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APPLICATION OF WATER AS PRESSURE MEDIUM IN HYDRAULIC HYBRID SYSTEM

Saiful Akmal Sabaruddin, Ahmad Anas Yusof, Mohd Noor Asril Saadun and Rozaimi Ghazali
Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, Durian Tunggal, Melaka, Malaysia
E-Mail: saif_knight90@yahoo.com

ABSTRACT

Typical hydraulic hybrid system vehicles depend on oil based hydraulic fluid. Therefore, natural concerns of environment and safety promote the uses of water-based hydraulic hybrid system. The main focus of this paper is to simulate the potential of water hydraulic technology in hydraulic hybrid system vehicle. This research will include extensive study on the mathematical modeling and simulation by using Matlab/Simulink to determine the value of torque, power and efficiency of hydraulic hybrid system and diesel engines. The simulation result indicates that the resulted value of torque and efficiency verify the good combination of water-based hydraulic hybrid system in assisting diesel engine. Therefore, this novel water-based hydraulic hybrid system will reduce the usage of diesel fuel that eventually create a new green technology.

Keywords: hydraulic hybrid system, water hydraulic, green technology.

INTRODUCTION

Hundred years ago transportation are mainly on animal power which was a green technology for urban transportation. As the civilization change, new technology were rapidly develop that produce various new invention that convenient for our mankind lifestyle. In adapting the advancement of technology, one of the most important element in our life are often neglected which is our environment. There is no doubt that living in a high technology environment make our daily life easier and more productive. What is more uncertain is the effect of technology on environment that might give a huge negative impact on our next generations.

Currently, transportation is the biggest contributor to the air pollution crisis. Although, fuel combustion, power plant emissions, and industrial wastes are also pollution burden (L. B. Hill, 2005). Economically, diesel engine been cheaper and versatile compared to gasoline engine or other medium of power that contribute the inclination towards diesel usage. Unfortunately, these engines exhaust substances that can cause a bad effect on human health (Ca. O. *et al*., 1998).

Diesel engines are a dominant element of fine-particle pollution. The senior citizens and people suffered serious disease such as asthma, lung disease, emphysema, and chronic heart are mostly harmed by the fine-particle pollution (Ca. O. *et al*., 1998). In addition, there are more than 40 gases extremely intricate mixtures and fine particles exhausted by diesel vehicles devastate the public health and environment. Essential pollutants expelled from diesel engines consists of [3]: Particulate emissions (PM) ,Carbon monoxide (CO), Carbon dioxide (CO2), Nitrogen oxides (NOx), Volatile Organic Compounds (VOCs) and Other chemicals classified as "Hazardous Air Pollutants: (HAPs).

As the worlds pursue economic expansion, countries acquire great demand for operation and technologies that have climate-friendly approach. A new method to green technology propagation should be studied in order to approach the demand among developing countries. The usages on non-renewable energy such as oil, natural gas, coal have to be decreased. In the future, civilization will be forced to research and develop renewable energy sources such as wind, wave, biomass and water (E. Trostmann. *et al.* 2001).

The implementation of water-based hydraulic in hydraulic hybrid system (HHS) is one possibility to increase more environmental friendly technology. Generally, the idea of hydraulic hybrid system (HHS) is to decrease the load on the combustion engine during acceleration, and the load on brake during deceleration. This system have a potential to improve the fuel consumption and brake wear of operating vehicles (E. Lindzus *et al.* 2008).

Hydraulic hybrid system

Heavy commercial vehicles that frequently in a stop and go mode such as garbage trucks or delivery trucks, produce an immense amount of energy in a moment (E. Lindzus *et al*., 2008). This energy which is produced from a high load on the engine is converted to wasted heat energy that released to the airstream. Specifically, when a conventional vehicle slows down or decelerates, the friction of brake pads and wheels produce heat that is converted from the kinetic energy. This heat is dissipates into the air that causes an effective wasted energy up to 30% of the vehicle's generated power (S. Valente *et al*., 2009).

Hydraulic hybrid system or hydraulic regenerative braking system is a mechanism that stored a portion of the kinetic energy that was a momentum as potential energy in form of pressure. It is stored by a short term storage system that is done by using a displacement pump to pump hydraulic fluid into an accumulator. That energy is kept until needed again by the vehicle, by which the pressure is released from the accumulator as the vehicle accelerates. This pressure will spin the drive shaft while the engine remains idle. As the vehicle achieve the

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desired speed or the accumulator is emptied, the engine will take over to continue the process that is beyond the capability of accumulator (E. Lindzus *et al*., 2008 - S. J. Clegg, 1996). Figure-1 shows the basic mechanism of hydraulic hybrid system.

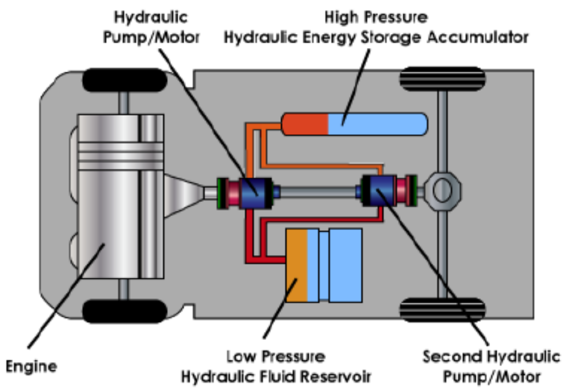

Figure-1. Hydraulic hybrid systems (S. Valente *et al.,* 2009).

Hydraulic hybrid configuration

Hydraulic Hybrid system is an alternative technology to Electric Hybrid system. Automotive companies such as Toyota, Honda are targeting on electric hybrid technology. Meanwhile, Eaton Corporation, Parker Hannifin Corporation are among the pioneer companies focusing on developing the hydraulic hybrid system (E. R. A. Kuma., 2012, K. Rydberg, 2009, K. Plymell, 2009). Electric hybrid system is not compatible to operate on large vehicles like bus or truck. Since delivery trucks, garbage trucks and bus are usually moves in stop and go mode, so they required a large amount of energy to accelerate and a lot of initial torque to move forward. A hydraulic hybrid system is the best suited technology to provide a huge amount of energy to the system because of its potential to absorb and release energy rapidly (K. Plymell, 2009).

Hybrid system for a particular vehicle can be recognize by the combination of two sources of propulsion which is an internal combustion engine (ICE) and an energy storage unit (ESU) (S. J. Clegg , 1998). A basic model of a power flow in hydraulic hybrid system has three internal power paths: Engine ICE (primary source power), energy storage unit ESU (medium to store and release energy) and wheel W. There are two pattern can be extract based on the relation of these paths (J. Stecki, *et al.,* 2005).

Series hydraulic hybrid systems (2nd pattern) transmit power directly to the wheel without conventional transmission or driveshaft (L. Kladder *et al*., 2011). This system is dealing with paths 2 and 3(ICE to ESU to W) as the energy converter is a closed circuit hydrostatic transmission with a high pressure accumulator are connected between the variable pump and reversible pump. The essential aspect of this transmission is its competence to restore a portion of the braking energy in the vehicle. This pattern is more efficient on engine operation as a looser connection between the wheels and speed of engine (J. Stecki, *et al*., 2005). As shown in Figure-2, energy converter 1 represents a hydraulics pump and energy converter 2 represents a hydraulics motor. The vehicle visual figure illustrated the real situation of series hydraulic hybrid inside a vehicle. In series hydraulic hybrid, the ICE is nonaligned with the vehicle operation. The vehicle recharges the accumulator by using regenerative braking or by ICE, either in static of mobile position. Series hybrid is more efficient as it does operate less component of energy, i.e., vehicle engine can be shut off as the hydraulics itself is driving the wheels (S. Valente *et al.,* 2009). This system are resulting more fuel savings potential, which is estimated to improve fuel economy up till 20% to 40% (K. Rydberg, 2009).

In a Parallel hydraulic hybrid systems (3rd pattern), conventional transmission and driveshaft are connected between the engine and wheel block which is in path 1(ICE to W), whereas accumulator is connected between ESU and wheels which is in path 3 as shown in Figure-3 (J. Stecki, *et al.,* 2005). ICE and ESU are able to assists the driveline in the same moment, that means the system support the engine while accelerating, but the engine are still operate even in immobile position. The basic mechanism is similar compared to the 2nd pattern, but parallel hybrid is able to operate even regenerative system breakdown (S. Valente *et al.,* 2009). The parallel hydraulic hybrid system increases the fuel economy up by 10-25% (K. Rydberg, 2009). Environmentally, CO_2 emission reduces till 20% and NO_x emission decrease to 17% (K. Plymell and R. Paccini, 2009).

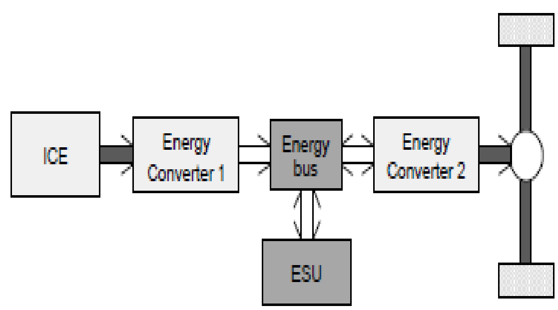

Figure-2. Series driveline layout (2nd pattern)[11].

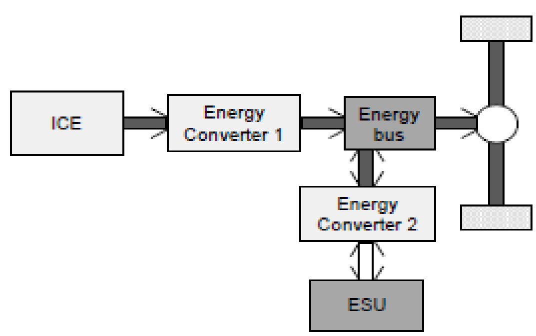

Figure-3. Parallel driveline layout (3rd pattern) (J. Stecki, *et al.,* 2005).

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Water hydraulic system

Generally, water hydraulics can be simplified as a fluid power system which is using water as a medium transmission of energy and power (Environmental Fact Sheet, 2014). The application of water as the transmission medium is totally a new concept in industry as commonly mineral oils or other fluids are more familiar in hydraulic machines. Many industries and companies are now involved in water hydraulics technology due to the concern about safety issues and environment crisis. The replacement of oil hydraulic to water medium bring the world one step forward towards a better future technology as water is environmentally friendly, nonflammable, nontoxic, and low costs(H. X. Chen *et al.,* 2005, W. Kobayashi *et al.,* 2011, A. anas Yusof *et al*., 2014). Moreover, physically water has a higher rate compared to electric and pneumatic in term of fluid power density, torque and power efficiency (F. Conrad, 2005).

Water properties

The implementation of water instead of oils is offering advantages, but certain factors need to have a deep study to match or surpass the current outcome by the oil hydraulics. The specific characteristics of water in term of corrosion, flow erosion, friction, internal and external leakage, lubrication, cavitation, freezing and microorganism are essential prospect that could affects the efficiency of water compare to oil (F. Conrad, 2005, G. Krutz and P. Chua, 2004).

Based on the nature of pure water, the permitted operational temperature range is between +3 °C to +50 °C max. Though, thermal conductivity of water is 4 to 5 times compared to mineral oil which is water hydraulic system have tendency on less cooling capacity[16]. However, the lowest daily temperature in the equatorial countries does not fall below 20 °C, means freezing is not an issue in these countries (G. Krutz and P. Chua, 2004).

Viscosity is a measure of the internal friction in a fluid. Hydraulic component efficiencies will be low if the viscosity is high because of power loss to overcome fluid friction during fluid flow (E. Trostmann, 2001). Nevertheless, it leads to less internal and external leakages. The viscosity of water (1 cSt at 20 °C and atmospheric pressure) and mineral oils (30 cSt at 55 °C and atmospheric pressure) that is the leakage rate for water is approximately 30 times compare to oil. The application of water hydraulic required a smaller size of hoses diameter and cooling systems compare to oil in generate the same power range (G. Krutz and P. Chua, 2004).

A novel method in water hydraulics is the implementation in hydraulic hybrid system which is the best alternative to oil hydraulics when health, environment and economics must be considered. Through the usage of water hydraulics hybrid system, problems related to safety and contamination of oil hydraulics in typical hydraulic hybrid technology can be avoided. The newly studied water hydraulic hybrid system will be in-line with the State Government Green Technology Initiatives (P. Chin) since it combines less emission effects due to the use of hydraulic hybrid system.

In this paper, the objective of the project is to understand the fundamental knowledge on how to utilize water hydraulics technology, through the simulation of a water hydraulic hybrid vehicle technology. Futhermore, the resulted torque, power and efficiency during water hydraulic-assisted acceleration are calculated to determine the capability of water hydraulic system in assisting diesel engine.

METHODOLOGY

Hydraulic hybrid system is consists of various components such as accumulators, pumps and motors. The function of each part, the process to identify the specifications, and the operation condition of the system will be described and analysed in the next explanation.

System description

The hydraulic hybrid system is made up of components such as fixed displacement pump which will channel pressurized water to occupied accumulator (charge mode). An accumulator is used to store energy and release it during acceleration (discharge mode). Fixed displacement motor is used to drive the wheel during acceleration. Besides that, 2 set of 2/2 way directional control valve (V1, V2) are used to control the water flow during charge and discharge mode. Pressure relief valve (PRV) is used to limit pressure in the system. Figure-4 has shown the basic hydraulics hybrid circuit.

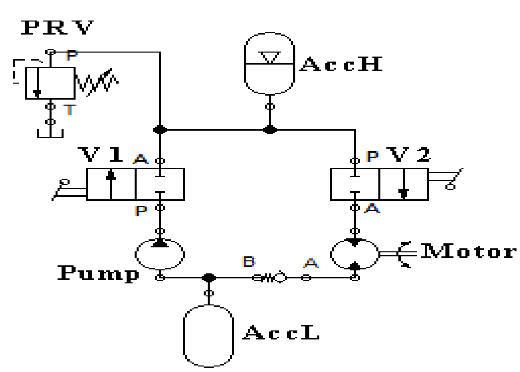

Figure-4. Simplified hydraulic hybrid circuit.

The hydraulic hybrid system is separated into two main processes: charge and discharge mode. Charge mode is a process of regenerating the energy from braking friction. While the vehicle is braking, the momentum of the vehicle is applied to drive the fixed displacement pump which in turn charge the accumulator. In this mode, V1 is considered as a brake pedal, which will generate the pump to occupy the accumulator with pressurized water. However, in this simulation, the pump is generated by an electric motor that we consider the output power of the electric motor is the value that regenerative braking system should gain to operate the water based hydraulic system. In Figure-5 shown the schematic of pressurized water movement in charging mode.

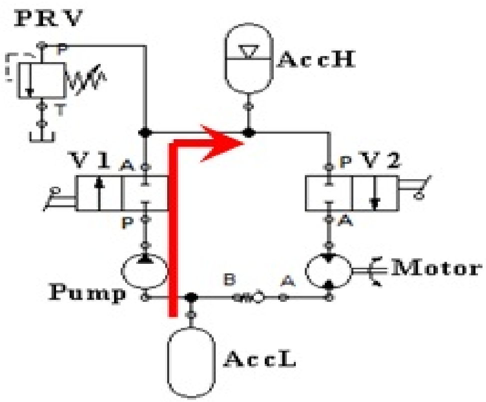

Figure-5. Hydraulic hybrids (Charge mode).

Subsequently, once the V2 (considered as the throttle) are applied to accelerate the vehicle, pressurized water in the accumulator are discharged to generate fixed displacement motor which will drive the wheel. This discharge mode is illustrated in circuit shown in Figure-6.

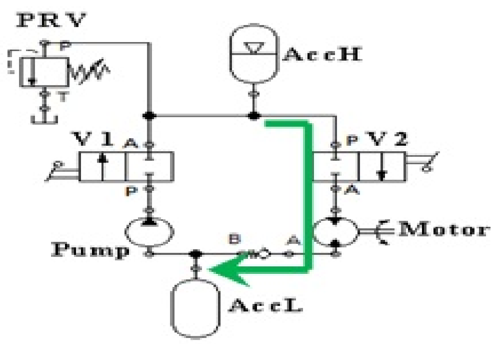

Figure-6. Hydraulic hybrids (Discharge mode).

Component specification determination

The specifications of element in the programmed system were simulated to identify the nature of a complete system of hydraulic hybrid applied in a diesel engine.

Water hydraulic hybrid system

The main parameters required in fixed displacement pump is the value of flow rate,q_p and pressure, p_p. The pump flow rate, q_p is given by the following equation:

$$q_p = V_g \omega - k_{leak} p \qquad (1)$$

Where V_g is volume displacement, ω is angular velocity, which is produced by the motor connected to the pump with a constant value. η is volumetric efficiency. Whereas the value of pressure is determined by the following equation:

$$p = \frac{T_p \eta_{mech}}{V_g} \qquad (2)$$

Where Tp is torque at the pump driving shaft, η mech is pump mechanical efficiency.

Pressurized water is channeled by the pump to the occupied accumulator in a particular preference. The relationship of the gas volume and gas pressure between the pre charge state and charge/discharge state is shown in the following equation:

$$(p_G + p_A)(V_T - V_F)^k = (p_{pr} + p_A)V_T^k \qquad (3)$$

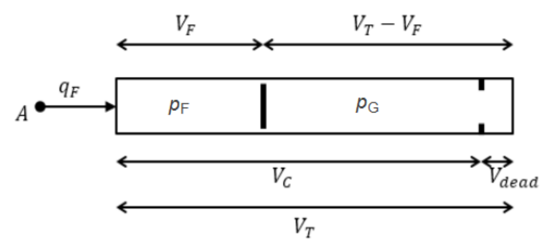

Figure-7. Accumulator's volume division.

In explaining equation (3), Figure-7 represents an accumulator. The total accumulator volume, V_T is separated into the fluid chamber (left side) and the gas chamber (right side). V_F is the fluid volume and (V_T – V_F) is the gas volume. Gas volume never becomes zero as the total accumulator volume, V_T is larger than the fluid chamber capacity, V_C. Subsequently, p_G is the gas pressure, p_{pr} is the precharge pressure (emptied fluid chamber) and p_A is the atmospheric pressure which is 101325Pa. Gas pressure, p_G in equation (3) is determined by using the following equation:

$$p_F = p_G + p_{HS} \qquad (4)$$

$$p_{HS} = \begin{cases} K_s(V_F - V_C) + K_d q_f (V_F - V_C) & \text{if } V_F \geq V_C \\ K_s V_F + K_d q_F V_F & \text{if } V_F \leq V_C \end{cases} \qquad (5)$$

Where, p_F is the fluid pressure which is equal to the pressure at the accumulator inlet, p_{HS} is the hard-stop contact pressure. Equation (5) is applied to calculate the value of p_{HS} whereas $q_{f\,(+ve)}$ and $q_{f\,(-ve)}$ are considered as charge and discharge mode. According to the type of compression process, the value of exponent k is determined based on the value of the adiabatic index which is 1.4.

In addition, the flow rate in and out the accumulator is the fluid volume's rate of change as shown in equation (6). At t = 0, the initial condition is fluid volume , V_F.

$$q_F = \frac{dV_F}{dt} \qquad (6)$$

Once valve, V2 are applied, accumulator,A1 release the pressurized water to operate hydraulic motor that drive the wheels. Basically, input for hydraulic motor is pressure, p and flow rate, q_m through the motor. Whereas, the output is torque, T_m and rotational speed, n at

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motor output shaft. Torque, T_m and notational speed, n is given by the following equation (7,8):

$$n = \frac{q_m - (k_{leak} p)}{V_g} \tag{7}$$

$$T_m = V_g p \eta_{mech} \tag{8}$$

Since medium of the hydraulic system is water based, certain value need to be considered in obtaining a precise result. The concept of dynamic viscosity and kinematic viscosity are often used. The kinematic viscosity, ν is defined by the ratio:

$$\nu = \frac{\mu}{\rho} \tag{9}$$

Where, μ is dynamic viscosity and ρ is the mass density. In equation (1) mention on k_{leak} which is leakage coefficient. Calculation of leakage is explained by the following equation:

$$k_{leak} = \frac{k_{HP}}{\nu \rho} \tag{10}$$

$$k_{HP} = \frac{V_g \omega_{nom} (1 - \eta_v) \nu_{nom} \rho_{nom}}{p_{nom}} \tag{11}$$

Where, k_{HP} is Hagen-Poiseuille coefficient, ω_{nom} is motor nominal angular velocity, ν_{nom} is nominal fluid kinematic viscosity, ρ_{nom} is nominal fluid density, p_{nom} is motor nominal pressure.

Diesel engine

The control of hydraulic and diesel engine vehicles entails translating the pedal input into power and torque command for the power train propulsion components. Simulation of the water hydraulic hybrid system is applied on a diesel engine truck manufactured by Mitsubishi Fuso. The following Table-1 is detailed on the specification of Mitsubishi Fuso 6D34-OAT2.

Table-1. Mitsubishi Fuso specification.

Diesel engine	6D34-OAT2
Kerb weight (kg)	5323kg
GVM (kg)	8162kg
Max Power (kW)	130 kW @ 2900 rpm
Max Torque (Nm)	440 Nm @ 2000 rpm

RESULTS AND DISCUSSION

In order to simulate the performance of water-based hydraulic system as well as to determine the suitable power required by the system in assisting the diesel engine, a water hydraulic hybrid system is established. In Figure-8 shown the simulation model implemented in Simulink using corresponded Simscape toolbox.

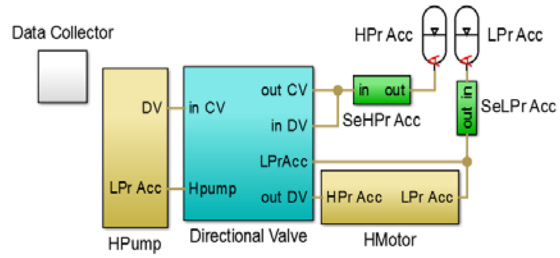

Figure-8. Simulink model of hydraulic hybrid system.

The following Table-2 and 3 shows the component specification and hydraulic fluid properties that used as the parameter in the simulation.

Table-2. Component specification.

Hydraulic fixed displacement pump	
Speed (rpm)	4000
Max displacement (cm³/rev)	125
Hydraulic fixed displacement motor	
Max displacement (cm³/rev)	125
Nom kinematic viscosity (cSt)	17.208
Nom fluid density (kg/m³)	825.6
Low pressure accumulator, AccL	
Total accumulator volume (l)	200
Min gas volume (l)	90
Precharge pressure (bar)	2
Initial Fluid Volume (l)	110
High pressure accumulator, AccH	
Total accumulator volume (l)	200
Min gas volume (l)	10
Precharge pressure (bar)	100
Initial Fluid Volume (l)	80
Pressure Relief Valve, PRV	
Valve pressure setting (bar)	400

Table-3. Hydraulic fluid properties.

Hydraulic fluid type	Water
Parameters	
Relative amount of trapped air	0.005
System temperature (c)	40
Viscosity operating factor	1
Fluid Properties	
Nom kinematic viscosity (cSt)	0.657161
Nom fluid density (kg/m³)	992.562
Bulk modulus (Pa) *	2.26E+9

* Bulk modulus at atm. pressure and no gas

The simulation results for the comparison of water hydraulic hybrid system and the diesel engine are shown in Figure-9. The torque characteristics of hydraulic motor are shown along with diesel engine. For hydraulic motor, a high torque is available at starting which is the rated torque of the motor. The rated torque of motor is 868Nm and the motor's torque cross the engine torque at 272Nm at 802rpm. This show the capability of hydraulic hybrid system to assist the diesel engine in reducing the usage of diesel engine which we can see the reduction is at the cross section of both motor and engine that resulted 22.9kW.

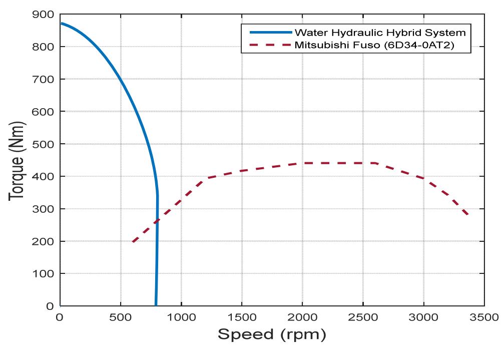

Figure-9. Hydraulic motor and diesel engine torque characteristics.

Besides that, Figure-10 show that the characteristics of torque produced by electric motor that implemented in electric hybrid system. The same concept applied to the hydraulic hybrid system but we do understand that resulted torque in electric motor have a constant torque region once the voltage limit of the power supply reached. This comparison show the method takes part in both systems in assisting engine.

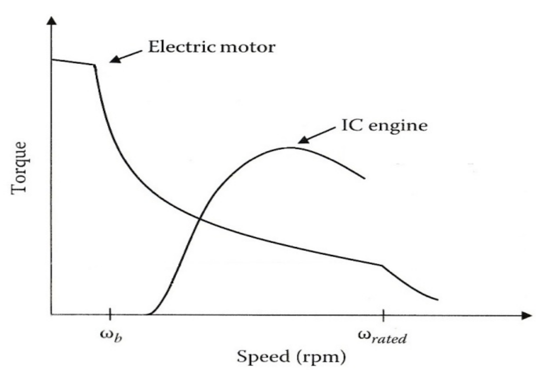

Figure-10. Electric motor and IC engine torque (I. Husain , 2003).

CONCLUSIONS

The hydraulic motor produces high torque even at zero speed. Therefore the hydraulic motor can be attached directly to the drive wheels accelerate the vehicle from the zero speed all the way up to the top speed in supporting diesel engine efficiently which eventually reduce the consumption of diesel engine that resulted reduction of harmful gases emission.

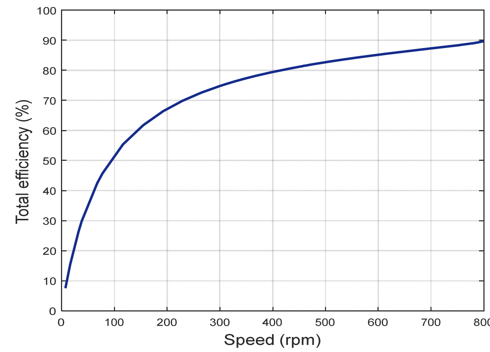

Figure-11. Total efficiency of hydraulic hybrid system.

In the other hand, the total efficiency of hydraulic motor at the rated power is 86.03% which shows a good performance of water hydraulic hybrid system as shown in Figure-11. In the future, experiment will be done based on the same parameter applied in this paper to validate the simulation result.

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