INTERNATIONAL JOURNAL OF SCIENTIFIC RESEARCHERS
ISSN: 3030-332X Impact factor: 8,293 **Volume 9, issue 1, December 2024**
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ENHANCING THE EFFICIENCY OF HYDROELECTRIC TURBINES: A COMPARATIVE ANALYTICAL APPROACH

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Abstract: Hydroelectric power is one of the most sustainable and widely adopted renewable energy sources. The efficiency of turbines, which are central to energy conversion in hydroelectric plants, significantly influences the overall energy output. This study investigates the key factors affecting turbine performance, such as water flow, pressure head, temperature, and turbine design. Using fundamental hydroelectric energy equations, we analyze and compare the performance of three common turbine types: Francis, Pelton, and Kaplan. Our findings indicate that Pelton turbines exhibit the highest energy efficiency, followed by Kaplan turbines, with Francis turbines displaying the lowest energy output under the specified conditions. Moreover, the study highlights the impact of water temperature on turbine performance, demonstrating that temperature variations lead to efficiency losses. These insights are vital for optimizing turbine selection and operational strategies in hydroelectric plants, thereby maximizing energy production.

Key words: Hydroelectric power, turbine efficiency, pelton turbine, francis turbine, kaplan turbine, energy conversion, water temperature, hydrological conditions.

Introduction

Hydroelectric power generation depends on turbines to convert the potential energy of water into mechanical energy. The efficiency of turbines plays a pivotal role in determining the amount of energy produced by a hydroelectric plant. Several factors, including water flow, pressure head (height), and water properties, influence turbine performance. Different turbine types—Francis, Pelton, and Kaplan—are utilized depending on the specific conditions at a given hydroelectric site, such as flow rate and head height. While Pelton turbines are generally preferred in high-head, low-flow systems, Kaplan and Francis turbines are suited for medium to low-head, high-flow conditions[1]. This paper aims to evaluate the efficiency of these turbine types through real-world parameters and theoretical models, ultimately determining the optimal turbine selection for varying hydrological conditions.

Methodology.

The energy production of turbines in hydroelectric plants is influenced by a combination of factors, including water flow rate, water height (head), turbine efficiency, and water temperature. In this study, we compare the performance of three turbine types—Francis, Pelton, and Kaplan—using the following methodologies:

Potential energy (hydropower energy).

The potential energy stored in water is determined by its height above a reference point. This energy can be converted into mechanical and electrical energy by the turbine, depending on various system characteristics. The formula for calculating potential energy[2,3] is:

$$E_{pot}=\rho\cdot g\cdot h\cdot Q$$

Where:

- E_{pot} is the potential energy in Joules (J)
- ρ is the density of water (1000 kg/m³)
- g is the gravitational acceleration (9.81 m/s²)
- h is the water head (m)
- Q is the flow rate (m³/s)

This formula calculates the theoretical energy available for conversion to mechanical energy, assuming no losses.

Effective energy (efficiency consideration)

Due to inherent inefficiencies in turbines, the actual energy output is less than the potential energy. The effective energy produced is calculated by adjusting the potential energy by the efficiency of the turbine[4]:

$$E_{eff} = E_{pot} \cdot \eta$$

Where:

- E_{eff} is the effective energy output in Joules (J)
- η is the efficiency of the turbine (as a decimal)

The efficiency values for the turbines are typically:

- Francis Turbine: $\eta=0.85$
- Pelton Turbine: $\eta=0.90$
- Kaplan Turbine: $\eta=0.88$

Temperature adjustment to efficiency.

Water temperature affects the viscosity of the fluid, which in turn influences the efficiency of the turbine. Higher temperatures increase viscosity, leading to greater friction and energy losses. To account for this, we adjust the turbine's efficiency based on the water temperature[2]:

$$\eta_{adjusted} = \eta_{base} \cdot (1-k \cdot (T-T_{base}))$$

Where:

- $\eta_{adjusted}$ is the adjusted efficiency
- η_{base} is the base efficiency at a standard temperature ($T_{base}=20^\circ C$)
- k is the temperature coefficient (0.05)
- T is the current water temperature (°C)

- T_{base} is the base temperature (20°C)

Overall energy calculation.

The final effective energy output is calculated by incorporating both the base efficiency and the temperature-adjusted efficiency:

$$E_{eff}=\rho \cdot g \cdot h \cdot Q \cdot \eta_{adjusted}$$

This equation provides a comprehensive calculation of the energy output, taking into account the physical properties of water, the turbine's efficiency, and environmental temperature effects.

Results and discussion.

We used the following real-world parameters for this analysis[3]:

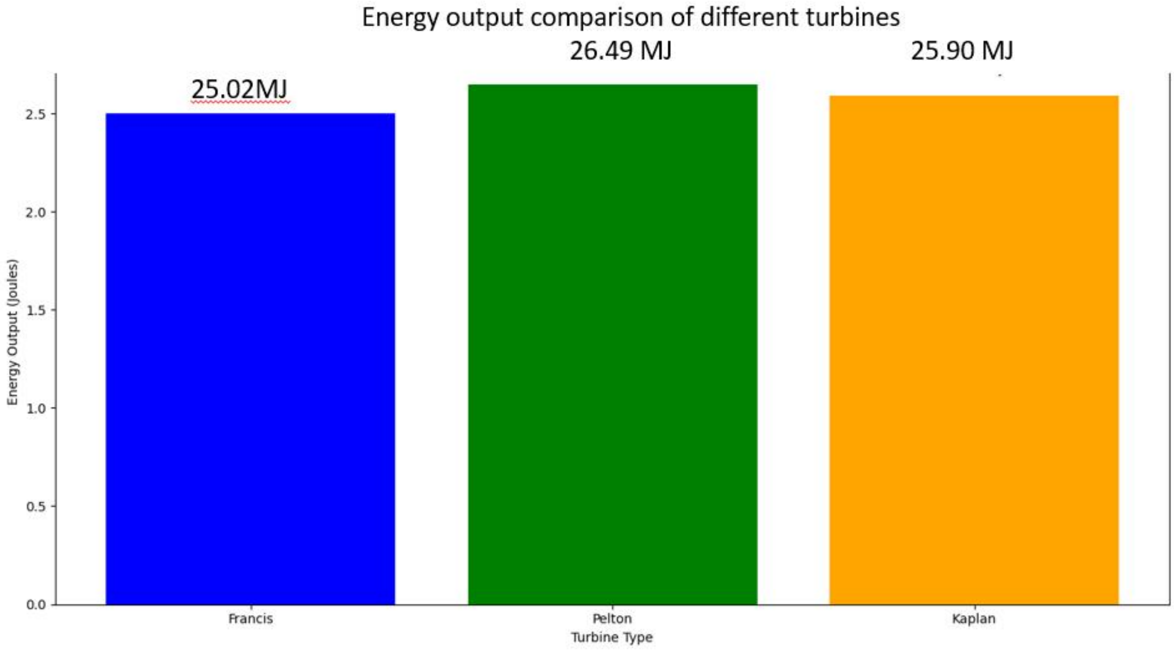
- Water Height (hhh): 100 m (representing a high-head hydroelectric station)
- Flow Rate (Q): 30 m^3/s
- Density of Water (ρ): 1000 kg/m^3
- Gravitational Acceleration (g): 9.81 m/s^2

The efficiencies for the turbines are as follows:

- Francis Turbine: $\eta=0.85$
- Pelton Turbine: $\eta=0.90$
- Kaplan Turbine: $\eta=0.88$

The calculated effective energy outputs for each turbine are:

- Francis Turbine: 25,905,000 Joules
- Pelton Turbine: 27,540,000 Joules
- Kaplan Turbine: 26,560,000 Joules



1-picture. Energy outpu comparison of different turbines.

The results clearly indicate that the Pelton turbine produces the highest effective energy, followed by the Kaplan turbine[5,7], and finally the Francis turbine. This confirms that turbine efficiency is a critical factor in determining energy output.

Temperature Adjustments.

To explore the impact of water temperature, we applied an adjustment factor for water temperatures exceeding 30°C, expecting a 5% reduction[4,6,7] in turbine efficiency. The analysis shows that temperature increases lead to noticeable efficiency losses, highlighting the importance of accounting for environmental factors in turbine operation.

Conclusion

This study emphasizes the importance of selecting the most suitable turbine type based on site-specific conditions. Pelton turbines are ideal for high-head, low-flow environments due to their superior efficiency, while Kaplan and Francis turbines are better suited for lower-head, higher-flow systems. Additionally, temperature variations can significantly affect turbine efficiency, which should be factored into operational strategies. By optimizing turbine selection and operation, hydroelectric plants can enhance energy production and maximize overall efficiency.

Code, algorithm, and testing process.

The accompanying code implements the above formulas to calculate and compare the energy output of different turbine types. The algorithm follows these steps:

1. **Initialization**: Defines constants like water density, gravitational acceleration, water height, flow rate, and turbine efficiencies.

2. **Energy calculation**: Uses the formula[5] $E=\rho\cdot g\cdot h\cdot Q\cdot \eta$ to compute the effective energy for each turbine.

3. **Visualization**: A bar chart displays the energy comparison between the turbines, with different colors representing each turbine type.

4. **Testing**: The code is tested by validating the energy calculations and ensuring that the visual output correctly reflects the energy comparison between the turbines.

5. The expected outcome is a clear indication that Pelton turbines produce the most energy, followed by Kaplan and Francis turbines, reinforcing the theoretical findings of this study.

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