

Article

Water Rocket Theory and Experiment: Bridging Ideal Models and Real Results in STEM Education

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Abstract: This study aims to examine the theoretical principles and experimental outcomes of water rocket launches as an engaging educational tool for elementary to middle school students. While water rockets are used to effectively demonstrate fundamental physics and engineering concepts, discrepancies are often observed between theoretical models and observed experimental results, which must be explained to help students accurately understand the related theory. In this study, the underlying causes of these differences, including unsteady flow, pressure loss, and internal forces, were explored, and key parameters influencing rocket acceleration and performance were identified. By comparing theoretical predictions with experimental data, the results of this study provide a basis for students to understand the complexities of real-world physics and engineering challenges and contribute to the development of STEM education by offering a realistic approach to water rocket experiments. They can also be used for discussion to enhance the students' critical thinking, problem-solving skills, and iterative design ability in engineering.

Keywords: Water rocket, Physics, STEM, Education, Data comparison, Experimental validation

1. Introduction

Science, technology, engineering, and mathematics (STEM) education is crucial for fostering innovation and critical thinking in students. Hands-on activities are effective in engaging students and demonstrating scientific principles. The water rocket experiment has been conducted widely at school as it stands out as an accessible, safe, and cost-effective tool for teaching fundamental concepts in physics and engineering (Tomita, Watanabe, and Nebylov, 2007; IJIERT, 2016). The experiments allow students to explore Newton's laws of motion, forces, aerodynamics, pressure, and energy transfer. Students can observe the principles of action and reaction, understand the relationship between mass, acceleration, and force, and investigate factors influencing projectile motion (NASA, n.d.; TeachEngineering, n.d.; AstroEDU, n.d.; Purdue University, n.d.; Monros-Andreau *et al.*, 2024). Beyond scientific principles, water rocket activities promote engineering skills, including design, construction, testing, and optimization (TeachEngineering, n.d.; IEEE TryEngineering, n.d). Students learn how to collaborate for the analysis of data, discussion of issues, refinement of designs, and iterative engineering process (TeachEngineering, n.d.; AstroEDU, n.d.; The PocketLab, n.d). However, simplified theoretical models might not fully capture the complex phenomena in water rocket experiments, leading to differences between expected and actual outcomes. This study was carried out to address such differences by providing an in-depth analysis of the differences to enhance the educational experience for elementary to middle school students and prepare them for advanced studies in STEM fields.

2. Water Rocket Experiment in STEM Education

Water rocket experiments have been widely used in STEM education due to their interactive nature and direct applicability to rocket science. They also serve as an introduction to scientific concepts and engineering principles. Water rockets demonstrate Newton's Laws of Motion. The law of conservation of momentum and Newton's Third Law of Motion are observed as pressurized water expels downwards, propelling the rocket upwards and reducing the rocket's mass (NASA, n.d.; Waterrocket.explorer.free.fr, 2005).

The law of conservation of momentum states that in an isolated system (no external forces), the total momentum remains constant before and after any interaction, for example, in a collision or explosion. Equation (1) shows that the momentum before the interaction equals the momentum after with no loss, no gain, just transfer.

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2 \quad (1)$$

where m_1 , m_2 are the masses of objects 1 and 2, u_1 , u_2 are their initial velocities, and v_1 , v_2 are the final velocities.

Newton's Third Law of Motion states, "For every action, there is an equal and opposite reaction." That is, when object A exerts a force on object B (F_{AB}), object B simultaneously exerts a force of equal magnitude but opposite direction on object A (F_{BA}). This law is the foundation of momentum conservation. During a collision, the forces between two bodies are equal and opposite, and they act for the same duration, leading to equal and opposite changes in momentum.

$$F_{AB} = -F_{BA} \quad (2)$$

Students learn about thrust, drag (air resistance), gravity, pressure, and the conservation of momentum and energy. Concepts, such as Bernoulli's principle, which explain fluid dynamics, can also be introduced to students. The experiment encourages students to engage in the engineering design cycle, comprising a problem, brainstorming solutions, designing, building, testing, and improving. They can experiment with different design parameters, such as fin shape and placement, nose cone design, and the ratio of water volume to air pressure, to optimize rocket performance. This process provides students with opportunities to practice problem-solving, critical thinking, and innovation (Purdue University, n.d.; Waterrocket.explorer.free.fr, 2005; IJERT, 2016; AstroEDU, n.d.; Waterrocket.explorer.free.fr, 2005).

Previous study results have shown that water rocket experiments enhance student engagement and interest in STEM education as the experiments promote teamwork, communication, and data analysis skills. Students learn how to collaborate to design, launch, and analyze their rockets. By integrating sensors and data collection tools, students learn how to quantitatively measure parameters, including acceleration, altitude, and velocity, leading to an evidence-based understanding of scientific principles (AstroEDU, n.d.; Tomita, Watanabe, and Nebylov, 2007; Monros-Andreu *et al.*, 2024).

Despite the benefits, the traditional water rocket experiment has limitations. Simplified mathematical models used for educational purposes require assumptions, such as neglecting air resistance or assuming steady flow, which might lead to inaccuracies in predictions, compared with actual flight data (ResearchGate, n.d.; Waterrocket.explorer.free.fr, 2005; Fischer *et al.*, 2020). The complex physics of fluid flow and air expansion within the rocket and the effects of dissipative forces are often oversimplified (ResearchGate, n.d.), which might make students wonder why their experimental results deviate from the theoretical calculations, and potentially be confused by unexpected complexities. A lack of consistent performance of self-made launchers and the need for accurate measurement tools sometimes hinder a robust scientific investigation (Fischer *et al.*, 2020).

3. Methodology

This study was conducted to investigate the differences between theoretical models and experimental results in water rocket experiments and identify the parameters that affect the rocket's acceleration. A water rocket launch process begins when the pressurized air inside the rocket forces the water downward and out through the nozzle. At a certain point, water with the compressed air starts to escape, continuing to provide thrust but with less efficiency. Finally, pure air rushes out but less effectively despite the rocket is still accelerating. As the air pressure drops and equalizes with the atmospheric pressure, the ejection slows and stops. In this study, the phase in which the water escapes through the nozzle was focused on. The experiment was conducted by using a standard water bottle rocket setup, allowing for systematic variation of key parameters.

In the experiment, we used the following components.

- Water bottle: A standard plastic soda bottle (1-liter capacity) as a rocket body
- Launchpad: A stable launch mechanism capable of releasing the rocket
- Air pump and pressure gauge to pressurize the air inside the bottle to a controlled initial pressure
- Nozzle and connector to direct the expelled water and connect the water bottle to the launch system
- Angle fixer to ensure consistent launch angles

For data acquisition, the Vernier LabPro system was used as a data interface for collecting sensor data, tracker software for the analysis of rocket trajectory and motion in recorded video clips, and a Vernier Accelerometer to measure the rocket's acceleration during flight.

The experiments were conducted to understand the impact of various physical parameters on water rocket acceleration and flight characteristics. The key parameters included the following.

- Initial bottle pressure (P_0): the initial pressure of the compressed air inside the bottle.
- Total volume of bottle (V_b): the full internal volume of the rocket bottle.
- Initial water volume (VW_0) or initial water height ($h_{initial}$): the amount of water loaded into the rocket at launch. The initial water height was set at 11 cm.
- Nozzle cross-sectional area (A_n): the area of the opening through which water is expelled.
- Bottle cross-sectional area (A_b): the cross-sectional area of the rocket body.

- Ratio of bottle area to nozzle area (A_b/A_n): this ratio is a critical design parameter influencing thrust efficiency

For each launch, the rocket's motion and data were collected from the accelerometer using the Vernier LabPro system. Video analysis with Tracker software allowed for precise measurement of kinematic variables such as velocity and position over time. The collected experimental data was then compared with the values of the theoretical models. Root mean square error (RMSE) was used as a metric to quantify the differences between theoretical predictions and experimental results, as it is widely used and easy to calculate for students. However, it must be noted that RMSE is less sensitive to outliers, scale dependent, and difficult to interpret the differences along. Therefore, in class, other metrics need to be calculated, too, including mean absolute error, mean squared error, mean absolute percentage errors, and the coefficient of determination.

4. Results

Theoretical predictions and experimental data were compared to explore the reasons for the difference between theory and experiment.

4.1. Theoretical Model

Theoretical models for water rockets simplify the complex dynamics of the propulsion phase. The theoretical model considers scenarios "without acceleration" or "with acceleration". These models rely on fundamental principles in physics, including the conservation of momentum and energy, using the following equations (Finney, 1999). Using Bernoulli's equation (3).

$$P_1 + \frac{1}{2}\rho v_1^2 + \rho g y_1 = P_2 + \frac{1}{2}\rho v_2^2 + \rho g y_2 \quad (3)$$

$$\begin{aligned} P_{n+1} &= P_n - \frac{P_n^2}{P_0 V_0} A_e \sqrt{\frac{2(P_n - P_a)}{\rho_w}} \Delta t, \\ v_{n+1} &= v_n + a(P_n, v_n) \Delta t, \\ y_{n+1} &= y_n + v_n \Delta t, \end{aligned} \quad (4)$$

where

$$a(P, v) = \frac{(2A_e(P - P_a) - D v |v|)}{M(P)} - g \quad (5)$$

where P is the pressure inside the rocket, ρ is the density, v is the velocity, g is the gravity, $\rho g y$ is the potential energy per unit volume, V is the volume, t is the time, and y is the height.

A predicted height is expressed as a function of initial water volume in the rocket (Fig. 1), while the difference between the analytical and numerical solution of a water rocket launch is presented in Fig. 2. The experimental results show deviations from the ideal predictions. Therefore, it is necessary to identify key factors contributing to such deviations.

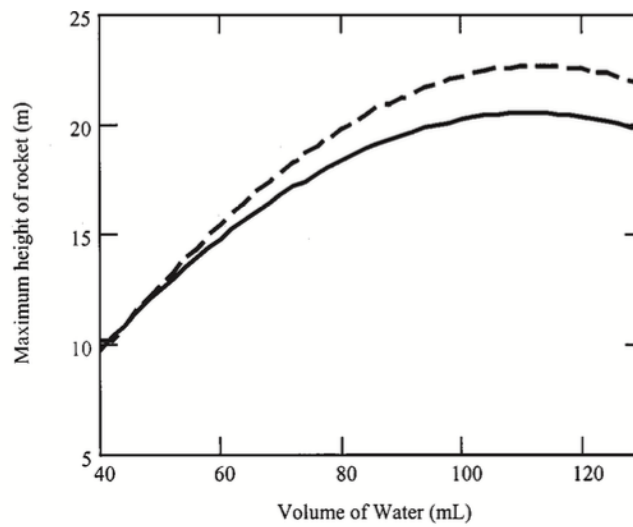


Fig. 1. Predicted height as function of initial water volume in water rocket. (solid line: numerical results, dashed line: experimental result) (Finney, 1999).

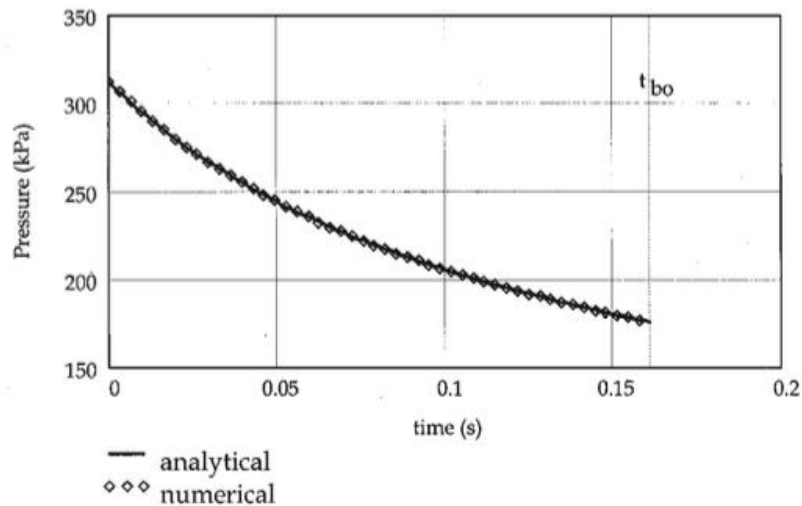


Fig. 2. Comparison of analytical result with the numerical solution (t_{bo} : burnout time) (Finney, 1999).

4.2. Factors and Parameters Affecting Deviation

The factors leading to the deviation of the experimental results from the theoretical predictions were examined in the situations with and without acceleration. When the water rocket launches downward from the propulsion of the internal pressure, the following equations are applied to estimate the velocity of the rocket. From Eq. (1), equations for air expansion (4) and the continuity equation (5) are as follows.

$$P_t = P_0 \left(\frac{V_0}{V_t} \right)^\gamma \quad (4)$$

$$A_c v_c = A_n v_n \quad (5)$$

Then, Eq. (6) is derived from Eqs. (1), (4), and (5).

$$v_n^2 = \frac{P_0 \left(\frac{V_{bot} - V_0}{V_{bot} - V_t} \right)^\gamma + \rho g h - P_0}{\frac{1}{2} \rho \left\{ 1 - \left(\frac{A_n}{A_c} \right)^2 \right\}} \quad (6)$$

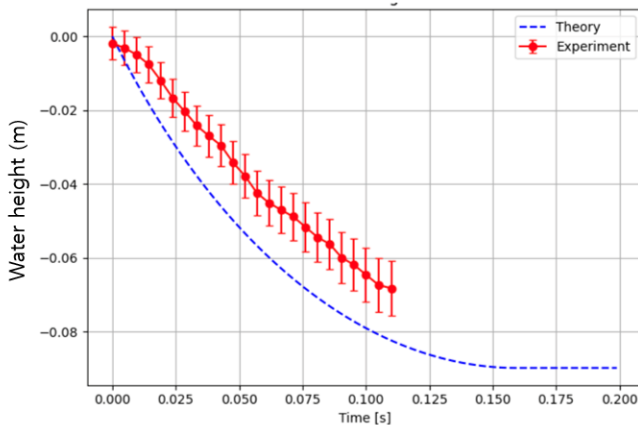
where

$$\frac{dV(t)}{dt} = -v_n A_n \quad (6-1)$$

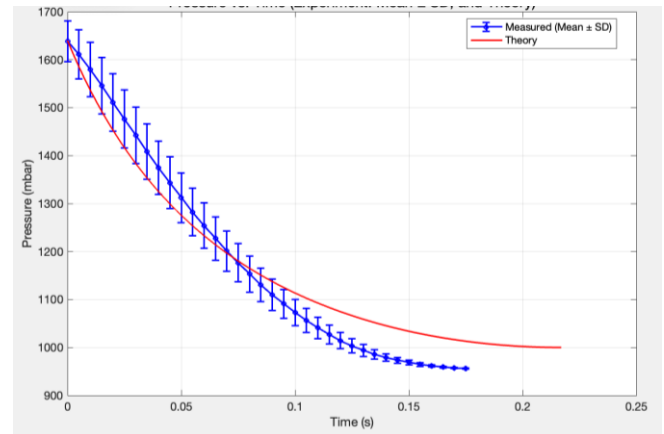
$$\frac{dh(t)}{dt} = \frac{-A_n v_n}{A_c} \quad (6-2)$$

Based on the equations, an experiment was conducted to observe the deviation from the theoretical prediction and measured result when the rocket was not launched but fixed to the launching pad (Fig. 3). For the measurement, Vernier Lam Pro was employed. The parameters set in the experiment included the following.

- Initial bottle internal pressure: 1.643 bar
- Total volume of the water tank: 1 L
- Initial water level inside the bottle: 11 cm
- Nozzle cross-sectional area: 0.00049 m²
- Bottle internal cross-sectional area: 0.005026 m²
- Pressure loss coefficient: 0.13
- Mass of the bottle: 35 g
- Air expansion index: 1.2



(a) Water height



(b) Pressure from rocket

Fig. 3. Deviation of theoretical prediction and measured result.

As time progressed, both the theoretical and experimental water surface heights decreased, which was expected as water was expelled from the rocket during launch. The rate of decrease in water height was non-linear, with the steepest decline occurring early in the launch and then gradually slowing down. In the initial stage (e.g., up to approximately 0.025 s), the experimental data were close to the theoretical value, suggesting an initial agreement. As time advanced, a noticeable divergence appeared. The water height consistently remained higher than the theoretical prediction. This indicated that in the experiment, the water was expelled more slowly than the theoretical model predicted, or less water was expelled than predicted at any given time. The gap between the theoretical and experimental curves widened as time progressed. At 0.10 s, the theoretical height was -0.08 m, while the experimental height was -0.07 m.

The deviation can be explained by the following three factors.

1. Unsteady flow

The rapid expulsion of water from the nozzle is an inherently unsteady flow. Ideal models assume quasi-steady flow, which overlooks the transient effects and turbulence during the expulsion, leading to less accurate thrust calculations. **Pressure Loss:** As the water flows through the nozzle and any internal constrictions, there is a loss of pressure due to friction and changes in cross-sectional area. This "pressure loss due to cross-section change" significantly reduces the effective thrust generated, a factor often simplified or ignored in basic theoretical frameworks.

2. Internal force

The internal dynamics of the air and water within the bottle during expulsion contribute to the deviations. The interaction between the expanding air and the accelerating water, beyond simple pressure forces, introduces complexities that are difficult to

model ideally. In the experiment, as water exits through the narrow nozzle opening, pressure loss occurs, which leads to errors. Therefore, three terms of pressure drop and unsteady flow were added to the theoretical model (7), and the coefficient γ was changed from 1.4 of the theoretical model to 1.15 in this study.

$$P_H - P_a + \frac{1}{2} \rho_w v_n^2 \left(\left(\frac{A_n}{A_H} \right)^2 - 1 \right) + \rho_w g H = 0 \quad (7)$$

$$\rho_w H A_n \frac{dv_n}{dt} + \left[P_0 \left(\frac{V_b - V_{w0}}{V_b - V_{wH}} \right)^\gamma - P_a + \frac{1}{2} \rho_w v_n^2 \left(\left(\frac{A_n}{A_H} \right)^2 - 1 \right) + \rho_w g H \right] - \frac{1}{2} \rho_w K v_n^2 = 0 \quad (8)$$

Equation (8) was used to predict the experimental results, and Fig. 4 shows that the deviation was reduced. The RMSE decreased from 0.013934 with Eq. (7) to 0.006411 with Eq. (8).

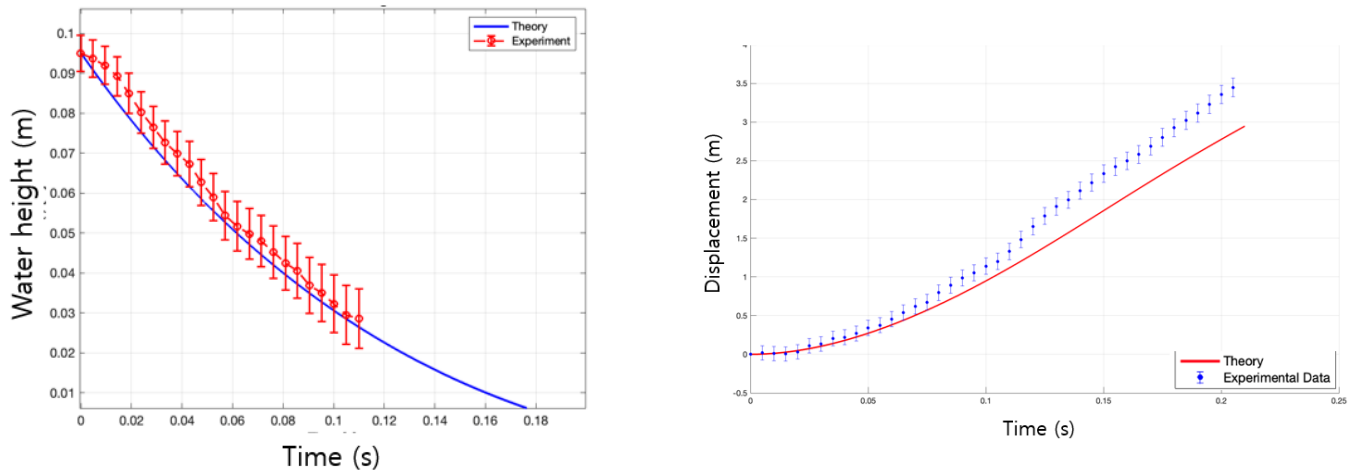


Fig. 4. Comparison of theoretical prediction and experimental results in water height change and displacement by time.

For precise measurement, a water rocket launcher was modified to control the water pressure and the diameter of the water nozzle (Fig. 5). Using the launcher, an experiment was designed to measure the parameters, considering the acceleration of water in the bottle to propel the rocket. In the experiment, the reaction force due to the internal acceleration of water in the rocket was considered.

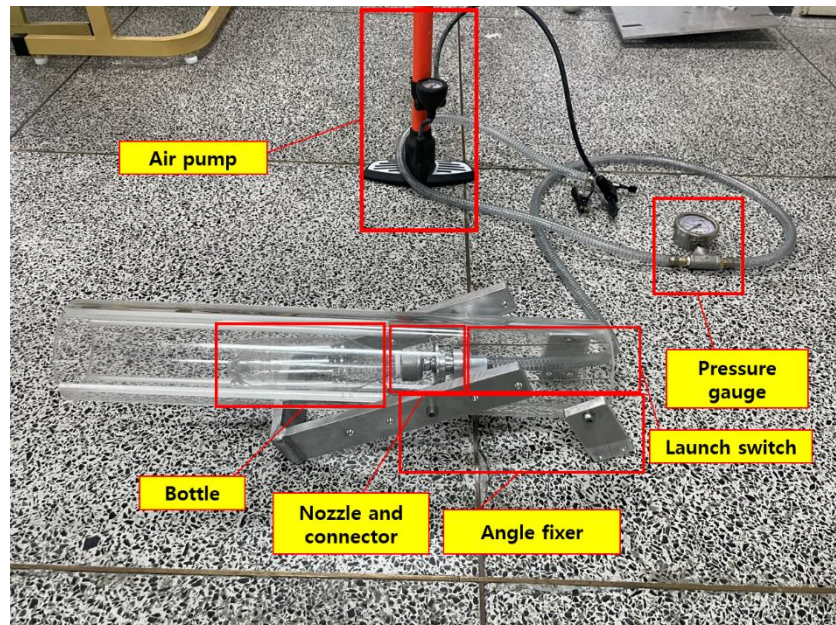


Fig. 5. Modified water rocket launcher.

With the acceleration equation (9), Eq. (10) was formulated.

$$a = \frac{F_{thrust} + F_{drag} + F_{internal}}{m_{total}} - g \quad (9)$$

$$\rho_w H A_n \frac{dv_n}{dt} + \left[P_0 \left(\frac{V_b - V_{w0}}{V_b - V_{wH}} \right)^\gamma - P_a + \frac{1}{2} \rho_w v_n^2 \left(\left(\frac{A_n}{A_H} \right)^2 - 1 \right) + \rho_w (a_b + g) H \right] - \frac{1}{2} \rho_w K v_n^2 = 0 \quad (10)$$

where $v_n = \frac{A_H}{A_n} \frac{dH}{dt}$

When applying Eq. (11), the theoretical prediction became almost identical to the experimental result as shown in Fig. 6.

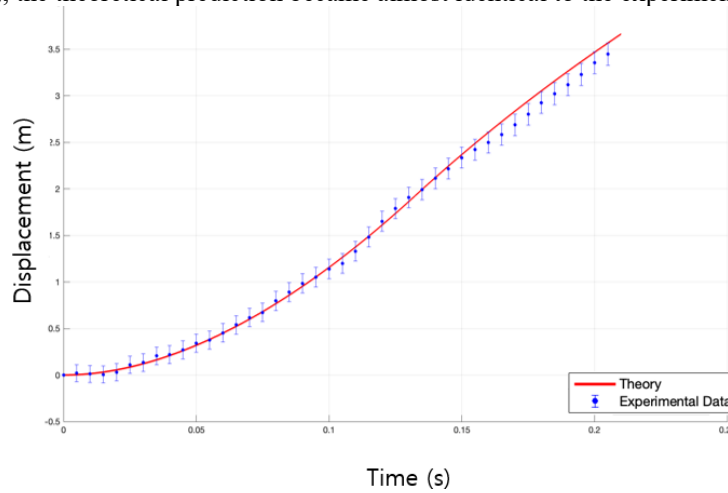


Fig. 6. Comparison of theoretical prediction and experimental result using Eq. (11).

From the experimental results and through the comparison of theoretical prediction and experimental results, the following parameters are important in understanding the physics of the water rocket experiment: initial chamber pressure (P_0), initial water volume (V_{w0}), the total volume of the bottle (V_b), the cross-sectional area of the nozzle (A_n), and the cross-sectional area of the bottle (A_b).

Therefore, experiments were conducted to estimate the parameter's effects on the water rocket acceleration by varying the parameters as follows.

- P_0 : 1.0, 1.5, 1.8, and 2.1 bar
- V_{w0} , V_b : 7, 11, 16, and 21 cm (the water height (H) in the water bottle)
- A_n , A_b : 10 and 15 (as A_n / A_b)

The acceleration of the water rocket was measured using a Vernier Accelerometer. The comparison of the measured and predicted acceleration, at $A_n / A_b = 10$, $P_0 = 1.8$, and $H_0 = 16$ cm, is presented in Fig. 7.

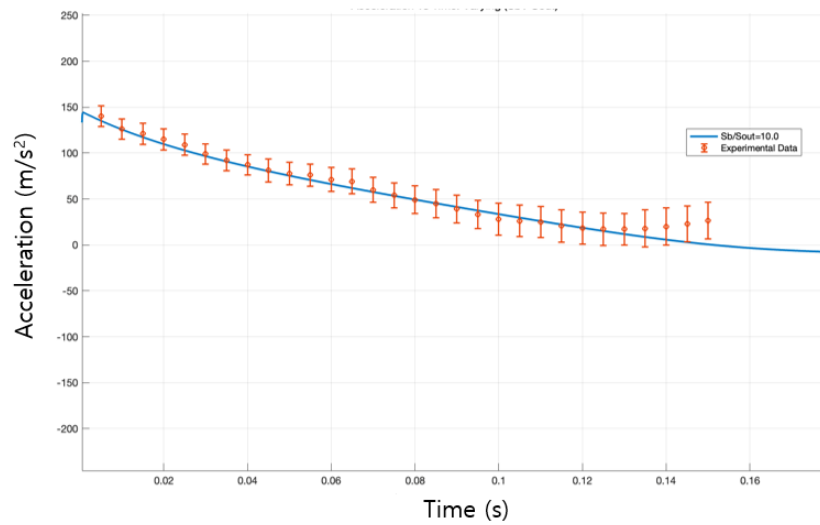
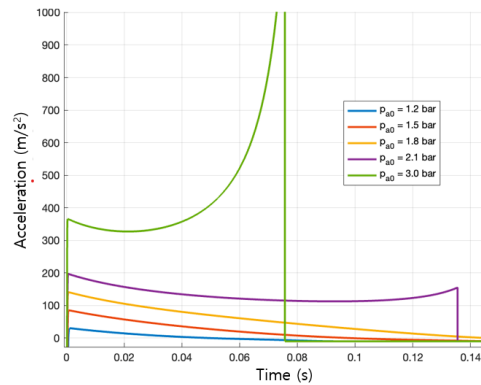
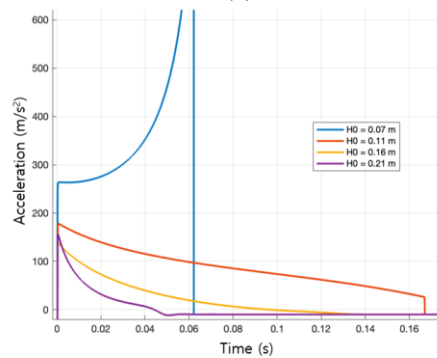


Fig. 7. Comparison of theoretical prediction and measured acceleration of water rocket.

The effect of P_0 , H , and A_n / A_b on the acceleration of the water rocket was examined by varying P_0 from 1.2 to 3.0 bar, H from 7 to 21 cm, and A_n / A_b from 3.0 to 15.0 (Fig. 8).



(a)



(b)

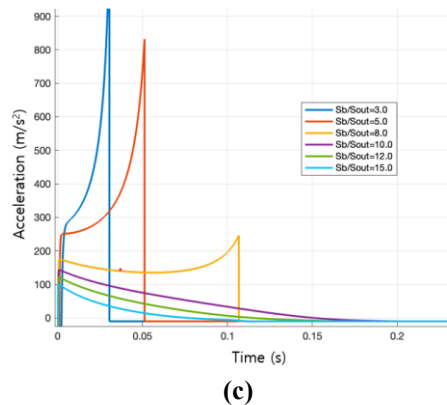


Fig. 8. Acceleration of water rocket at different (a) P_0 , (b) H , and (c) A_n / A_b .

Although Eq. (11) fitted well to the measured acceleration, deviations were observed, especially after 0.12 s after launch. Such errors can be reduced by adjusting two key parameters for better fitting. The first one is an adiabatic index (γ). The ideal gas law assumes an adiabatic process (no heat exchange), typically with $\gamma \approx 1.4$ for diatomic gases such as air. However, in the water rocket, heat exchange with the water and bottle walls might occur, making the expansion process polytropic rather than perfectly adiabatic. The fitted γ value was 1.1 to 1.2 in this study, necessitating a more realistic representation of the air expansion process. The second parameter to be adjusted is the pressure loss coefficient (K fitting). The pressure loss coefficient (K) accounts for energy losses due to turbulence and friction at the nozzle. By fitting K values (approximately 0.1 to 0.2) to experimental data, the model (Eq. (11)) can more accurately reflect the reduced effective pressure driving the water expulsion, thereby improving the agreement between theoretical predictions and observed accelerations. By adjusting these parameters based on the experimental data, the theoretical model can be significantly improved to reflect real-world conditions more accurately.

5. Application of Results to Lesson Plan

The experiments were designed and conducted to help students understand the physics involved without complexity. To make the water rocket experiment accessible while maintaining theoretical rigor, key parameters in the theoretical model must be adjusted to align with experimental results to explain discrepancies between simplified theoretical models and experimental outcomes, which might confuse students. Two specific parameters need to be adjusted: the adiabatic index and the pressure loss coefficient. An ideal model assumes a perfectly adiabatic process (no heat exchange), using a γ of 1.4 for air. However, in a real water rocket, heat exchange occurs with the water and the bottle walls, making the process polytropic. Students can adjust the value from 1.1 to 1.2, to see how it improves the model's accuracy. The pressure loss coefficient is used to explain the energy lost due to friction and turbulence as water is expelled through the nozzle. By fitting the value between 0.1 to 0.2, students can test their theoretical models that have the reduced effective pressure, thereby improving the agreement between predictions and observations.

To help students engage with complex concepts, a tiered lesson plan and visual simulations are essential.

In the tier 1 lesson, the basic theoretical model with simplified assumptions can be used to predict flight characteristics based on factors like initial pressure and water volume. This helps them understand the fundamental principles, such as Newton's laws of motion, thrust, and pressure. In the tier 2 lesson, students can launch their water rockets and obtain experimental data using sensors or video analysis. They can compare their results to the predictions from the simplified model and observe the discrepancies, which stimulates critical thinking about why the theoretical and experimental results differ. In the tier 3 lesson, the concepts of unsteady flow, pressure loss, and internal forces can be introduced to explain the discrepancy. More complex equations need to be explained to introduce adjustable parameters. By adjusting these parameters, a better fit between their model and their experimental data can be obtained.

To enhance learning engagement and outcomes, visual simulation needs to be employed to help students visualize the concepts they learn.

6. Conclusion

The water rocket experiment is a pedagogical tool for introducing the principles of physics and engineering (NASA, n.d.; AstroEDU, n.d.; Monros-Andreu *et al.*, 2024). It presents an example of Newton's laws and fluid dynamics in action. It is important to understand the importance of simplistic ideal models to embrace the complexities of real-world phenomena. However, the differences between theoretical predictions and experimental results are often observed, which need to be explained theoretically.

Therefore, this study was carried out to investigate factors that cause the differences and propose a new equation that fits the measured results of the water rocket experiment. To improve the model fitting, unsteady flow, pressure loss, and internal forces were examined for a nuanced and accurate understanding of the scientific modeling of students. Although the proposed equation fitted the measured results excellently, deviations were observed, probably due to the differences in adiabatic index (γ) and pressure loss coefficient (K). By adjusting such parameters and through empirical data and refinement, the accuracy of the predicted value using the equation can be enhanced.

Based on the research process presented in this study, students can develop new equations to design the process and explain the results of water rocket experiments. They can also be trained to think critically about assumptions, understand sources of error, and appreciate the iterative nature of scientific discovery and engineering design. Such experimental experiences can be transformed into a rich learning opportunity that delves into advanced concepts of fluid mechanics and thermodynamics. The results of this study can help students understand rocket science and cultivate problem-solving and analytical skills crucial for STEM education.

To advance the experiment, it is necessary to integrate sophisticated sensors (e.g., GPS, gyroscopes, altimeters) and real-time data logging for more detailed analysis of flight trajectories, rotation, and stability (The PocketLab, n.d.; Monros-Andreu *et al.*, 2024). In the experiment, students can vary parameters virtually and see their impact, bridging the gap between hands-on experimentation and theoretical modeling. This facilitates the exploration of complex fluid dynamics and aerodynamic effects that are difficult to measure directly in a simple experiment (Monros-Andreu *et al.*, 2024; Unit Overview STEM Stage 5: Water Rockets, n.d.). Students need to engage in iterative design challenges, where they systematically modify their rocket designs based on experimental results and refine their theoretical models to strengthen their engineering design skills (TeachEngineering, n.d.; The PocketLab, n.d.). By incorporating these advancements, water rocket experiments can be used as a dynamic and impactful tool for STEM education, inspiring the next generation of scientists and engineers to tackle complex real-world challenges with critical thinking and an evidence-based approach.

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Data Availability Statement: The data of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest

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