Analysis Of Submersible Pump Performance In A Waterlogged Environment

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ABSTRACT

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| This study investigates the performance of a submersible pump in a waterlogged environment, focusing on the relationship between pressure, flow rate and angular velocity. The system, consisting of a centrifugal pump, hydraulic pipeline, and local resistances, was simulated using MATLAB/Simulink for a duration of 44 seconds. Pressure measurements was conducted using a hydraulic pressure sensor connected to both the pump and pipeline to capture data at varying angular velocities ranging from 100 rad/s to 550 rad/s. The results showed a linear increase in both pump and pipeline flow rates with increasing angular velocity. The pump pressure ranged from 6.4209e+04 Pa to 1.9228e+06 Pa, while the pipeline pressure varied from 6.4159e+04 Pa to 1.9078e+06 Pa over the same range. Flow rate measurements was also conducted using a hydraulic flow rate sensor connected to both the pump and pipeline to capture data at varying angular velocities ranging from 100 rad/s to 550 rad/s as well. The results showed a linear increase in both pump and pipeline flow rates with increasing angular velocity. The pump flow rate ranged from 0.0021 m³/s to 0.0115 m³/s, while the pipeline flow rate varied from 0.0007 m³/s to 0.0042 m³/s over the same range. The difference in both the pressure and flow rates was attributed to frictional losses and minor flow restrictions within the pipeline. These findings provide insights into the operational efficiency of submersible pumps in waterlogged environments and offer a basis for optimizing pump performance in similar hydraulic systems. |

*Keywords: submersible pump,* *pump pressure, pump flow rate, investigation, simulation, MATLAB/Simulink.*

1. INTRODUCTION

Waterlogged environments, characterized by excessive accumulation of water in the soil or surface, pose critical challenges to infrastructure, agriculture, and urban planning [1, 2]. These conditions often result from prolonged rainfall, poor drainage systems, or natural disasters, leading to flooding and damage to properties. Effective water management in such scenarios requires reliable systems to drain excess water efficiently. Submersible pumps, designed to operate fully submerged in water, have become an essential tool for mitigating the adverse effects of waterlogging by transferring water to drainage or storage systems [3, 4].

The performance of submersible pumps in waterlogged environments depends on several factors, including pump design, hydraulic pipeline configuration, and local resistances [5, 6]. A properly designed system ensures efficient water transfer, reduces energy consumption, and minimizes wear and tear on pump components. Conversely, a poorly configured system can lead to inefficiencies, pressure losses, and mechanical failures.

Hydraulic pipeline characteristics, such as length, diameter, and surface roughness, play a significant role in determining system efficiency. Longer pipelines and narrower diameters, for example, increase frictional losses, which can significantly reduce the flow rate and overall performance of the system. Additionally, local resistances, such as bends, fittings, and valves, contribute to pressure losses and must be carefully optimized to minimize their impact on the system’s efficiency.

The fluid flow regime, determined by the Reynolds number, is another critical aspect of hydraulic system design [7, 8, 9]. The transition from laminar to turbulent flow affects pressure losses and flow stability. Understanding these transitions and designing systems to operate within optimal flow regimes is crucial for maintaining system reliability and efficiency. Furthermore, submersible pump performance is heavily influenced by the angular velocity of the pump’s drive mechanism, which directly affects the flow rate and pressure head generated by the system.

Recent studies have highlighted the importance of integrating advanced modeling and simulation techniques to analyze and optimize submersible pump systems. For instance, [10] emphasized the role of fundamental ideas and principles of fluid dynamics, the basic characteristics of fluids, such as density, pressure, and viscosity, were first introduced. As the foundation of fluid dynamics, the Navier-Stokes equations was use to explain the behavior of viscous fluids with important phenomena which include boundary layers, vortices, and turbulent and laminar flows. The authors concluded by emphasizing the importance of fluid dynamics in multiple real-world applications.

 [11, 12] present a paper on fluid dynamics and its future application, and summarizes by linking the practical applications of fluid mechanics in aviation, engineering application, shipbuilding and daily life. Fluid mechanics and its engineering applications was studied in [13, 14] while [15] provide an insight into the design and operation of centrifugal pumps, and carried out analysis using a single-stage end suction centrifugal pump. The design and performance analysis were chosen base on the most useful mechanical rotodynamic machine in fluid works which are widely used in domestic, irrigation, industry, large plants and river water pumping system [16].

[17, 18] studied on design and analysis of centrifugal pump impeller for performance enhancement Centrifugal pump usage has increased over the past year due to its importance and efficiency, the design and simulation was conducted using ANSYS CFX with Navier-Stokes equation. Shear Stress Transport (SST) was chosen for turbulence model and from the simulation results, it was observed that as the rotation speed of the impeller increases, the pressure within the impeller increases, and as the pressure increases gradually from impeller inlet to impeller outlet the efficiency of the impeller was also increase as the rotation speed increases. Effect of geometrical changes of impeller on centrifugal pump performance was studied in [19, 20] while [21, 22] research on the effect of impeller blades number on the performance of a centrifugal pump.

Similarly, the impact of design parameters on the performance of centrifugal pumps was carried out in [23, 24], the area of significance to the pump design was the impeller geometric parameters which aim to achieve pump performance. The consumption of energy by the pump was discovered to be caused by the failure to choose the right pump size for the system, a design modification casing wear rings or impeller neck rings was recommended to smooth the entry of water into the eye of the impeller by reducing the gap between the casing wear ring and the impeller neck ring.

[25, 26] discussed the significance of pipeline roughness and flow regime transitions in determining system performance, while characterization of the effect of surface roughness and texture on fluid flow past, present, and future was discussed in [27, 28]. A systematic investigation of roughness height and wavelength in turbulent pipe flow in the transitionally rough regime was discussed in [29, 30] and the results obtained provide evidence that turbulent pipe flow over the present sinusoidal surfaces adheres to Townsend’s notion of outer-layer similarity, which pertains to statistics of relative motion. [31] present a paper on logarithmic scaling of turbulence in smooth- and rough-wall pipe flow while [32, 33] discussed on scaling of rough-wall turbulence by the roughness height and steepness, the results obtain shows that coupling scale provides a useful alternative to the equivalent sand grain roughness. Turbulent flow over transitionally rough surfaces with varying roughness densities was presented in [34] while the rough-wall turbulent boundary layer from the hydraulically smooth to the fully rough regime was studied in [35], and [36] discussed on roughness effects in turbulent pipe flow.

[37] explored methods for calculating pressure losses in hydraulic systems. [38] determine the pressure losses in hydraulic pipeline by calculating pressure losses within flat pipelines based on the Reynolds number, taking into consideration were viscosity and density of the fluid, internal pipe friction coefficient, pipe geometry, and oil circulation velocity. A numerical model was developed in the paper which takes into account the actual changes in density and viscosity under the current oil pressure and temperature in order to overcome the above weaknesses of standard calculation procedures. The approach was novel and provides a new capacity for an accurate pressure drop analysis of advanced hydraulic systems.

Influence of the temperature factor on the hydraulic resistance of pressure pipes was presented in [39, 40], the authors identify the nature of changes in the hydraulic friction value in relation to the temperature conditions of the transferred water temperature and environmental conditions in the designed ranges, with the subsequent possible control of the transportation process with minimum electrical energy consumption, and concluded by showing a positive effect of reducing hydraulic resistances depending on the increase in the temperature of the transported water. [41, 42] improve on modeling of laminar flows in pressure collector-pipelines.

This paper aims to investigate the performance of submersible pumps in waterlogged environments through a comprehensive analysis of hydraulic parameters, pipeline design, and operational conditions. By combining theoretical modeling with practical experimentation, this study seeks to identify key factors influencing system efficiency and provide actionable recommendations for optimizing submersible pump systems.

2. methodology

The system analysis consists of the following components: Reservoir: Configured with specific pressurization levels, fluid volumes, and return line properties. Centrifugal Pump: Defined by angular velocity, torque, and flow rate coefficients. Hydraulic Pipeline: Characterized by internal diameter, length, surface roughness, and flow regime transitions. Local Resistances: Modeled with pressure loss coefficients for both direct and reverse flow. Ideal Angular Velocity Source to provide a consistent and controllable input to the centrifugal pump.

**2.1 Flow Rate and Pressure Relationship**

The flow rate and pressure in a fluid system have a direct relationship. In general, if the pressure increases, the flow rate will also increase, assuming that all other variables such as pipe diameter and fluid viscosity remain constant. This is described by the Bernoulli's principle, which states that an increase in fluid pressure results in an increase in fluid velocity and vice versa, as long as the total energy of the fluid remains constant [43].

However, there are limits to this relationship, as increasing pressure can also lead to turbulence and other factors that may actually decrease the flow rate. Additionally, the relationship between flow rate and pressure is affected by the specific properties of the fluid being transported, as well as the design and characteristics of the piping system. Therefore, it is important to consider these variables when designing and operating fluid systems to ensure optimal performance and efficiency.

The formula for the relationship between flow rate and pressure in a fluid system is given by the Bernoulli's equation:

$P\_{1}+\frac{1}{2}ρv\_{1}^{2}+ρgh\_{1}=P\_{2}+\frac{1}{2}ρv\_{2}^{2}+ρgh\_{2}$ (1)

where:

$P\_{1}$and $P\_{2}$ are the pressures at two points in the fluid system

ρ is the density of the fluid

$V\_{1}$and $V\_{2}$ are the velocities of the fluid at the two points

g is the acceleration due to gravity

$h\_{1}$ and $h\_{2}$ are the heights of the fluid at the two points

This equation describes the conservation of energy in a fluid system, and relates the pressure, velocity, and height of the fluid at any two points along the system. From this equation, we can solve for the flow rate (Q) using the equation:

$Q = A\*v$ (2)

where A is the cross-sectional area of the pipe and v is the velocity of the fluid.

**2.2 Ideal Angular Velocity Source and Pump Relationship**

An ideal angular velocity source provides a constant and controllable rotational speed (ω) to drive the pump. It is used to simulate perfect mechanical input, independent of system dynamics like load variations, losses, or motor inefficiencies. The relationship between the angular velocity source and the pump's performance is defined by the interplay of angular velocity, torque, flow rate, and pressure.

The mechanical power provided by the ideal angular velocity source is related to torque and angular velocity and is given by:

$P\_{mechanical}=τ\*ω $ (3)

Where:

$P\_{mechanical}$ = Power supplied by the angular velocity source (in watts).

$τ$ = Torque demanded by the pump (in N\*m/pa).

$ω$ = Angular velocity supplied by the source (in rad/s).

The hydraulic power generated by the pump is expressed as:

$P\_{h}=Q\*ΔP$ (4)

Where:

 $P\_{h}$= Hydraulic power output of the pump (in watts).

$Q $= Volumetric flow rate (in m3/s).

$ΔP$ = Pressure rise across the pump (in Pascals, Pa).

The mechanical power provided by the source is converted into hydraulic power by the pump, with losses accounted for by efficiency (η):

$η=\frac{P\_{h}}{P\_{mechanical}}​​$ (5)

Rewriting $P\_{mechanical}$​ using the angular velocity source:

​$η=\frac{Q\*ΔP}{τ\*ω}$ (6)

For a centrifugal pump, the flow rate $(Q)$ and head $(H)$ are proportional to the angular velocity $(ω)$ and is given by:

$Q∝ω,H∝ω^{2}$

Where $H$ is the height, the pump can lift the fluid:

⸫ $H=\frac{ΔP}{ρg}$ (7)

Here:

$ρ$ = Fluid density $(in kg/m^{3}).$

$g$ = Gravitational acceleration $(in m/s^{2})$

3. SIMULATION TEST CASE

The framework proposed in this research work is to investigates the performance of a submersible pump system operating under waterlogged conditions. The system consists of a reservoir, a centrifugal pump, hydraulic pipelines, and local resistances, modeled to reflect real-world conditions. The investigation combines experimental and simulation approaches, as detailed below:

Reservoir: The reservoir is configured to simulate varying waterlogged scenarios, incorporating: pressurization levels which are adjusted to reflect different levels of submersion and system pressure. Fluid volumes set to represent typical operational capacities of submersible pump systems. Return line properties modeled to handle fluid backflow and maintain consistent flow dynamics.

Centrifugal Pump: The centrifugal pump is the primary component under analysis, defined by: Angular velocity to monitored and controlled assess performance under varying operational conditions. Torque to measured and evaluate the mechanical load during operation. Flow rate coefficients to analyze the relationship between pump efficiency and flow dynamics.

Hydraulic Pipeline: Hydraulic pipelines are modeled to evaluate fluid transport dynamics, characterized by: Internal diameter to determines flow capacity and velocity. Length to simulates real-world distances for fluid transport. Surface roughness to accounts for frictional losses affecting flow efficiency. Flow regime transitions to captures changes between laminar and turbulent flow regimes under varying conditions.

Local Resistances: Local resistances, such as bends and fittings, are modeled using: Pressure loss coefficients which quantifies the losses in both direct and reverse flow scenarios. Reverse flow analysis to evaluates the impact of backflow on overall system efficiency.

Ideal Angular Velocity Source: An ideal angular velocity source is implemented to provide a consistent and controllable input to the centrifugal pump. This ensures accurate analysis of the pump's performance characteristics across different scenarios. Fig 1 displays the finalized model, while Table 1 and 2 outlines the key components parameters used for the analysis.



**Fig.1. Simulation setup as represented in MATLAB’s workspace**

**Table. 1. Centrifugal Pump Parameters**

|  |  |  |
| --- | --- | --- |
| **Number**  | **Parameters**  | **Value**  |
| 1 | First approximating coefficient | 326.8 Pa/(kg/m^3) |
| 2 | Second approximating coefficient  | 3.104e+4 Pa\*s/kg |
| 3 | Third approximating coefficient  | 1.097e+7 Pa\*s^2/(kg\*m^3) |
| 4 | Fourth approximating coefficient | 2.136e+5 Pa\*s^2/(kg\*m^3) |
| 5 | Correction factor | 0.8 |
| 6 | Pump design delivery | 130 lpm |
| 7 | Reference angular velocity | 1.77e+3 rpm |
| 8 | Reference density | 920 kg/m^3 |
| 9 | Leak resistance | 1e+8 Pa/(m^3/s) |
| 10 | Drive shaft torque | 0.1 N\*m |
| 11 | Torque-pressure coefficient | 1e-6 N\*m/Pa |

**Table. 2. Hydraulic Pipeline Parameters**

|  |  |  |
| --- | --- | --- |
| **Number**  | **Parameters**  | **Value**  |
| 1 | Pipe internal diameter | 0.01 m |
| 2 | Pipe length | 50 m |
| 3 | Geometrical shape factor | 64 |
| 4 | Internal surface roughness height | 1.5e-5 m |
| 5 | Laminar flow upper margin | 2e+3 |
| 6 | Turbulent flow lower margin | 4e+3  |

From table 1, we can calculate the required fluid volume, we first need to determine the pump flow rate in cubic meters per second $(Q)$ and then calculate the fluid volume needed for the system's operational duration.

The pump design delivery is given as 130 liters per minute (lpm). Converting to cubic meters per second $(m^{3}/s):$

$Q=\frac{130}{1000}\*\frac{1}{60}=0.002167m^{3}/s$

Let’s assume the system operates continuously for t seconds. For example: at t = 60 s.

The required fluid volume will become:

$Q×t=0.002167m^{3}/s×60s=0.13m^{3}$

Applying a safety margin of 30%, the final required volume become:

$0.13m^{3}×1.3=0.169m^{3}$, so $0.169m^{3}$ fluid volume was used.

Also, we can determine the ideal angular velocity source value to matches with system analysis by aligning the pump's reference angular velocity and the system's operational parameters.

The pump's reference angular velocity is given as 1.77×103 rpm1 (revolutions per minute). Converting to radians per second (rad/s), as the standard unit for angular velocity in our analysis we have that: discussion

$ω=\frac{rpm\*2π​}{60}=\frac{1770\*2π}{60}=185.85rad/s$, the investigation was conducted using $100-1000rad/s$.

4. RESULTS AND DISCUSSION

**4.1. Pressure Variation with Velocity**

The analysis conducted on the submersible pump system involved evaluating pressure changes across both the pump and the hydraulic pipeline at varying angular velocities ranging from 100 to 550 rad/s. The results highlight the pressure response of the system components as velocity increases, which provides insight into the pump's performance and the dynamic behavior of the connected pipeline. Table 3 and 4 shows the pressure value of the pump and the hydraulic pipeline at varying angular velocities while Fig (2 – 5) present the simulated graph with Simulink and plotted graph with MATLAB.

**Table. 3. Value of the Pump Pressure at Different Velocity Level**

|  |  |  |
| --- | --- | --- |
| **Number**  | **Velocity Sources (rad/s)**  | **Value (Pa)** |
| 1 | 100 | 6.4209e+04 |
| 2 | 150 | 1.4421e+05 |
| 3 | 200 | 2.5592e+05 |
| 4 | 250 | 3.9914e+05 |
| 5 | 300 | 5.7370e+05 |
| 6 | 350 | 7.7942e+05 |
| 7 | 400 | 1.0164e+06 |
| 8 | 450 | 1.2862e+06 |
| 9 | 500 | 1.5884e+06 |
| 10 | 550 | 1.9228e+06 |

**Table. 4. Value of the Hydraulic Pipeline Pressure at Different Velocity Level**

|  |  |  |
| --- | --- | --- |
| **Number**  | **Velocity Sources (rad/s)**  | **Value (Pa)** |
| 1 | 100 | 6.4159e+04,  |
| 2 | 150 | 1.4402e+05 |
| 3 | 200 | 2.5534e+05 |
| 4 | 250 | 3.9774e+05 |
| 5 | 300 | 5.7082e+05 |
| 6 | 350 | 7.7412e+05 |
| 7 | 400 | 1.0078e+06 |
| 8 | 450 | 1.2751e+06 |
| 9 | 500 | 1.5752e+06 |
| 10 | 550 | 1.9078e+06 |



**Fig. 2. Pump pressure result against time as simulated in Simulink**

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**Fig. 3. Graph of pump pressure against velocity as plotted in MATLAB**

As seen in Fig. 2. The pump pressure increases as the angular velocity increases, from 0 to 2 second when the velocity was at 0 rad/s the pump pressure also remains at 0 Pa, but from 2 second onward, as the angular velocity increased from 100 rad/s to 550 rad/s the pump pressure also increases from 6.42 × 104 Pa to 1.92 × 106 Pa this shows that the increases in pump pressure depends in the angular velocity levels

It can be seen in Fig. 3. the angular velocity increased from 100 rad/s to 550 rad/s, the pump's pressure increased non-linearly from 6.42 × 104 Pa to 1.92×1061.92 Pa. This trend aligns with theoretical principles where the pump pressure is proportional to the square of the angular velocity.



**Fig. 4. Pipeline pressure result against time as simulated in Simulink**

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**Fig. 5. Graph of Pipeline pressure against velocity as plotted in MATLAB**

As seen in Fig. 4. Similarly, the pressure within the pipeline followed a rising trend, with values ranging from 6.42 × 104 Pa to 1.91 × 106 Pa. However, the pipeline pressure was slightly lower than the pump pressure at each velocity level, indicating pressure losses due to friction and other resistive forces within the pipeline.

It can be seen in Fig. 5. As the angular velocity increased from 100 rad/s to 550 rad/s, the pipeline pressure increased non-linearly from 6.42 × 104 Pa to 1.91 × 106 Pa. The increase in pressure drop at higher velocities aligns with the expected rise in frictional losses due to increased flow turbulence and higher flow rates.

**4.2.** **Flow Rate Variation with Angular Velocity**

The analysis was conducted at varying angular velocity levels ranging from 100 rad/s to 550 rad/s. The flow rate of both the pump and the hydraulic pipeline were measured and compared to assess system behavior under different operating conditions. Table 5 and 6 shows the pressure value of the pump and the hydraulic pipeline at varying angular velocities while Fig (2 – 5) present the simulated graph with Simulink and plotted graph with MATLAB.

**Table. 5. Value of the Pump Flow Rate at Different Velocity Level**

|  |  |  |
| --- | --- | --- |
| **Number**  | **Velocity Sources (rad/s)**  | **Value (m3/s)** |
| 1 | 100 | 0.0021  |
| 2 | 150 | 0.0031 |
| 3 | 200 | 0.0042 |
| 4 | 250 | 0.0052 |
| 5 | 300 | 0.0063 |
| 6 | 350 | 0.0073 |
| 7 | 400 | 0.0084 |
| 8 | 450 | 0.0094 |
| 9 | 500 | 0.0104 |
| 10 | 550 | 0.0115 |

**Table. 6. Value of the Pipeline Flow Rate at Different Velocity Level**

|  |  |  |
| --- | --- | --- |
| **Number**  | **Velocity Sources (rad/s)**  | **Value (m3/s)** |
| 1 | 100 | 0.0007  |
| 2 | 150 | 0.0011 |
| 3 | 200 | 0.0015 |
| 4 | 250 | 0.0019 |
| 5 | 300 | 0.0023 |
| 6 | 350 | 0.0026 |
| 7 | 400 | 0.0030 |
| 8 | 450 | 0.0034 |
| 9 | 500 | 0.0038 |
| 10 | 550 | 0.0042 |

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**Fig. 6. Pump flow rate result against time as simulated in Simulink**

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**Fig. 7. Graph of pump flow rate against velocity as plotted in MATLAB**

As seen in Fig. 6. The flow rate of the pump increased progressively with angular velocity, indicating a linear relationship between flow rate and rotational speed. It can be observed that the increase in flow rate with angular velocity is consistent with the theoretical behavior of centrifugal pumps, where flow rate is linearly proportional to the angular velocity.

It can be seen in Fig. 7. The linear behavior of the plotted graph is consistent with centrifugal pump theory, where the flow rate is directly proportional to the angular velocity of the pump impeller. As the angular velocity increases, the kinetic energy imparted to the fluid also increases, resulting in a greater volume of fluid being discharged per unit time.

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**Fig. 8. Pipeline flow rate result against time as simulated in Simulink**



**Fig. 9. Graph of pump flow rate against velocity as plotted in MATLAB**

As seen in Fig. 8. The flow rate measured in the pipeline also increased with angular velocity but remained consistently lower than the pump's flow rate. This difference between the pump and pipeline flow rates suggests energy losses due to friction and minor flow restrictions.

It can be seen in Fig. 9. The plotted graph follows a linear trend similar to the pump, the pipeline flow rate values were consistently lower. This reduction is primarily attributed to frictional losses within the pipeline and minor losses due to bends, fittings, and pipe surface roughness.

5. CONCLUSIONS

The simulation of the submersible pump system using MATLAB/Simulink provided valuable insights into its performance in a waterlogged environment. The results demonstrated a linear increase in both pump and pipeline flow rates with increasing angular velocity. Specifically, the pump flow rate increased from 0.0021 m³/s at 100 rad/s to 0.0115 m³/s at 550 rad/s, while the pipeline flow rate increased from 0.0007 m³/s to 0.0042 m³/s over the same range. Similarly, the pump pressure rose from 6.4209e+04 Pa to 1.9228e+06 Pa, while the pipeline pressure ranged from 6.4159e+04 Pa to 1.9078e+06 Pa, demonstrating a consistent pressure drop due to flow resistance.

The observed reduction in pipeline flow rate compared to the pump flow rate underscores the impact of frictional losses and minor restrictions within the hydraulic pipeline. These findings highlight the need for careful consideration of flow resistance when designing submersible pump systems. Optimizing pipeline design and minimizing resistance can enhance operational efficiency, ensuring improved performance in waterlogged environments.

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1.

2.

3.

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