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The CFD Application in Analyzing The 024P108 Centrifugal Pump Damage as The Effect of High Vibration using Fluid Flow Discharge Capacity Parameters

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ABSTRACT

Petroleum is one of the natural resources that can produce energy both for fuel and for generating electricity. One of the most important and widely used equipment in this industry is a pump. A pump is a device for distributing fluids from one place to another. A centrifugal pump is a device for distributing move liquids from one place to another by converting the fluid's kinetic energy into potential energy through an impeller that rotates in the housing. The objective of this research is to analyze the damage of pump 024P108, which indicated high vibration due to using a high-speed shaft. The research is done by using an analytical method, using CFD Fluent analysis with flow discharge capacity under normal conditions and minimum flow conditions, and comparing the results by API 610. Afterward, the right maintenance will be known for the 024P108 centrifugal pump to reduce the high vibration that occurred in the pump. The pump is run at minimum flow with a flow rate of 22 m^3/hr and the normal flow rate of the pump is 97.9 m^3/hr so that the results show that the pump head has decreased to 198.74 m and the pressure drop has increased by 2.5995×10^5 Pa. The vibration test data shows that high vibration of 8.5 mm/s is produced by a minimum flow state of 22 m^3/hr, this low fluid flow is the cause of high vibration on the pump. High vibration has an impact on pump performance, that is decreasing pump performance (efficiency) and if left continuously it can cause damage to the pump.

1. Introduction

A Centrifugal pump is a pump that operates by converting the liquid kinetic energy to potential energy, which is to lift the fluid to a higher place through an impeller in the housing pump [1, 2]. The range of utilization of centrifugal pumps is generally utilized by all types of industrial companies involving energy components such as power generation, mining, oil and gas, petrochemical, and water desalination. And the Refinery Unit (RU) is currently one of the real applications [3]. This type of pump is easy to acquire because of its strong construction and can be mass-produced so that the

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purchase price is lower. Moreover, easy to install, operate (there are various types of water discharge output capacity options available), and maintain so it has a long useful life [4–6], making it suitable for use sustainably. 024P108 Centrifugal pump is a pump in the oil and gas industry used to drain HVI 650 lubricant. This pump is using a closed impeller with 3 blades in it.

One of the characteristics of centrifugal pumps is the use of high rotation in their operation to transfer liquids. So that this condition conduces a vibration in the pump. However, the operation of this 024P108 centrifugal pump exhibits very high vibrations. The source of vibration in the pump is caused by many reasons, including fluid hydraulic energy (cavitation, hydraulic imbalance, recirculation flow, system instabilities, and so on), misalignment between shafts connections, AC/DC motor problems, mechanical looseness, hydraulic forces, aerodynamics, and so on [7–9]. An exaggerated vibration can decrease the performance of the pump and can cause a failure [10]. This condition can interrupt the process products in the industry so that they need a treatment strategy for a pump in a high-speed rotation. It is widely known that vibration-based fault diagnosis played a critical role in the preventive maintenance of critical machinery [11, 12]. Figure 1: 024P108 centrifugal pump to be analyzed.

Fig. 1. Centrifugal Pump 024P108

From previous studies, centrifugal pumps that experience high vibration can be caused by cavitation. Cavitation is an effect of repetitive internal circulation and can damage the internal pump so that the impeller is subjected to pitting and bent conditions [13]. This effect causes the impeller to become unbalanced, which will affect the damage to other components. So, proper maintenance is needed to overcome this problem. The method used in this research is a vibration-based analytical method and a numerical simulation method. The more days that the development of technology encourages people to use Computational Fluid Dynamic (CFD) in solving high vibration simulation cases because it has the potential to predict the characteristics of pressure distribution in centrifugal pumps, besides saving costs and time [14, 15]. According to Zhang *et al.,* [16] numerical simulation with computational fluid dynamics (CFD) technique is considered an effective method to predict the performance of scroll machines and optimize their design. According to Lorusso *et al.,* [17] the major advantage of the chosen CFD approach lies in the fact that with knowing the kinetics of the heat/mass transfer and especially flowing fluid. Any fluid may be added to the presented CFD model. Therefore, with the developed CFD model, it should be possible to simulate the flowing fluid of any kind of centrifugal pump to resolve the damage, especially high vibrations. Moreover, the advantage is that it can identify potential damage before it becomes severe which can lead to unscheduled downtime [18].

The main purpose of this research is to analyze centrifugal pump damage caused by high vibration so that the pump function does not work optimally. Research on the detection of high vibrations on the 024P108 centrifugal pump is still rarely carried out. So, in this research, it is proposed to investigate the high vibrations on the centrifugal pump using the analytical method and numerical simulation methods. The analytical method is by making visual observations carried out by observing the impeller and pump directly. Then, proceed with the numerical simulation method which is carried out by simulating the impeller with CFD application (flow discharge capacity parameters). To overcome these problems, the SOLIDWORKS application is used to draw a 3D model Impeller and CFD Fluent is used to compute in analyzing a fluid debt that flows in the 024P108 centrifugal pump and gets the results of numerical analysis of the pressure distribution at normal flow and minimum flow. And also proofing that the source of high vibration occurs due to the use of minimum flow than normal flow in centrifugal pumps.

2. Methodology

2.1 Analysis Method

This research used a single-stage centrifugal pump with the tag number 024P108 as the analysis medium. Single-stage centrifugal pump analysis uses an analytical methodology to process the data obtained. Based on the 024P108 centrifugal pump datasheet, that pump to be analyzed is shown in Figure 2. Table 1 shows the description of centrifugal pump part.

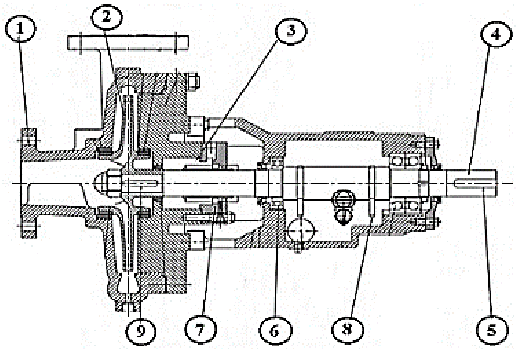


Fig. 2. 024P108 Centrifugal Pump [19]

Table 1
Description 024P108 Centrifugal Pump

No.	Name Part
1	Casing
2	Impeller
3	Mechanical Seal
4	Shaft
5	Key-Shaft Coupling
6	Bearing
7	Mechanical Seal Gland
8	Oil Ring
9	Impeller Key

To get the research result, the Computational Fluid Dynamics (CFD) analysis is to be done. Then the results will be matched with vibration analysis to determine the position where the high vibration source occurs. In this research, the problems and assumptions are given as follows: The Similarity of Kinetic Turbulence Energy as basic equations, the flowing fluid in a steady-state condition, constant fluid characteristic, incompressible fluids flows, and the assumptions that the walls are fine and there is no disruption at the flow, including the rough surface is to be ignored. CFD analysis in this model applies the governing equations stated by Eq. (1):

$$\frac{\delta\rho K}{\delta\tau} + \frac{\delta\rho K U_j}{\delta x_i} = \frac{\delta}{\delta x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\delta_k}{\delta x_i}\right] + P_k - G_k - \rho_\varepsilon \quad (1)$$

By comparing the condition of the pump design and the actual condition of the pump, it is possible to determine the feasibility of the pump operation. Table 2 is a design specification of the 024P108 centrifugal pump [19].

Table 2
Specifications of the 024P108 Centrifugal Pump Design [19]

Data	Value	Units
Debit	99	m^3/hr
Head Total	213	meter
NPSHa	6	meter
HHP	67	horsepower
BHP	118	horsepower
η Pompa	57	%

Using Eq. (2) will get the density of the flowing fluid, while Eq. (3) and (4) can determine the flow velocity and Reynolds Number. The flow will generally be laminar for Re ≤ 2300 and turbulent for larger values.

$$\rho_{oil} = SG \times \rho_{water} \quad (2)$$

$$v = \frac{Q}{A} \quad (3)$$

$$Re = \frac{\rho \cdot v \cdot D}{\mu} \quad (4)$$

Loss of energy due to piping installations causes the flowing fluid to occur head loss. Eq. (5) shows that pressure drop is a function of diameter, pipe length, pipe roughness, fluid velocity, density, and viscosity.

$$\Delta p = \Delta p(D, L, e, V, \rho, \mu) \quad (5)$$

Table 3 is pipeline installation data on the 024P108 centrifugal pump [19].

Table 3
Installation of 024P108 Centrifugal Pump Piping [19]

Data	Dimension	Length/quantity
Pipa (1)	Ø 6”	4 m
Pipa (2)	8”	22.5 m
Elbow 90^o	8”	2
Elbow 45^o (1)	6”	1
Elbow 45^o (2)	8”	1
Tee Branch	6”	2
Tee Line	8”	1
Gate Valve	6”	1
Strainer	6”	1

The relative roughness of the pipe is used to obtain the friction factor. then the relative roughness can use Eq. (6). Furthermore, to obtain major and minor head losses using Eq. (7) and (8).

$$\varepsilon = \frac{e}{D} \quad (6)$$

$$h_{L,major} = f\,\frac{L \cdot v^2}{D \cdot 2g} \tag{7}$$

$$h_{L,minor} = n \cdot K_L\,\frac{v^2}{2g} \tag{8}$$

The addition of major and minor head loss in Eq. (7) and (8) will produce the total head loss as shown in Eq. (9).

$$h_{L,total} = h_{L,mayor} + h_{L,minor} \tag{9}$$

The calculation data uses the actual 024P108 centrifugal pump data as shown in Table 4.

Table 4
Specifications of the 024P108 Centrifugal Pump Design [19]

Data	Value	Units
Debit	22	m^3/hr
Head Total	198.74	meter
NPSHa	9.412	meter
HHP	129.31	horsepower
BHP	680.57	horsepower
η Pompa	18.97	%

Net Positive Suction Head Available (NPSHa) is a measure of the suction head available in the pump system. For the pump not to be cavitated, NPSHa must be greater than NPSHr. It is using Eq. (10), NPSHa will be obtained.

$$NPSHa = \frac{P_s - P_v}{\gamma} + h_s - h_l \tag{10}$$

Hydraulic power is the power required to flow a certain amount of liquid, also called Hydraulic Horse Power (HHP). Shaft Power (BHP) is the power supplied by the motor to the pump through the pump shaft. it is used Eq. (11) and (12) to obtain HHP and BHP.

$$HHP = \frac{Q \cdot H \cdot \gamma}{75}, HP \tag{11}$$

$$BHP = \frac{HPP}{\eta_{pump}} \tag{12}$$

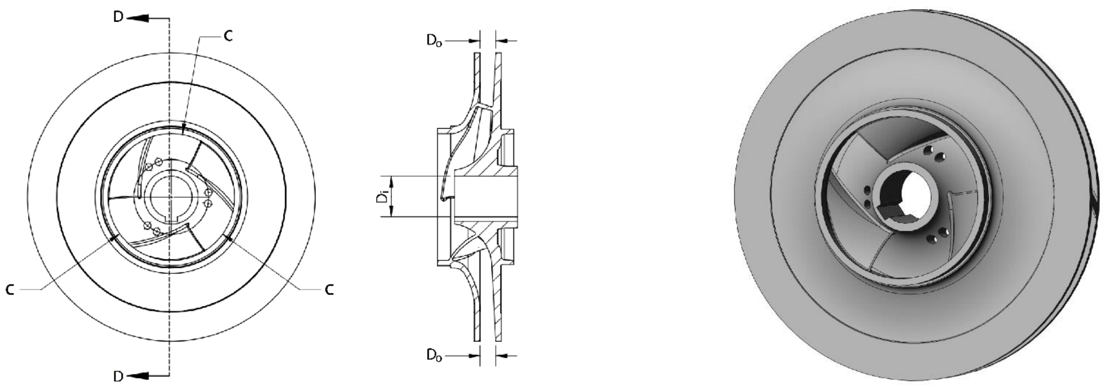
2.2 Centrifugal Pump Design

The Impeller model was obtained from the 024P108 data drawing which is redesigned using SOLIDWORK software. The model is adjusted for optimal circumstances while being operated in the normal flow (Q) = 97.9 m^3/hr, and speed (n) = 3000 rpm. The Data for the 024P108 geometry centrifugal pump impeller shows on Table 5.

Table 5
024P108 Geometry Centrifugal Pump Impeller

Geometry	Dimension	
Inlet Diameter, D_i	75	[mm]
Outlet Diameter, D_o	520.1	[mm]
Number of Blade, n	3	
Width of Each Blade, C	96	[mm]

Figure 3(a) shows the 2D picture (front and side part) of the 024P108 impeller and Figure 3(b) shows 3D these geometrical pictures are based on the 024P108 centrifugal pump design.



(a) (b)

Fig. 3. (a) Tech Drawing (b) 3D Model of Impeller

2.3 Meshing

The element method is used to get the effective meshing process. The meshing process in this research uses CFD Fluent software. The basic principle of meshing is to decide the number of elements on each block using the command Pre-Mesh parameter-edge parameter. In this meshing process, the tetrahedron shape will be used to adjust the geometrical impeller shape which has many curves and small spokes. Then sizing max to be adjusted less than 75 mm as the inlet diameter to be 75 mm so that it can produce the solid and neat meshing result.

The resulting element will be matched to the geometry of the impeller model, this research has 304 edges, 137 faces, and 728,585 nodes so that the result data of the meshing is as shown on Table 6. The meshing in this research is considered by the acceptable meshing as the resulting meshing quality is 0.84951 of skewness score, which is less than the allowed one, i.e, 0.95 [20]. The studied Meshing sizing of the 024P108 pump impeller is as shown on Table 7.

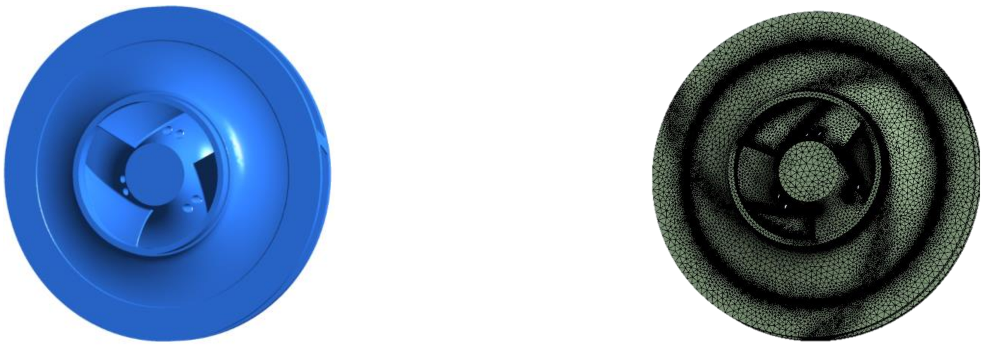
Table 6
Geometry Impeller for Meshing Information

Domain	Edge	Faces	Nodes	Elements
Impeller	304	137	728,685	3,780,700

Table 7
Meshing Sizing for Impeller

Domain	Span Angle Center	Minimum Size [mm]	Maximum Size [mm]	Skewness Max	Maximum Tet Size [mm]	Growth Rate	Minimum Edge Length [mm]
Impeller	Fine	0.753570	75.3570	0.84951	150.710	1.20	6.4171×10^{-2}

Figure 4(a) shows the representation of fluid flow which goes through the 024P108 pump impeller and the view of the impeller in 728,685 nodes. While the impeller with 3,780,700 elements is as shown in Figure 4(b).



(a) (b)

Fig. 4. (a) Fluid flow in Impeller (b) Meshing Model of Impeller

2.4 Setting Up

Boundary conditions are the formed layers around the surface that are passed by the fluid. As it gets some resistances which caused of some factors, such as frictions and some viscous effects. The border condition of this simulation applies a domain feature in which the fluid gets in through the inlet and comes out through the diffuser (outlet). This condition determines the flow on the impeller model borders [21].

Setting up Conditions of this pump has various components such as inlet (suctions), outlet (discharge), impeller, and volute casing (as the wall). The edge condition for the inlet is 1atm atmosphere pressure and the flowing mass should be on the minimum flow which is 22 m^3/hr. The variable of flow discharge capacity against to minimum flow condition and normal condition on 97.9 m^3/hr will be the main comparison factor.

Set-up for the equation model applies K-Eps (k-ε) method, the turbulent flow modeling in a steady-state condition, and Y-direction as the impeller rotation shaft [22]. This “set-up” use HVI 650 fluid which is a type of paraffin hydrocarbons C_8H_{18} (SG = 0.8; $\rho = 800\ \mathrm{Kg/m^3}$). The impeller rotation speed should be constant (3000 rpm) for both flow capacities. The convergent condition will be reached on the 1745th iteration and then the calculation result has been correct.

2.5 Validation

To validate the analysis method program in this research should be based on the existing analysis method program or similar. The research journal which is used to validate the program is “Numerical Study and Analysis of Cavitation Performance in Centrifugal Impellers” [23]. Being in the “steady-set” condition and using the k-epsilon (k-ε) method in this research is to solve Reynold Averages Navier-Stokes equation. The research result will be used to validate as shown on Table 8.

Table 8
3-Blades Head Validation

Speed	Method	Flow Condition	Head Reference	Head Validation	Error (%)
2560 rpm	k-$\boldsymbol{\varepsilon}$	Normal flow	198	198.74	0.37
3000 rpm	k-$\boldsymbol{\varepsilon}$	Normal flow	234	213	8.97

3. Results

3.1 The Result of CFD Analysis

Based on the numeric result of CFD analysis will obtained a pressure distribution score at both flow capacity, the Bernoulli Eq. (13) was used for seeking the head pump. Figure 3 shows the inner part of the centrifugal pump, where the fluid flows from the suction and goes out to discharge.

$$H = \frac{P}{\rho \cdot g} \pm z_1 - H_{loss} + \frac{{v_1}^2}{2 \cdot g} \tag{13}$$

The Impeller in Figure 3 is an example of a closed impeller in the centrifugal pump that will be analyzed using CFD Fluent with element method and k-Epsilon (k-ε) as a flow model. Based on the results of pressure-flow simulation at the 22 mr^3/hr minimum flow, shows that the pump impeller runs into a pressure enhancement from the pump suction to pump discharge that is marked with a color-changing from yellow to orange as seen in Figure 6. P_1 (yellow) describes the pressure score on the centrifugal pump impeller on -1.5441×10^5 Pa, moreover P_2 (orange) describes the impeller pump pressure score on 1.0554×10^5 Pa.

Condition: 22 (m3/hr)

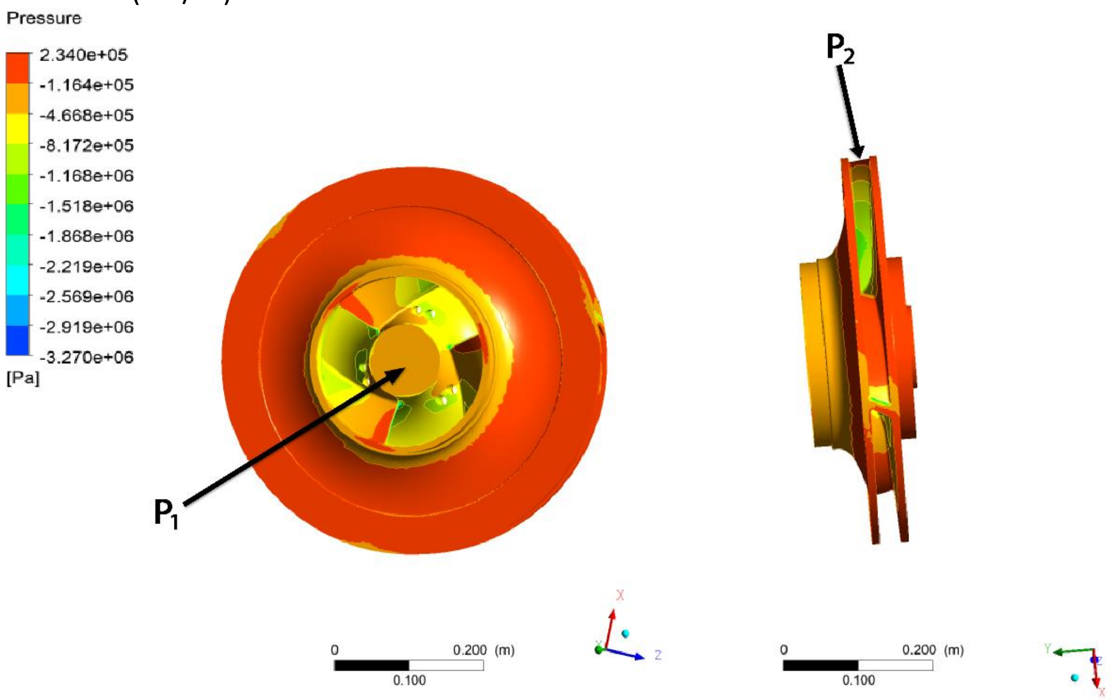


Fig. 6. Pressure Distribution on 22 m^3/hr

The below Figure 7 shows the increasing pressure distribution and it can be seen as the changing color from yellow to orange on the normal flow 97.9 m^3/hr of the 024P108 pump impeller, P_1 (yellow) describes the pressure score of the impeller pump on 2.5985×10^6 Pa, then P_2 (oranges) describes the pressure score of the impeller pump on 2.8137×10^6 Pa. From the pressure distribution of both flow discharges, it can be concluded that decreasing flow discharge will raise the pressure on the P_2 side (discharge) of the impeller pump. The pressure score data of the 024P108 pump impeller analysis result is as shown on Table 9.

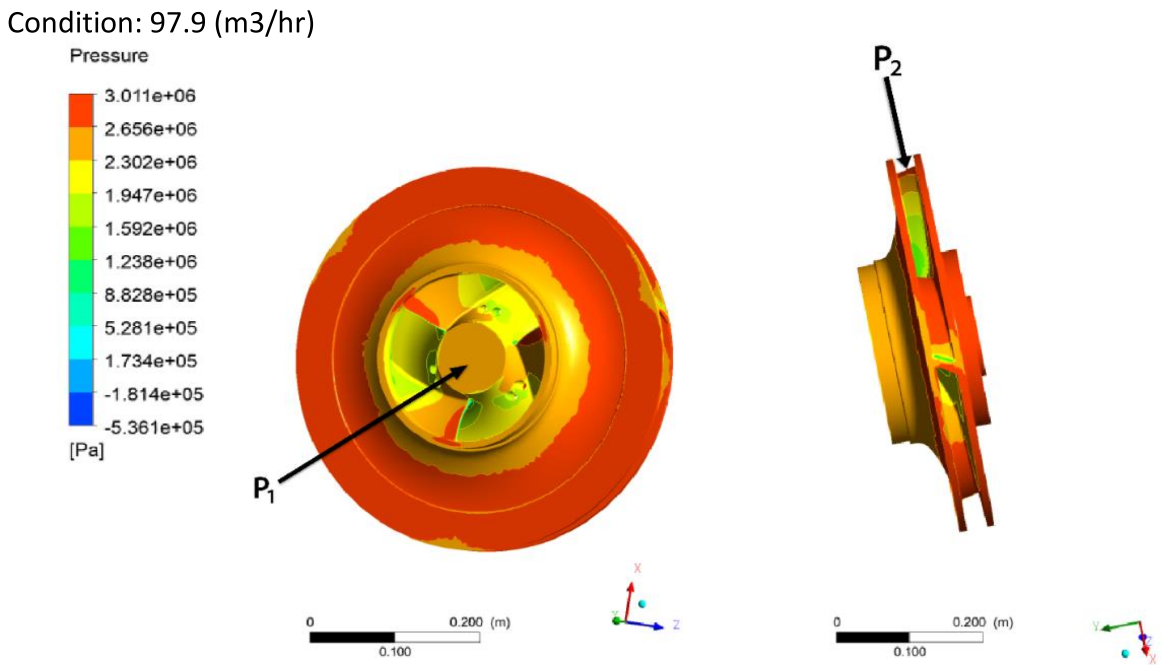


Fig. 7. Pressure Distribution on 97.9 m^3/hr

Table 9
Pressure score from the analysis results

3000 [rpm]	P_{max} [Pa]	P_{min} [Pa]	P_1 [Pa]	P_2 [Pa]	ΔP [Pa]	H [m]
22 [m^3/hr]	2.3396×10^5	-3.2698×10^6	-1.5441×10^5	1.0554×10^5	2.5995×10^5	198.74
97.9 [m^3/hr]	3.0112×10^6	-5.3608×10^5	2.5985×10^6	2.8137×10^6	2.1520×10^5	213

While using the normal flow of 97.9 m^3/hr on the impeller pump, the head comes out on 213 m and the pressure drop comes out on 2.1520×10^5 Pa, however, while using the minimum flow capacity on 22 m^3/hr, it decreases to 198.74 m (head pump) and the pressure drop on impeller increases to 2.5995×10^5 Pa. The decrease of flow discharge capacity is equal to the increase of the pressure on the discharge part [24]. So that the increasing pressure is equal to increasing the pressure drop on the impeller causes more impacts between the fluid and pump housing which causes high vibration.

3.2 Vibration Analysis of The Pump

This research does the vibration examination using the vibration meter and it restricts the vibration direction as in Figure 8 below. Between the motor and the pump, there is a connection which is to be called coupling, then the Inboard (IB)'s position is next to the coupling, while the outboard (OB) is on the outer side, farthest from the coupling. After setting the position of vibration measurement, then the measurement to vertical, horizontal, and axial directions are to be done. The position of vibration measurement is as shown in Figure 8.

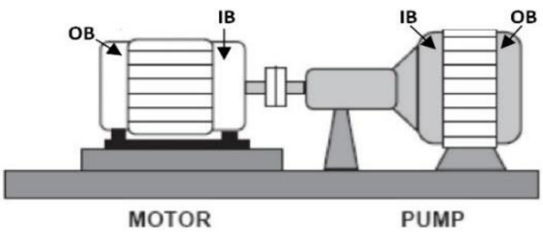


Fig. 8. The Position of Vibration Measurement

After setting the position and the direction, then the vibration measurement was to be done, the flow capacity is 22 m^3/hr and inlet pressure 1 atm (on 14th January 2020) and flow capacity 97.9 m^3/hr and the same inlet pressure on 024P108 centrifugal pump on 20th January 2020, after that a high vibration indication was found on the pump, it was on vertical direction of IB which is the impeller pump rotating direction. The result of vibration measurement is shown on Table 10. Based on the condition monitoring vibration data, it is known that the pump has a vibration value that has passed the danger limit determined by the ISO 10816-1 standard [25]. The following vibration measurement data are shown in Table 10.

Table 10
Result of vibration measurement

Domain	Position	January 14, 2020 22 m^3/hr	January 20, 2020 97.9 m^3/hr
Motor	IB Axial	1.38	1.51
	IB Horiz	1.81	2.03
	IB Vert	1.14	0.29
	OB Horiz	1.71	1.75
	OB Vert	1.43	0.84
	OB Axial	4.25	2.50
Pump	IB Horiz	3.79	3.07
	IB Vert	8.5	7.01
	OB Horiz	2.66	1.75
	OB Vert	5.41	2.19

On Table 10, it is seen that the highest vibration measurement is 8.5 mm/s which is on IB pump vertical direction. Based on ISO 10816-1 standard, the above value is beyond the danger limit, i.e 7.01 mm/s [25]. The spectrum graph as the results of IB vibration measurement on the vertical direction with rotation 3000 rpm as shown in Figure 9.

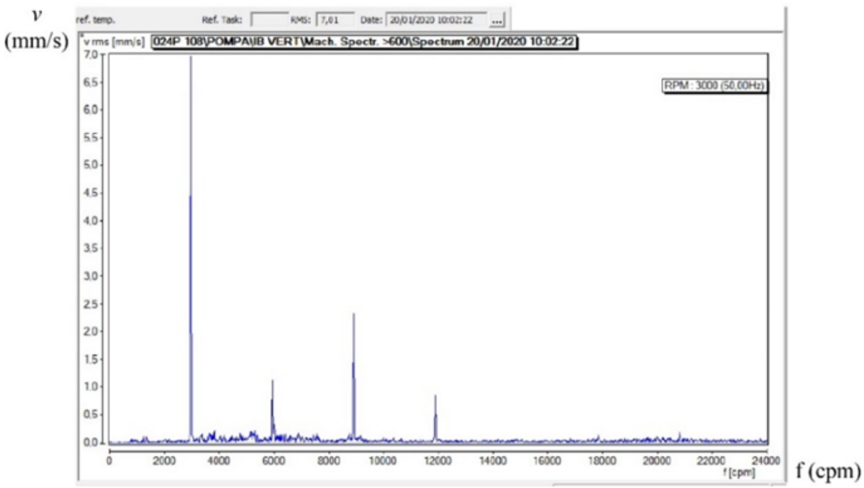


Fig. 9. Pump Graphic Spectrum IB VERT Direction

Figure 9 shows the spectrum graph which comes from the IB pump vibration measurement on the vertical direction, the graph shows the vibration on that position is 7.01 mm/s and the flow discharge is 97.9 m^3/hr, and the frequency is 2500 cpm. This shows the decreasing of vibration, i.e. 8.5 mm/s with the outset minimum flow 22 m^3/hr. Then, the spectrum results are compared with API 610 and Technical Associates regarding the typical spectrum that occurs.

If the vibration value is beyond the allowed limit by API 610, it shows that the pump doesn't work normally and it can cause damages. This vibration analysis data is to prove that the source of the high vibration is the IB pump vertical position. In this position, the fluid flow bumps the housing pump part which has high pressure and this condition causes high vibration. It can be concluded the pump is needed for a temporary repair [26].

3.3 Discussion

The actual performance of the 024P108 centrifugal pump can be obtained by the analytical method as shown in Table 4. And, the actual performance will be compared with the pump design performance to determine the state of the 024P108 centrifugal pump. Table 11 is a comparison of the design performance with the actual pump performance.

Table 11
Comparison of Design and Actual Performance 024P108 Centrifugal Pump

Data	Design Value	Actual Value	Units
Debit	99	22	m^3/hr
Head Total	213	198.74	meter
NPSHa	6	9.412	meter
HHP	67	129.31	horsepower
BHP	118	680.57	horsepower
η Pompa	57	18.97	%

After comparing the design performance with the pump's actual performance, it was found that the actual NPSHa value increased by 3.412 m which was caused NPSHA is an absolute pressure received by suction pumps, and it has been known that suction pressure is obtained because there is additional atmospheric pressure from the vessel and the difference in the height of the vessel with the pump.

The results of the vibration analysis carried out before carrying out the pump performance test showed that there was a high vibration that could cause damage, amounting to 8.5 on the IB Vert in the Pump. The data listed on the ampere meter on the motor show that the voltage released by the pump is so high, that the flow rate must be lowered but still can meet the operating needs, namely, the pump is run below its flow capacity. But it is recommended to use a fluid flow of more than 22 m^3/hour. Meanwhile, the actual pump efficiency value is will significantly be decreased compared to the pump efficiency value contained in the design data. The decrease was due to the pump running below its flow capacity and due to losses along the pipeline.

4. Conclusions

Through the analysis of high vibrations on the 024P108 centrifugal pumps using analytical methods and numerical simulation methods and the results are described in the discussion, it can be concluded that the centrifugal pumps experience high vibrations, due to the minimum flow rate. The following was reached after performing a simulation using CFD Fluent with the parameter of flow rate at the pump impeller, the pressure drop value at 97.9 m^3/hr flow rate is 2.1520×10^5 Pa, and the pressure drop value at 22 m^3/hr minimum flow rate is 2.5995×10^5 Pa. The increasing pressure drop on the impeller causes more impacts between the fluid and pump housing which causes high vibration. By reducing the flow rate capacity, it is relational to the decrease of the head pump from 213 m to 198.74 m.

Moreover, the result of the vibration analysis performing the highest vibration occurred at the IB vertical pump, with the result of 8.5 mm/s at the 22 m^3/hr flow rate, in the meantime at the 97.9 m^3/hr flow rate, the vibration is decreased to 7.01 mm/s. So, the results of the analysis prove that the high vibration source is caused by the vertical position of the IB pump, as a result, the fluid flow crashes into the pump housing section which has high pressure. This condition is what causes high vibration in the 024P108 centrifugal pump.

Acknowledgment
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References
[1] Karassik, Igor J., Joseph P. Messina, Paul Cooper, and Charles C. Heald. *Pump handbook*. Vol. 4. New York: McGraw-Hill, 2008.
[2] Yang, Sun-Sheng, Shahram Derakhshan, and Fan-Yu Kong. "Theoretical, numerical and experimental prediction of pump as turbine performance." *Renewable Energy* 48 (2012): 507-513. https://doi.org/10.1016/j.renene.2012.06.002
[3] *WARTA PERTAMINA: Modernisasi kilang*. PDF file. January 8, 2011. https://www.pertamina.com/media/2933d405-7d82-4105-a01d-dd69fcd3a610/wpjanuari2011.pdf
[4] Vásquez, Diego Penagos, Jonathan Graciano Uribe, Sebastián Vélez García, and Jorge Sierra del Rio. "Characteristic Curve Prediction of a Commercial Centrifugal Pump Operating as a Turbine Through Numerical Simulations." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 83, no. 1 (2021): 153-169. https://doi.org/10.37934/arfmts.83.1.153169
[5] Motwani, K. H., S. V. Jain, and R. N. Patel. "Cost analysis of pump as turbine for pico hydropower plants–a case study." *Procedia Engineering* 51 (2013): 721-726. https://doi.org/10.1016/j.proeng.2013.01.103
[6] Binama, Maxime, Wen-Tao Su, Xiao-Bin Li, Feng-Chen Li, Xian-Zhu Wei, and Shi An. "Investigation on pump as turbine (PAT) technical aspects for micro hydropower schemes: A state-of-the-art review." *Renewable and Sustainable Energy Reviews* 79 (2017): 148-179. https://doi.org/10.1016/j.rser.2017.04.071
[7] Al-Obaidi, Ahmed Ramadhan. "Investigation of effect of pump rotational speed on performance and detection of cavitation within a centrifugal pump using vibration analysis." *Heliyon* 5, no. 6 (2019): e01910. https://doi.org/10.1016/j.heliyon.2019.e01910
[8] Kim, J. H., K. T. Oh, K. B. Pyun, C. K. Kim, Y. S. Choi, and J. Y. Yoon. "Design optimization of a centrifugal pump impeller and volute using computational fluid dynamics." In *IOP Conference Series: Earth and Environmental Science*, vol. 15, no. 3, p. 032025. IOP Publishing, 2012. https://doi.org/10.1088/1755-1315/15/3/032025
[9] Albraik, A., Faisal Althobiani, Fengshou Gu, and Andrew Ball. "Diagnosis of centrifugal pump faults using vibration methods." In *Journal of Physics: Conference Series*, vol. 364, no. 1, p. 012139. IOP Publishing, 2012. https://doi.org/10.1088/1742-6596/364/1/012139
[10] Yu-qin, Wang, and Ding Ze-wen. "Influence of blade number on flow-induced noise of centrifugal pump based on CFD/CA." *Vacuum* 172 (2020): 109058. https://doi.org/10.1016/j.vacuum.2019.109058
[11] Scheffer, Cornelius, and Paresh Girdhar. *Practical machinery vibration analysis and predictive maintenance*. Elsevier, 2004.
[12] Rahman, Abdul Razak Abdul, Eddy Azrai Ariffin, Muhammad Helmi Abu, Fudhail Abdul Munir, and Azma Putra. "Experimental Investigation of Thermally Induced Vibration in Sulphur Recovery Unit (SRU)." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 56, no. 1 (2019): 78-87.
[13] Yohana, Eflita, Bachtiar Yusuf, Muhammad Arrafi Lazuardi, Mohamad Endy Julianto, and Vita Paramita. "Analysis of High Vibration Causing 211-P-25A Centrifugal Pump Damage in Hydrocraker Process." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 80, no. 2 (2021): 13-21. https://doi.org/10.37934/arfmts.80.2.1321
[14] Andersson, Bengt, Ronnie Andersson, Love Håkansson, Mikael Mortensen, Rahman Sudiyo, and Berend Van Wachem. *Computational fluid dynamics for engineers*. Cambridge university press, 2011. https://doi.org/10.1017/CBO9781139093590
[15] Zhao, Qiang, Baoyu Cui, Dezhou Wei, Tao Song, and Yuqing Feng. "Numerical analysis of the flow field and separation performance in hydrocyclones with different vortex finder wall thickness." *Powder Technology* 345 (2019): 478-491. https://doi.org/10.1016/j.powtec.2019.01.030

[16] Zhang, Qingqing, Jianmei Feng, Jie Wen, and Xueyuan Peng. "3D transient CFD modelling of a scroll-type hydrogen pump used in FCVs." *International Journal of Hydrogen Energy* 43, no. 41 (2018): 19231-19241. https://doi.org/10.1016/j.ijhydene.2018.08.158

[17] Lorusso, Michele, Tommaso Capurso, M. Torresi, B. Fortunato, F. Fornarelli, S. M. Camporeale, and Rosario Monteriso. "Efficient CFD evaluation of the NPSH for centrifugal pumps." *Energy Procedia* 126 (2017): 778-785. https://doi.org/10.1016/j.egypro.2017.08.262

[18] Adistya, Irman Supriadi. "Pengembangan sistem monitoring vibrasi pada kipas pendingin menggunakan accelerometer ADXL345 dengan metode FFT berbasis labview." (2014).

[19] Jackson, Byron. (2014). *Data sheet pompa 024P108*. PT. Pertamina RU-IV Cilacap.

[20] Sugihartono, Muhammad Bima. "Analisis Pengaruh Variasi Geometri Terhadap Perpindahan Panas Helical Heat Exchanger Pada Small Modular Reactor." PhD diss., 2020.

[21] Subramanian, R. Shankar. "Boundary Conditions in Fluid Mechanics." *Department of Chemical and Biomolecular Engineering, Clarkson University* (2019).

[22] Shirzadi, Mohammadreza, Parham A. Mirzaei, and Mohammad Naghashzadegan. "Improvement of k-epsilon turbulence model for CFD simulation of atmospheric boundary layer around a high-rise building using stochastic optimization and Monte Carlo Sampling technique." *Journal of Wind Engineering and Industrial Aerodynamics* 171 (2017): 366-379. https://doi.org/10.1016/j.jweia.2017.10.005

[23] Binama Maxime, and Prof. Feng Chen - Li. "Numerical Study and Analysis of Cavitation Performance in Centrifugal Impellers." *International Journal of Engineering Research and* Technology 4, no. 9 (2015): 552–556. https://doi.org/10.17577/IJERTV4IS090444

[24] Muis, Abdul, Muchsin Muchsin, and Muhammad Hasan Basri. "KARAKTERISTIK KAVITASI PADA POMPA SENTRIFUGAL." *Jurnal Mekanikal* 10, no. 2 (2019).

[25] ISO, BS, and BRITISH STANDARD. "Mechanical vibration—Evaluation of machine vibration by measurements on non-rotating parts." (2009).

[26] Standard, A. P. I. "Centrifugal pumps for petroleum, petrochemical and natural gas industries." *American Petroleum Institute,* (2010).