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Volume Displacement Simulation Impact on the Water Hydraulic Hybrid Driveline Performance

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ABSTRACT

The impact of volume displacement simulation on the Water Hydraulic Hybrid Driveline performance is presented in this paper. Hydraulic hybrid system vehicles depend on oil based hydraulic fluid. Therefore, natural concerns of environment and safety promote the uses of the water-based hydraulic hybrid system. The focus of this paper is to gather simulation data of the potential on using water hydraulic technology in hydraulic hybrid systems. In this paper, an extensive study on the mathematical modeling and simulation by using Matlab/Simulink has been conducted to determine the feasibility of water compared to oil, HyspinAWS68 in term of the performance of the hydraulic hybrid driveline. The simulation result indicates that the best performance of hydraulic hybrid driveline is at the specification of volumetric displacement of 250 cm^3/rev.

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1. Introduction

The main function of a hydraulic fluid in a hydrostatic power system is to transmit power and movement. In addition to the power transmission, the hydraulic fluids serve to lubricate the contact surfaces, cool different elements and clean the system [1-3]. Typical hydraulic technology depends on petroleum-based hydraulic fluid. Mineral oil has come to be the most popular choice primarily because of its excellent protection against corrosion and good lubricity [4]. However, mineral oil used in oil hydraulic equipment poses a fire hazard in the event of a spillage or leakage. This is especially critical in vehicle accident scenarios where the oil spillage might trigger fire mishaps as explained in the previous study [5-10]. Typical concerns of fire and safety in hydraulic systems promote the uses of the water-based hydraulic system. Through the usage of water hydraulics, problems related to safety and contamination of oil hydraulics in typical hydraulic hybrid technology can be avoided. Water was used in the early days for the transmission of the fluid power. The main advantage of water as pressure medium is its availability, fire resistance, and low cost. On the other hand, the disadvantage of water is poor lubricity, high tendency of rust and has a

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narrow range of working temperature [11]. Consequently, fire-resistant fluids are often used in hydraulic systems that are mainly water-based [12]. Besides that, water is available in abundance and which mean it is very inexpensive. Water is also very environmental friendly that alleviates the concerns for contamination in term of hydraulic spillage and failure [13]. On the other hand, the implementation of water instead of oils is offers advantages, but certain factors need to be studied in depth to match or surpass the current outcome of 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 prospects that could affect the efficiency of water compared to oil as in the previous study [14-15]. In respect to the above statement, some water properties are explained in this section. The density of hydraulic fluid affects the value of hydraulic energy losses in the system because the latter is proportional to the density. Changes in the pressure and temperature state in a hydraulic pressure medium will change the value of its density. In order to keep the pressure losses small and to reduce the dynamic effect on control valves, it is important to keep the density of the pressure medium as low as possible [16]. Viscosity is one of the most important properties of a hydraulic fluid and it influences the performance of a hydraulic system. If the viscosity is high the system efficiency will be low because of the power loss (pressure drop) to overcome fluid friction during fluid flow. Meanwhile, low viscosity will increase external and internal leakage thereby increasing power loss. The viscosity of mineral oil are more sensitive to temperature changes compare to water show that water is more stable in term of efficiency and flow velocity.

Generally, water hydraulics can be simplified as a fluid power system which is using water as a medium transmission of energy and power [17]. The application of water as the transmission medium is a new concept in the industry as commonly mineral oils or other fluids are more familiar with 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, non-flammable, nontoxic, and low costs [18]. Moreover, physically water has a higher rate compared to electric and pneumatic in term of fluid power density, torque and power efficiency.

Besides that, in this research, water hydraulic technology was applied on a new technology known as hydraulic hybrid system. Generally, during 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 dissipated into the air that causes an effective wasted energy up to 30% of the vehicle’s generated power [19-20]. 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 a form of pressure. It is stored by a 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 desired speed or the accumulator is emptied, the engine will take over to continue the process that is beyond the capability of accumulator [21-23].

This paper concerns on the performance of the novel water-based hydraulic hybrid system instead of the established oil-based hydraulic system. Therefore, a simulation was conducted to analyze these two objectives. The first objective of this paper is to analyze the performance of high pressure accumulator as an energy storage during charge mode. The second objective of this paper is to analyze the feasibility of using hydraulic motor in utilizing water as a pressure medium instead of hydraulic oil. Hence, the effects of hydraulic fluid in term of efficiency, leakage and power losses were analyzed to compare both pressure medium performance. In additional, pressure, flow rate, volume and energy density during charge and discharge mode are studied deeply to determine the best performance for both hydraulic fluid.

2. Modelling A Hydraulic Hybrid Driveline

The hydraulic hybrid system consists of various components and the main parts are 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. The hydraulic hybrid driveline is made up of components as shown in Figure 1 such as fixed displacement pump, HP which will channel pressurized liquid to occupied high pressure accumulator, HPAcc during charge mode. The HPAcc is used to store energy and release it during acceleration (discharge mode). Fixed displacement motor, HM is used to drive the wheels during acceleration. Besides that, 2 set of 2/2 way directional control valve (CV, DV) are used to control the fluid flow during charge and discharge mode. Pressure relief valve, PRV is used to control the pressure in the system. In respect to that, in order to simulate the performance of water-based hydraulic hybrid driveline as well as to determine the suitable specification required by the system in assisting the Mitsubishi Fuso 6D34-0AT2, a hydraulic hybrid driveline was established by implemented in Matlab/Simulink using corresponded Simscape toolbox as shown in Figure 2.

The hydraulic hybrid system is separated into two main processes: charge and discharge mode. Charge mode is a process of regenerate the kinetic energy from braking friction and stored the energy in form of pressure in accumulator. Meanwhile, discharge mode occurs as the throttle is applied, the energy stored in the accumulator is released to run the motor that eventually will drive the vehicle forward.

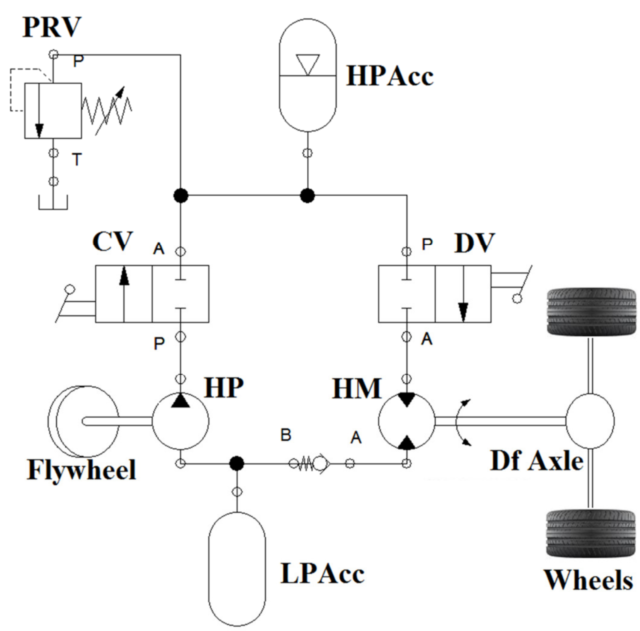


Fig. 1.Simplified hydraulic hybrid driveline circuit

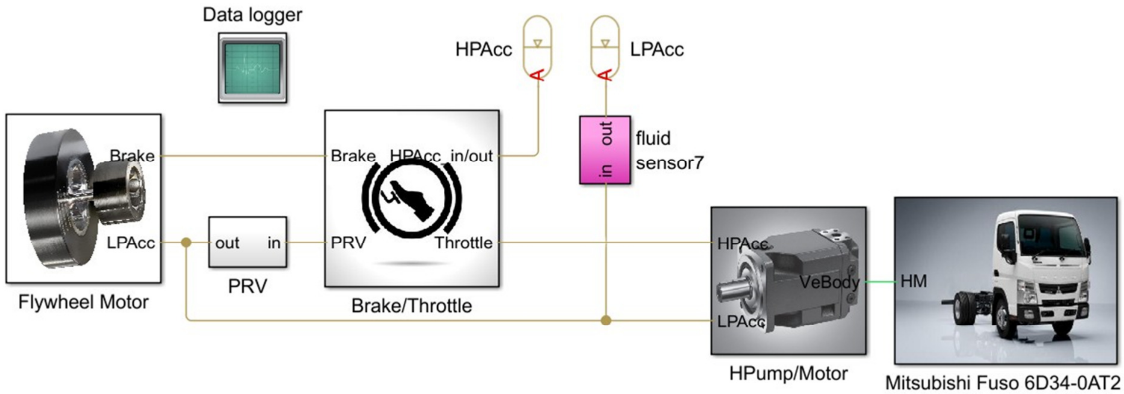


Fig. 2. Hydraulic hybrid driveline circuit by using Matlab/Simulink

The simulation was run for 400s per simulation. As shown in Figure 3, the brake pedal was applied at t=15s and stop at t=160s. Next, throttle was applied at t=215s and stop at t=430s. Thus, the period of charge mode was 145s and discharge mode was 215s. Hence, the next part explained the process of charge and discharge mode applied at the circuit of Matlab/Simulink.

Charge Mode: Figure 4 shown the schematic of pressurized liquid movement in charging mode (red arrow). While the vehicle is in braking mode (brake pedal, CV are applied), the momentum of the vehicle is stored in form of kinetic energy by flywheel that were attached at the shaft of the engine. This kinetic energy was applied to drive the fixed displacement pump, HP which in turn channels the pressurized liquid from low pressure accumulator, LPAcc to occupied high pressure accumulator, HPAcc. The pressurized liquid is stored inside the HPAcc until the discharge mode is applied. In addition, the excessive of pressure limit in the system, will channel the liquid back to the LPAcc. In consequence, Figure 5 shows that the pressurized liquid movement (red arrow) in charging mode by using the implementation of Matlab/Simulink. However, there are some limitation in this simulation, the flywheel is generated by an electric motor and fixed displacement hydraulic pump, HP as shown in Figure 6. The input speed, rpm of the electric motor is considered as the value that the momentum of the braking process gains from the driven flywheel. To maximize the precision of simulation, several values of input speed were set as a control variable as explained in section parameter of simulation.

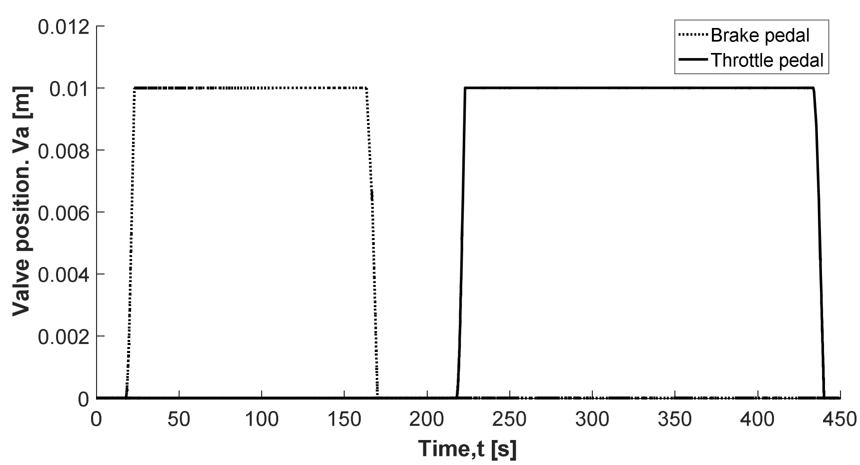


Fig. 3. Brake pedal and throttle position based on time

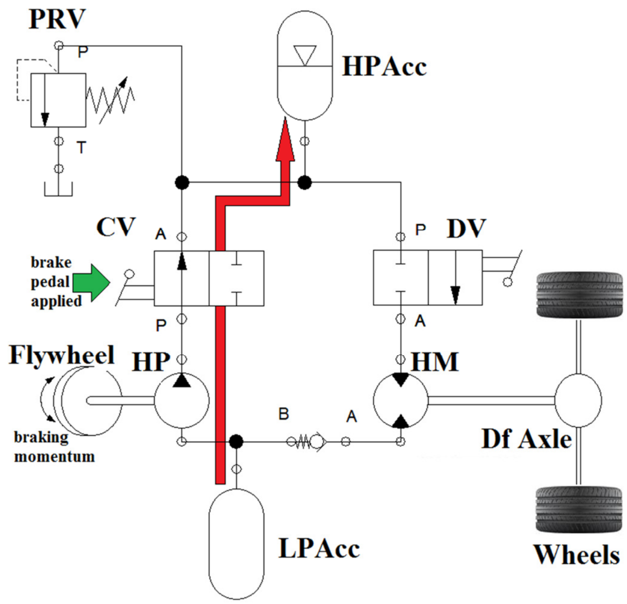


Fig. 4. Hydraulic hybrids driveline (Charge mode)

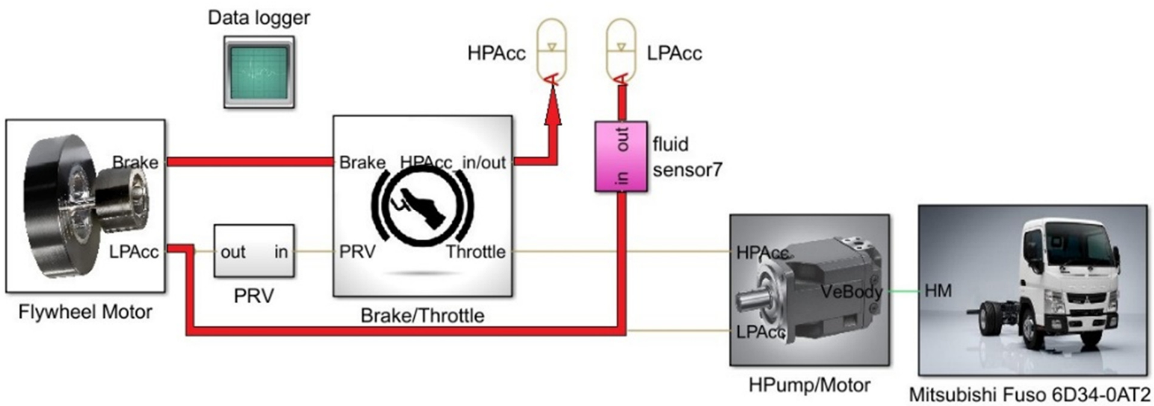


Fig. 5. Hydraulic hybrids driveline (Charge mode) by using Matlab/Simulink

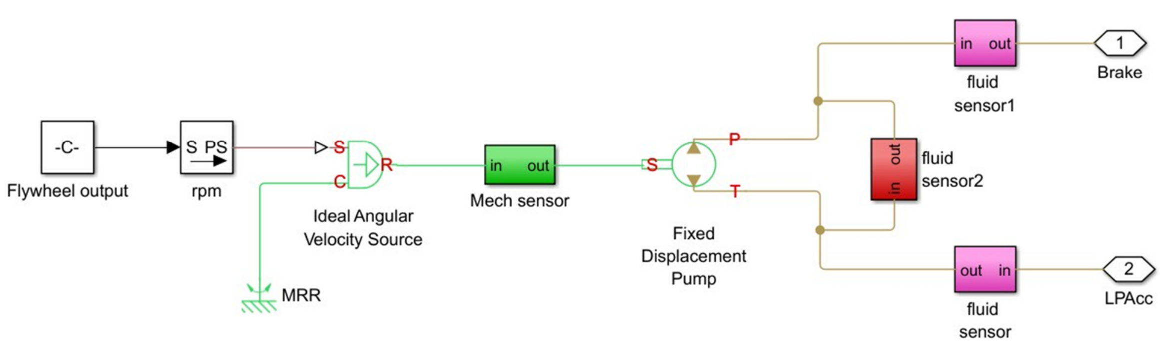


Fig. 6. Input speed at flywheel motor mask

Discharge Mode: Subsequently, once the throttle, DV are applied to accelerate the vehicle, pressurized liquid in the HPAcc are released to generate HM which will drive the wheels. At last, the pressurized liquid will have reoccupied the LPAcc. The red arrow at Figure 7 shows the pressurized liquid movement.

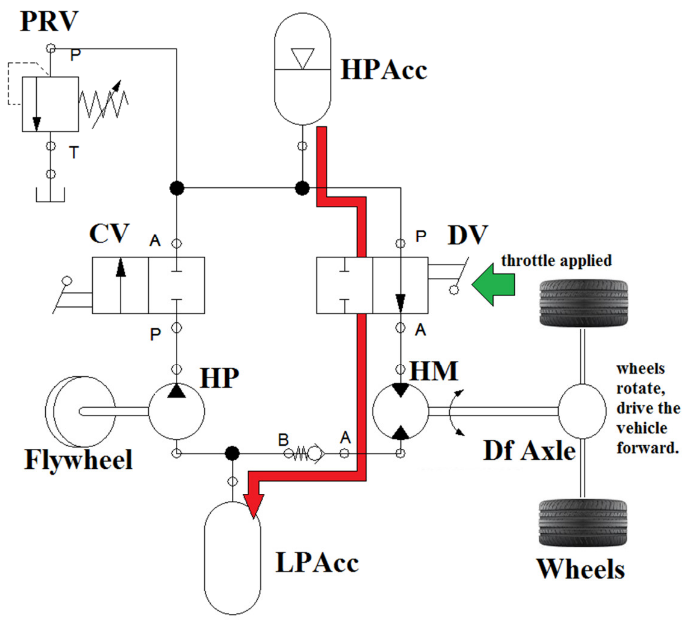


Fig. 7. Hydraulic hybrids driveline (Discharge mode)

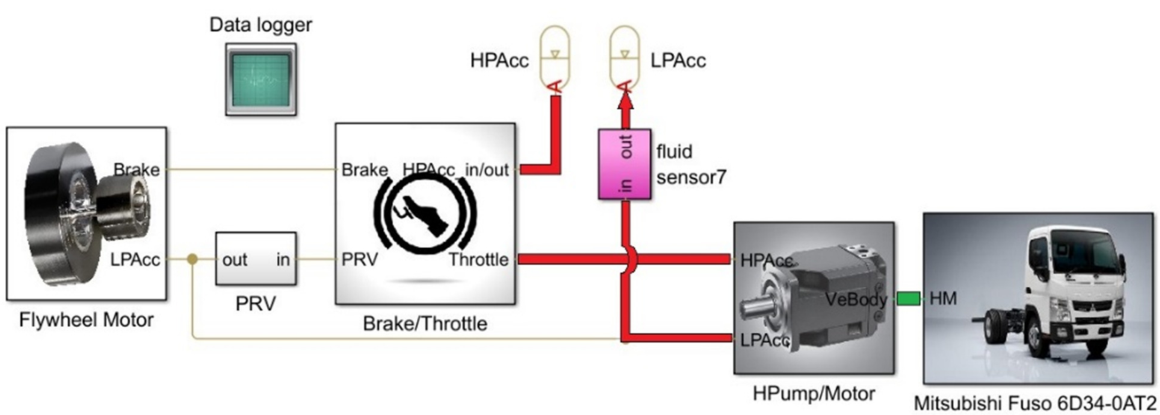


Fig. 8. Hydraulic hybrids driveline (Discharge mode) by using Matlab/Simulink

Accordingly, Figure 8 shows the discharge mode circuit based on the simulation done by Matlab/Simulink. The green line shows the mechanical movement that generated by the HPump/Motor to drive the Mitsubishi Fuso 6D34-0AT2. Figure 9 shows the simple structure of Mitsubishi Fuso 6D34-0AT2. However, as mention before that this research's scope is only on the part of driveline, so the diesel engine of the vehicle were not applied on the system. In order to create a mechanical relation on the current diesel engine of Mitsubishi Fuso 6D34-0AT2, a transmission are established before the differential axle that connected to the wheels. Block diagram labelled as simple gear 1 and simple gear 2 are considered as the gear 1 in the real situation. So that, after gear 1(Hydraulic hybrid driveline) completed its task, gear 2 (diesel engine) will take over the system and it will carry on up till gear 5. Moreover, the gear ratio 1 of simple gear 2 also consider as a control variable, in purpose to determine the suitable gear ratio suit for the driveline. This simulation parameter is explained clearly at next section.

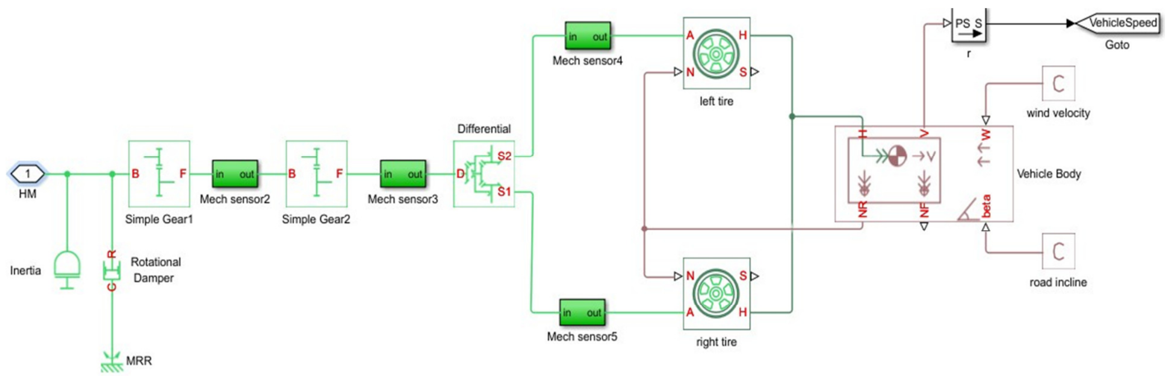


Fig. 9. Mitsubishi Fuso 6D34-0AT2 simple transmission, wheels and truck body structure

2.1 Hydraulic Hybrid Simulation Setup

The specifications of an element in the programmed system were simulated to identify the nature of a complete system of hydraulic hybrid applied in a diesel engine. The main parameters required in HM are the value of flow rate, q_F and pressure, Δp_{HM}. The HM flow rate, q_F is given by the following equation:

$$q_F = D_{HM} \cdot \omega_{HM} \tag{1}$$

where D_{HM} is volume displacement, ω_{HM} 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

$$T_{HM} = D_{HM} \cdot \Delta p_{HM} \tag{2}$$

where T_{HM} is torque at the HM driving shaft, η_{mech} is pump mechanical efficiency.

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

$$(p_G + p_{atm})(V_T - V_F)^k = (p_o + p_{atm})V_T^k \tag{3}$$

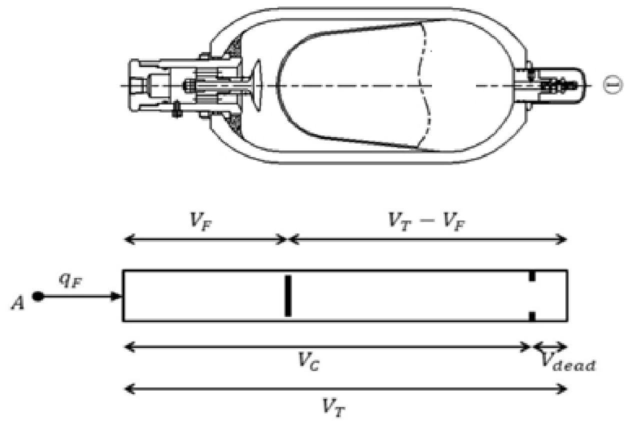


Fig. 10. Acccumulator internal volume division

In explaining equation (3), Fig. **10** 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

$$p_F = p_G + p_{hs} \tag{4}$$

$$p_{hs} = \begin{cases} K_s(V_F - V_C) + K_d q_F^+ (V_F - V_C),\ if\ V_F \geq V_C \\ K_s V_F - K_d q_F^- V_F,\ if\ V_F \leq 0 \\ 0,\ otherwise \end{cases} \tag{5}$$

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.

$$q_F = \frac{dV_F}{dt} \tag{6}$$

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

$$v = \frac{\mu}{\rho} \tag{7}$$

where, μ is dynamic viscosity and ρ is the mass density. Leakage coefficient, q_{leak} which is mention in equation (1) is calculated by the following equation

$$q_{leak\ HM} = K_{poi}\Delta p_{HM} \quad (8)$$

$$K_{poi} = \frac{v_{nom}}{\rho v}\frac{\rho_{nom}\omega_{nom}D_{HM}}{\Delta p_{nom}}\left(\frac{1}{\eta_{v\ nom}} - 1\right) \quad (9)$$

where, k_{poi} is Hagen-Poiseuille coefficient, ω_{nom} is motor nominal angular velocity, v_{nom} is nominal fluid kinematic viscosity, ρ_{nom} is nominal fluid density, p_{nom} is motor nominal pressure.

2.2 Simulation Parameter

In this simulation, the comparison was done based on the type of hydraulic fluid which is Hyspin AWS68 and water and each simulation was run by controlling the volumetric displacement from 28 cm^3/rev till 500 cm^3/rev. In addition, HyspinAWS68 was selected as an example of oil to compare with water. HyspinAWS68 is based on highly refined mineral oil with low zinc containing anti-wear system. HyspinAWS68 is classified as DIN51502 (ISO 6743/4) under the classification of HLP. HLP fluids are suitable for most fields of application [24].The following Table 1 and Table 2 shows the component specification and hydraulic fluid properties that used as the parameter in the simulation.

Table 1
Hydraulic Fluid Properties

Fluid Properties	Hyspin AWS68	Water
Relative amount of trapped air	0.005	0.005
System temperature [°C]	40	40
Viscosity operating factor	1	1
Nom kinematic viscosity [cSt]	68	0.657161
Nom fluid density [kg/m^3]	880	992.562
Bulk modulus [Pa] *	1.20E+09	2.26E+09

* Bulk modulus at atm. Pressure and no gas

Specifications for every component are based on the specification sheet provided by the supplier. Specification for oil-based HP and oil-based HM were based on the axial piston fixed motor A4FM manufactured by Rexroth Bosch Group. Meanwhile, specification for water-based HP and water-based HM are based on the axial piston fixed motor MC160-70W manufactured by The Water Hydraulics Co.Ltd., whereas value of nominal kinematic viscosity and nominal fluid density are assume based on the optimum range reading on viscosity index based on each spec. Besides that, the input speed of HP/M was fixed as 1000rpm as we assumed the value of momentum which the system received from flywheel while deceleration (braking) takes part in the truck's motion.

Meanwhile, low and high pressure accumulator's values were determined based on the specification sheet of standard bladder accumulator manufactured by Hydac Corporation [25]. This hydraulic hybrid system is applied on a diesel engine truck, Mitsubishi Fuso 6D34-0AT2 manufactured by Mitsubishi Fuso Truck and Bus Corporation. This truck model was selected as this model is often used by certain waste management company as a garbage truck which is our main target vehicle to apply hydraulic hybrid system.

Table 2
Components Specification and Simulation Parameter

Component	Specification	Values Bosch A4FM (oil)	Values Janus Motor (water)
Fixed displacement pump/motor, HP/M	Input speed, n (rpm)	1000	1000
	Volumetric displacement, V_g [cm^3/rev]	28,40,56,71,125,250,500	
	Volumetric efficiency, η_v	0.65	0.65
	Nom pressure, p [bar]	350	350
	Nom angular velocity, ω [rpm]	3200	3200
	Nom kinematic viscosity, v [cS]	36.14	0.6572
	Nom fluid density, ρ [kg/m^3]	865.4	992.56
High Pressure Accumulator, HPAcc (Hydac SB330 70)	Total Accumulator Volume, V_T [L]	70	
	Min gas volume, V_m [L]	17.5	
	Initial fluid volume, V_F [L]	7	
	Precharge pressure, p_o [bar]	50	
Low Pressure Accumulator, LPAcc (Hydac SB330 70)	Total Accumulator Volume, V_T [L]	70	
	Min gas volume, V_m [L]	17	
	Initial fluid volume, V_F [L]	53	
	Precharge pressure, p_o [bar]	3	
Pressure relief valve, PRV	Valve Pressure, p (bar)	200	
Gear Ratio	Simple gear ratio	1.2	
Mitsubishi Fuso 6D34-0AT2	Gross Vehicle Mass, GVM [kg]	11000	
	Wheel radius, [m]	0.4	
	1st Gear ratio	5.494	
	2nd Gear ratio	3.196	
	3rd Gear ratio	1.689	
	4th Gear ratio	1	
	5th Gear ratio	0.723	
	Differential gear ratio	5.285	

3. Results and Discussions

3.1 Effect of the Volumetric Displacement on the Hydraulic Hybrid Driveline

The discussion on the effect of volumetric displacement on the hydraulic hybrid driveline is separated into two part which is charge mode and discharge mode. At charge mode, the analysis and discussion are focusing on the capability of HPACC based on the parameter of HM volumetric displacement. In other word, the effectiveness of energy storage is determined. Meanwhile, the next section which is discharge mode will discuss the output of the driveline. To put it in another way, this part analyzes the effect of volumetric displacement on the performance of HM and Mitsubishi Fuso 6D34-0AT2.

3.1.1 Charge Mode

During charging mode, several values are measured to analyze the capability of HPAcc as shown in Table 3. Meanwhile, simulation results for the effect of volumetric displacement in hydraulic hybrid driveline while charging are showed from Figure 11 to Figure 13.

Table 3
Charge Mode – At High Pressure Accumulator, HPAcc

	Hydraulic Fluid	Volumetric Displacement [cm^3/rev]						
		28	40	56	71	125	250	500
HPAcc Volumetric Flowrate [L/min]	Hyspin AWS68	26.11	37.29	52.28	65.83	115.22	220.74	396.34
	Water	24.43	34.89	49.03	61.35	107.00	198.40	333.93
HPAcc Pressure [bar]	Hyspin AWS68	204.83	204.88	204.94	204.99	205.23	205.74	206.65
	Water	204.78	204.80	204.89	204.88	205.08	205.49	206.21
HPAcc volume [L]	Hyspin AWS68	44.16	44.16	44.17	44.17	44.19	44.24	44.32
	Water	44.15	44.15	44.16	44.16	44.18	44.22	44.28
HPAcc time taken to fully charged [s]	Hyspin AWS68	110.45	72.15	54.67	46.48	24.95	15.10	10.50
	Water	138.83	94.03	64.31	55.81	29.40	17.92	12.29
HPAcc Energy Density [kJ/L]	Hyspin AWS68	20.48	20.49	20.49	20.50	20.52	20.57	20.66
	Water	20.48	20.48	20.49	20.49	20.51	20.55	20.62

From the curve in Fig. 11(a), it is apparent that the input volumetric flow rate, q_F at HPAcc is clear trend of increasing linearly to volumetric displacement, *D*. As can be seen from the equation 1, the relation of *q* and *D* shows that the increasing of *D* causes the increasing q_F. What is interesting in this data is that the correlation between HyspinAWS68 and water. It can be seen from the Table 3 and Fig. 11(a) that the HyspinAWS68 has a higher value of q_F compared to water and the difference is greater as the *D* increased. Interestingly, this correlation is related to the fluid properties of both medium. This is due to the density of the fluid, as mention in Table 1 that water with density of 992.562 kg/m^3 are higher compared to HyspinAWS68 which is 880 kg/m^3. Density of a substances is its mass, *M* per unit volume, *V* as shown at this equation, $\rho=M/V$. This equation shows that the decreasing of density causes decreasing of mass flow rate and the increasing of volumetric flow rate. If we now turn to the application, density should be low as possible to minimize losses. Further analysis on Fig. 11(b) shows that water consumes longer time to fully charged the HPAcc but the difference is decreasing throughout the *D*. Related to the previous discussion of Fig. 11(a), time taken to fully charged has a specific relationship to the volumetric flow rate. As mention by Noor *et al.*, [25] that flow rate is the flow of volume of liquid through a surface per unit time or in other words it was written as m^3/s. Therefore, a high value of q_F which is HyspinAWS68 will shorten the time taken to fully charged HPAcc compared to a low value of q_F which is water.

As shown in Fig. 11(a), the pressure, p_F reading throughout the D changes is slightly increasing but almost insignificant to be worth consideration. It is due to a very small different of p_F between the smallest D, 28 cm^3/rev and the largest D, 500 cm^3/rev which is 1.82 bar for HyspinAWS68 and 1.43 bar for water as shown at Table 3. The most striking result to emerge from the curve is that the higher value of HPAcc pressure at HyspinAWS68 compared to water. Furthermore, the gap between HyspinAWS68 and water are gradually increasing throughout the changes of D. A strong relationship between HyspinAWS68 and water has been reported in the literature related to the theory of bulk modulus. Water has a larger bulk modulus compared to HyspinAWS68 as mention in Table 1 . Theories from several sources have defined bulk modulus as the ability of liquid to change its volume when its pressure varies. Specifically, a higher value of bulk modulus required more pressure to compress compared to a lower value of bulk modulus as mention from the previous study [26]. Figure 12(a) and 12(b) has expressed a similar view that HyspinAWS68 is compressible compared to water that causes the increasing of effective volume and pressure. However, the small different p_F value between HyspinAWS68 and water indicate that the changes of volumetric displacement, D have no significant impact to the pressure of HPAcc. A part of that, the effective volume, V_T of HPAcc is slightly increasing to the changes of D as shown in Fig. 12(b). There is a very small different of V_T between the smallest D, 28 cm^3/rev and the biggest D, 500 cm^3/rev which is 0.16 L for HyspinAWS68 and 0.13 L for water as shown at Table 3. So that, with the similar explanation as above, the effective volume of HPAcc has no significant impact from the changes of D.

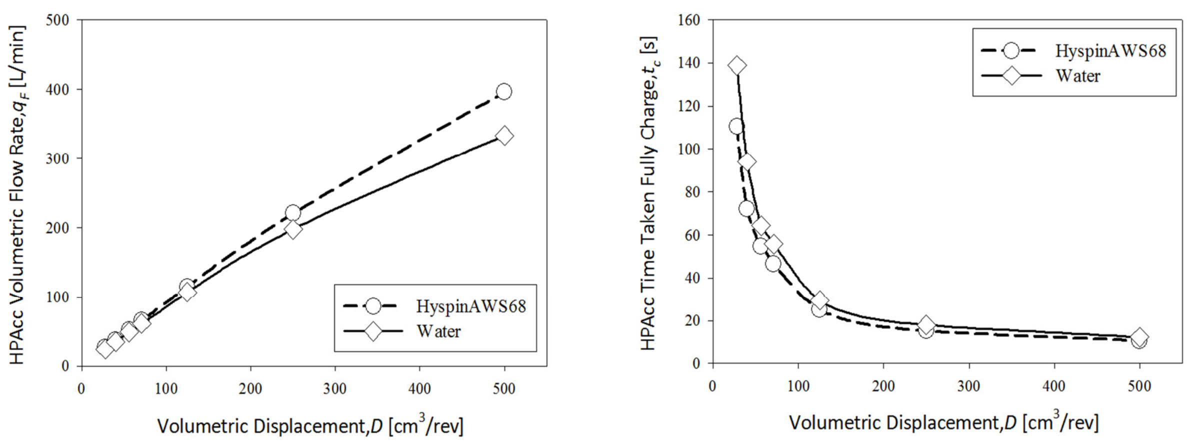


Fig. 11. The effect of input volumetric flow rate at HPAcc during charge mode (left), The effect of time taken to fully charged HPAcc (right)

This section set out to determine the impact of the capability of HPAcc as energy storage with the changes of volumetric displacement, D. In consequence, the capability of energy storage is analyzed by the value of energy density of HPAcc as shown in Fig. 13. The curve shows that the energy density, $E_{d\ HPAcc}$ of HPAcc is slightly increasing to the changes of D with an average difference between maximum and minimum value is 0.16 kJ/L. Based on the equation, $E_{d\ HPAcc}$ is related to the rate of HPAcc pressure, p_F and HPAcc effective volume, V_T. Therefore, as explain in the previous discussion of Fig. 12(a) and 12(b) that there are no significant impact to the changes of D. It can thus be determined that the $E_{d\ HPAcc}$ is not effected by the changes of D. In other word, these findings suggest that in general the variation of volumetric displacement doesn't has a significant effect to the capability of energy storage.

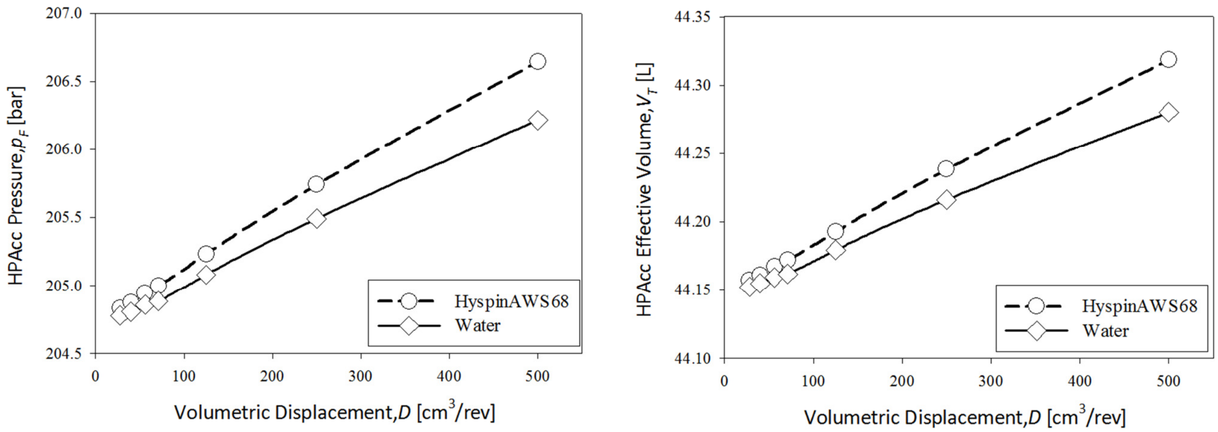


Fig. 12. The effect of pressure in HPAcc during charge mode (left), The effect of effective volume of HPAcc during charge mode (right)

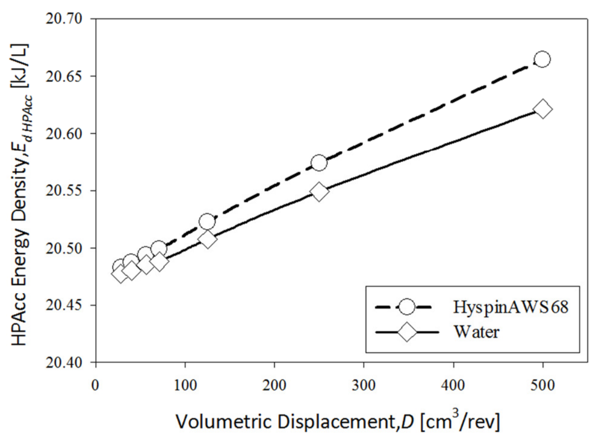


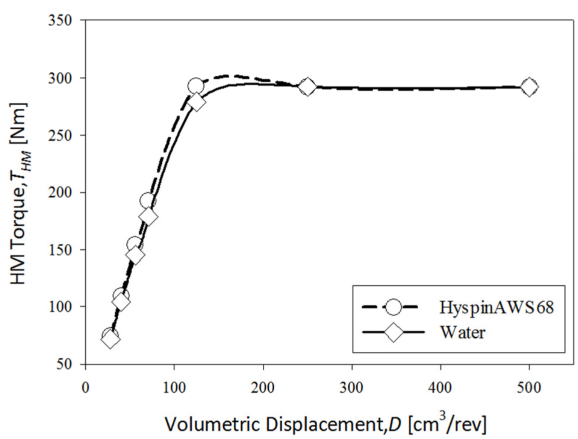
Fig. 13. The effect of energy density in HPAcc during charge mode

3.1.2 Discharge Mode

During discharge mode, several values is measured to analyze the capability of HM as shown in Table 4. Meanwhile, simulation results for the effect of volumetric displacement in hydraulic hybrid driveline while charging are showed from Figure 14 and Figure 15. As shown in Fig. 14(a), the highest torque achieve by the HM for HyspinAWS68 is at 125 cm^3/rev but water is at 250[cm^3/rev]. Unfortunately, the highest power losses achieved was at 125 cm^3/rev for both fluids as shown in Fig. 14(b). The interesting part is, water has a higher power loss compared to HyspinAWS68. This is due to the high internal leakage at water compared to HyspinAWS68 as shown in Table 4. The internal leakage occurs because of the hydraulic fluid properties, which is the viscosity of the liquid [27-29]. Water with a kinematic viscosity of 0.657161cSt has a lower kinematic viscosity compared to HyspinAWS68 which is 68cSt.

Table 4
Discharge Mode – At HM and Mitsubishi Fuso 6D34-0AT2

	Hydraulic Fluid	Volumetric Displacement [cm^3/rev] 28	40	56	71	125	250	500
HM Torque, T_{HM} [Nm]	Hyspin AWS68	74.20	109.10	153.84	192.13	292.26	292.19	292.00
	Water	71.72	104.26	145.40	178.78	279.03	292.23	292.02
HM Input Power, $P_{In\ HM}$ [kW]	Hyspin AWS68	7.52	10.76	14.82	18.43	33.14	22.42	17.86
	Water	10.09	13.55	17.34	21.45	29.91	23.31	16.56
HM Output Power, $P_{Out\ HM}$ [kW]	Hyspin AWS68	4.55	7.02	10.27	12.73	29.04	19.23	16.10
	Water	3.55	5.51	8.10	9.91	15.71	17.16	13.52
HM Power Losses, $P_{lo\ HM}$ [kW]	Hyspin AWS68	2.97	3.74	4.56	5.71	4.09	3.19	1.77
	Water	6.54	8.03	9.24	11.55	14.20	6.15	3.04
HM Internal Leakage, $q_{leak\ HM}$ [L/min]	Hyspin AWS68	16.12	21.31	26.25	32.81	39.59	32.98	26.76
	Water	29.81	38.96	47.48	58.42	72.32	63.11	51.20
Mitsubishi Fuso Speed, v [km/h]	Hyspin AWS68	21.55	22.11	22.32	21.78	17.24	11.88	7.86
	Water	18.59	19.28	19.67	19.17	17.28	11.22	7.32
Total Efficiency, η_t	Hyspin AWS68	0.647	0.703	0.742	0.748	0.876	0.914	0.901
	Water	0.541	0.574	0.592	0.602	0.635	0.841	0.816



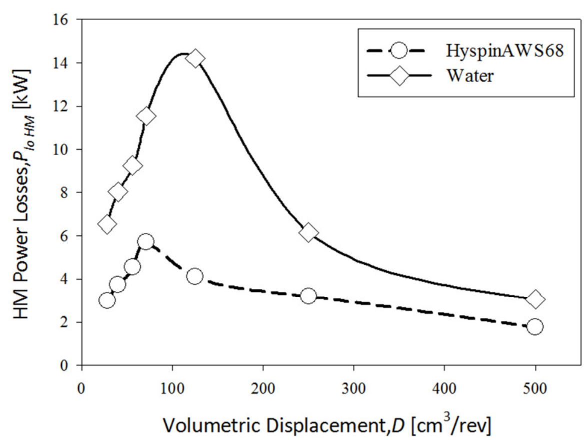


Fig. 14. The effect of torque at HM during discharge mode (left), The effect of power losses at HM during discharge mode (right)

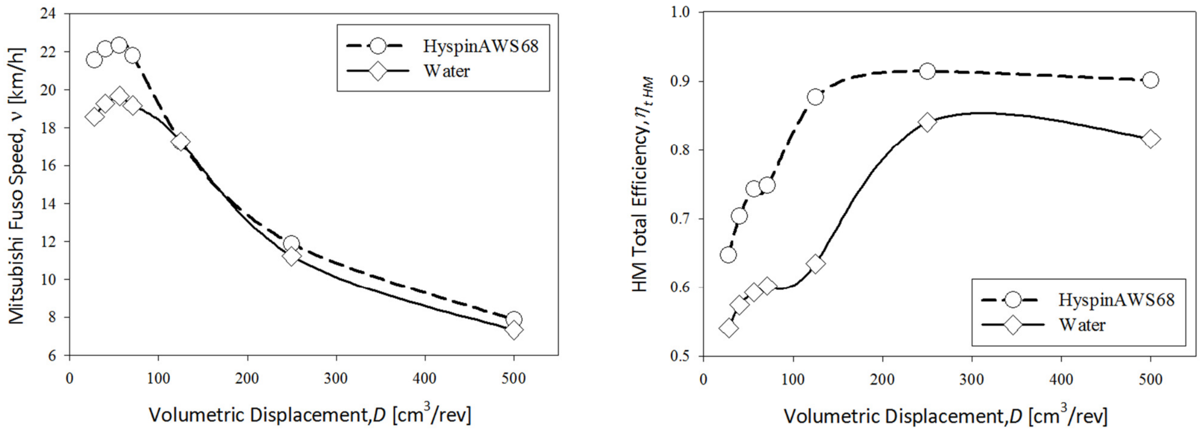


Fig. 14. The effect Mitsubishi Fuso 6D34-0AT2 speed during discharge mode (left), the effect of total efficiency at HM during discharge mode (right)

From the curve in Fig. 15(a), it is apparent that the usage of HyspinAWS68 made the Mitsubishi Fuso 6D 34-0AT2 moves faster compared to water. This due to the power and efficiency of HyspinAWS68 is higher than water. The most striking result emerge from the curve is that the fastest speed of both liquid is at 71 cm^3/rev with the speed of 21.78 km/h for hyspinAWS68 and 19.17 km/h for water as shown in Table 4. A faster speed at the 1^{st} gear of vehicle gives one step advantages compared to other D as it will reduce the usage of diesel oil that is consume by the truck currently. Nevertheless, as shown in Fig. 15(b), the best efficiency of HyspinAWS68 and water is at 250 cm^3/rev. This shows that the best performance of Mitsubishi Fuso 6D34-0AT2 in term of total efficiency is at 250 cm^3/rev.

4. Conclusion

In conclusion, the fluid properties of both pressure medium have a significant effect on the performance of the hydraulic hybrid system during charge and discharge mode as the different for both fluid is clearly shown on every curve. However, the effect of volumetric displacement on the hydraulic driveline was insignificantly identified at the charge mode as the energy storage performance for both fluid is almost the same. Contradict to the discharge mode as the impact of volumetric displacement does influence the output of the driveline. Based on this simulation result it can be concluded that the most optimum output gain from the volumetric displacement for both fluid is at 250 cm^3/rev. This is due to the hydraulic hybrid driveline was applied for a starting momentum of a vehicle, so that the higher toque is required to move the vehicles. Even the output speed of the 250 cm^3/rev is not the highest but, speed is not the main point for the selection.

Besides that, even water can't overcome the performance of hyspinAWS68 with a lower performance and efficiency but there are several issues that should be taken to achieve the best performance of water-based hydraulic hybrid driveline. The issues are the specification of accumulator in term of size and precharge pressure. Besides that, the system pressure and gear ratio also a significant point that should be studied deeply.

Despite this, future research should be conducted, especially on the alteration of the fluid properties such as temperature, viscosity, bulk modulus, water hammer, enthalpy and vapor pressure of water throughout the system. This fundamental study is important to ensure the optimal design and the performance of water based hydraulic hybrid system.

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