JOURNAL OF MODERN MANUFACTURING SYSTEMS AND TECHNOLOGY (JMMST)
e-ISSN: 2636-9575
VOL. 5, ISSUE 1, 80 – 88
DOI: https://doi.org/10.15282/jmmst.v5i1.6280

ORIGINAL ARTICLE

Custom centrifugal pump performance in supplying high viscos liquid

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ABSTRACT – Viscosity is one of the factors affecting the performance of the centrifugal pump. A centrifugal pump is a device that used a driven motor called impeller to move fluid by rotational mechanism. This study is about the performance of a custom centrifugal pump when transferring viscous liquids. The main aim is to design and fabricate a device that can pump liquid with various viscosity using centrifugal pump. Liquids used in the experiment are comprised of a mixture of detergent and water with a different ratio to alter the viscosity. The viscosity is being identified by the usage of Zahn Cup Method with the temperature kept constant at 26°C throughout the experiment. Performance of the centrifugal pump is being investigated by four parameters which are the flow-rate, Total Dynamic Head (TDH), power and efficiency. Performance of the centrifugal pump can be accessed by altering the pump shaft speed in order to get various reading for the flow rate. In order to alter the pump shaft speed, the usage of the motor with Variable Frequency Drive (VFD) is implemented. The values for the flow-rate and pump shaft power are measured by flowmeter and Variable Frequency Drive (VFD). The Total Dynamic Head (TDH), hydraulic power and pump efficiency is calculated based on the reading of the flowmeter and pump shaft power displayed at Variable Frequency Drive (VFD). At the end of this project, the pump performance while pumping different viscous liquids at different flow rates is being identified.

ARTICLE HISTORY
Revised: 31st March 2021
Accepted: 31st March 2021

KEYWORDS
High viscos liquid
Centrifugal pump
Liquid flowrate
Pump performance
Total dynamic head

INTRODUCTION

In heavy industry, transferring of liquid products during processing is an essential need for most medium and large-scale production. The selection of the right pump is important, as it requires an attentive consideration of the different pump types and their respective specifications. One of the important parameters to be considered while choosing pump is the maximum viscosity of liquids transferable as it will influence how it behaves during the process [1-2].

Centrifugal pumps are kinetic-energy pump that rely on the usage of a driven motor called impeller to create rotational energy to transfer fluids. The two crucial parts in the centrifugal pump to create the rotational energy are the impeller and the casing [1-2]. The rotating part of the pump is called impeller and the passage which surrounds the impeller is the casing. While fluid passing through the impeller, there is an increase of the pressure and velocity while also directing the fluid towards the outlet of the pump [1]. The pump casing compresses the fluid while simultaneously directing it into the impeller towards the discharge of the pump. The design of the centrifugal pump offer economical solutions to large capacity and low pressure pumping applications. Applications for centrifugal pumps can vary widely throughout the industry but are mainly focused on low viscous fluids that are relatively easy to pour out of a container such as water, solvents, and light oils.

Viscosity is a measure of the liquids resistance to flow because of the internal friction within the fluid. The internal friction within the fluid required an extensive amount of force to cause movement [3]. The force called shear occurs whenever the fluid is being transferred or moved, such as an act of pouring and mixing. Therefore, more force is required to move highly viscous fluids compared to the less viscous fluid [3].

The efficiency of the centrifugal pump while operating depends on the consistent rotation speed of the pump impeller. As viscosity increases, pump performance decreases because of friction loss [3]. The centrifugal pumps experienced a higher pressure and resistance needed in order to sustain a particular flow rate while pumping viscous fluid [4]. The higher resistance existed in the system will cause the centrifugal pump to become increasingly inefficient. Viscous fluid will drag imparts on the impeller, resulting in the pump head and flow rate reduction and increasing the horsepower required to move the fluid. All these factors combined, resulting in the performance's reduction of the centrifugal pump.

In an ideal operation, a centrifugal pump performance curve would be a straight line. However, in the actual operation, the pump performance will be curved because of losses in the pump. The major factors contributed to these losses are from mechanical, leakage, shock, and disc friction losses[5]. The curves are based on the pump performance while handling water, but with applications on viscous fluids, the curves must be corrected for the system to run. The head, flow, efficiency, and brake horsepower (BHP) curves will all require corrections. The pump performance could be

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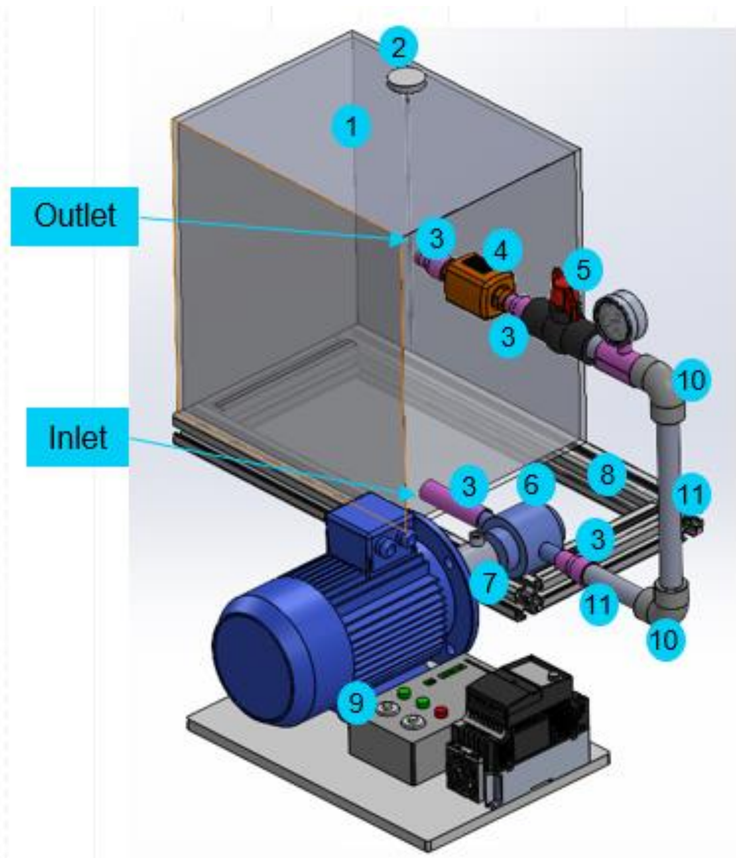
accessed by a few parameters such as flow rate, Total Dynamic Head (TDH), power and efficiency while handling liquids with higher viscosity. Generally, the flowrate, Total Dynamic Head (TDH) and efficiency decrease while handling viscous liquids. However, the pump shaft power increase while pumping liquids with higher viscosity because of the higher friction loss [6].

The common issue that the industry face is its limitation to identify the performance of the centrifugal pump when transferring viscous liquid. High viscosity liquid is having higher opportunity in improving any industrial process such as machining, because of its higher lubricity [7-11]. The properties of the fluids such as their viscosity have its effect on the performance of the centrifugal pump. The efficiency of centrifugal pump drops during the pumping of viscous fluids. In addition, the performance curves of centrifugal pumps which are included by the manufacturer are based on the pump performance while handling water, which has a much lower viscosity. Performance curves provide realistic values when the liquid has a viscosity that is about the same as water, which is 1 cSt. However, most times, the liquid pumped may be more viscous [6]. In these cases, pump performance considerably changes from that shown by the curves. Thus, the performance curves must be corrected during applications involving viscous fluids for the pump system to be able to run. Pump performance can be accessed by studying the flow rate, the Total Dynamic Head (TDH), power and efficiency to expect the depletion rate of the centrifugal pump performance when transferring viscous fluids.

METHODOLOGY

The centrifugal pump design process comprising four steps which are the planning, fabricating, testing and analysing. The viscosity test is conducted to obtain the viscosity of the detergent mixture by implementing the Zahn Cup method. The analysing process, in which consists of pumping system testing and analysing the result, is being conducted to identify the project conclusion.

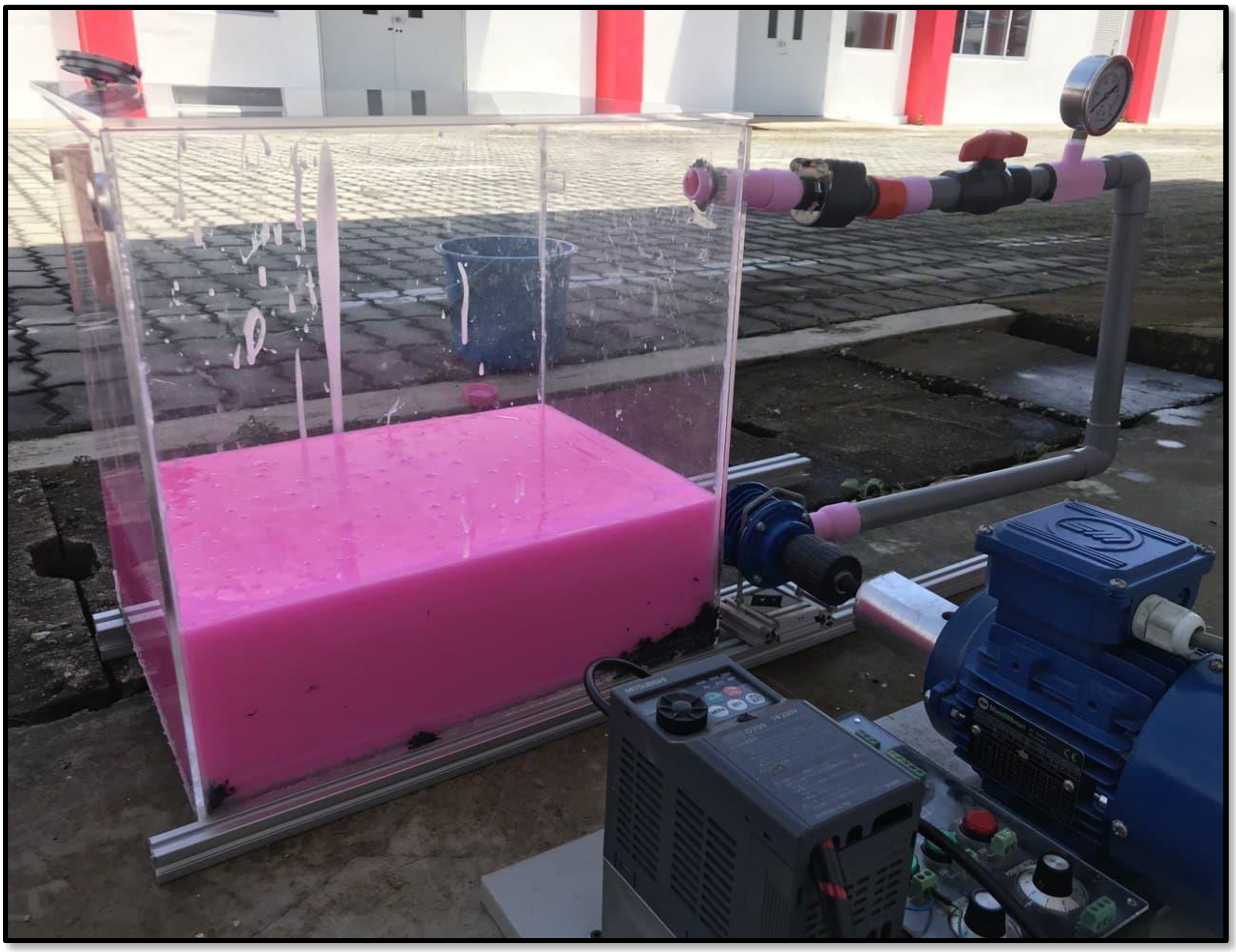


1. Tank
2. Temperature Gauge
3. Reducers
4. Flowmeter
5. Pipe Ball Valve
6. Centrifugal Pump
7. Motor Coupler
8. Aluminum Profile Base
9. Motor with Variable Frequency Drive
10. Elbow Pipe
11. Pipe

Figure 1 Schematic diagram of specially designed pumping system components

A specially designed pumping system is fabricated as shown in Fig. 1 in order to run the test to observe the pump performance while handling viscous liquids. The pumping system is consisted of a tank with respective inlet and outlet for the liquids to be able to flow in and out of the system. Both the inlet and outlet are at the side of the tank, with the inlet is at the lower part of the tank, while the outlet is at the higher part of the tank. The experimental liquids are continuously flowing out of the tank from the inlet and flows into the tank again at the outlet while running the pumping system. The pump is powered by a motor with Variable Frequency Drive (VFD) to control the speed of the motor. The pumping system is also equipped with a flowmeter and temperature gauge to observe the flow rate and temperature of the liquids while running. The fittings for the pipeline consist of elbow pipes and reducers. The reducers are 3D printed and used as fitting between the tank to the pump and the pump to pipeline. Motor coupler has also been machined to transmit power from the motor to the pump. The actual pumping system is shown in Fig. 2. Density of each of the experimental liquids needs to be identified in order to calculate the pressure loss in order to find the Total Dynamic Head (TDH).

Figure 2 Actual specially designed Pumping system components



The detergent mixture is comprised of detergent and water being mixed to produce a different viscosity mixture. The detergent mixture sample is needed in order to conduct the viscosity test and to find the density of each mixture. The density of the mixture is used to identify the Total Dynamic Head (TDH) of the system. In this experiment, 200 ml total volume of liquid is produced by mixing the fluids with a different ratio as shown in Table 1. The viscosity is altered by reducing the percentages of the detergent. The 0% percentage of detergent showed the liquid being used is pure water while the 100% showed the liquids used are only detergent.

Zahn Cup method is used to determine the viscosity of each of the experimental liquids. Zahn Cup method uses Zahn numbers to express the viscosity of a liquid measured. Zahn numbers is the time taken for a fixed volume of 44 ml liquid to flow through the viscosimeter and usually expressed in the unit of seconds. The Zahn Cup method includes dipping the cup into the liquid at a certain temperature. The cup will then be pulled out, and the time taken for the liquid to be fully drop is immediately taken. For this experiment, the Zahn Cup three is used because of its availability and the Zahn seconds for the detergent mixture falls under this category.

The viscosity of the detergent mixture is determined by measuring the time taken when the steady flow through the orifice breaks. The time taken will then be used to find the Zahn seconds using the **Eq. 1**. The detergent mixture is tested within three set of data to obtain an average and valid value of time taken while conducting this experiment.

$$v = (11.7)(t - 7.5) \tag{1}$$

Where t represents the time taken in (s) and v represent the kinematic viscosity in (cSt). Before conducting the experiment, make sure the cup is clean and is free of residual by cleaning the device with a suitable solvent and then dry. The experiment is being conducted to access the performance of the centrifugal pump while transferring various viscous liquids. The parameters that need to be accessed to determine the performance of the centrifugal pump are the flow rate, pump shaft power and temperature of the liquids.

Table 1 Ratio of Detergent Mixture Sample

Percentage of Detergent (%)	Detergent Volume (ml)	Water Volume (ml)
0	0	200
50	100	100
75	150	50
100	200	0

Where t represents the time taken in (s) and v represent the kinematic viscosity in (cSt). Before conducting the experiment, make sure the cup is clean and is free of residual by cleaning the device with a suitable solvent and then dry. The experiment is being conducted to access the performance of the centrifugal pump while transferring various viscous liquids. The parameters that need to be accessed to determine the performance of the centrifugal pump are the flow rate, pump shaft power and temperature of the liquids.

Once the detergent mixture has been prepared, the experiment using the pumping system will take place. The experiment is being conducted to access the performance of the centrifugal pump while handling various viscous liquids. The pump shaft speed is being altered to find the performance of the pump while running under a different flow rate. In order to alter the pump shaft speed, the usage of the motor with Variable Frequency Drive (VFD) is being implemented. The pump shaft power while conducting experiment with various viscosity and at different motor speed are also recorded. From the data got, the Total Dynamic Head (TDH), hydraulic power and pump efficiency can be calculated.

The Total Dynamic Head (TDH) is the total of the difference in pressure exerted by a pump as it is running. In addition, TDH produced by a pump is the difference between the discharge pressure and suction pressure of the pump while it is running. A certain amount of head is necessary to push a flow through the hydraulic system as viscosity can increase friction losses. The parameters needed to be identified in order to find the TDH while operating under different flow rate is the suction head, discharge head and the head loss, or also known as friction or pressure loss. TDH is actually a combination of suction head, discharge head and head loss in the system as shown in **Eq. 2**. Head can be expressed as a pressure in pascal (Pa) but it is preferable to express head in meter of liquid as this is independent of the temperature of the liquid being pumped. However, these terms are mutually convertible one to the other as **Eq. 3**.

$$TDH = H_s + H_D + H_L \tag{2}$$

Where, TDH represents the Total Dynamic Head in (m), TDH represent the suction head in (m), TDH represent discharge head in (m) and TDH represent a head loss in (m).

$$H = \frac{P}{\rho g} \tag{3}$$

Where, H represent the head in (m), represent the pressure in (Pa), represent the fluid density in (kg/m^3) and represent gravitational acceleration in (m/s^2). Suction head is the height of the liquid will be reached before arriving at the pump. However, because of the design of the pumping system, the suction head appeared to be zero and thus negligible. Discharge head is the peak height achieved by the pipe after the pump. The pressure at discharge could be calculated by the **Eq. 4**.

$$P_D = \rho g H \tag{4}$$

Where, PD represent discharge pressure in (Pa), ρ represent fluid density in (kg/m3), g represents a gravitational acceleration in (m/s2), and h represent height of liquid in (m). Head loss is the loss of friction that occurs in pipe and components because of the fluid viscosity at the surface of the pipe. The more flow going through a pipe, the more friction loss occurred. In addition, other factors such as specific gravity, viscosity, and temperature can greatly affect the friction loss in the system. The movement of fluid against the wall of the pipe or against each other caused a friction loss in the system while in operation. The friction coefficient could be calculated using **Eq. 5**, where, λ represent friction coefficient, and Re represents Reynolds number.

$$\lambda = \frac{64}{R_e} \tag{5}$$

The Reynolds number is a dimensionless number used to categorize the fluids systems whether the fluid flows is laminar or turbulence. Reynolds number needs to be identified as viscosity can affect the velocity or the fluid flow pattern (J. F. Giilich, 2019). The Reynolds number is the proportion of inertial forces to viscous forces. Inertial force happens when the force is in the opposite direction to an accelerating force acts on a body. The friction on the pipe surface because of viscosity causes energy losses. In addition, the transition from laminar to turbulence could happened. This happened as the roughness on the surface of the pipe increases because of a high viscosity liquid. Reynold number determine the energy losses as friction factor because of the roughness on the inner surface of a pipe (J. F. Giilich, 2019). The Reynold number to determine friction losses can be calculated by the **Eq. 6**. First, the velocity of the fluid in operation needed to be calculated to find the Reynold number of the system using **Eq. 7**, where, u represent velocity in (m/s), dh represents hydraulic diameter in (m), and v represent kinematic viscosity in (m^2/s).

$$R_e = \frac{u d_h}{v} \tag{6}$$

$$u = \frac{Q}{A} \tag{7}$$

Where, u represent velocity in (m/s), Q represents flow rate in (m3/s) and A representation area of the pipe in (m2). The length and hydraulic diameter of pipes are kept constant at 1.32 m and 0.027 m for all operations. The hydraulic diameter for the circular tube is showed by the diameter of the tube. Hydraulic diameter is identified to find the pressure drop and fluid flow rate. The pressure loss of each of the viscous liquids at different flow rate could be calculated by the **Eq. 8.**

$$P_L = \lambda \frac{l}{d_h} \frac{\rho u^2}{2} \tag{8}$$

Where, PL represent pressure loss in (Pa), λ represent friction coefficient, l represents length of pipe in (m), dh represents hydraulic diameter in (m), ρ represents fluid density in (kg/m3), and u represent velocity in (m/s). The TDH is calculated under certain assumptions in which the friction losses occurred is mainly losses in pipe and the losses in valves and fittings is negligible. The suction head appeared to be zero because of the design of the pumping system where the tank inlet is in line with the centrifugal pump. There are assumed that there are no volumetric losses, disk friction losses and mechanical loss throughout the system. The viscous liquids used have a property of Newtonian liquids which has a constant viscosity and independent of rate of shear.

The hydraulic power represents the energy transferred to the fluid while being pumped to increase the velocity and pressure in the system. A hydraulic power of pump happened when the mechanical power produced by the motor is converted into hydraulic energy such as flow and pressure when passing through the pump shaft. Hydraulic power could be calculated by **Eq. 9**, where, Ph represents hydraulic power in (kW), Q represent flow rate in (m3/h), and HTDH represent Total Dynamic Head in (m).

$$P_h = \frac{Q \rho g H_{TDH}}{1000} \tag{9}$$

Pump efficiency is closely related to hydraulic power and the pump shaft power. Pump efficiency can be computed by dividing the hydraulic power with the pump shaft power. In addition, pump efficiency is used to calculate the drive power required by a pump at a specific pressure and flow. Pump efficiency refers to the capability of a pump to convert one form of energy to another based on the difference between the input and output power. The efficiency for the pumping system while operating under a certain flow rate could also be calculated by the **Eq. 10**, where, η represent pump efficiency, Ph represent hydraulic power in (kW), and Pp represent pump shaft power in (kW).

In an ideal pump operation, the input power of the pump would equal to the output power. This further produce an astonishing 100% efficiency while in operation. Unfortunately, in actual application, the friction, leakage, and other energy losses will reduce the efficiency of the pump. Thus, the pump shaft power will always be higher than the hydraulic power while operating.Pump efficiency is closely related to hydraulic power and the pump shaft power.

$$\eta_p = \frac{P_h}{P_P} \tag{10}$$

RESULT AND DISCUSSION

Viscosity and density of the detergent mixtures

The Zahn Cup experiment is conducted by observing the flow of the liquid until there is a breakage of the liquids leaving the Zahn cup. The measurement of the stopwatch is ended at the same time as the first liquid breakage is observed. The validity of this test is repeated thrice, and the average time is calculated as shown. The result of the experiment is shown in Table 2 along with the density result of the liquid. Density of each of the experimental liquids is identified to calculate the pressure loss for Total Dynamic Head (TDH).

Table 2 Viscosity and density of the Detergent Mixtures

Percentage of Detergent (%)	**Volume of Liquid (ml)**	**Kinematic Viscosity (cSt)**	**Mass of Liquid (g)**	**Density of Liquid (kg/m^3)**
0	200	1.2	206.0	1030
50	200	45.6	160.1	800
75	200	236.3	176.0	880
100	200	769.9	191.8	960

The lowest viscosity of the fluid is as expected comes from the 0% detergent sample, which consist of pure water as it took the shortest time for the liquid to show its first breakage. Based on the experiment, the viscosity of 0% detergent is 1 cSt. It can also be observed that the viscosity is gradually increasing as more percentage of detergent is added into the mixture. The viscosity of 50% detergent mixture is 46 cSt while the viscosity at 75% is 236 cSt. As expected, 100% detergent shown the highest viscosity as it took the longest time taken for the liquid to show its first breakage while conducting the experiment with the viscosity of 770 cSt. Based on the experiment result, the density of the 0% detergent is the highest with 1030 kg/m3. The density of the 50%, 75% and 100% detergent mixture gradually increases with 800 kg/m3, 880 kg/m3 and 960 kg/m3, respectively.

Relationship of pump revolution speed (RPM) and generated flowrate (m^3/h)

The flow rate shown by the flowmeter is being recorded for various viscosity starting from 0%, 50%, 75% and 100% detergent mixtures, while the flowmeter only has the setting of liters per minute, however the value will then be converted into the unit meter cube per seconds to keep the units consistent. Based on **Fig. 3**, it could clearly be seen that the flow rate increases as the motor speed increases for all the experimental liquids. All the detergent mixtures experience a zero flow rate at 2000 rpm. This is because the system failed to overcome the Total Dynamic Head (TDH) while running at a motor speed of 2000 rpm. However, for 100% detergent mixture, these phenomena prolong for the motor speed of 2000 rpm, 2500 rpm and 3000 rpm as shown by the zero flow rate. This is expected, as 100% detergent has the highest viscosity among the experimental liquids. Based on Poiseuille's law as shown in **Eq. 11**., where, Q represent flow rate in (m3/h), π represent pi, P represent pressure in (Pa), r represents a radius of pipe in (m), η represent kinematic viscosity in (cSt), and l represent length of pipe in (m). It is known that from the equation that the flow rate is inversely proportional to viscosity. This showed with the increase of viscosity, the flow rate will decrease. This is showed as the viscosity of the detergent mixture increases, there is a significant decrease of flow rate, with 100% of detergent mixture as the lowest flow rate.

$$Q = \frac{\pi P R^4}{8 v l} \tag{11}$$

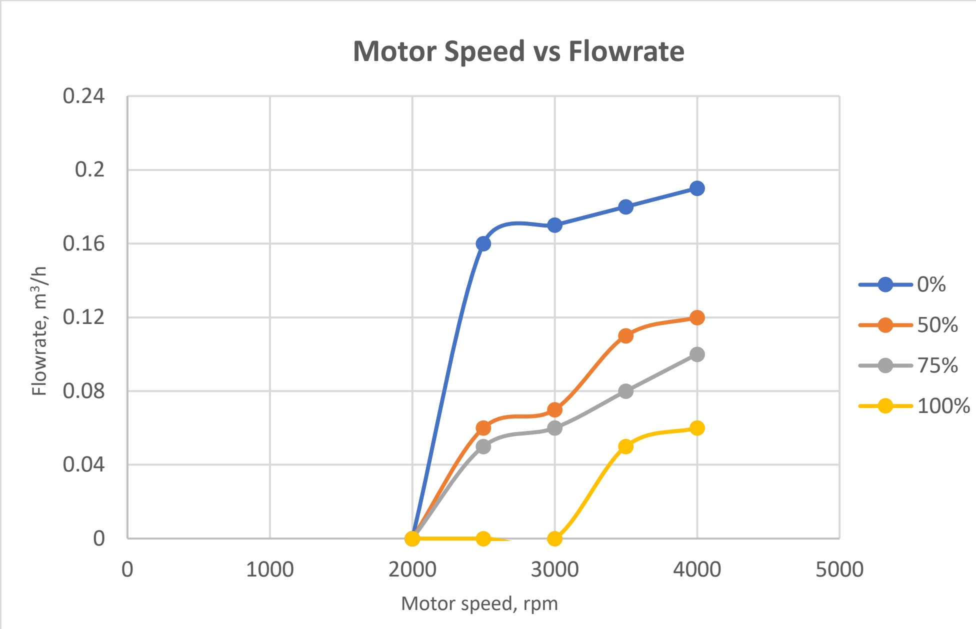


Figure 3 Relationship of pump revolution speed (RPM) and generated flowrate (m^3/h)

Relationship of flowrate (m^3/h) and hydraulic power (kW)

Hydraulic power happened when the mechanical power produced by the motor is converted into hydraulic energy, such as flow and pressure when passing through the pump's shaft. Hydraulic power needs to be identified in order to find out the pump efficiency. Based on **Fig. 4**, the hydraulic power increases with an increase of flow rate for all the experimental liquids. It can be observed that the 0% detergent has the highest hydraulic power with 0.60 kW at a flow rate of 0.19 m3/h. A lower hydraulic power is shown by the remaining 50%, 75% and 100% detergent mixture with the value range of 0.12 kW to 0.27 kW. The hydraulic power is mainly affected by the density of liquid rather than the viscosity [2]. The 0% detergent mixture shows the highest hydraulic power because of the higher density among all the liquids with 1080 kg/m3. Although hydraulic power does not have a direct effect on viscosity, hydraulic power needs to find out to find the pump efficiency while handling viscous liquids.

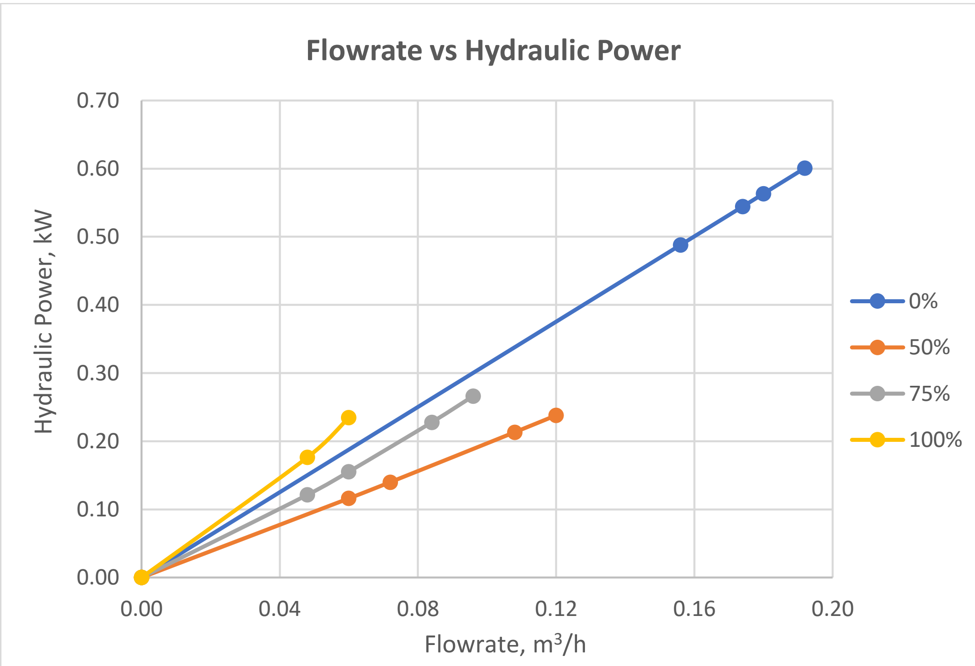


Figure 4 Hydraulic power of detergent mixture

Relationship of flowrate (m^3/h) and pump efficiency (%)

Pump efficiency is represented as the ratio of useful hydraulic power transferred to the fluid to the power input at the drive shaft. Accessing and analysing the pump efficiency is important, as it can act as an indicator whether the pump used is suitable for the system. Based on **Fig. 5**, it can clearly be seen that the pump efficiency for 0% detergent is the highest compared to the other detergent mixture, which has the astonishing efficiency between 80% with the highest reached up to 89%. An increase in viscosity will drastically lead to a decrement of the pump efficiency together with a reduction in flow rate. For 50%, 75% and 100% detergent, the pump efficiency gradually drops and stops between 21% to 36%. The pump efficiency started dropping as high as 68% for 50% detergent mixture, which shows a pump efficiency of 21% at a flow rate of 0.06 m3/h and 0.07 m3/h. It can also be observed that the efficiency for all the liquids dropped at a certain flow rate. Thus, it can be assumed that while the pump shows a high performance while handling 0% detergent mixture, the pump used is not suitable and inefficient in handling higher viscous liquids.

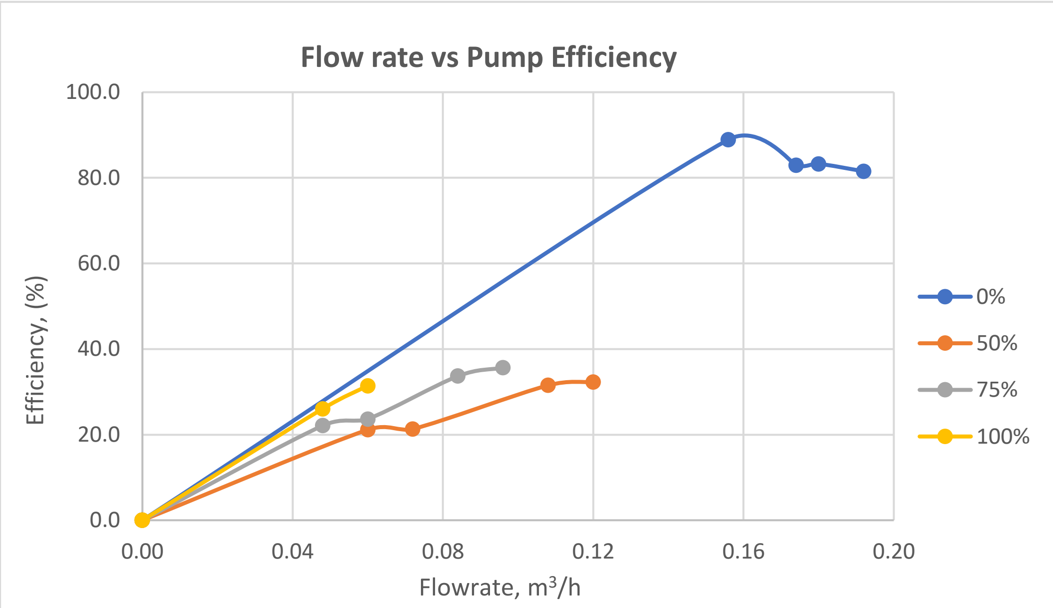


Figure 5 Pump efficiency of detergent mixture

CONCLUSION

In conclusion, this research achieved the objectives and had analysis the performance of the centrifugal pump while handling viscous liquids. Besides, the pumping system is designed and fabricated in order to access the performance of the centrifugal pump. The viscosity test is conducted by using Zahn cup method to identify the viscosity of the mixture with the percentage of detergent varies starting from 0% up to 100%. Lastly, the experiment is being performed by altering the speed of the pump shaft by the usage of Variable Frequency Drive (VFD). The flow rate, pump shaft power and temperature of the experimental liquids is being measured using the flowmeter, Variable Frequency Drive (VFD) and temperature gauge. Based on the data got from the experiment, the Total Dynamic Head (TDH), hydraulic power and pump efficiency are identified by theoretical calculation. Based on the results got, the flow rate decreases as the viscosity of the liquids increases. For 100% detergent mixture, the system failed to overcome the Total Dynamic Head (TDH) and thus resulting in zero flow rate at motor speed of 2000 rpm, 2500 rpm and 3000 rpm. When a fluid moves through pipes, it will experience frictional resistance and thus lead in the dissipation of energy from the transported liquids. Thus, it can be observed at the higher viscosity liquids of 50%, 75% and 100% detergent mixture consumes larger shaft power at lower flow rate compared to 0% detergent mixture. The pump efficiency while handling low viscosity, 0% detergent mixture is as high as 89%. However, the pump efficiency drops as high as 63% to only 26% while handling 100% detergent mixture. Thus, the centrifugal pump used in the experiment is inefficient to be used to transfer viscous liquid as high as 770 cSt.

ACKNOWLEDGEMENT

The authors would like to thank Ministry of Higher Education for funding the research under Fundemental Research Grant Scheme (FRGS/1/2019/TK03/UMP/02/12) and UMP for funding this work under Postgraduate Research Scheme PRGS1903177.

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