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EFFECT OF IMPELLER TRIMMING ON CENTRIFUGAL PUMP

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Pumps, especially centrifugal pumps, play an important role in engineering application, such as petroleum and petro-chemical industries, agricultural industries, portland cement industries etc. To obtain the best performance of the pumps, one has to operate the pumps at their design conditions. In some circumstances, however, the pumps must operate lower than their design conditions and result in the decrease in their performances. In such cases, it is possible to replace the pump impeller with the smaller impeller diameter or to cut its original impeller to smaller size as necessary. The cut of the impeller, or it is frequently referred to as impeller trimming, in some extence is preferable than replacing with new impeller or even by replacing with new pump with smaller head and capacity. In this study, we examine the effect of the pump impeller trimming to the pump performaces. The study was performed in the Fluid Mechanics Laboratory, Mechanical Engineering Department of ITS, Surabaya. The pump impellers were cut up to approximately 19 percent of its original pump impeller diameter, where the original pump impeller diameter is 129 mm. The pump has the maximum capacity of 100 liters/min and the total head of 31.5 m. The pump is powered by a 300 Watt electrical motor. Parameters to be studied in this research include pump capacity, pump head, pump power, and pump efficiency. The results of this study show that all data are in good agreement with the pump affinity laws. Pump capacity, pump head, and pump power decresase as the pump impeller diameter decreases. The pump efficiency is, however, in some extent, increases as the pump impeller diameter decreases. The maximum increase in pump efficiency is obtained when the ratio between the trimmed impeller to its original pump impeller diameter is approximately 89 percent (i.e. D_2/D_1 *= 0.89), with the increase in pump efficiency of approximately 20 percent.*

***Keywords:** Centrifugal Pump, Impeller Trimming, Affinity Law, Pump Efficiency*

1. INTRODUCTION

One of the most widely used fluid machineries is pump, especially centrifugal pumps. The centrifugal pumps play important role in industries, such as the petroleum industry, chemical industry, petro-chemical industries, food industry, and the power generation industry. In the case of irrigation and distribution of clean water, centrifugal pumps play a very important role. From the literature, it is obtained that in certain industrial facilities, pumps can absorb electrical energy around 25 to 50 percent of the total use of electrical energy [1]. Therefore, in order to save the energy use, the centrifugal pump must be operated in a condition of maximum efficiency. The maximum efficiency of large centrifugal pumps can reach around 93 percent, while the maximum efficiency of small centrifugal pumps can reach around 70 percent [2].

In practices, the efficiency of centrifugal pumps often does not match the efficiency provided by pump manufacturers or the design efficiency. Several factors can reduce pump efficiency compared to the design efficiency. Those factors are incompatibility of the piping system with pump capability, deviation from the operating capacity of the pump from the design capacity, and the speed of rotation of the pump motor that is not in accordance with the design speed of rotation. Other factors that also can reduce pump performances

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include the physical properties of the fluid being pumped and pump age factor. Cavitation is also one of the important phenomena that must be considered in the design and applicaion of a centrifugal pump. Because of the significant effect of the cavitation on the pump performance, it has been studied intensively, for example see Berli et al. [3].

Centrifugal pumps will operate with maximum efficiency if the characteristic curve of the piping system matches the pump head-capacity curve under design conditions. Under such operating conditions, the pump will produce a head and capacity in accordance with the pump design capacity and head, and the pump is said to work at the "best efficiency point (BEP)"[4]. However, pumps are often operated with a capacity greater or smaller than the design capacity. In such operations, the pump will operate at a lower efficiency than its maximum efficiency, which is said the pump is working at "off-design" condition. The pump operation in the "off-design" condition is still permitted in short time, or in a temporary period. Pumps that work outside of the BEP will absorb excessive power usage and cause excessive vibration.

In practice, many installed centrifugal pumps have the capacity and head greater than the required capacity and head. In this case, the capacity adjustment is carried out using a discharge valve, which is to "throttle" it [4]. Thus, the operating capacity of the centrifugal pump can be adjusted according to needs, where the pump actual capacity is smaller than the design capacity of the pump. With this condition, the head produced by the pump exceeds the design head. It is already known that if the pump is operated at the design head and capacity, it will provide maximum operating efficiency. The increase in pump head due to "throttling" is used to overcome the compressive losses arising from the "throttling". Therefore, the operation of the pump at this throttling condition will reduce pump operating efficiency, or it is often said that the pump is operated at the "off design" condition, as mentioned in the previous paragraph. At this operating condition, the pumps is said to be over design, where the actual pump capacity exceeds the needs of the existing piping system.

To overcome the existence of pumps that are over-designed or operated in "off-design" conditions, several methods can be carried out, such as replacing pumps of the right size, operating pumps with a lower speed, or using smaller impellers. Pump replacement is the easiest method, but requires a large cost. Meanwhile, changing the rotation of a pump motor to a lower one requires a motor with a variable speed rotating motor (variable speed motor), which also requires a rather expensive cost. Furthermore, reducing the diameter of the pump impeller will have an impact on reducing the efficiency of the pump operation [5].

Reducing the pump impeller diameter within certain limits is the best alternative to overcome "over design" pumps. Operation of the pump with a reduction in the impeller diameter can save energy usage and costs. In practice, the reduction in the pump impeller diameter is limited to maximum of 25 percent of the maximum diameter of the original diameter of the pump impeller. Cutting the diameter of the pump impeller is commonly called as "impeller trimming". Cutting the pump impellers more than of 25 percent of the original diameter can result in a very large reduction in the pump efficiency. This is because excessive impeller cutting will result in the increase in the "clearance" between the impeller and the pump casing that causes excessive flow circulation. This excessive flow circulation greatly affects the increase in the flow head loss and decrease the pump efficiency. Savar et al. [6] also showed that trimming the centrifugal pump impeller reduces the pump efficiency. Wang et al. [7] show a study result that reduction in impeller diameter (trimming) up to 6 percent for two-stage centrifugal pumps results in a reduction in head by 13 percent and a maximum efficiency reduction of approximately 1.69 percent. Wang et al also showed a reduction in radial forces on the pump casing and on the guide vanes.

With numerical and experiment study, Bai et al. [8] evaluated the performance of centrifugal pumps using trimmed impellers. In general, the results obtained by Bai et al are in agreement with the results of Wang et al study, where the impeller "trimming" not only affects the pump head, capacity and efficiency, but also affects the forces, pressure distribution, and pressure fluctuations that occur in a centrifugal pump. Secondly, Matlakala et al. [9] studied numerically the effect of impeller diameter on pump performance. They showed a conventional result of their study, that the pump head increases as the pump impeller diameter increases. Next, Li [10], examine the effect of the trimmed impeller and fluid viscosity on the pump affinity law. The results showed that the affinity law is significantly affected by the reduced impeller diameter and fluid viscosity. Furthermore, Khoeini and Tavakoli [11] performed six methods of pump impeller trimming. They obtained that the method of polygon trimming resulted in the highest efficiency compared to the other trimming methods, but this method resulted less efficient compared to that of conventional (straight) trimming method. Other studies regarding the pump impeller trimming and other methods to improve pump performances can be seen in [12, 13, 14, 15].

The impeller trimming is usually performed based on the impeller affinity law. The diameter ratio of the impeller diameter after trimming (D_2) to the impeller diameter before trimming (D_1), i.e. (D_2/D_1), depends on the required head ratio (H_2/H_1), or the required capacity ratio (Q_2/Q_1). In this case, subscript 1 indicates the impeller diameter, head, and pump capacity before impeller cutting, while subscript 2 indicates the impeller diameter, head, and pump capacity after impeller cutting.

In a widely variety of literature has been studied, both experimentally and numerically, the trimming on the pump impeller has a very significant effect on pump performance, including head, capacity, power consumption, and pump overall efficiency. In a relatively recent study, Shu et al. [16] cut the centrifugal pump impeller not only in diameter ratios, but also considering the slope of the impeller cutting angle. They conducted a study using numerical methods in which the cutting angle was varied from -10 degrees to +10 degrees. The size and direction of the cutting angle affect significantly on the pump power consumption and on the vortex structure inside the pump impeller.

This study was carried out experimentally to evaluate the effect of impeller cutting/trimming to a certain percentage to its initial diameter to a centrifugal pump performance. The largest cut is 19 percent of the initial diameter, or the minimum diameter of the impeller after cutting is 81 percent of the initial impeller diameter. Seven values of impeller cutting are conducted, where each time the cut is equal to approximately 2.7 percent of the initial diameter. The pump performances to be evaluated include capacity, head, power output and power input to and from the pump, and the pump efficiency before and after cutting of the impeller. Changes that occur at the pump speed are also observed during this experimental study.

2. EXPERIMENTAL METHOD

The study was conducted experimentally. The experiments were carried out using a piping system driven by a centrifugal pump. The centrifugal pump used in this study is a one-stage centrifugal pump with the power input of 300 W. The maximum capacity of this pump is 100 liters/min., and the total head is 31.5 m. The pump is connected to an electrical motor with a speed of rotation of 2850 RPM. The electric motor is connected with an alternating current source at a voltage of 220 V. The diameters of the pump suction and discharge pipes are the same, i.e. 1 inch. The suction and discharge pressures of the pump are measured using a Bourdon type manometer mounted on the suction and the discharge sites of the pump. The measurement uncertainty of the pressure measurement based on the pressure gage scale is approximately 3.2percent at the maximum head that can be attained by the pump. Meanwhile, to measure the flow capacity, a Fisher series 2000 flow meter is installed at the discharge site of the pump. The flow meter has the uncertainty measurement of approximately 2 percent at the flow rate of 50 liters/min. This flow rate uncertainty is estimated based on the minimum scale of the flow meter. The electrical power input was calculated based on the measured electrical voltage (V) and measured electrical current (I). A clamp ampere was used to measure both electrical voltage and current.

The pump impeller is a closed type with the width of the blade edge of the exit section is 7 mm (Figure 1). The impeller blades are the back-ward curved vanes and consist of six blades. The original outer diameter of the pump impeller is 129 mm, with the relative intlet angle of the blade (β_1) is 125°, while the relative outlet angle of the blade (β_2) is 120°. The inlet radius of the blade is 17 mm or the peripheral diameter at the blade inlet section is 34 mm.

In this study, the outer diameter of the impeller was cut seven (7) times, so there are 8 impeller sizes, including the original impeller (Figure 2). Figures 3 and 4 show the original impeller and the impellers after cut, respectivelly. The maximum cutting is done so that it does not exceed up to 25 percent of the initial diameter of the impeller. In other words, the smallest diameter of the impeller after cutting will not be smaller than 75 percent of the initial diameter of the impeller. With each cut, the diameter of the impeller is reduced by cutting by approximately 3.5 mm, or about 2.71 percent of the initial diameter of the impeller. Table 1 shows the outer diameters of the impeller after cutting, including the impeller diameter before cutting. The angle β_2 is also shown in Table 1, where angle β_2 for impellers No. 2 and 3 are very slightly different from the angle β_2 the original impeller (Impeller No. 1).

To guarantee the quality of the experiment, in this study, impeller trimming follows the procedure of BS EN ISO 9906:2012 [17]. This will provide some guidances how to cut the outer impeller diameter not to exceed of 3 percent for pumps with type K type number ≤ 1.

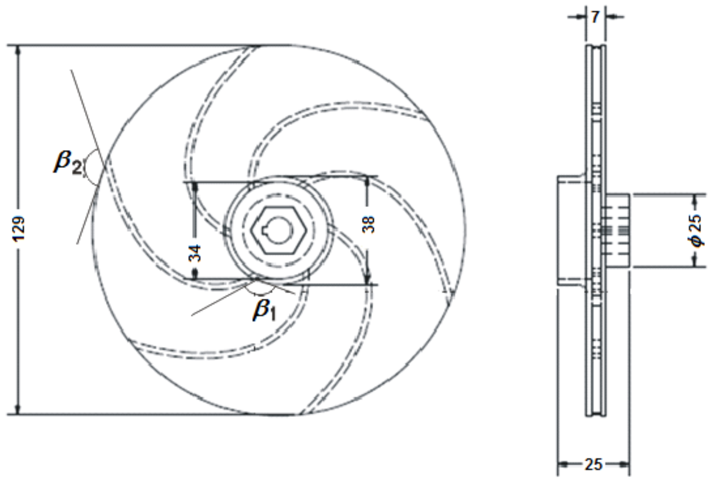

Figure 1. Original dimension of the pump impeller (units are in mm).

Table 1. Outlet diameter and relative blade angle (β_2) of the impeller.

Impeler No.	Impeller outer Diameter (mm)	Blade outlet Angle β_2	Note
1	129.0	120	Before trimming
2	125.5	120	After trimming
3	122.0	120	After trimming
4	118.5	119	After trimming
5	115.0	117	After trimming
6	111.5	115	After trimming
7	108.0	113	After trimming
8	104.5	110	After trimming

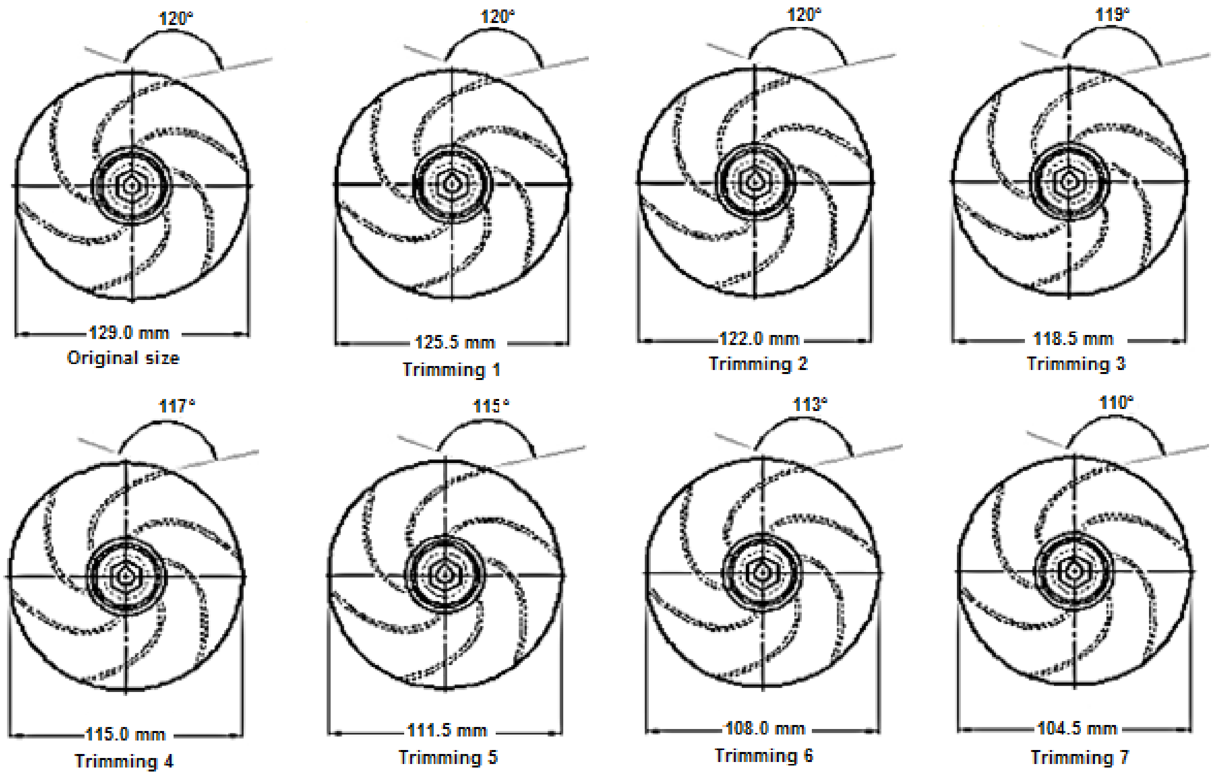

Figure 2. Original impeller and seven trimmed impellers.

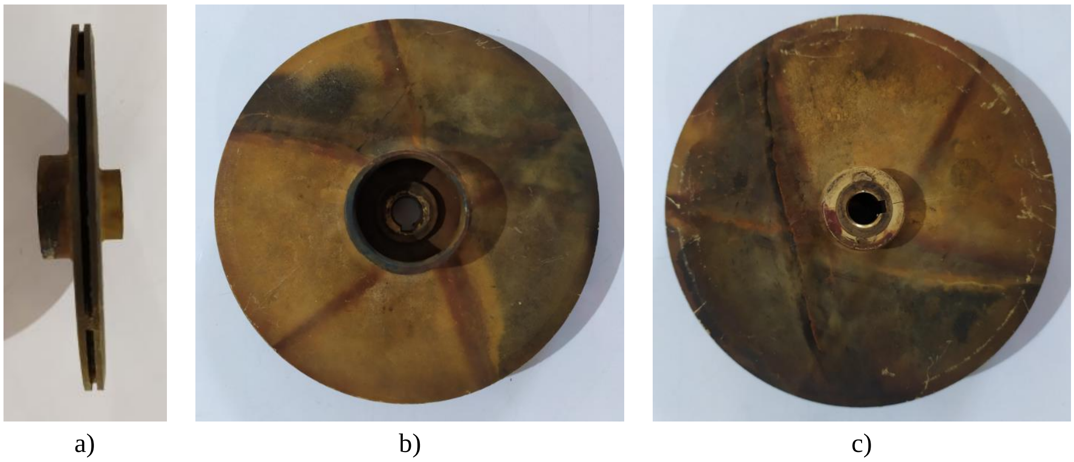

Figure 3. Pump impeller before trimming: a). discharge site view; b) suction site view; c). key site view.

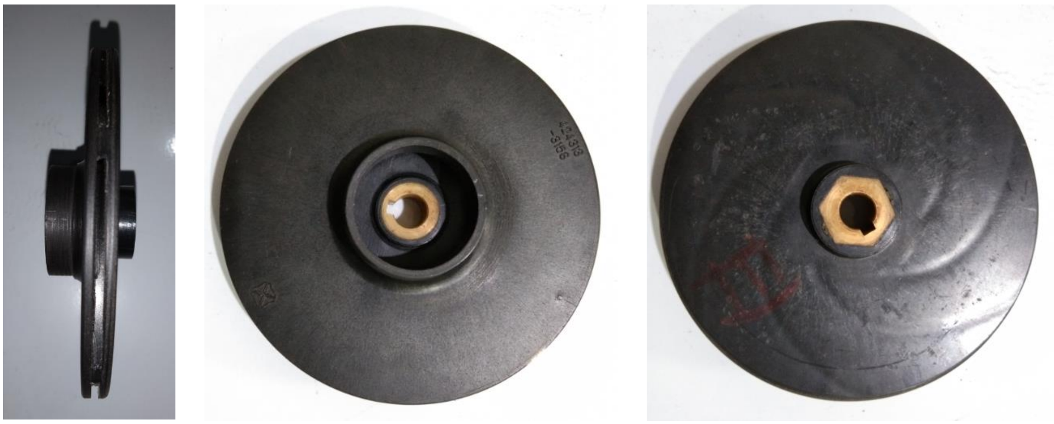

Figure 4. Pump impeller after trimming: a). discharge site view; b) suction site view; c). key site view.

Figures 5 shows pump and piping system arrangement with complete piping accesories such as flow meter, elbows, valves, and other fitting components. During this study, however, it was concentrated on the evaluation of pump performance. Therefore, a simplified arrangement around the centrifugal pump is depicted in Figure 6. The discharge and the suction pressures of the pump are measured using manometers that are attached at the discharge site and suction site of the pump, respectively. The flow rate of the pump is then controlled using a discharge valve attached between the pump discharge manometer and the flow meter. A bypass valve is attached at the discharge line of the pump and is operated only prior to gain the experimental data. During the collecting the experimental data, the bypass valve is completely closed.

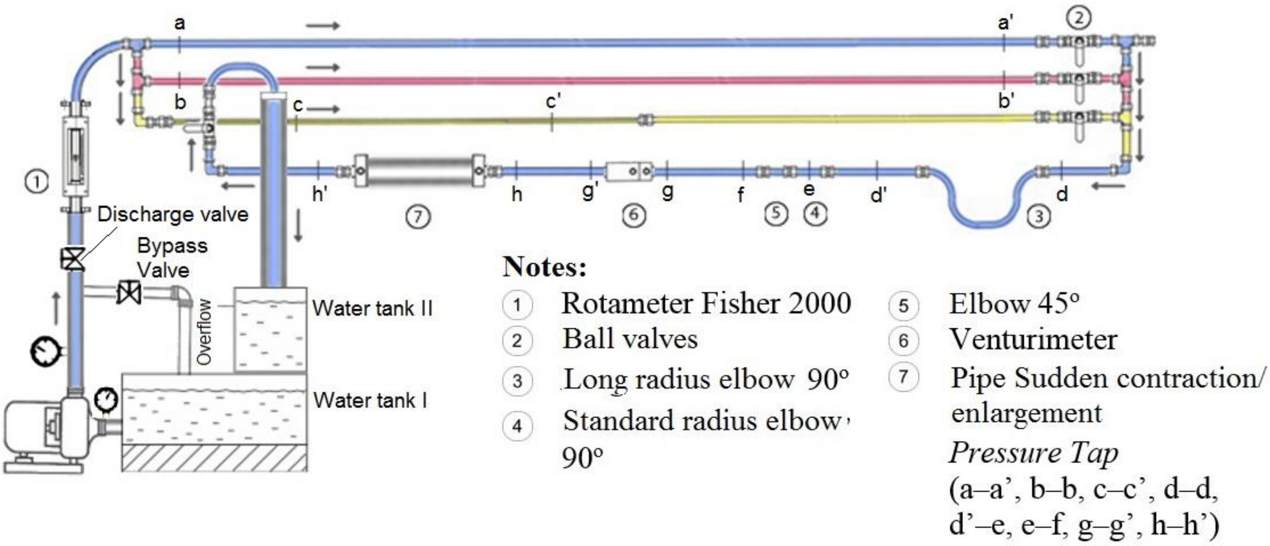

Figure 5. Pump and piping system arrangement.

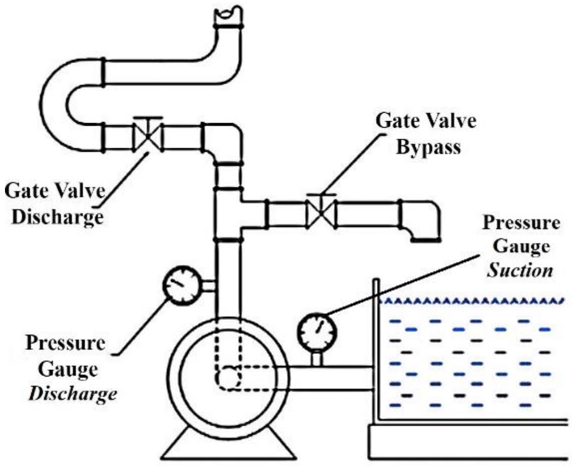

Figure 6. Pump discharge and suction pressure measurements.

The pump power output, which is referred to as the pump water horse power (WHP) or hydraulic horse power, is calculated using following the Equations (1).

$$WHP = \rho g Q H_p \, , \tag{1}$$

where,
WHP = pump water horse power (Watt)
ρ = fluid density (kg/m^3)
g = earth gravitational acceleration (9.81 m/s^2)
Q = pump flowrate (m^3/s)
H_p = pump head (m).

Pump head (H_p) is calculated based on the two reference points as shown in figure 6, where point (1) is at the pump suction site , while point (2) is at the pump discharge site. H_p can be calculated by using the Equations (2).

$$H_p = \frac{p_2 - p_1}{\rho g} + \frac{\overline{V}_2^{\,2} - \overline{V}_1^{\,2}}{2g} + h_g \, , \tag{2}$$

where,
H_p = pump head (m)
p_2 = pump discharge pressure (N/m^2)
p_1 = pump suction pressure (N/m^2)
$\overline{V}_2$ = average fluid velocity at pump discharge (m/s)
$\overline{V}_1$ = average fluid velocity at pump suction (m/s)
ρg = γ = fluid specific weight (kg/m^{2}s^2)
h_g = different in elevation of pressure taps at discharge and suction sites of the pump (m).

Pump break horse power (BHP) or pump shaft power is calculated using following the Equations (3).

$$BHP = \eta E_p = \eta V I \cos\phi \, , \tag{3}$$

where,
BHP = pump break horse power (Watt)
η = transmission efficiency
E_p = pump motor power imput (Watt)
V = measured electrical voltage (volt)
I = masured electrical current (A)
$\cos\phi$ = power factor.

There are two definitions of pump efficiency used in this study. The first is the pump overall efficiency *(η_{op})* and the second is the pump break efficiency, or simply referred to as pump efficiency (η_p). The pump efficiency (η_p) is defined as the ratio of the pump power out put (WHP) to the pump shaft power (BHP), which can be calculated by using the Equations (4).

$$\eta_P = \frac{WHP}{BHP} \times 100\% . \tag{4}$$

While the pump overall efficiency (η_{op}) can be calculated by using the Equations (5), where: $P_{input} = V$ x I (Watt).

$$\eta_{op} = \frac{WHP}{P_{input}} \times 100\% , \tag{5}$$

3. RESULTS AND DISCUSSION

3.1. Pump Capacity, Pump Head, and Pump Power

Figure 7 shows the main pump characteristics for eight different impeller sizes that are D = 129.0, 125.5, 122.0, 118.5, 115.0, 111.5, 108.0, and 104.5mm. The largest impeller diameter (129.0 mm) develops the highest shut-off head of approximately 20 m, while the smallest impeller diameter (104.5 mm) develops the smallest shut-off head of approximately 12.6 m. As the flowrate increases, the pump head decreases monotonically regardless the impeller sizes. Although the data are slightly scatter, those showed good agreement with data provided in many literatures.

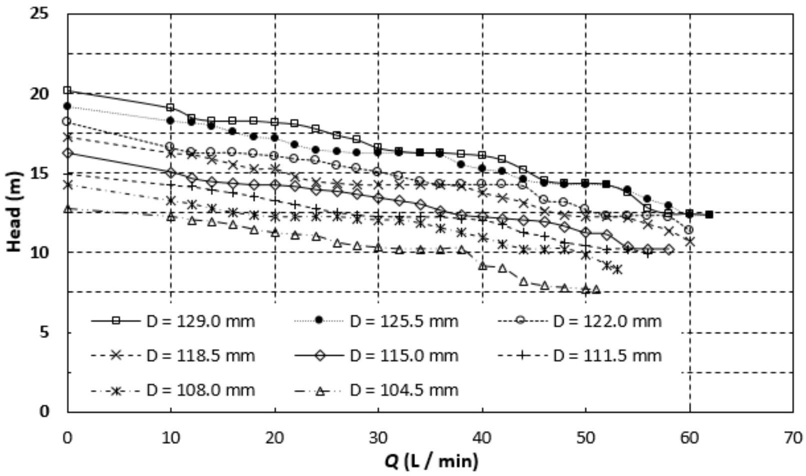

Figure 7. Pump head (H) as a function of pump capacity (Q) for eight different impeller diameter sizes.

To simplify analysis, in the next paragraph and so fort it will be analyzed only the five representative impeller diameters, i.e. D = 129.0, 122.0, 115.0, 108.0, and 104.5mm.

Figure 8 is similar that of Figure 7, but it shows only the results obtained from the five impeller diameters. It can be seen from figure 8 that the different distribution of pump head (H) as function of its capacity (Q) clearer than that shown in Figure 7. Figure 8 also shows that the maximum pump capacities decrease as the impeller diameters decrease. For the largest pump impeller, the maximum flow rate that can be attained by the pump is approximately 62 liters/min, while the smallest pump impeller only develops the flow rate of approximately 51 liter/min. This results is in-line with the pump affinity law as mentioned in the Equations (6).

$$\frac{Q_2}{Q_1} = f\left(\frac{D_2}{D_1}\right), \tag{6}$$

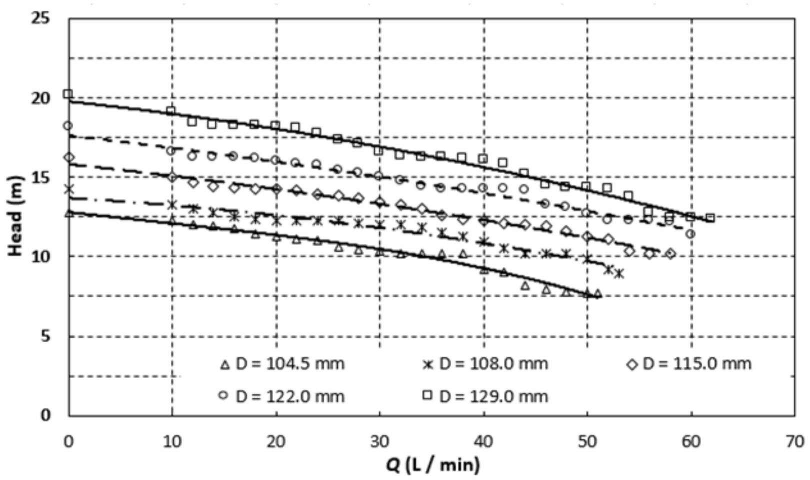

Figure 8. Pump head (*H*) as a function of pump capacity (*Q*) for five different impeller diameter sizes.

Another important parameter of a centrifugal pump is the pump power output, or is commonly called as water horse power of the pump and is denoted as *WHP* (water horse power). This *WHP* is calculated using Eq. (1) and the results are shown in Figure 9 for different impeller diameters. Similar to the pump head, the effect of the impeller diameter on the *WHP* is in-line with the pump affinity law, that the larger pump impeller diameter develops larger WHP and capacity. The largest impeller diameter in this study is 129 mm and such pump develops WHP approximately of 125 Watt at capacity of approximately 61 L/min. As the impeller diameter decreases, the maximum WHP of the smallest impeller diameter is only approxiamtely 63 Watt at capacity of approximately 51 L/min, or only approximately 50 percent WHP can be developed by the smallest impeller campared to the largest one.

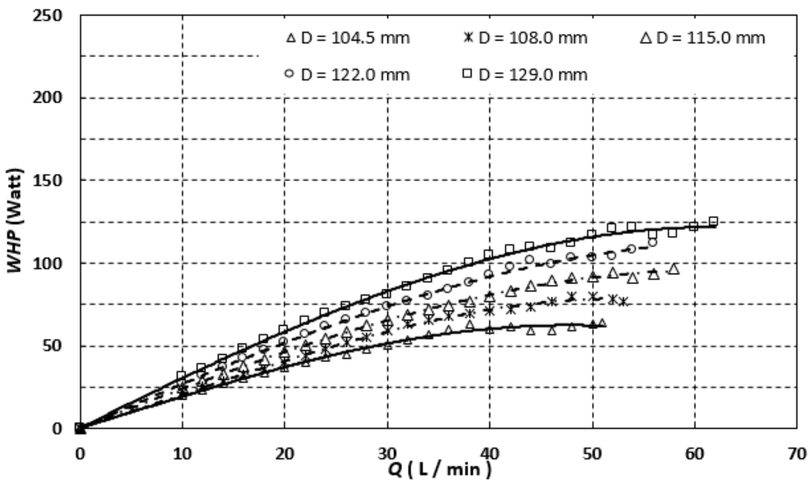

Figure 9. Pump water horse power (*WHP*) as a function of *Q* for five different impeller diameters.

Figure 10 shows the effect of pump impeller diameter on the pump power input (P_{input}), where P_{input} is calculated from the measured voltages and currents supplied to the pump motor, i.e. = *V* x *I* (Watt). For a given impeller diameter, the P_{input} increases almost linearly with the flowrate (*Q*). At zero flowrate, all P_{input} is used to overcome the shut-off head, i.e. head of the pump at zero flowrate. At this condition, the pump motor is continuously rotating, while there is no pump flow rate at all. It is not permissible to operate the pump at such condition for long periode that can cause the pump failure. There will be a lot of heat dissipation and it will cause severe vibration if the pump operates at zero flow rate for long periode.

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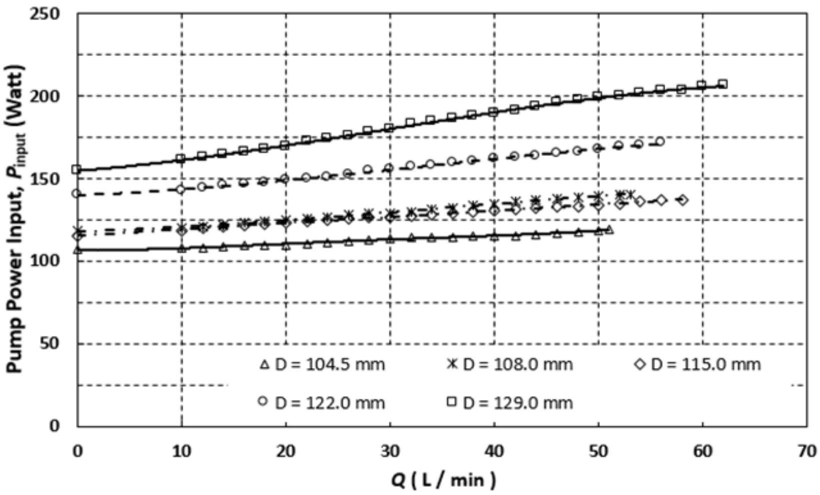

Figure 10. Pump power imput (P_{input}) as a function of Q for five different impeller diameters.

3.2. Pump Efficiency

Figures 11 and 12 show the pump efficiency (η_p) and pump overall efficiency (η_{op}), respectively. The pump efficiency is calculated using Eq. (4), while pump overall efficiency is calculated using Eq. (5). From the figures 11 and 12, it is clear that there is significant effect of the impeller diameter to the pump efficiencies. The original impeller size (D = 129.0 mm) operates at the maximum efficiency of approximately 74 percent. When the impeller is then cut to smaller sizes, the slight increase in the maximum pump efficiency is discerned. For the present study, the maximum pump efficiency of approximately 88 percent (or increase of approximately 20 percent) can be achieved by the pump with impeller diameter of 115.0 mm, or the impeller size of approximately 89 percent of the original size. The further cuts of the impeller cause the reduction of the pump efficiency. For the smallest size of the impeller being studied, i.e. 104.5 mm or 81 percent of the original size, develops the pump efficiency of approximately 65 percent. This reduction in pump efficiency at larger cuts is probably due to the increase in the fluid circulation in the area between the pump casing and the pump impeller. The increase fluid circulation means the increase in the energy dissipation into heat so that the pump comsumes more power input for given pump output or WHP.

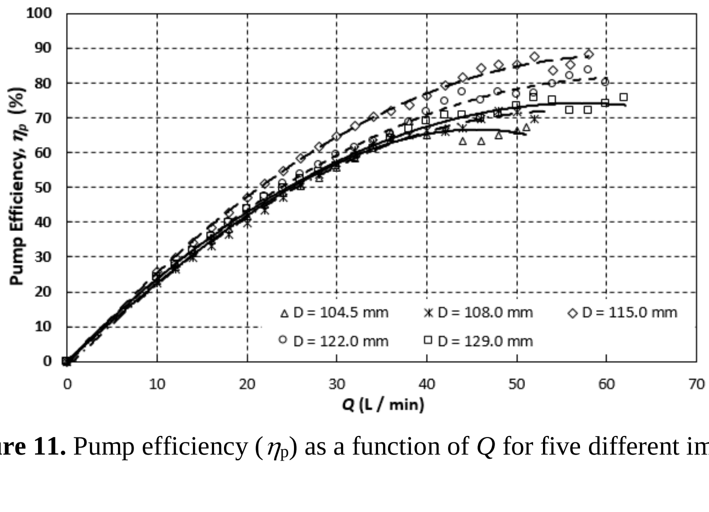

Figure 11. Pump efficiency (η_p) as a function of Q for five different impeller diameters.

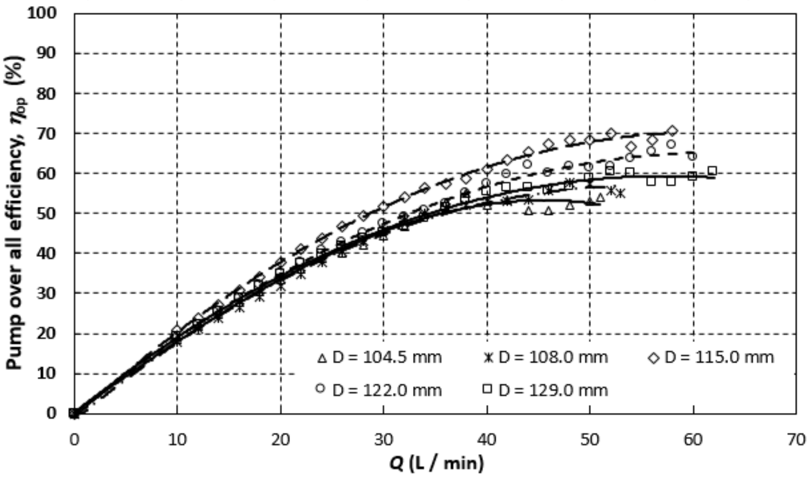

Figure 12. Pump over all efficiency (η_{op}) as a function of Q for five different impeller diameters.

Although there is a limitation of the data, we can construct the iso-efficiency line using the method described by Kethagurov [18]. The efficiency lines are shown in Figure 13 for the pump efficiencies of 67 and 75 percents. Because of the limited and scattered data, only two efficiency lines can be drawn, and we slightly use the smoothed lines to construct them. Based on the current data obtained in this study, the maximum pump efficiency is approximately 88 percent and occured at the 115 mm pump impeller diameter.

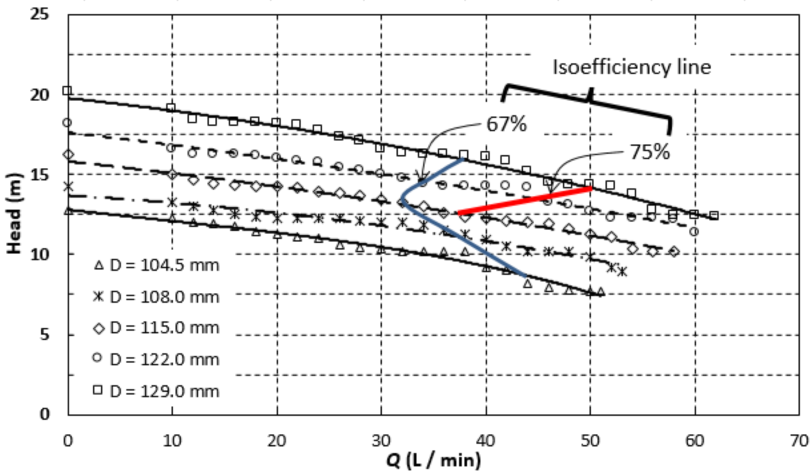

Figure 13. Iso-efficiency lines of the pump for different impeller sizes.

Figure 14 shows the effect of the pump impeller diameter to the maximum pump efficiency. The original pump impeller diameter can operate at the maximum efficiency of approximately 74 percent. As the size of pump impeller is reduced, the pump efficiency increases. At an impeller size of about 89 percent of its original impeller size, the pump attains its maximum value of the efficiency of approximately 88 percent. Further reducing of the pump impeller size, the pump efficiency is also reduced, as explained in previous paragraph.

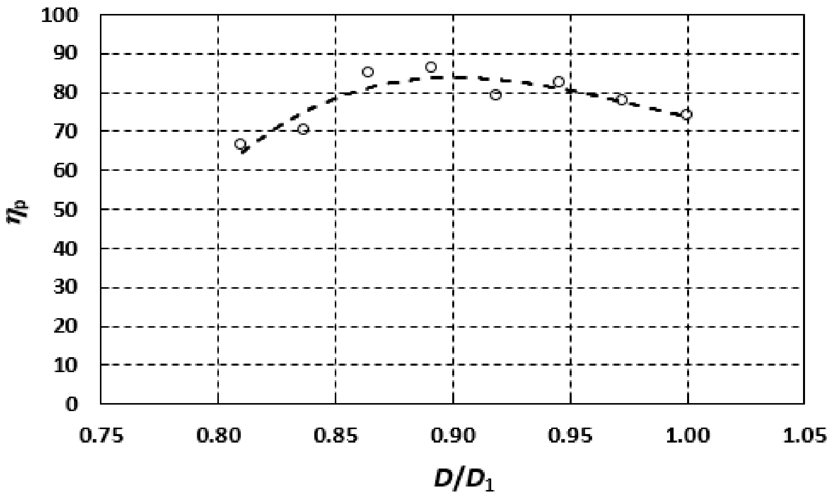

Figure 14. The effect of the pump impeller diameter to the maximum pump efficiency.

4. CONCLUSION

An experimental study on the effect of pump impeller cut (impeller trimming) on the pump characteristics have been performed. The maximum cut of the impeller is up to approximately 19 percent of the original impeller, or the smallest impeller that has been evaluated is approximately 81 percent of the original impeller. Some conclusion from this study can be summarized as follow.

1). In general, all data, including pump capacity, pump head, and pump power follow the pump affinity laws, that are capacity, head, and power of the pump decrease as the pump impeller size decreases.

2). The pump impeller trimming can improve pump efficiency up to some extence. Based on the results of the current study, the maximum pump efficiency is obtained at the pump cut (or $(D_2 - D_1)/D_1$) of approximately 10 to 11 percent of its original pump impeller diameter. The improve of the maximum efficiency is up to opproximately 20 percent compared the maximum efficiency of the original impeller size.

3). Due to the scattered nature of the experimental data, it is difficult to obtain smooth curves for pump iso-efficiency.

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