Backup Water System Design for Off the Grid Housing

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Abstract *— This study designs and analyzes a backup water distribution system for off-grid housing in response to Puerto Rico's unreliable electrical grid. The system includes a ravine water source, a 600-gallon storage tank, and an energy-efficient piping and pump design. Using Computational Fluid Dynamics (CFD) in COMSOL Multiphysics, key parameters such as pressure distribution, velocity profiles, volumetric flow rate, and Reynolds number were evaluated. Results indicate maximum pressure at the inlet due to the pump and minimum pressure at the outlet from elevation changes and pipe bends. A steady velocity profile and consistent volumetric flow rate confirm system stability. The Reynolds number (1.55×10^5) indicates turbulent flow, ensuring efficient energy dissipation. The system meets performance criteria, providing efficient water transport with minimal energy consumption. Future improvements include integrating a submersible pump and further optimization to enhance system efficiency for sustainable off-grid applications.*

Key Terms *— Computational Fluid Dynamics, Off-grid water system, Pressure distribution, Turbulent flow*

INTRODUCTION

Water, a fundamental resource for life, plays a pivotal role in sustaining ecosystems and meeting the diverse needs of communities. In the face of growing global challenges such as population growth, climate change, and urbanization, the demand for reliable and efficient water distribution systems has never been more critical. This report dives into the intricate world of water distribution system design, exploring the key principles, challenges, and innovative solutions that contribute to the development of sustainable and resilient water infrastructure.

Puerto Rico's electrical system has been in decline since the economic recession began in 2006. [1] The lack of funds due to the economic recession directly affects electricity generation since the necessary maintenance cannot be given to the generation plants. In the past two decades, the government of Puerto Rico has contracted private companies to increase power generation. Solar power has been Puerto Rico's fastest-growing source of renewable generation, increasing from 0.004% of the total generation in 2011 to 1.38% in 2020.[2]

As if that were not enough, in September 2017, the impact of hurricanes Irma and Maria destroyed 80% of the distribution lines. The Government used the few resources and funds available in the restoration of the transmission system, forgetting, even more, the generation of energy. The efforts of PREPA and other private companies took 11 months to restore energy in Puerto Rico [3], from that moment on, the electrical system has fallen exponentially.

On January 7, 2020, a 6.4 magnitude earthquake damaged the island's natural gas-fired power plants (Costa Sur and EcoEléctrica), causing approximately 900,000 of Puerto Rico's 1.5 million customers to lose power [2]. Although by January 13, 99% of consumers had energy, petroleum generation had to be increased from 38% in 2019 to 60% in January 2020. It was not until July 26, 2020 (almost seven months later) that it was possible to repair Unit 5 of Costa Sur, but latent damage to all generation plants was unavoidable.[4]

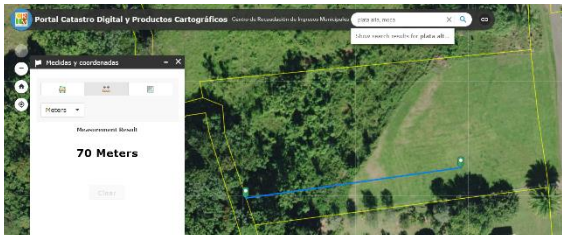
Due to the power deficiency that Puerto Ricans encounter daily other necessity such as potable water are affected. Since water distribution systems all over Puerto Rico uses pumps, which use our energy system for power, many people have moved to sustainable systems such as solar power and water tanks with pumps to survive any outage. Other people have created off-grid housing to not depend on Puerto Rico’s water or power systems. This system is created with different water resources such as rain or a body of water on the land. A piping system for a body of water using an energy efficiency pump to use the least energy possible will require sources of water, water storage, piping diagram, pipe sizing, and pump selection.

LOCATION AND DESIGN

The location and storage capacity of the water system are crucial factors in ensuring a reliable and efficient supply for off-grid housing. The selection of the water source is based on accessibility and sustainability, while the storage capacity is determined by expected water demand and system feasibility. Proper planning of these elements ensures consistent water availability and optimal system performance.

Water source and Location

Water sources depend on the resources available in the land where the system will be built. In this case, we will develop a system for taking water from a water ravine located on the land. The distance between the water ravine and the location of the water tank is determined to be 70 meters, showed in Figure 1 [1], with a height of 15.24 meters.



Meters

Measurement Result

70 Meters

Figure 1
Portal Catastro Digital Land Measurements

Water source and Location

Water storage capacity is determined by the expected water usage. For this off-grid small home backup water system, the water usage will depend on the amount of water available. We decided to use a 600-gallon tank, but more crucial than the tank's capacity is the time required to fill it. Our system is designed to fill the 600-gallon tank, shown in Figure 2, in less than 8 hours.

Figure 2
Tank Visualization

Considering the landform, height, and different lengths, a diagram was designed. To initiate the calculations 3 inches (.0762m) tube is assumed as the tube diameter. In addition to the 3 in piping used for the system and the pumps and tanks it is also used with different types of connectors. A total of 2 90^{o} and 2 45^{o} elbow connectors are part of the piping design. There are also connectors for pumps and tanks, a total of 2 additional connectors. See Figure 3 for diagram.

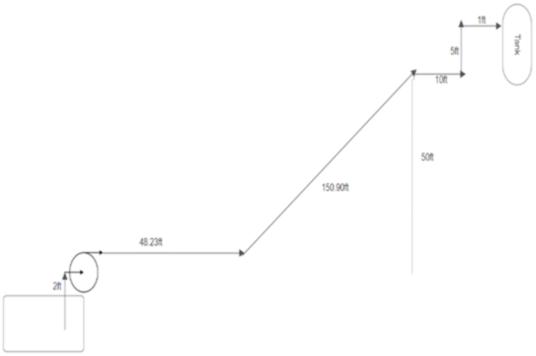


Figure 3
Piping System Diagram

METHODOLOGY AND RESULTS

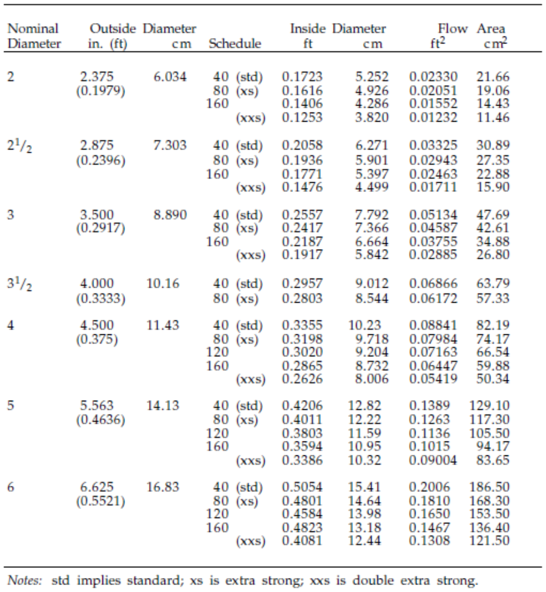
Several numerical simulations and analyses were conducted to evaluate the efficiency of the backup water distribution system, incorporating key principles from fluid dynamics and mechanical engineering. Computational Fluid Dynamics (CFD) simulations using COMSOL Multiphysics were performed to analyze parameters such as pressure distribution, velocity profiles, volumetric flow rate, and Reynolds number. The methodology involved first designing the system using traditional mechanical engineering principles, including Bernoulli’s equation and Reynolds number verification, followed by applying these techniques to simulate real-world water transport conditions.

Calculations for Pump Selection: Piping System Design

For the piping system design mathematical process, we use the book by William S. Janna. [5] The following is the suggested and used Procedure to design our piping pump system:

- Given the economic parameters associated with the system, determine the economic line size. If the cross section is noncircular and/or contains fittings, perform calculations for a straight run of circular pipe. Use the calculated economic diameter to find the optimum economic velocity. Use the economic velocity to complete the details of the system design, including the placement of hangers. Table 1 gives results of calculations of economic or reasonable velocity ranges for many fluids.

Table 1
Pipe Information



Nominal Diameter	Outside Diameter in. (ft)	Outside Diameter cm	Schedule	Inside Diameter ft	Inside Diameter cm	Flow Area ft^2	Flow Area cm^2
2	2.375 (0.1979)	6.034	40 (std)	0.1723	5.252	0.02330	21.66
			80 (xs)	0.1616	4.926	0.02051	19.06
			160	0.1406	4.286	0.01552	14.43
			(xxs)	0.1253	3.820	0.01232	11.46
$2^1/_2$	2.875 (0.2396)	7.303	40 (std)	0.2058	6.271	0.03325	30.89
			80 (xs)	0.1936	5.901	0.02943	27.35
			160	0.1771	5.397	0.02463	22.88
			(xxs)	0.1476	4.499	0.01711	15.90
3	3.500 (0.2917)	8.890	40 (std)	0.2557	7.792	0.05134	47.69
			80 (xs)	0.2417	7.366	0.04587	42.61
			160	0.2187	6.664	0.03755	34.88
			(xxs)	0.1917	5.842	0.02885	26.80
$3^1/_2$	4.000 (0.3333)	10.16	40 (std)	0.2957	9.012	0.06866	63.79
			80 (xs)	0.2803	8.544	0.06172	57.33
4	4.500 (0.375)	11.43	40 (std)	0.3355	10.23	0.08841	82.19
			80 (xs)	0.3198	9.718	0.07984	74.17
			120	0.3020	9.204	0.07163	66.54
			160	0.2865	8.732	0.06447	59.88
			(xxs)	0.2626	8.006	0.05419	50.34
5	5.563 (0.4636)	14.13	40 (std)	0.4206	12.82	0.1389	129.10
			80 (xs)	0.4011	12.22	0.1263	117.30
			120	0.3803	11.59	0.1136	105.50
			160	0.3594	10.95	0.1015	94.17
			(xxs)	0.3386	10.32	0.09004	83.65
6	6.625 (0.5521)	16.83	40 (std)	0.5054	15.41	0.2006	186.50
			80 (xs)	0.4801	14.64	0.1810	168.30
			120	0.4584	13.98	0.1650	153.50
			160	0.4823	13.18	0.1467	136.40
			(xxs)	0.4081	12.44	0.1308	121.50

Notes: std implies standard; xs is extra strong; xxs is double extra strong.

- Calculate the pump power required for the system using the optimum economic line size. Check to ensure that the pressure drop is not excessive, which leads to objectionable vibrations. Prepare a system curve of ΔH versus Q. Refer to Table 2.

Table 2
Fluid Economic Velocity Range

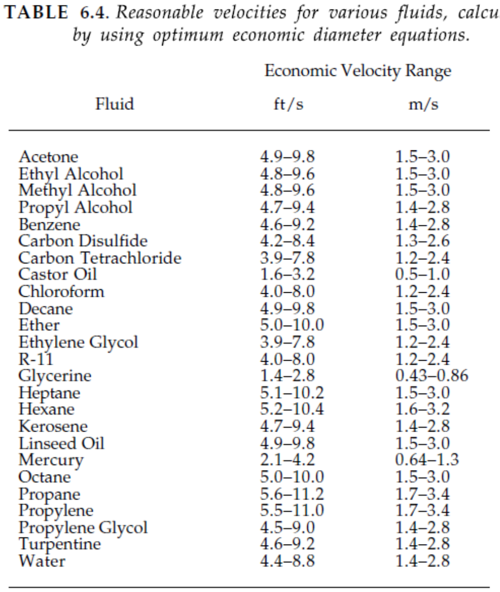


TABLE 6.4. *Reasonable velocities for various fluids, calculated by using optimum economic diameter equations.*

Fluid	Economic Velocity Range ft/s	Economic Velocity Range m/s
Acetone	4.9–9.8	1.5–3.0
Ethyl Alcohol	4.8–9.6	1.5–3.0
Methyl Alcohol	4.8–9.6	1.5–3.0
Propyl Alcohol	4.7–9.4	1.4–2.8
Benzene	4.6–9.2	1.4–2.8
Carbon Disulfide	4.2–8.4	1.3–2.6
Carbon Tetrachloride	3.9–7.8	1.2–2.4
Castor Oil	1.6–3.2	0.5–1.0
Chloroform	4.0–8.0	1.2–2.4
Decane	4.9–9.8	1.5–3.0
Ether	5.0–10.0	1.5–3.0
Ethylene Glycol	3.9–7.8	1.2–2.4
R-11	4.0–8.0	1.2–2.4
Glycerine	1.4–2.8	0.43–0.86
Heptane	5.1–10.2	1.5–3.0
Hexane	5.2–10.4	1.6–3.2
Kerosene	4.7–9.4	1.4–2.8
Linseed Oil	4.9–9.8	1.5–3.0
Mercury	2.1–4.2	0.64–1.3
Octane	5.0–10.0	1.5–3.0
Propane	5.6–11.2	1.7–3.4
Propylene	5.5–11.0	1.7–3.4
Propylene Glycol	4.5–9.0	1.4–2.8
Turpentine	4.6–9.2	1.4–2.8
Water	4.4–8.8	1.4–2.8

- In systems where the exit is lower (physically) than the inlet and where friction plus minor losses are small, the pressure at the exit might be calculated to be greater than that at the inlet for the specified flow rate. This means the fluid will flow under the action of gravity and a pump may not be needed. Further, it might be impossible to satisfy optimum velocity conditions as well. However, if a pump is to be used, determine from the appropriate chart which pump should be selected. Refer to the pump performance map if available and superimpose the system curve on it to find the exact operating point. Use NPSH data to specify the exact location of the pump.
- If tanks are present, specify the minimum and maximum liquid heights in them.
- Prepare a drawing for the system and a summary of specifications sheet that lists results of calculations only. Attach the calculations to the summary sheet.

Following the steps above, calculations were made:

1. **Step 1**. Economic Line Size: The fluid to evaluate in this paper is water therefore looking at Table 2 the economic velocity range for water will be.

$$1.4\frac{m}{s} \leq V_{opt} \geq 2.8\frac{m}{s} \tag{1}$$

For the volume flow rate of a 600-gallon tank to be filled up in a matter of less than 3 hours, we determine a minimal volume flow rate of

$$Q = 7.2\frac{m^3}{h} \tag{2}$$

To determine the pipe size, we will make calculations for both limits, upper and lower.

$$A_{upper} = \frac{Q}{V} = \frac{2.10*10^{-4}}{1.4} = 1.5 * 10^{-4}m^2 \tag{3}$$

$$A_{lower} = \frac{Q}{V} = \frac{2.10*10^{-4}}{2.8} = 2.75 * 10^{-5}m^2 \tag{4}$$

Since in our Flow Area results, we have a very low area to compare to the table in the book the smallest Nominal diameter was chosen to continue with the needed calculations. This pipe size corresponds to the economical pipe size which refers to the optimal diameter of the pipe that balances cost and performance requirements. This pipe size may be changed during this analysis to an optimal pipe size due to pump selection, this change may increase cost. Even though the purpose of this study is to design a cost efficiency pipeline to satisfy the water need in case of emergency, the need for water in the determined time frame will be considered more important. The following pipe size will be used in the start of this calculation:

- Nominal Diameter = 1/8
- Outside Diameter = 1.029 cm
- Schedule = 40(std)
- Inside Diameter = .683 cm =.00683 m
- Flow Area = .366 cm2

2. **Step 2.** Pump Power: To calculate the power of the pump we will need the properties of the fluid and pipe material.

Fluid: Water

$$\rho = 1000\frac{kg}{m^3}$$
$$\mu = .001Pa * s$$

Pipe: PVC

Since PVC is smooth the roughness will be determined to be

$$\varepsilon = 0$$

The modified Bernoulli equation with pump power:

$$\frac{P_1 g_c}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2 g_c}{\rho g} + \frac{V_2^2}{2g} + z_2 + \sum\frac{fL}{D_h}\frac{V^2}{2g} + \sum\frac{V^2}{2g} + \frac{g_c}{mg}\frac{dW}{dt} \tag{5}$$

We define pressure and Velocity. Since pressure at the inlet and at the outlet will be atmospheric and the velocity at inlet of the pump and outlet of the pipe will be define as zero the:

$$P_1 = P_2 = 101.325\,Pa \tag{6}$$

$$V_1 = V_2 = 0 \tag{7}$$

The velocity of the pipe will be defined as

$$V = \frac{2.10*10^{-4}m}{.00366s} = .0573\frac{m}{s} \tag{8}$$

System Height

$$z = 15.24m + 1.52m = 16.76m \tag{9}$$

Pipe Length

$$L = 41.81m + 3.5m + 1.52m + .305m = 47.135m \tag{10}$$

Losses

$$\sum K = K_{in} + K_{90} + K_{45} + K_{exit} = 0.5 + 2(1.4) + 2(.35) + 1.0 = 5.0 \tag{11}$$

Reynolds Number

$$Re = \frac{\rho VD}{\mu g_c} = \frac{1000*.0573*.00683}{.001}\frac{\frac{kg}{m^3}*\frac{m}{s}*m}{\frac{kg}{m*s^2}*s} = 391.359 \tag{12}$$

Therefore

$$f = \frac{64}{Re} = \frac{64}{391.359} = .1635 \tag{13}$$

Simplify Bernoulli equation

$$z_1 = z_2 + \frac{fL}{D_h}\frac{V^2}{2g} + \sum K\frac{V^2}{2g} + \frac{g_c}{mg}\frac{dW}{dt} \tag{14}$$

Pump Power

$$-\frac{g_c}{mg}\frac{dW}{dt} = \Delta H \tag{15}$$

Modify Bernoulli

$$\Delta H = z_2 - z_1 + \left(\frac{fL}{D_h} + \sum K\right)\frac{V^2}{2g} = 16.76m - 0m + \left(\frac{.1635 * 47.135m}{.00683m} + 5.0\right)\frac{.0573^2\left(\frac{m}{s}\right)^2}{2 * 9.81\frac{m}{s^2}} = 35.04m \tag{16}$$

Power for the pump will be

$$\frac{dW}{dt} = \frac{\rho Q g \Delta H}{g_c} = 1000\frac{kg}{m^3} * 2.10 * 10^{-3}\frac{m^3}{s} * 35.04m = .6378watts \tag{17}$$

CFD (COMPUTATION FLUID DYNAMICS) ANALYSIS DEFINITIONS

In the deciding process of software to use to develop the CFD analysis we encounter a few problems using Ansys therefore we opt for COMSOL Multiphysics as the preferred computational fluid dynamics (CFD) software. COMSOL is a user-friendly interface and superior versatility in Multiphysics simulations. While Ansys is a powerful tool, COMSOL's emphasis on Multiphysics simulations and user accessibility aligns more closely with my specific needs for intricate fluid dynamics studies, making it the preferred choice for my simulation work. Its extensive range of pre-built modules and customization options provides flexibility in modeling various fluid dynamics scenarios and can be an opportunity to use modules for specific piping in the future.

Cad Development

The first step analyzing our conclusion was the pipe modeling process was to define our ping design define by the land. Refer to Figure 1 and 3 for details. Our design consists of 70 meters in distance from the inlet and outlet and a height of 16.76 meters of height shown in Table 3.

The 2D COMSOL modeling was used to define all sections with their specific distance and height from inlet to outlet. Figure 4 shows the 2D COMSOL schematic for the analysis.

Table 3

Pipe Measurements

x (m)	y (m)
0	0
14.7	0
41.81	15.24
46.83	15.24
46.83	16.76
47.135	16.76

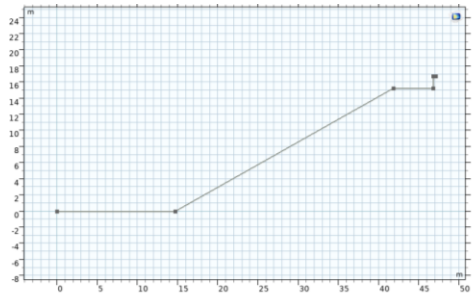


Figure 4
2D Piping System Cad Design

Pump Inlet Definition

Inlet specification where define by our calculations results a pump with a 35 m of head is needed for our piping design. Define inlet shown in Figure 5.

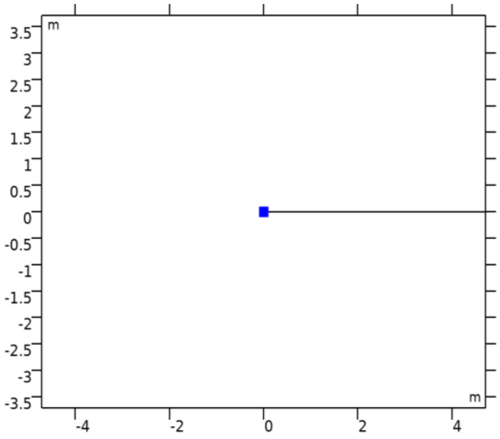


Figure 5
Inlet Reference from Cad

The analysis was started by a head of 35m and by different iterations and run table 4 will correspond to the pump minimal requirements in result of the iterations.

Table 4
Pump Selected Specifications

Flow Rate (m3/h)	Head (m)
7.2	25

Pressure Analysis

In a CFD contour diagram, maximum pressure typically occurs at points of flow constriction, like near a pump or narrowing in the pipe, where energy is added to the fluid. In this case we see that the highest pressure is at the inlet where our pump is defined. On the other hand, minimum pressure is often found at locations where there are losses, such as bends. In our case the minimal pressure in the system is located at the outlet. This occurs due to height and losses due to bending.

The image below shows a maximum pressure value (346051 Pa) and the minimum pressure value (101325 Pa) are highlighted at specific points on the line. On the right side of the graph, there is a color bar serving as a legend to interpret the pressure gradient, shown in Figure 6.

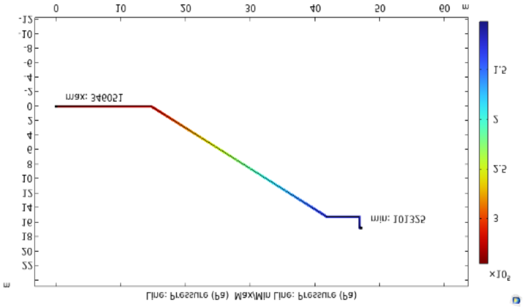


Figure 6
Maximum and Minimal Pressure Contour Diagram

The graph reveals three main regions: an initial section with constant pressure (red zone), a linear increase in pressure (multicolor gradient), and a final section where the pressure drops abruptly to its minimum (blue zone). This could correspond to a physical system analysis, such as fluid flow in a conduit, atmospheric modeling, or a simulation in fluid mechanics. The highlighted points allow for the identification of the system's extreme conditions and their locations.

Velocity

In a CFD contour diagram, maximum velocity mostly appears at points where the fluid is constricted, such as in a nozzle. In our analysis this is shown at the first section of the pipe which is a result of the inlet pump. On the other side, minimal velocity is observed in areas of solid boundaries where flow slows down. In our analysis this minimal velocity is shown in the exit of the pipe system due to height, and vertical sections in the pipe system.

Figure 7 shows the graph highlights the maximum velocity of 3.08946 m/s and the minimum velocity of 1.54473 m/s at specific points along the line. The velocity profile is smooth and continuous, transitioning gradually between the maximum and minimum values. The color bar on the right provides a visual reference for interpreting the velocity changes across the system.

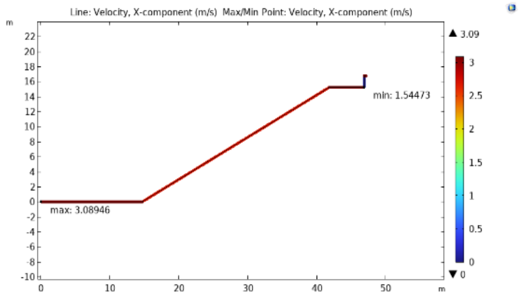


Figure 7
Maximum and Minimal Velocity Contour Diagram

Flowrate

In a piping system, the volumetric flow rate can remain constant even if velocity and pressure change due to the principle of conservation of mass, often described by the continuity equation. Therefore, if the velocity increases in a section of pipe, it coincides with a decrease in cross-sectional area, ensuring that the flow rate remains constant. Pressure variations may arise from factors like friction or elevation changes not altering the steady-state flow rate. Therefore, while local conditions fluctuate, the total volumetric flow rate can stay unchanged, which is what is observed in Figure 8.

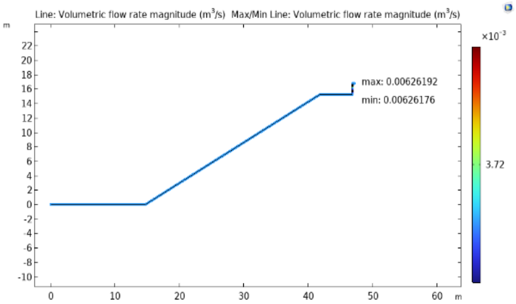


Figure 8

Maximum and Minimal Volumetric Flowrate Contour Diagram

The curve exhibits three distinct regions: a flat initial segment, a steady incline, and a plateau toward the end. In the first segment (0 to ~20 m), the flow rate remains constant, indicating no significant variation in the volumetric flow. The middle region (20 to ~45 m) shows a linear increase in flow rate, suggesting a uniform rise in flow magnitude, potentially due to increasing pressure or flow acceleration in this range. Beyond 45 m, the flow stabilizes at a maximum value of approximately 0.00626192 m3/s.

Reynolds

In a piping system, the Reynolds number (Re) can remain constant even if velocity and pressure change due to the relationship between these variables and the properties of the fluid. Therefore, in our analysis a Reynolds of $1.55x10^5$ is constat throughout the system. Generally, a Reynolds number greater than 4000 is considered turbulent, while values below 2000 are typically laminar. A Reynolds number of $1.55x10^5$ indicates a flow regime that is likely turbulent, shown in Figure 9.

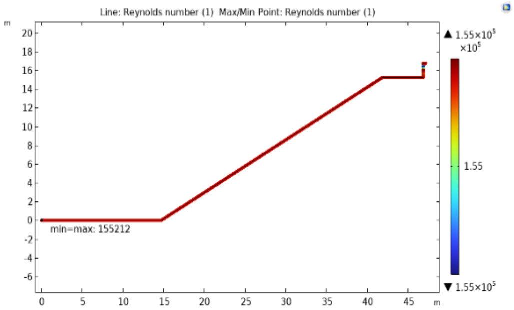


Figure 9

Maximum and Minimal Volumetric Flowrate Contour Diagram

Result Analysis

In Figure 6 it is shown that the maximum pressure value (346051 Pa) and the minimum pressure value (101325 Pa) are highlighted at specific points on the line. Beyond 45 m, the flow stabilizes at a maximum value of approximately 0.00626192 m3/s flowrate shown in Figure 8. The minimal variation shown in Figure 8 between the max and min values highlights a nearly uniform flow pattern, with only slight changes across the observed range. The plot effectively demonstrates the flow's behavior along the spatial axis and emphasizes the peak stability toward the end.

The consistent velocity gradient in figure 7 suggests that the system maintains a steady flow along the analyzed path, with no evidence of stagnation or sudden disruptions. The non-zero velocity values at every point indicate that water is moving continuously, a key requirement for the system's functionality. Additionally, the moderate range of velocity values implies that the flow remains stable, with no extreme variations that might suggest inefficiencies or blockages. These factors collectively indicate that the system operates smoothly in terms of fluid dynamics. The velocity demonstrates that water flows throughout the system without interruptions or flow reversal, meeting the primary objective. Thus, based on the data provided, the system can be considered effective for transporting water as intended.

CONCLUSIONS

The evaluation of pump specifications and simulation results in COMSOL confirms the selected pump specifications will efficiently fill the 600-gallon tank within the required time. COMSOL Multiphysics significantly enhanced the analysis of the thermal dynamics in the piping system, enabling optimization of the design and confirmation of system performance. The minimum required pump head is 25 meters with a volumetric flow rate of 0.002 m³/hr, meeting the project's objectives for timely tank filling.

Key parameters, including pressure, velocity, and flow rate, validate the system's effectiveness. The pressure distribution follows fluid dynamics principles, showing maximum pressure at the pump inlet and a gradual decline due to height differences and bending losses. The smooth gradient reflects efficient energy transfer, ensuring stable operation.

The velocity profile demonstrates steady fluid transport with no stagnation or turbulence. Maximum velocity occurs near the pump, tapering off smoothly along the pipeline. Consistent flow rates confirm efficient operation and adherence to mass conservation principles. The turbulent flow regime, characterized by a Reynolds number of 1.55×10^5, ensures stable and reliable performance under operational conditions.

This analysis confirms the system is well-designed, efficient, and reliable for its intended application. The findings validate the use of the selected pump specifications and provide a strong foundation for future development. The system also supports the broader objective of sustainable housing design, offering a scalable and robust solution for similar applications.

FUTURE RECOMMENDATIONS

Based on the calculations and COMSOL analysis findings, we propose considering a submersible pump for subsequent evaluations and evaluating adding more pumps to the system.

After reviewing various pump options, we recommend using a submersible pump due to the specific conditions of the water source, which is a ravine with significant depths. The choice between a submersible and a surface pump depends on the water system's requirements and installation characteristics. Below are the advantages of a submersible pump:

- **Design and Operation**: Submersible pumps are engineered to be submerged in the fluid they pump, operating efficiently below the water level. In contrast, surface pumps are installed above the water level and require priming, which can lead to complications such as air pockets.
- **Efficiency**: Submersible pumps typically offer greater efficiency because they are directly immersed in the fluid, minimizing friction losses associated with pumping water over long distances. Surface pumps may incur higher energy losses due to the vertical lift required.
- **Space and Aesthetics**: Submersible pumps are often more compact and can be installed directly in the water source, conserving space and reducing visibility. In contrast, surface pumps require additional structures, such as a pump house, requiring more installation space.

For these reasons, we recommend proceeding with a submersible pump for further in-depth system analysis.

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