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Optimization of impeller blade number in centrifugal pump for crude oil using Solidworks Flow Simulation

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Abstract: Every type of fluid to be transferred has specific characteristics such as viscosity, density, friction, and others, thus requiring the selection of the appropriate pump type. One of the factors influencing the performance of a centrifugal pump is the number of blades used. This research aims to explore the influence of the number of blades on a centrifugal pump used as a fluid transfer device for crude oil. The study was conducted using the Computational Fluid Dynamics (CFD) method. The analyzed variations of the number of blades included three options, namely centrifugal pumps with 12, 14, and 16 blades. Based on the simulation results conducted using Solidworks Research License 2021-2022 software, it was found that the centrifugal pump with 12 blades exhibited the most optimal performance. The simulation results show uniform flow and pressure around the mid-span plane of the 12-blade impeller. In the case of the 12-blade impeller, the flow thrown by the centrifugal force is concentrated in the middle of the channel towards the outlet, resulting in higher pressure and volume flow rates.

Keywords: *Internal analysis, mesh independent test, fluid region, solve time*

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1. Introduction

A Centrifugal Pump is a device used to transfer fluids from one location to another (Abo Elyamin et al., 2019). A centrifugal pump consists of main components, which include the drive motor, casing, impeller, and shaft. Its principle of operation is to convert mechanical energy into kinetic energy. The impeller serves two primary functions, which are to suction the fluid and propel it (Nadaraja et al., 2023). At the inlet section, the suction pressure is lower than atmospheric pressure, while at the outlet section, the discharge pressure is higher (Kang et al., 2019). Pressure within the pump increases by creating a pressure difference, with low pressure (lower than atmospheric pressure) at the pump's suction side and high pressure at the pump's discharge side (Subroto & Effendy, 2019).

Centrifugal pumps, often referred to as turbo machines, are commonly used devices in the oil and gas sector, chemical industry, and power generation. They offer several advantages, including high and consistent flow rates, low costs, ease of maintenance, improved operational stability, and the ability to work effectively with high-temperature fluids (H. Wang et al., 2020). Generally, these pumps are designed by manufacturers to move fluids in a single phase, tailored to their intended applications (Anagnostopoulos, 2009). The impeller plays a crucial role in the performance of a centrifugal pump by transferring fluid from one location to another through pipelines while adding energy to the transferred fluid (Fingas, 2011). Pump components, particularly the impeller, operate based on the principle of creating a pressure difference between the suction and discharge sections (Jurmut et al., 2020). Research results indicate that increasing the number of impeller blades leads to higher fluid pressure generation (Zhou et al., 2003).

Every fluid has different characteristics, so the type of impeller used also varies. For crude oil, the commonly used impeller type is the closed impeller (Bellary & Samad, 2016; Bozorgasareh et al., 2021). A closed impeller has a shroud or walls in front and behind it, providing a sturdy mechanical construction (Cancan et al., 2022; Kan et al., 2022). The oil industry uses closed impellers because they are more efficient in the fluid circulation process they handle (Asfar et al., 2021; Erizon et al., 2022; Putra et al., 2022; Riady et al., 2022). With this closed design, the fluid entering the impeller doesn't come into contact with the casing, and the fluid transferred to the discharge nozzle cannot flow back into the impeller's circulation.

This research discusses the influence of the number of blades of a closed impeller with variations of 12, 14, and 16 blades. The method used is Computational Fluid Dynamics (CFD) with an analysis of pressure and the material transport flow rate of Crude Oil. The advantage of CFD simulation is the speed of time to obtain research data (Hu et al., 2022; Mrope et al., 2021; Szpicer et al., 2023). In the oil industry, the number of blades on the impeller commonly used in centrifugal pumps ranges from 12 to 16. This study employed CFD simulations to elucidate the optimal number of impeller blades for use in a centrifugal pump for transferring crude oil. Parameters examined included pressure and volume flow rate at the inlet and outlet, pressure drop, and efficiency. Three variations of impeller blade numbers were simulated, namely 12, 14, and 16. The research outcomes are expected to serve as a reference for manufacturing impellers for centrifugal pumps utilized in the transfer of crude oil.

2. Material and methods

2.1 Centrifugal pump

This research utilized the CFD method, employing the Solidworks Research License 2021-2022 software. The analysis was performed within the Solidworks Flow Simulation module. In this study, the components of the centrifugal pump to be used include the fluid Inlet pipe, casing, and impeller. The pump's design is illustrated in Fig. 1.

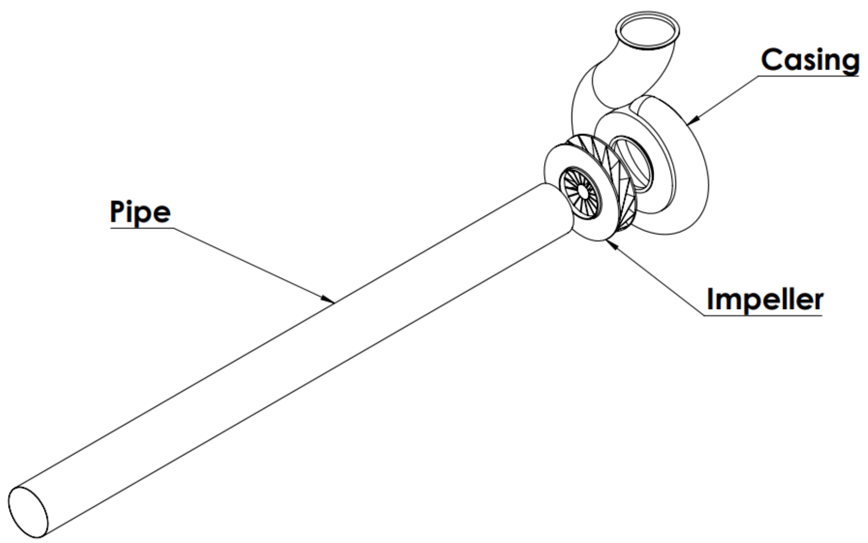


Figure 1. Centrifugal pump

The impeller design employed in this study features a closed impeller with a diameter of 490 mm, a blade height of 154 mm, a 250 mm impeller inlet diameter, a total impeller height of 194 mm, and a blade angle of 40°. The impeller design is depicted in Fig. 2.

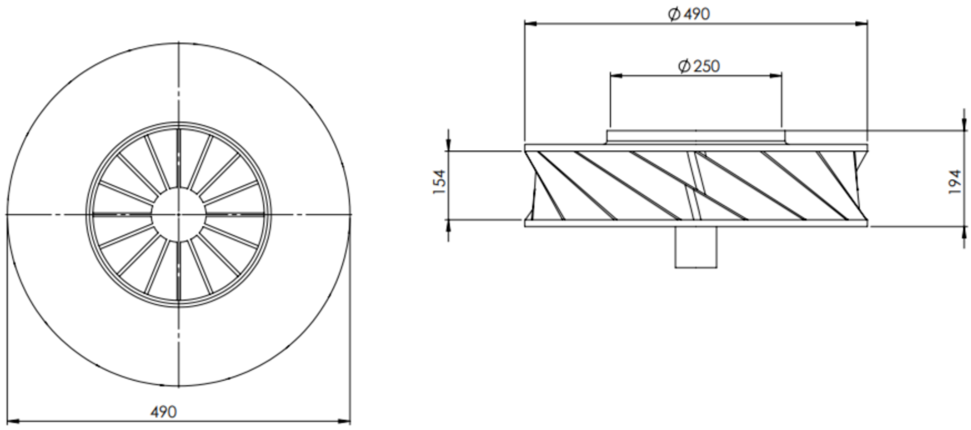
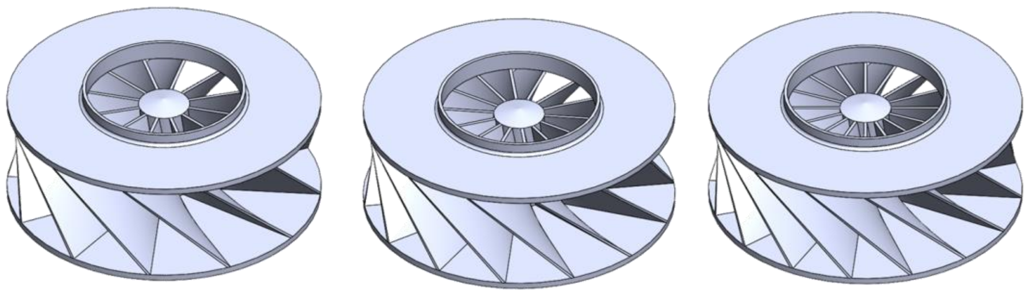


Figure 2. Dimension of impeller

This research examines the influence of the number of blades, with variations of 12 blades, 14 blades, and 16 blades. The design of the impeller for each blade count variation is illustrated in Fig. 3.



(a) (b) (c)

Figure 3. Modeling of impeller, (a) 12 blades, (b) 14 blades, and (c) 16 blades

2.2 Crude oil

Crude oil, also known as petroleum, is a complex mixture of hydrocarbons and other organic compounds. This study presents the properties of crude oil, which are used as inputs in the SolidWorks Engineering Database, in Table 1.

Table 1. The properties of crude oil

Property	Value
Temperature	T 29^0 C
Density (ρ)	850 kg/m³
Dynamic viscosity (μ)	9,33 mPa.s
Specific heat	1822 J/kg.K
Thermal conductivity	0.13 W/m.K

2.3 Parameter simulation

The simulation parameters conducted using SolidWorks Flow Simulation in this study are presented in Table 2.

Tabel 2. Parameter simulation

Unit System	Pressure	Mpa
	Volume Flow	m^3/s
	Torque	N.m
Analsis Type	Internal Analysis	
	Total analysis time	0
	Output time step	0
	Rotating Local Region	Sliding
Rotational speed of the impeller	3000 RPM (314.2 rad/s)	
Fluid	Crude Oil	see table 1
Wall Condition	Default Wall Conditions	
Initial condition	Default initial conditions	

2.4 Fluid region

This research analyzed the flow of rotating fluids, employing the 'Rotation' feature with the 'Local Region Sliding' type in SolidWorks Flow Simulation. The 'Fluid Region' component was created and not treated as a 'Solid Body' but rather utilized as a 'Local Rotating Region.' This 'Fluid Region' rotated at a speed of 3000 RPM (See Fig. 4).

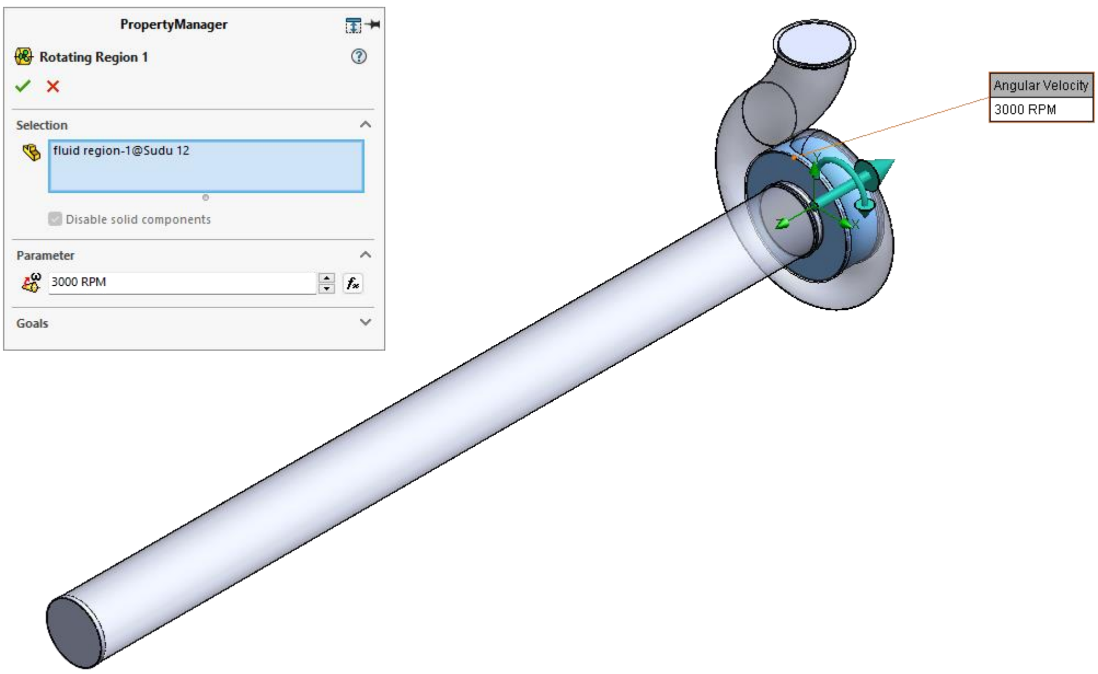


Figure 4. Fluid region

2.5 Boundary conditions

Boundary conditions in this study were conditioned at the inlet and outlet by creating lids and installing them at the respective inlet and outlet. Both lids were configured using the 'Environment Pressure' type (See Fig. 5).

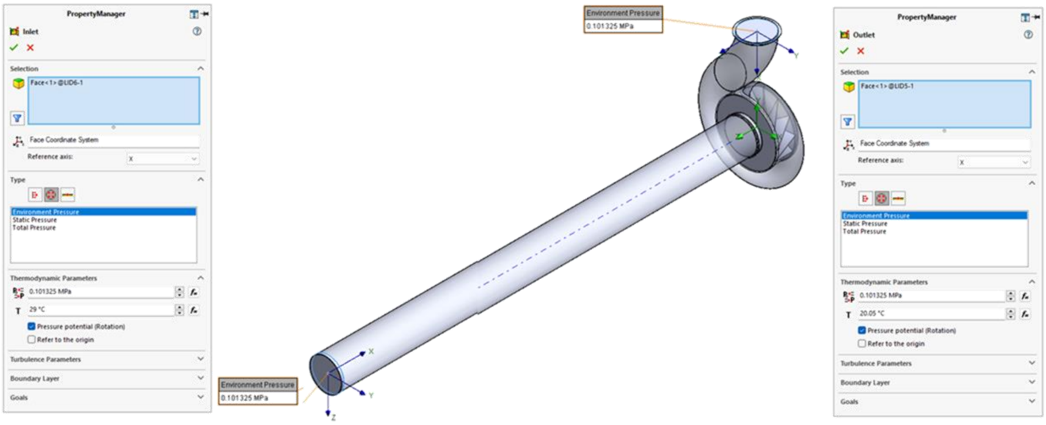


Figure 5. Boudary conditions

2.6 Goals of simulation

To elucidate the sought-after parameters arising from the difference in the number of blades in a centrifugal pump when pumping crude oil, goals were defined in SolidWorks Flow Simulation. Surface goals were employed to observe the pressure at the inlet and outlet by selecting lids on the inner side (See Fig. 6).

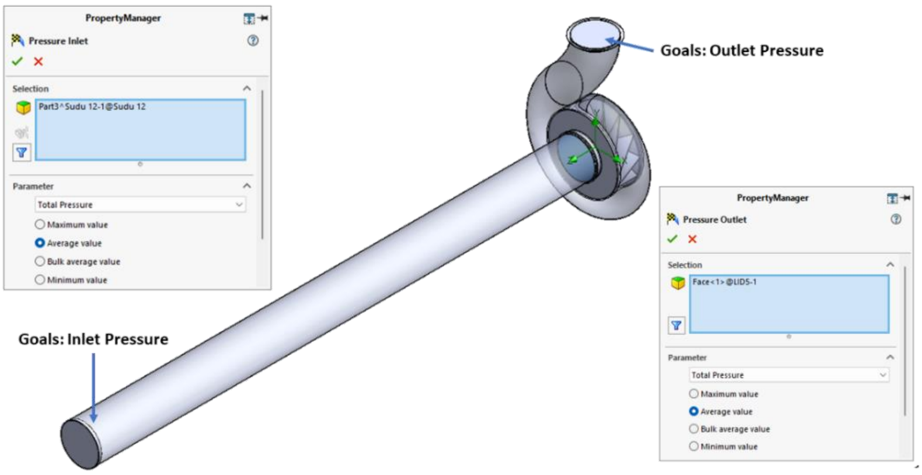


Figure 6. Configuration to visualize pressure at the inlet-outlet

To measure the pressure drop or the difference in pressure between the inlet and outlet, these steps were implemented by formulating equations in the goal equation feature within SolidWorks Flow Simulation (See Fig. 7). The pressure drop is calculated as the difference between the pressure at the inlet and the pressure at the outlet.

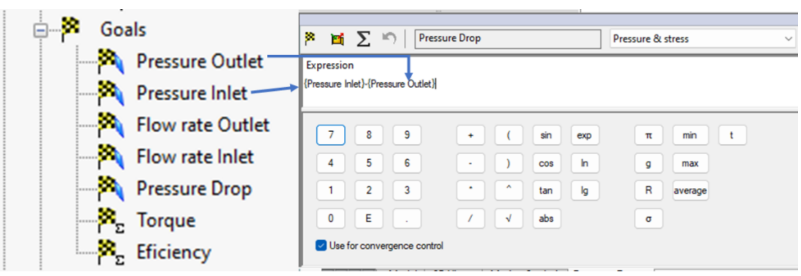


Figure 7. Pressure drop

To observe the volume flow rate at the inlet and outlet, in the parameters of surface goals, the volume flow rate was selected. In the selection, faces at the inlet and outlet were chosen by clicking or selecting them (See Fig. 8).

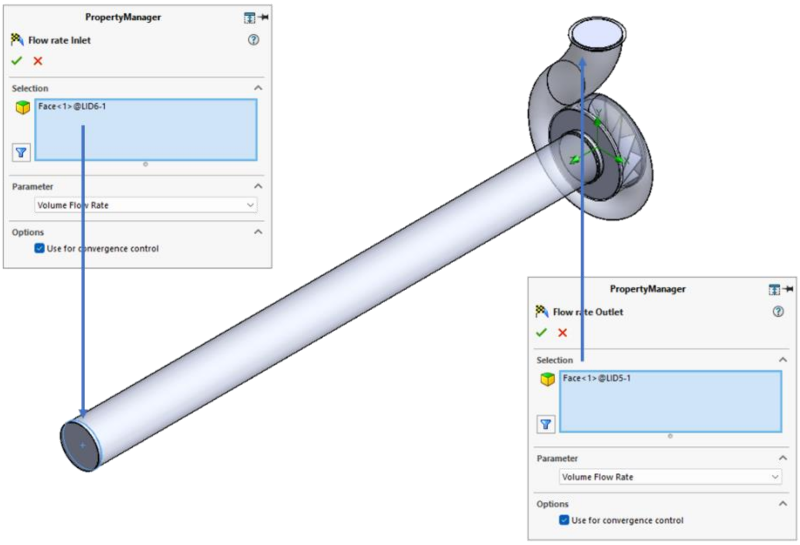


Figure 8. Configuration to observe the volume flow rate at the inlet-outlet

The efficiency of a centrifugal pump is calculated by multiplying the pressure drop with the volume flow rate at the inlet, and the result is then divided by the product of the rotational speed (3000 RPM = 314.2 rad/s) and torque. The equation for calculating centrifugal efficiency is presented in Eq. 1.

$$Efficiency = \frac{Pressure\ drop \times Volume\ flow\ inlet}{Rotational\ speed \times Torque} \quad (1)$$

To examine the magnitude of the torque on the rotating impeller, in the surface goals feature, the selection was filled with the impeller (selected or clicked on the impeller), and in the parameters, the torque was checked (See Fig. 9).

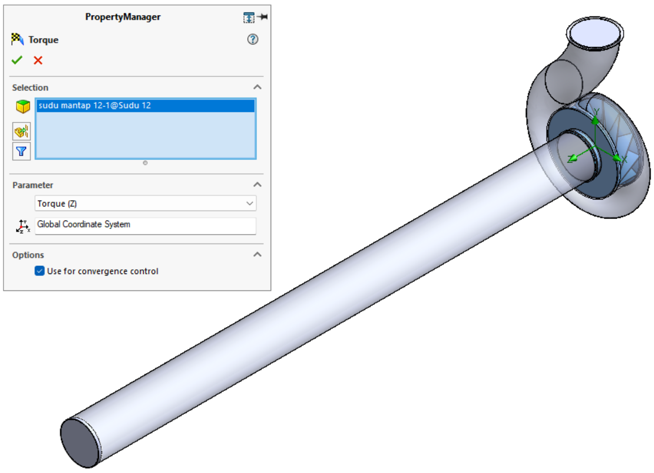


Figure 9. Torque

To assess the pump's efficiency, an equation goal was added by translating equation 1 into a programming language, and it was filled in the property expression (See Fig. 10).

Abs(({Pressure drop}*{Volume Rate Inlet})/(314.2*{Torque}))

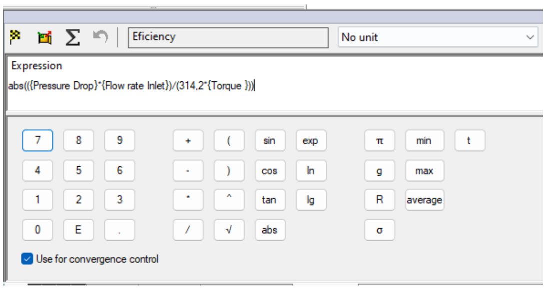


Figure 10. Centrifugal Pump Efficiency

2.7 Mesh independent test

In this study, mesh independent test was conducted to determine the optimal mesh density for use in Solidworks Flow Simulation. Each mesh density level utilized was analyzed in relation to the pressure at the outlet and subsequently evaluated for the most appropriate mesh density based solve time. The simulation was performed on a centrifugal pump with an impeller with 12 blades.

The comparison of simulation results, including outlet pressure, total cells, and solve time for each mesh density level, is presented in Fig. 11. Simulation results with varying mesh density levels exhibit differences in outlet pressure, cell count, and solve time. The simulations indicate that in Solidworks Flow Simulation, as the mesh density increases, the cell size decreases, and the total cell count increases. This phenomenon is also reflected in the problem-solving time, where the simulation duration becomes longer with an increase in mesh density. Furthermore, the outlet pressure shows a tendency to increase with higher mesh density.

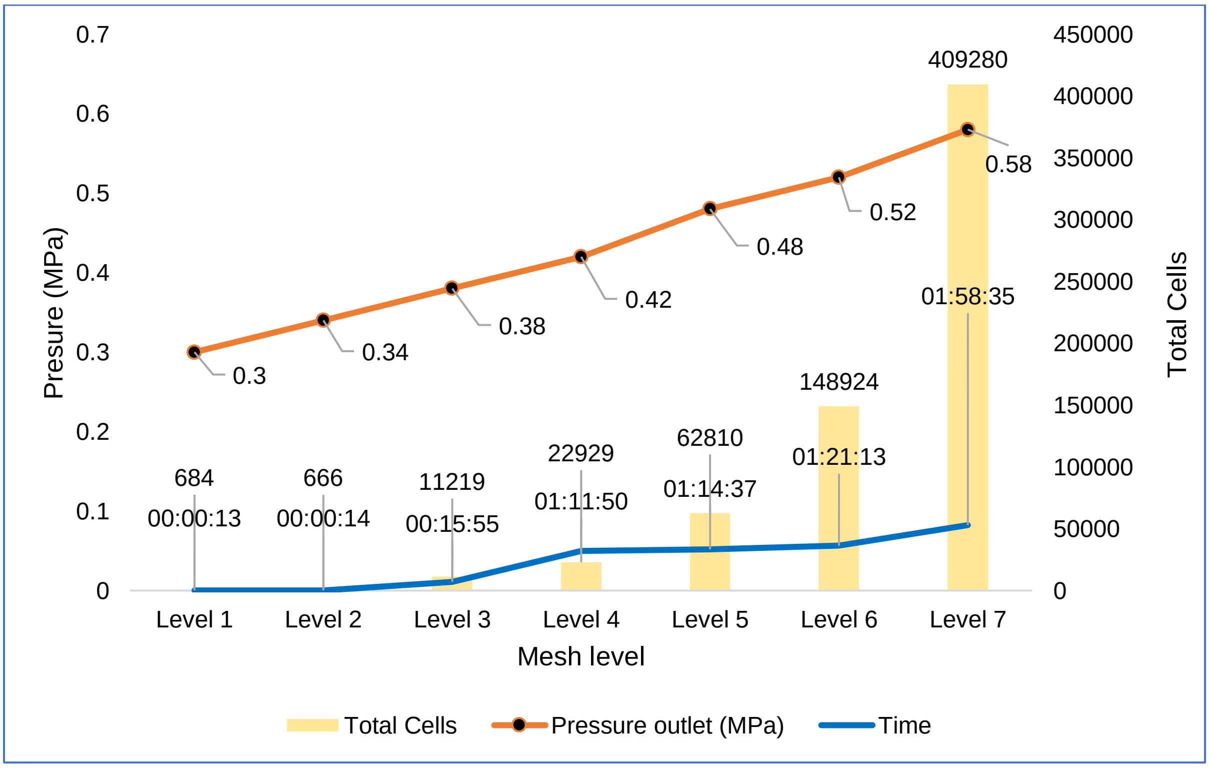


Figure 11. Total cells, outlet pressure, and solve time at each mesh level

The result of research indicated that as the mesh size decreases, the simulation results tend to approach the experimental results (Volk et al., 2018; Xie et al., 2021). Therefore, in this study, it was decided to use mesh level 7 with the consideration of achieving a balance between simulation and experimental results. Mesh level 7 consists of 409,280 cells and requires a solution time of 1 hour 58 minutes 35 seconds. The meshing representation of the centrifugal pump is displayed in Fig. 12. The inlet is located at the end of the pipe connected to the centrifugal pump, with the pipe length reaching 3525 mm.

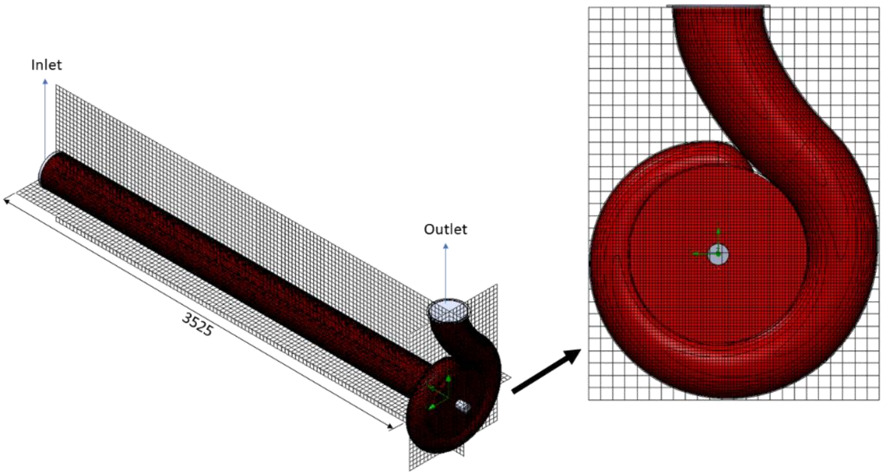


Figure 12. Mesh

3. Results and discussion

3.1 Inlet and outle pressure, and pressure drop

Comparison of pressure (MPa) at the inlet and outlet of each centrifugal pump with varying blade numbers can be found in Fig. 13. The simulation indicates that a centrifugal pump with an impeller 12 blades has the highest pressure, namely 0.46 MPa at the inlet and 0.58 MPa at the outlet. Conversely, a pump with an impeller 16 blades has the lowest pressure, namely 0.43 MPa at the inlet and 0.54 MPa at the outlet. Simulation results show a pressure difference at the inlet and outlet of the centrifugal pump used for crude oil flow, depending on the number of impeller blades.

Figure 13. Pressure at the inlet and outlet of each centrifugal pump with varying blade numbers

The pressure drop resulting from the difference in the number of blades on the impeller of the centrifugal pump used for transferring crude oil is presented in Fig. 14. Simulation results indicate that the highest pressure drop occurs in the centrifugal pump with an impeller equipped with 12 blades, while the lowest pressure drop is observed in the one with 16 blades.

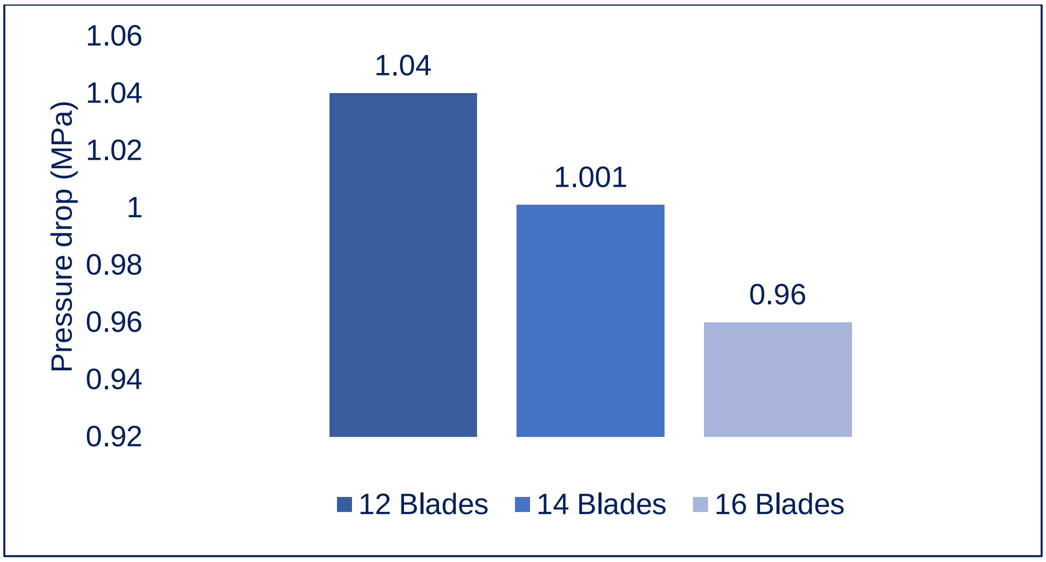


Figure 14. Pressure drop

3.2 Volume flow rate

The volume flow rate (m^3/s) at the inlet and outlet of each centrifugal pump with varying blade numbers on the impeller is presented in Fig. 15. Simulation results indicate that the highest volume flow rate occurs in the centrifugal pump with a 12-blade impeller, where the inlet volume flow rate reaches 1.35 m^3/s, and the outlet volume flow rate is 1.36 m^3/s. The lowest performance of the centrifugal pump is observed with a 16-blade impeller, with an inlet volume flow rate of 1.29 m^3/s and an outlet volume flow rate of 1.29 m^3/s. These findings also suggest that an increase in the number of blades on the centrifugal pump impeller will result in a decrease in the suction (at the inlet) and discharge (at the outlet) volume flow rates of crude oil.

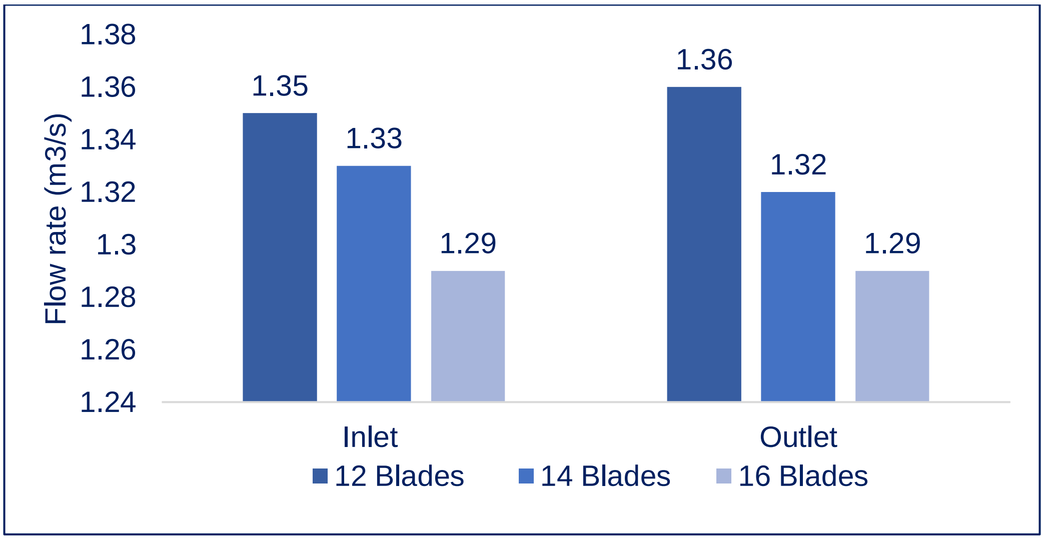


Figure 15. The volume flow rate at the inlet and outlet of each centrifugal pump with varying blade numbers

3.3 Efficiency

Analysis of the efficiency for each blade count on the impeller used in the centrifugal pump for transferring crude oil can be found in Fig. 16. Simulation results indicate that the centrifugal pump achieves the highest efficiency with an impeller featuring 12 blades, while the lowest efficiency occurs in the centrifugal pump with an impeller having 14 blades. The efficiency of the centrifugal pump with a 12-blade impeller reaches 0.17, whereas the pump with a 14-blade impeller achieves an efficiency of 0.13. Meanwhile, in the centrifugal pump with a 16-blade impeller, the efficiency reaches 0.16.

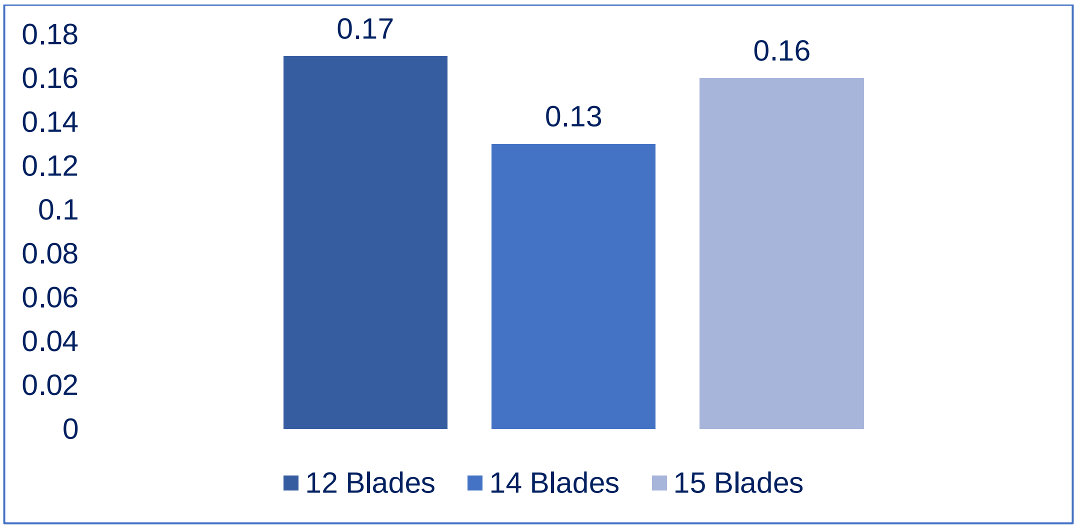


Figure 16. Efficiency of centrifugal pump with variations in the number of blades for crude oil

3.4 Discussion

Simulation of flow has been conducted on a centrifugal pump with variations in the number of blades for the transfer of crude oil. The considered blade numbers on the impeller are 12, 14, and 16. Simulation results indicate that a centrifugal pump with a 12-blade impeller achieves optimal performance in terms of pressure, volume flow rates at the inlet and outlet, as well as efficiency. Despite the 12-blade impeller being optimal for pressure, volume flow rate, and efficiency, it has a high pressure drop, indicating a weakness. An increase in the number of blades results in increased blade friction losses (profile loss) and mixing losses (Subroto & Effendy, 2019).

A detailed explanation of the changes in flow behavior resulting from the variation in the number of blades can be observed from the flow trajectories, velocity contours, and pressure distributions on the mid-span plane of the pump. As depicted in Figure 17, marked with ellipses, for the 12-blade impeller, the flow pressure is concentrated in the center of the pipe channel, while for the 14-blade and 16-blade impellers, the flow is distributed more extensively, touching the walls of the pipe channel. This phenomenon contributes to an increase in friction losses. The number of blades on the impeller influences changes in the impeller channel aspect ratio, affecting the flow mechanism and the formation of various sources of losses (Abo Elyamin et al., 2019; Sakran et al., 2022). Another factor contributing to the lower pressure and volume flow rate in impellers with more blades is recirculation, where the backflow is rotated by the impeller, leading to suboptimal trajectories directed towards the outlet channel.

In the case of the 12-blade impeller, there is an increase in the volume flow rate from the inlet, initially at 1.35, which rises to 1.36 at the outlet (see Fig. 14). In centrifugal pumps used for

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transferring water, an increase in the number of blades enhances flow direction and reduces slip (Abo Elyamin et al., 2019). However, in this study, different results were obtained, where an increase in the number of blades led to a decrease in pressure, volume flow rate at the inlet and outlet, and pump efficiency. This is influenced by the viscosity of the fluid, as crude oil has a higher viscosity than water. This is attributed to heat transfer due to friction, which can increase more significantly in crude oil compared to water, where heat transfer due to friction is not a major concern.

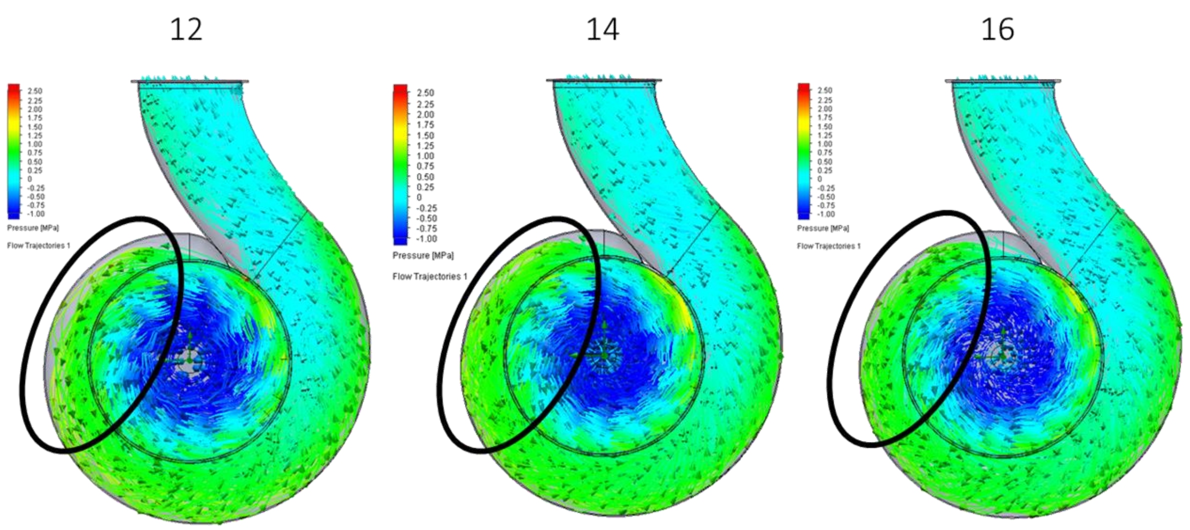

Figure 17. Flow trajectories for each centrifugal pump

In the flow pattern (See Fig. 17) and pressure distribution (See Fig. 18) near the impeller, where there is a difference in flow velocity, the centrifugal pump with a 12-blade impeller exhibits higher flow velocity around the impeller compared to the centrifugal pump with 14 blades and 16 blades. Similarly, the fluid ejected due to centrifugal force is thinner, reducing the distance traveled by the fluid towards the outlet. In contrast, for the 14-blade and 16-blade impellers, a larger diameter is observed, resulting in a greater distance traveled by the fluid towards the outlet.

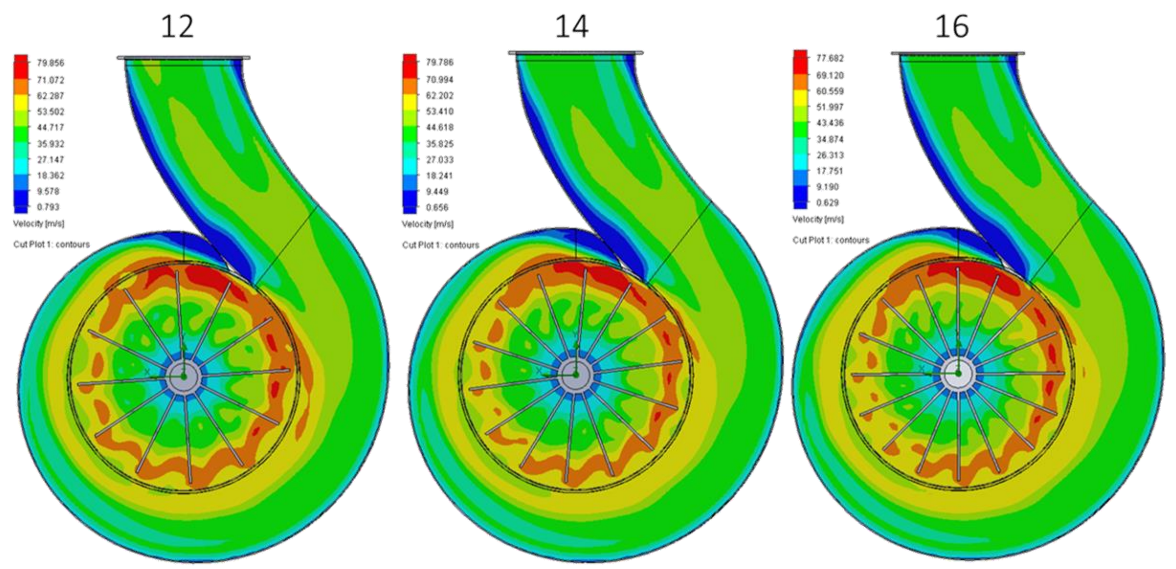

Figure 18. Velocity contours for each centrifugal pump

The drawback of the centrifugal pump with a 12-blade impeller lies in the higher pressure drop compared to impellers with 14 and 16 blades. In addition to the number of blades, another factor influencing the performance of centrifugal pumps is the blade angle (Chen et al., 2021; Ding et al., 2019; Li et al., 2020; Peng et al., 2020; Susilo & Setiawan, 2021; Y. Y. Wang et al., 2023). This study employed a blade angle of 40° on the impeller, and further research is needed to determine the optimal blade angle.

4. Conclusion

This research reveals that the optimal number of blades for the impeller in a centrifugal pump used for transferring crude oil is 12 blades. The analysis was conducted using Solidworks Flow Simulation. Three types of impellers with 12, 14, and 16 blades were simulated, with observed parameters including pressure at the inlet and outlet, volume flow rates at the inlet and outlet, pressure drop, and efficiency. Simulation results indicate that the impeller with 12 blades exhibited the most optimal performance. The analysis captured a uniformity in pressure and flow velocity around the mid-span plane of the 12-blade impeller. Through the visualization of flow trajectories on impellers with 14 and 16 blades, recirculation was observed, leading to suboptimal fluid discharge towards the outlet. Another factor contributing to the flow pattern of the 12-blade impeller is the concentrated high-flow region in the middle of the pipe channel towards the outlet, reducing fluid friction with the channel walls. In contrast, impellers with 14 and 16 blades showed flow thrown by the centrifugal force of the impeller concentrating pressure and flow velocity on the channel walls, resulting in higher frictional forces. The 12-blade impeller has a disadvantage in terms of pressure drop, and one possible contributing factor is the blade angle. Therefore, subsequent research needs to pay attention to and further examine this factor.

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Declarations

Author contribution

Muhammad Fikhri Aldio: Performed the simulation and wrote the original article; Waskito: Formulated a research concept and editing; Purwantono: Analysis and interpretation of data and Review; Remon Lapisa: Analysis and interpretation of data.

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Competing interest

This author declares that they have no competing interests.

Ethical Clerance

There are no human subjects in this manuscript and informed consent is not applicable.

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