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Experimental Study of Single Stage Centrifugal Pump Characteristics and Cussons Friction Loss Apparatus

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Abstract

Water is a primary need for human life. Because of its important use, an integrated system was built consisting of pumps and pipes to distribute water. The phenomenon of energy loss is found in the process of distributing water using pumps and pipes. To understand the energy loss phenomenon that occurs, an experimental test is carried out on a piping installation. Fluid mechanics and turbomachinery laboratories have experimental test equipment in the form of CUSSONS friction loss in pipe apparatus with a single-stage centrifugal pump to study the energy loss phenomenon that occurs in piping installations. This test equipment is composed of two kinds of pipe materials, namely PVC and acrylic, with variations in pipe diameter of 0.75 and 1.0 inch, flow meters in the form of venturi and orifice, pipe fittings in the form of elbow 45°, long radius elbow 90°, short radius elbow 90°, a valve in the form of ball-valve and pump connected to the NEWMAN electric motor which has a power of 1.5 HP and a rotational speed of 2850 RPM. The pressure drop in the piping installation was measured using a mercury manometer, the increase in pump pressure was measured with a pressure gauge, and the current and voltage of the motor pump were measured using a clamp meter. The flow rate for the installation was varied between 10L/min to 55 L/min with an increase in the flow rate of 5 L/min for the data collection on straight-pipe line I, fittings, and ball valves, on straight-pipe line II the variation of discharge only reached 40 L/min, while the variation of discharge for the flow meters was from 10 L/min to 30 L/min with an increase in the flow rate of 2 L/min for the orifice and 4 L/min for the venturi. Based on the experimental test data, it was found that the loss coefficient value (K_l) for K_{90}= 0.58, for K_{45}= 0.38, K_{BV}= 0.62, and K_{LRE}= 0.611. Relative roughness (e/D) on pipe line I= 0.0043 and pipe line II = 0.024. The coefficient of discharge (C_d) on the venture-type flow meter C_e= 0.91 and C_o= 0.72 at maximum discharge. Maximum pump efficiency (η_p) was 27.1% when the pump head= 18.79 m.

Keywords: Pressure drop, fitting, flow meters, pump

1. Introduction

Industrial world currently has an important role in running the wheels of human life. One example is the fluid distribution industry that uses a piping system. To get an effective piping system, data that helps in the design process of the piping system are needed, such as the type of fluid that is flowing, the flow capacity, and distance reached by the fluid, besides that, estimation from energy loss data from the fluid flow is also needed because energy losses cannot be avoided in the fluid distribution process. One of the causes of energy loss in piping installations is the friction that occurs between the flowing fluid and the pipe surface, this type of energy loss is called major losses, there is also an energy loss that occurs due to the installation of fittings, valves, and flow meters. This energy loss is called minor losses. Estimation of energy losses that occur in piping installations can help in getting a pump that is suitable for the piping installation.

Through the above description, the writer intends to conduct experiments on the CUSSONS friction loss in pipe apparatus test equipment in fluid mechanics and turbomachinery laboratories. Previously, the experimental test to determine the phenomena that occurred in the piping installation had been tested by Dahmani [1] and Sihombing [2]. However, in the tests that have been carried out, problems were found during reading the data on the mercury manometer because the pressure changes that occur in the straight line I pipe were quite small, thus reducing the accuracy of the data obtained.

After knowing the existing constraints, the writer wants to do an experimental test by replacing the installation on line I, which originally used a pipe diameter of 3/2 inch to a pipe with a diameter of 1 inch. The results of this experimental test will then be compared with the results of experimental tests that have been conducted by Dahmani [1] and Sihombing [2] to see if there is any improvement in the resulting data after changing the experimental test equipment's equipment.

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2. Research Description

2.1. Experimental Set-up

Initial evaluation of integrated test equipment into CUSSONS friction loss in pipe apparatus and water circulating unit. CUSSONS friction loss in pipe apparatus consists of four pipe installation lines with a diameter variation of 1 inch and 0.75 inch, the pipe material used is PVC and acrylic, there is an installation of flow meters in the type of venturi and orifice, ball valves, and pipe fittings in the form of a long radius elbow 90°, 90° elbow, and 45° elbow. The water circulating unit consists of a single-stage centrifugal pump, NEWMAN electric motor, and reservoir. The CUSSONS friction loss in pipe apparatus is shown in the Figure 1 and a schematic illustration of the test equipment in the Figure 2.

The motor used in this experimental test is the NEWMAN Electric Motor with a power specification of 1.5 hp and a rotational speed of 2850 RPM.

The measuring instrument used in this experiment is in the form of a mercury manometer as illustrated in Figure 3, a pressure gauge, and a clamp meter.

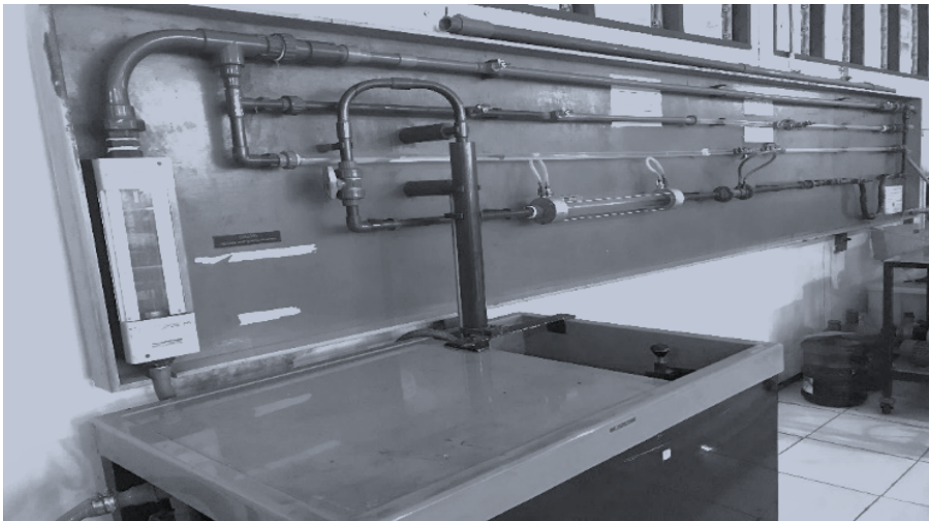
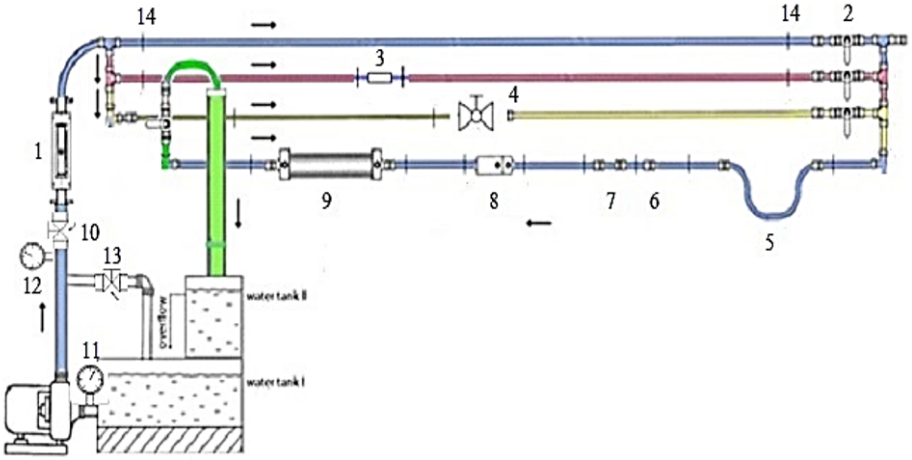


Figure 1. CUSSONS *friction loss* in pipe apparatus test equipment installation.



1. Rotameter Fisher 2000
2. Gate Valve
3. Orifice
4. Ball valve
5. Long Radius Elbow 90°
6. Standard Elbow 90°
7. Elbow 45°
8. Venturimeter
9. Sudden Contraction dan Sudden Enlargment
10. Gate valve discharge
11. Pressure gauge suction
12. Pressure gauge discharge
13. Gate valve bypass
14. Pressure tap

Figure 2. Schematic illustration of the CUSSONS friction loss in pipe apparatus.

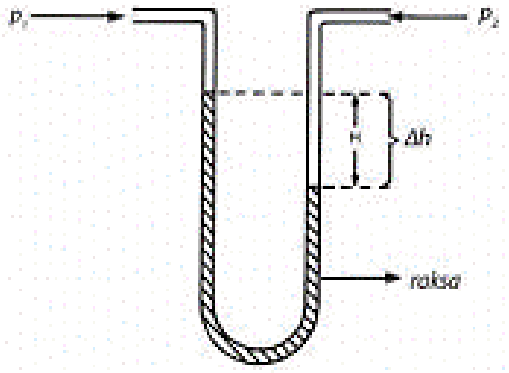


Figure 3. Mercury manometer illustration.

The function of the mercury manometer is to determine the pressure changes that occur in straight pipes, fittings, and flow meters by connecting the mercury manometer to the pressure tap. The difference in the height of the mercury level describes the number of pressure changes that occur. The pressure change that occurs can be calculated through Equation 1.

$$\Delta p = (SG_{Hg})\rho g \Delta h \tag{1}$$

By knowing the value of pressure drop on fittings, flow meters and straight pipes we can calculate the value of coefficient loss (K_l), coefficient of discharge (C_d), and friction factor (f).

$$K_l = 2\frac{\Delta p}{\rho \overline{V}^2} \tag{2}$$

$$C_d = \frac{Q\sqrt{\rho(1-\beta^4))}}{A\sqrt{2\Delta p}} \tag{3}$$

$$f = 2\frac{D}{L}\frac{\Delta p}{\rho \overline{V}^2} \tag{4}$$

where:

K_l	=	loss coefficient (dimensionless)
f	=	friction factor (dimensionless)
D	=	pipe diameter (m)
d	=	neck diameter on the flow meters(m)
β	=	$\frac{D}{d}$ (dimensionless)
L	=	pipe length which the fluid passes (m)
Δp	=	pressure different (Pa)
$\overline{V}$	=	average velocity of fluid flow (m/s)
C_d	=	coefficient of discharge (dimensionless)
Q	=	volumetric flow rate (m^3/s)
A	=	neck area on flow meters (m^2).

The pressure gauge is used to measure the pressure changes that occur on the pump's suction and discharge sides, from which this data can be processed into pump head data (H_p) where it is calculated through Equation 5.

$$H_p = \frac{p_2 - p_1}{\gamma} + \frac{\overline{V}_2{}^2 - \overline{V}_1{}^2}{2g} + z_2 - z_1 \tag{5}$$

where:

H_p	=	pump head (m)
$\frac{p_2-p_1}{\gamma}$	=	pressure head difference (m)
$\frac{\overline{V}_2{}^2-\overline{V}_1{}^2}{2g}$	=	dynamic head difference (m)
$z_2 - z_1$	=	static head difference (m).

The pump hydraulic power ($\dot{W}_{hp}$) is determined after the pump head value (H_p) is obtained, Here is the equation used to calculate the hydraulic power at the pump.

$$\dot{W}_{hp} = \gamma Q H_p = \rho g Q H_p \tag{6}$$

where:

$\dot{W}_{hp}$	=	pump hydraulic power (Watt)
γ	=	fluid weight density (kg/m^2 ·s^2)
ρ	=	fluid mass density (kg/m^3)
g	=	gravitational acceleration (m/s^2)
Q	=	pump capacity (m^3/s)
H_p	=	pump head (m).

Clamp meter is used to determine the current and voltage flowing in the pump motor, by knowing the value of the voltage and electric current on the pump motor, we can find out the value of the pump shaft power ($\dot{W}_{sh}$).

$$\dot{W}_{sh} = \eta_m \cdot \dot{W}_e \tag{7}$$

where:

$\dot{W}_{sh}$	=	pump shaft power (Watt)
η_m	=	motor work efficieny (dimensionless)
$\dot{W}_e$	=	electrical power (Watt).

The value of the pump motor work efficiency (η_m) in the above formula is obtained using Equation 8.

$$\eta_m = \frac{P_r \times N}{\dot{W}_e} \tag{8}$$

where:

P_n	=	motor power on the name plate (Watt)
N	=	transmission efficiency (dimensionless).

Transmission efficiency is the ratio between the value of the current (I) and the voltage (V) when the pump is running against the current (I_r) and voltage (V_r) listed on the motor name plate.

$$N = \frac{I}{I_r} \times \frac{V}{V_r} \tag{9}$$

where:

I_r = electrical current on the name plate (Ampere)
V_r = voltage on the name plate (Volt)
I = electrical current when the pump is running (Ampere)
V = voltage when the pump is running (Volt).

Thus, the value of the motor shaft power ($\dot{W}_{sh}$) is obtained, after obtaining $\dot{W}_{sh}$, pump efficiency (η_p) can be obtained. Pump efficiency (η_p) is the ratio between the power given by the pump to the fluid to the power given by the electric motor to the pump.

$$\eta_p = \frac{\dot{W}_{hp}}{\dot{W}_{sh}} \tag{10}$$

where:

η_p = pump efficiency (dimensionless)
$\dot{W}_{hp}$ = pump hydraulic power (Watt)
$\dot{W}_{sh}$ = pump shaft power (Watt).

3. Result and Analysis

3.1. Friction Factor

Figure 4 shows the relationship between the friction factor (f) and Re. Based on data from previous research conducted by [1], with a pipe diameter used of 1.5 inches with a flow rate ranging from 10 L/min to 70 L/min with the value of f at a minimum discharge of 0.475 and a maximum discharge of 0.025.

Based on research conducted by Dahmani [1] it was found that the f value was 0.475 at Re = 6221 and continued to decline until Re = 2 x 10^4, then it tended to be constant at Re > 2.7 x 10^4 with an average friction factor of 0.029. The mismatch in the value of the friction factor that occurred at Re < 2 x 10^4 with the previous studies could be due to the small pressure drop so that the difference in height on the mercury manometer was difficult to read by the observer. To increase the difference in height on the mercury manometer measuring instrument, it can be done by reducing the diameter of the pipe or extending the pipe through which the fluid passes so that the difference in height on the mercury manometer increases and with the increase in the height difference on the measuring instrument the accuracy in the process of reading the data will increase.

The value of pressure drop in this study is increased by changing the pipe diameter on line I with a fixed pipe length. The diameter used in line I pipe is 1 inch and on line II is 0.75 inch with a pipe length of 1.8 m, the variation of discharge from 10 L/min to 60 L/min for line I and 40 L/min for line II. Figure 4 shows the value of the friction factor at a discharge of 10 L/min of 0.17 for line I and 0.23 for line II. Both curves show a similar trend line decreasing with increasing Re. The decrease in the value of f to the increase in Re at f_1 dan f_2 decreased sharply between Re = 1 x 10^4 to 2 x 10^4 and at Re > 4.5 x 10^4 the values of the friction factors f_1 dan f_2 tended to be constant around 0.03 for f_1 dan 0.05 for f_2.

Based on previous and current research shows the relationship between pipe diameter and the value of the friction factor, where reducing the pipe diameter will increase the value of the friction factor (f). Apart from pipe diameter (D) large f can be relied on by pipe length (L), pressure change (Δp), flow velocity (V), and relative roughness (e/D).

$$f = 2\frac{D}{L}\frac{\Delta p}{\rho \overline{V}^2} \tag{4}$$

$$\frac{1}{\sqrt{f}} = -1.8\, log\left[\left(\frac{e/D}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right] \tag{11}$$

Based on the above equatiom, e/D can be determined after obtaining the f value.

$$\frac{e}{D} = 3.7\left[10^{\frac{1}{1.8\sqrt{f}}} - \frac{6.9}{Re}\right]^{\frac{1}{1.11}} \tag{12}$$

The material used in line I is PVC, and in line II is PVC and acrylic, which have a standard surface roughness value (e) between 0.0015 mm to 0.007 mm. The results of the calculation of the value of e/D on line I pipe obtained a value of 0.0043 at the dischage of 60 L/min therefor the e value is obtained of 0.11 mm, while in line II the e/D value is 0.024 at the discharge of 35 L/min then the value of e is obtained equal to 0.48 mm. Based on these results, the two pipe surface roughness value has not entered into the predetermined standard. This happens because the flowing flow has not been fully developed, so the data obtained is not accurate enough.

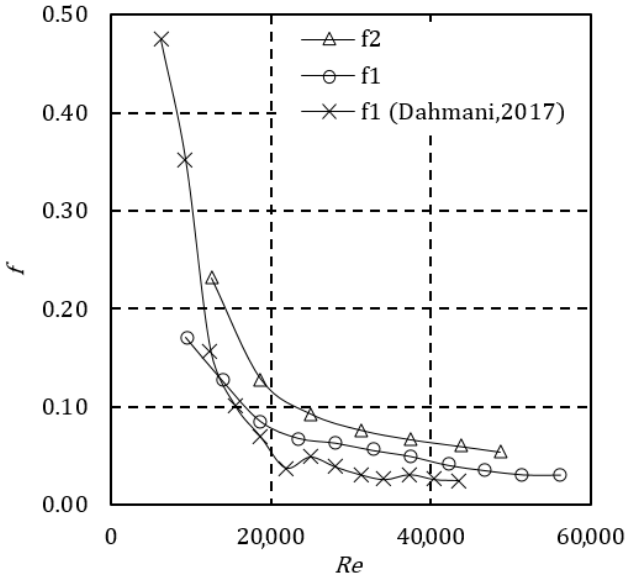


Figure 4. The relationship between friction factor (f) and Re in line I, II, and previous research.

The f_1 and f_2 curves in Figure 4 show friction factor's value exceeding the number 0.1 at Re = 1 x 10^4 to Re = 2 x 10^4, This is because the fluid flowing in the pipe has not entered into the fully developed flow category, where the conditions for fully developed flow will satisfy if the distance between the initial end of the pipe and the pressure tap location is 25 to 40 times the value of the pipe diameter with a straight pipe without a connection. If there is a flow that has not been fully developed it can cause the data taken to deviate from [3].

3.2. Loss Coefficient

Figure 5 shows the loss coefficient value of long radius elbow 90° (K_{LRE}), standard radius elbow 90° (K_{90}), elbow 45° (K_{45}), dan ball valve (K_{BV}) on the increase in Reynolds number with a flow rate variation of 10 L/min to 55 L/min. The 90° standart radius elbow has the highest loss coefficient value of 1.94, then the 45° elbow and ball valve of 1.55, and finally the 90° long radius elbow of 1.16 at the same Re, which is 12500. The loss coefficient value of the four types of fittings has decreased then tends to be constant along with the increase in Re.

The value of the loss coefficient (K_l) is influenced by the change in pressure (Δp) that occurs in the fitting, and fluid flow velocity (V).

$$K_l = 2\frac{\Delta p}{\rho \overline{V}^2} \tag{2}$$

The greater the pressure change that occurs, the greater the value of K_l. The pressure changes that occur at the fitting can be seen from the geometry of the piping fitting. When the fluid is forced to change the direction of the flow or is given a sudden restriction, then there is an energy loss in the flow, the sharper the change, the greater the energy loss.

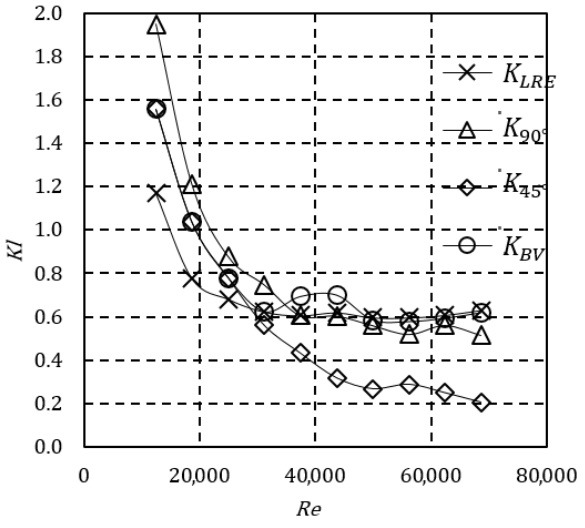


Figure 5. The relationship between K_l with Re for several types of *fitting*.

The square of flow velocity also affects the K_l value, The greater the velocity, the smaller the K_l value, This shows that the K_l value tends to decrease with increasing Re, and gradually becoming constant at high Re because the pressure change at high Re is quite significant compared to the increase of flow velocity squared.

The value of K_l tends to be constant at high Re, because at high Re the flow is fully turbulent, so that the increase in Re has no effect on changes in the value of K_l. The minor losses and Haaland equations describe these conditions where at high Re the f value is only influenced by the relative roughness (e/D) of the pipe material.

$$H_{lm} = f\frac{L_e}{D}\frac{\overline{V}^2}{2g} \tag{13}$$

$$\frac{1}{\sqrt{f}} = -1.8\ log\left[\left(\frac{e/D}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right] \tag{14}$$

The average K_l value is taken between Re = 3.1 x 10^4 to Re 6.8 x 10^4 with a K_{90} value of 0.58, for K_{45} = 0.38, K_{BV} = 0.62, and K_{LRE} = 0.611. If sorted based on the highest K_l, so that ball valve fully open, long radius elbow 90°, standar radius elbow 90°, dan elbow 45°.

Based on the experimental test results, there is a discrepancy between the experimental data and the literature data [4] where the K_l of the long radius elbow 90° is greater than the standard standar radius elbow 90°. The error at K_l value is calculated by dividing the K_l value of the experiment against the K_l from the literature.

$$\Delta K_l\% = \left[\frac{K_l eks - K_l lit}{K_l eks} \times 100\%\right] \tag{15}$$

Table 1 shows the comparison between the average value of the experimental loss coefficient in the range from Re = 3.1 x 10^4 to Re = 6.8 x 10^4 with the literature loss coefficient and errors that occur in experimental data. The discrepancy between experimental data and literature occurs because the pipes have been used for a long time, causing a fouling factor in the installation of pipe fittings and valves.

Table 1. Comparison of experimental loss coefficient values with literature.

Fitting	$K_l eks$	$K_l lit$ [4]	$\Delta K_l\%$
Long Radius Elbow 90°	0.611	0.40	52.75
Standard Elbow 90°	0.587	0.80	26.63
Elbow 45°	0.380	0.34	11.76
Ball Valve fully open	0.620	0.05	1140

3.3. Coefficient of Discharge

Figure 6 shows the coefficient of discharge from the venturi and orifice with the increase in Re. The C_d venturi curve increases with Re's increase, while the C_d orifice curve tends to be constant with the increase in Re. The flow rate variation on flow meters starts from 10 L/min to 30 L/min. The C_d value of the venturi at the time of the minimum discharge is 0.35 and continues to increase until the maximum discharge is 0.91, while the C_d orifice value at the minimum discharge is 0.71 and tends to be constant to the maximum discharge with a C_d value of 0.72.

The value of C_d is the ratio between the actual flowrate that flows on the flow meters to the theoretical discharge, where the value of C_d depends on the value of the pressure change, the variation of the flow rate, and the diameter of the inlet and neck of the flow meters.

$$C_d = \frac{Q\sqrt{\rho(1-\beta^4)}}{A\sqrt{2\Delta p}} \tag{3}$$

The C_d venturi curve has a gradual increase at Re = 2 x 10^4 to Re = 6 x 10^4, while the C_d orifice curve tends to be constant at Re = 2.5 x 10^4 to Re = 7.4 x 10^4. There are differences in trend lines on the two C_d curves due to pressure changes that occur at the orifice is much larger when compared to the pressure changes that occur in the venturi. Sudden contraction of the cross-sectional area of fluid flow causes a considerable energy loss. In the orifice geometry, changes in the cross-sectional area are made suddenly, in contrast to the geometry in venturi, where changes in the cross-sectional area are carried out gradually, which minimize the energy loss.

Based on the literature [5] the value of C_d for venturi ranges from 0.94 to 0.99 at $Re > 10^4$, the variation of

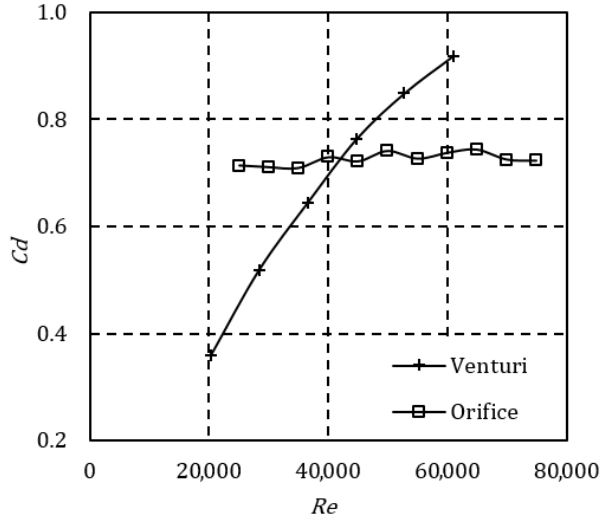


Figure 6. The relationship between C_d with Re in flow meters.

Re in the experimental test ranges from Re = 2 x 10^4 to Re = 6 x 10^4, where at Re 2 x 10^4 the value of C_d = 0.35 is obtained if Compared with literature [5], the value of C_d > 0.94 should be obtained. The difference in data obtained between the experimental results and the literature occurs because the condition of the tool is experiencing erosion on the surface so that it increases the surface roughness of the venturi, at low Re causes a decrease in the C_d value, and at high Re the C_d value moves to increase close to the value in accordance with the literature with the highest difference between the values is 6%.

Experimental tests on orifice type flow meters were carried out at Re = 2.5 x 10^4 to Re = 7.4 x 10^4, and the C_d value for the orifice tended to be constant with an average C_d value of 0.72. Based on the literature, the C_d value for orifice decreases at Re = 10^4 to Re = 10^6, then tends to be constant at Re> 5 x 10^5, in the comparison of the neck diameter value with the inlet (β) of 0.5, the value range of C_d = 0.61 is obtained, so that the difference between the C_d value in literature and experiment by 11%. The difference between the literature data and the experimental test is caused by deposits in the orifice neck diameter, thereby reducing the separation around the orifice neck diameter.

The error that occurs in the C_d value is calculated by dividing the difference between the experimental and literary Cd values then percentage.

$$\Delta C_d\% = \left|\frac{C_d eks - C_d lit}{C_d eks}\right| \times 100\% \tag{16}$$

Table 2 shows the comparison between the C_d value of the experiment against the literature and the errors that occur in the experimental data.

3.4. Centrifugal Pump

Figure 7 shows the working characteristics of the centrifugal pump used in this study. The graphic contained in Figure 7 shows the relationship between head (H_p) and pump efficiency (η_p) to flow capacity (Q). The amount of pump head at a flow capacity of 0 L/min is 22.7 m and continues to decrease gradually until a H_p is obtained of 18.6 m at Q of 60 L/min. Pump efficiency has increased from 0 L/min of 0% to 60 L/min of 27.1%.

The H_p value is determined from the increase in pressure that occurs on the discharge side against the pump suction side plus the difference in height between the water levels in the reservoir. Along with the increase

Table 2. Comparison of experimental loss coefficient values with literature.

Flow meters	$C_d eks$	$C_d lit$ [5]	$\Delta C_d\%$
Orifice	0.72	0.61	18
Venturi	0.91	0.97	6.2

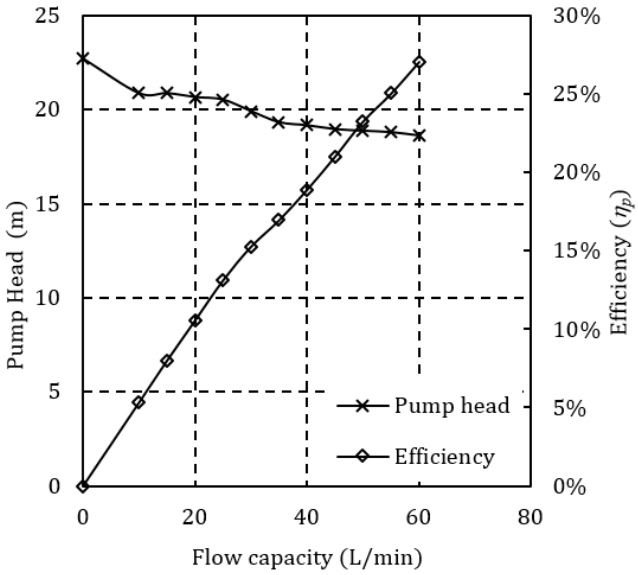


Figure 7. Pump work characteristic.

in Q, the H_p value decreases. This is due to the energy losses that occur in the pump.

$$H_p = \frac{P_d - P_s}{\gamma} + z_2 z_1 \tag{17}$$

The energy loss that occurs in the pump is due to the friction that occurs between the pump impeller and the flowing fluid (friction loss). Besides that, there is also energy loss due to fluid entering the impeller with an incidence angle that does not match the pump impeller, causing shock loss (*friction loss*).

There is a difference in the H_p curve of the experimental results with [6] where the experimental Hp curve decreases along with the increase in Q. H_p is supposed to increase at the beginning of the increase in Q then decreasing until the maximum flowrate pump can run. The difference that occurs in the H_p experimental results with the literature is due to the instability of the pressure gauge on the discharge side at a discharge of 0 L/min, making it difficult to read the data on the measuring instrument.

The pump efficiency value (η_p) continues to increase along with the increase in flow capacity (Q), where at a flow capacity of 0 L/min, an efficiency of 0% is obtained, and at a maximum Q of 60 L/min an 27.1% is obtained, this happens because along with the increase in flow capacity also increases the hydraulic power of the pump. The pump efficiency value itself is the ratio between the pump's hydraulic power ($\dot{W}_{hp}$) to the motor shaft power ($\dot{W}_{sh}$)

$$\dot{W}_{hp} = \rho g Q H_p \tag{6}$$

$$\eta_p = \frac{\dot{W}_{hp}}{\dot{W}_{sh}} \tag{10}$$

The amount of pump hydraulic power ($\dot{W}_{hp}$) is influenced by the amount of flow capacity (Q) and pump head (H_p), so that there is an increase in ($\dot{W}_{hp}$) from Q of 0 L/min to 60 L/min, although H_p decreases with increasing Q but the magnitude is not proportional to the increase in Q and the value of the shaft power ($\dot{W}_{sh}$) ends to be constant, so that the η_p curve is obtained which continues to increase along with the increase in Q.

4. Conclusion

Based on the results of experimental tests on CUSSONS friction loss in pipe apparatus and single-stage centrifugal pump with NEWMAN electric motor, the following conclusion is obtained. Reducing the diameter of the pipe increases the pressure changes that occur in straight pipes thereby increasing the accuracy in reading the data on the mercury manometer gauge, this is evidenced by comparing the value of the friction factor (f) in research conducted by [1] dan [2] where the value (f) both reached 0.48, while in this study the highest (f) value was 0.17. The value of loss coefficient (K_l) on *long radius elbow* 90° = 0.611, *standar elbow* 90° = 0.58, *elbow* 45° = 0.38, and *ball valve fully open* = 0.62. The highest efficiency value occurs at a flow capacity of 60 L/min with an efficiency of 27.1% and a pump head of 18.62 m.

The friction factor (f) and the loss coefficient (K_l) decreased sharply along with the increase in Re, this happens between Re = 1 x 10^4 to Re = 3 x 10^4 then tends to be constant at Re > 4.5 x 10^4. The relationship between the coefficient of discharge (C_d) and (Re) on the venturi type flow meter has increased along with the increase in Re = 2 x 10^4 to Re = 6 x 10^4, for the orifice type flow meter the value of C_d tends to be constant at Re = 2.5 x 10^4 to Re = 7.4 x 10^4. Referring to the data from the experimental test results that have been carried out, there are data that are not in accordance with the existing literature standards, this can happen because, during the data collection process, the flow that occurs in the pipe has not been fully developed, there is dirt carried away during the data collection process. the fluid flows, the condition of the surface of the pipe is dirty, and the ability of the measuring instrument to read the data decreases, causing the inaccuracy of some of the data obtained in the experimental test.

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