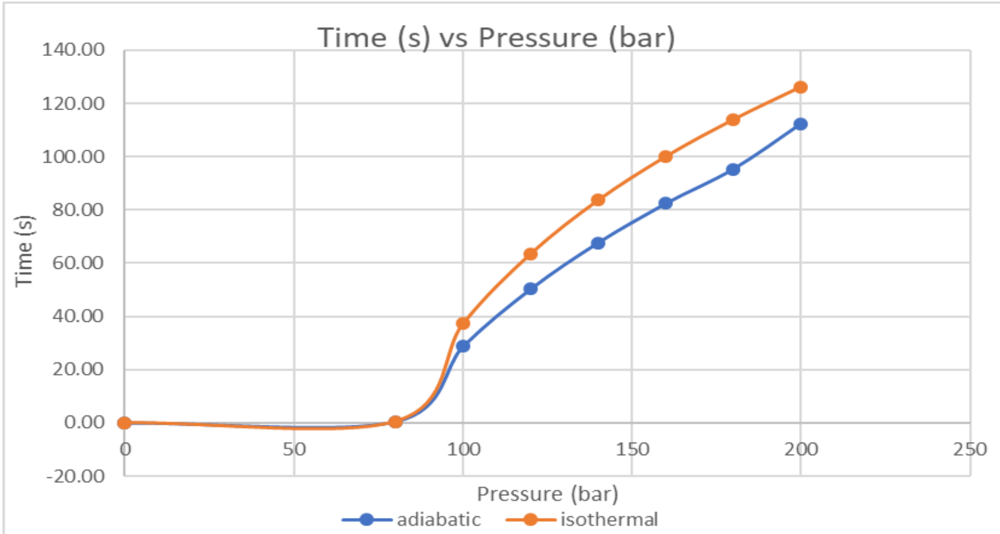

Figure 24: Effect on filling time

Figure 23 shows that the result that has been done from a previous paper. The results show the adiabatic process gives less time to fill the accumulator compared to isothermal process. The adiabatic process takes 8.2 seconds to achieve 22 litre while the isothermal process takes more time which is 9.8 second to achieve 25.5 litre. This previous result has been compared with this new finding result, and the comparison have been made by looking the profile of both processes. In this finding as shown in Figure 24, the result shows adiabatic process its only take 112.37 s to reach 200 bar while for isothermal it takes 126.27 s to reach 200 bar. From this finding results, it can be concluded that the profile of both processes is the same compared to previous research which gives adiabatic process take less time than isothermal process.

4.5.3 Result validation for energy

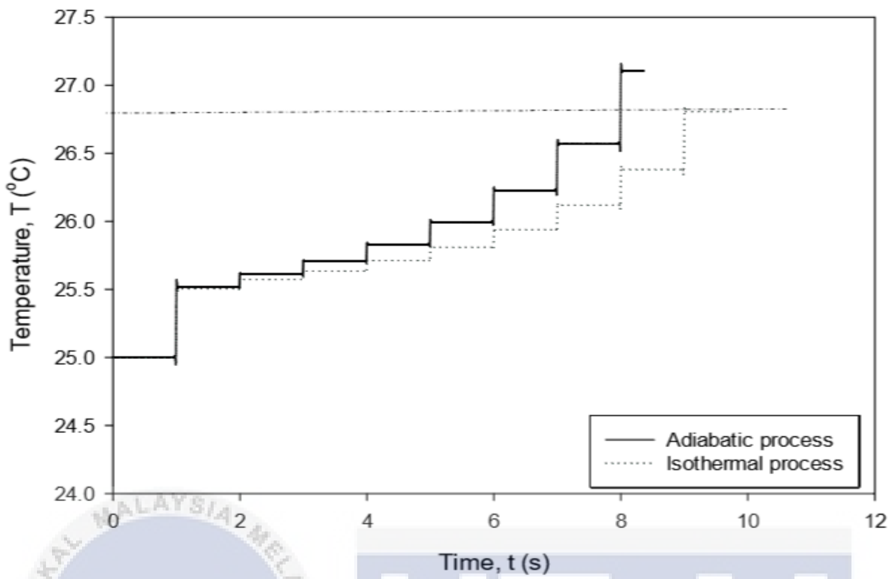

Figure 25: Temperature elevation

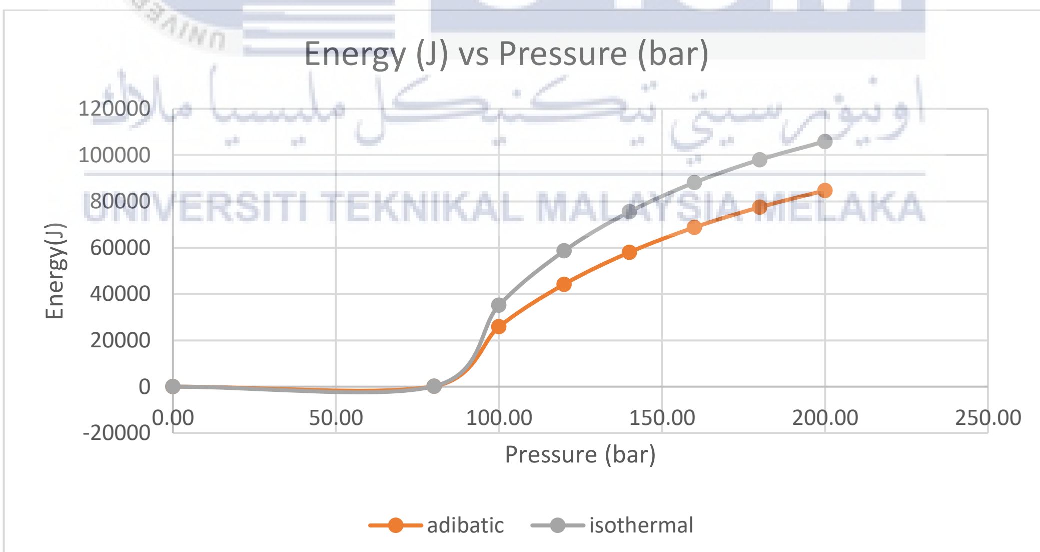

Figure 26: Effect on energy

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Figure 25 shows the result of temperature elevation from previous research. The result of energy can be compared to temperature elevation as shown in Figure 26. Regarding the temperature profile, the temperature increases as well as the pressure. According to ideal gas law, when the temperature increases, the pressure also increases and will affect to energy produce. This is because as the temperature increase, the molecule in the gas move faster, impacting the gas's container more frequently and exerting greater force. The energy produce of isothermal process and adiabatic process will become higher due to the high temperature and high pressure. Therefore, a comparison has been made by looking at the profile for both processes, and it shows that they are similar. To conclude, the isothermal process gives higher energy produce compared to adiabatic process.

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CHAPTER 5

CONCLUSION AND RECOMMENDATION

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5.1 Conclusion

In a nutshell, the hydraulic, electric hybrid vehicle uses less electricity which is 11.4% compared too pure electric vehicle proving that hydraulic-electric hybrid able to provide the best energy cost compared to the other configurations. The statement had been proven by the previous research in the literature review above.

Next, the simulation has been done by using the automation studio. This simulation is very important to investigate the behavior of both processes which are an isothermal process and adiabatic process. The performance of regenerative braking has been observed for isothermal process and adiabatic process. It's clearly shows that isothermal process gives higher volume effectiveness and energy efficiency which is 13.55% and 17%

compared to adiabatic process. Regarding charging speed (filling time), the adiabatic process gives higher result which is 18.31% compared to isothermal process. Adiabatic process only takes 112.37 s to reach 200 bar while isothermal process took 126.27 s to reach 200 bar but it is lack in term of storage capacity due to the flow rate is high. An isothermal process gives the best result compared if the capacity and temperature change is the reference to make the selection. However, the adiabatic process gives the best result if filling time is the reference to make the selection. Lastly, the isothermal process gives higher energy efficiency compared to adiabatic process. This is due to volume effectiveness, and power produce from the isothermal process is higher than adiabatic process.

5.2 Recommendation

5.2.1 Accumulator

As a future recommendation, there have a few issues that need to be overcome. The technology has been implemented in trash truck which did not give any issues about the sizing of the accumulator. If this technology wants to be implemented in normal vehicle, space and sizing of accumulator issues need to settle for making it successful.

5.2.2 Process in energy storage

Other than that, if the future research study more about how to combine these two processes which are an isothermal process and adiabatic process it will give a better result and a very good efficiency to the hydraulic energy storage.

5.2.3 Experiment and Schematic diagram

Next, the experiment need to be held in order to get the overview for real situation and to validate the result. The schematic diagram also can be improving by single charging to continues charging.

5.2.4 Implementation

Furthermore, this technology is in the early stage of implementation. There have a few steps need to be taken which are exploration, installation, initial implementation and full implementation. These steps are very important for the early stage of implementation.

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