Backup Water System Design for Off the Grid Housing

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Abstract

This study presents the design and analysis of a backup water distribution system for off-grid housing, addressing Puerto Rico's unreliable electrical grid. The system utilizes a nearby ravine as a water source, a 600-gallon storage tank, and an energy-efficient piping and pump design. Computational Fluid Dynamics (CFD) simulations in COMSOL Multiphysics evaluated pressure distribution, velocity profiles, volumetric flow rate, and Reynolds number to ensure efficiency. The results confirm a smooth and steady flow, a turbulent regime (Re = 1.55×10^5), and effective water transport with minimal energy consumption. Future improvements include using a submersible pump and further optimizing system performance for sustainable off-grid water infrastructure.

Key Terms - Computational Fluid Dynamics, off-grid water system, pressure distribution, turbulent flow

Introduction

Water is a vital resource for ecosystems and communities, the growing challenges of climate change, urbanization, and population growth have made reliable distribution systems more critical than ever. This report examines water distribution system design, highlighting key principles, challenges, and innovative solutions for sustainable infrastructure. Puerto Rico's electrical system has been in decline since the 2006 recession, with limited funds preventing necessary maintenance. [1] The government has relied on private companies to boost power generation, with solar power increasing from 0.004% in 2011 to 1.38% in 2020. [2] Natural disasters have worsened the crisis—hurricanes Irma and Maria in 2017 destroyed 80% of the distribution lines, leading to an 11-month recovery period. [3] A 6.4 magnitude earthquake in 2020 further damaged power plants, cutting electricity for 900,000 customers. [2] Petroleum reliance increased from 38% to 60%, and power plant damages had long-term effects. [4] Power instability has directly affected potable water access, as water distribution relies on energy-powered pumps. Many Puerto Ricans have turned to solar energy, water tanks, or off-grid systems utilizing rainwater or nearby water sources, requiring efficient pump and piping solutions.

Background

Water distribution systems are essential for ensuring access to potable water and supporting communities worldwide. However, efficient distribution depends on a stable power supply. Puerto Rico's electrical system has been deteriorating since the 2006 economic recession, with financial struggles limiting necessary maintenance. [1] To address this, private companies have been contracted to support power generation, particularly in renewable energy sources like solar. [2] Despite these efforts, Puerto Rico's energy grid has been severely impacted by natural disasters. Hurricanes Irma and Maria in 2017 destroyed much of the infrastructure, delaying power restoration for nearly a year. [3] In 2020, a major earthquake caused further damage, increasing dependence on petroleum for power generation. [2] These events have weakened the overall power system, making electricity access unreliable for residents.

Problem

The instability of Puerto Rico's electrical system has created a significant challenge for water distribution. Since most systems rely on energy-powered pumps, frequent outages have disrupted access to potable water. This has led many residents to seek alternative solutions, such as solar-powered pumps, water tanks, and off-grid water collection methods. However, implementing these systems requires careful planning, including water sourcing, storage, piping, and energy-efficient pump selection. Addressing this issue is critical to ensuring sustainable and reliable access to water for Puerto Rico's residents.

Methodology

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.

Results and Discussion

The piping system design follows the methodology from William S. Janna [5], ensuring a balance between cost efficiency and system performance. The process begins with determining the economic line size using the velocity range for water:

$$1.4\frac{m}{s} \leq V_{opt} \geq 2.8\frac{m}{s} \qquad (1)$$

For a 600-gallon tank to be filled in under three hours, the minimum volume flow rate is:

$$Q = 7.2\frac{m^3}{h} \qquad (2)$$

The required flow area for upper and lower limits is calculated as:

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

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

The smallest nominal diameter was selected:
- Nominal Diameter = 1/8 inch
- Inside Diameter = 0.00683 m
- Flow Area = 0.366 cm²

For pump power calculations, the system height and pipe length were determined as:

$$z = 15.24m + 1.52m = 16.76m \qquad (5)$$

$$L = 41.81m + 3.5m + 1.52m + .305m = 47.135m \quad (6)$$

Total head loss was calculated, considering minor losses:

$$\sum K = K_{in} + K_{90} + K_{45} + K_{exit} = 0.5 + 2(1.4) + 2(.35) + 1.0 = 5.0 \quad (7)$$

The Reynolds number was computed as:

$$Re = \frac{\rho V D}{\mu g_c} = \frac{1000 * .0573 * .00683}{.001} \frac{\frac{kg}{m^3} * \frac{m}{s} * m}{\frac{kg}{m * s^2} * s} = 391.359 \quad (8)$$

From this, the friction factor was determined:

$$f = \frac{64}{Re} = \frac{64}{391.359} = .1635 \qquad (9)$$

Applying the modified Bernoulli equation:

$$\Delta H = z_2 - z_1 + \left(\frac{fL}{D_h} + \sum K\right)\frac{V^2}{2g}$$

$$= 16.76m - 0m + \left(\frac{.1635 * 47.135m}{.00683m} + 5.0\right)\frac{.0573^2 \left(\frac{m}{s}\right)^2}{2 * 9.81\frac{m}{s^2}}$$

$$= 35.04m \qquad (10)$$

Finally, pump power was calculated as:

$$\frac{dW}{dt} = \frac{\rho Q g \Delta H}{g_c} = 1000\frac{kg}{m^3} * 2.10 * 10^{-3}\frac{m^3}{s} * 9.81\frac{m}{s^2} * 35.04m$$

$$= 721.86\, watts \cong 1HP \qquad (11)$$

This ensures an efficient pump selection to maintain water flow during emergencies.

CFD Software Selection

During the selection process for CFD software, challenges were encountered with Ansys, leading to the choice of COMSOL Multiphysics. COMSOL was preferred due to its user-friendly interface, versatility in Multiphysics simulations, and its flexibility in modeling complex fluid dynamics scenarios. Future applications may include specific piping modules for enhanced analysis.

The piping system was modeled based on land-defined specifications. The system extends 70 meters from inlet to outlet with a height of 16.76 meters. A 2D COMSOL model was developed to define sections with respective distances and elevations. The inlet specifications were defined based on calculations, determining that a pump with a 35m head was required. Iterative simulations yielded the following minimal pump requirements:

Table 1: Pump Selected Specifications

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

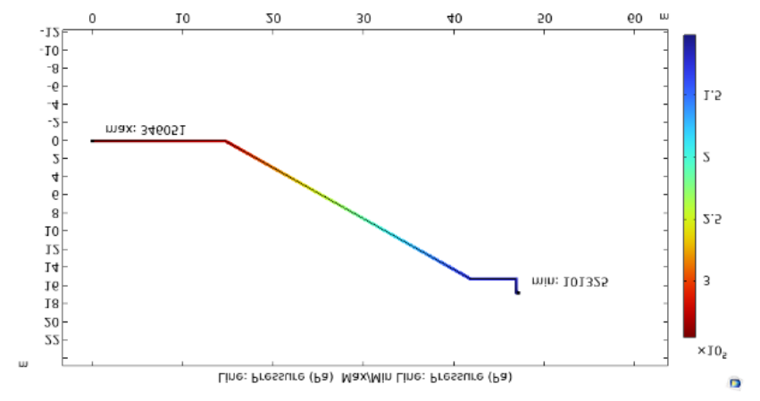

Figure 1
Maximum and Minimal Pressure Contour Diagram

The CFD contour diagram reveals that maximum pressure (346051 Pa) occurs at the inlet where the pump is located, while minimum pressure (101325 Pa) is at the outlet due to elevation and flow resistance. The graph shows three regions: constant initial pressure, a gradual increase, and a steep drop at the outlet, providing insight into system flow behavior.

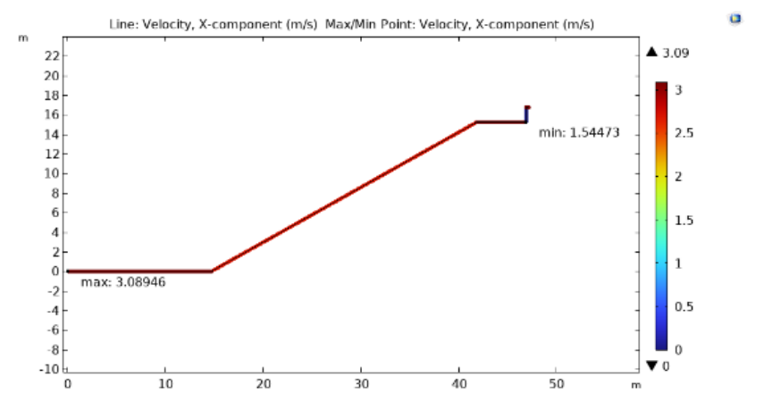

Figure 2
Maximum and Minimal Velocity Contour Diagram

In the velocity contour, maximum velocity (3.08946 m/s) is observed at the pipe's inlet due to the pump, while minimum velocity (1.54473 m/s) appears at the pipe's outlet, impacted by elevation and system constraints. The velocity profile is smooth, transitioning continuously between max and min values.

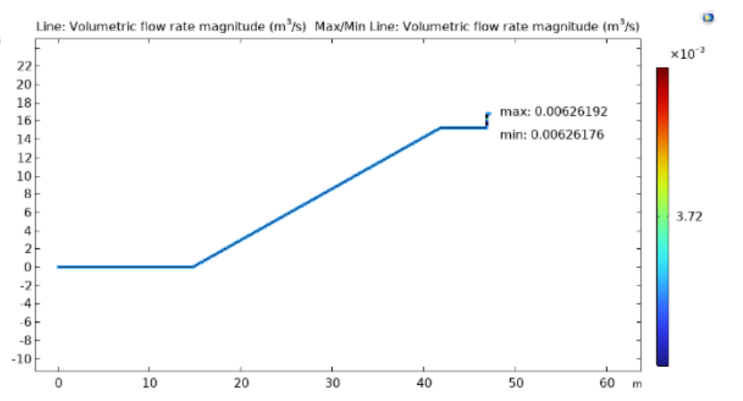

Figure 3
Maximum and Minimal Volumetric Flowrate Contour Diagram

The system maintains a steady volumetric flow rate due to the continuity equation, despite local pressure and velocity changes. The curve indicates three stages: a steady initial flow, a linear increase due to flow acceleration, and a plateau at 0.00626192 m³/s, confirming the flow stability.

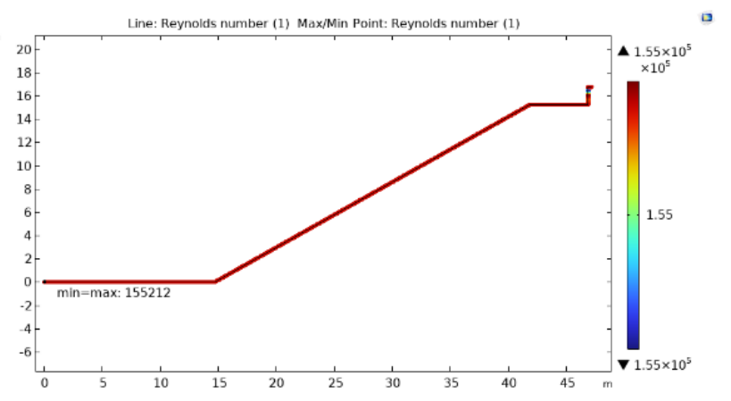

Figure 4
Reynolds Number Contour Diagram

The Reynolds number remains 1.55 × 10^5 throughout the system, classifying the flow as turbulent (Re > 4000). This analysis confirms that the system operates in a high-energy flow regime, where turbulence effects must be considered in further optimizations.

The analysis shows a maximum pressure of 346051 Pa and a minimum pressure of 101325 Pa, with flow stabilizing at 0.00626192 m³/s beyond 45 meters, indicating a nearly uniform flow pattern. Figure 2 confirms a consistent velocity gradient, ensuring steady flow without stagnation or disruptions. The continuous movement of water at all points supports system functionality, with moderate velocity variations suggesting no inefficiencies or blockages. The velocity data indicates smooth fluid transport, with no interruptions or flow reversals. Overall, the system is effective in ensuring reliable water distribution 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/s, 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 Work

The analysis and calculations suggest evaluating the use of a submersible pump and considering additional pumps for system optimization. Given the ravine's depth, a submersible pump is recommended over a surface pump due to its efficient operation below water level and elimination of priming issues. Submersible pumps provide higher efficiency by reducing friction losses and minimizing energy consumption compared to surface pumps, which require vertical lift. Additionally, they offer space-saving advantages, as they are installed directly in the water source without the need for external structures. Based on these benefits, a submersible pump is the preferred choice for further system analysis.

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