Science and Technology Publishing (SCI & TECH)
ISSN: 2632-1017
Vol. 7 Issue 9, September - 2023

Design And Production Of A Pressure-Boosting Water Closet System For Conservation And Sustainability

Okon Aniekan Akpan[1]

Monday, Sampson I.[2]

Umoren Ubong Saviour[3]

[1,2,3] Department of Mechanical and Aerospace Engineering,
University of Uyo, Akwa Ibom Nigeria

Email: [1]drokonaniekan@gmail.com

***Abstract*—Water closets play a crucial role in sanitation practices for public health. The evolution of the water closet has experienced notable advances in recent times thanks to the integration of smart technology. However, the need for local design and production of such systems with locally sourced materials for production becomes very crucial, especially in developing nations of the world. This work designs and produces a pedal pressure-booster water closet system to reduce water consumption. The water was pressurized so that the resulting momentum flushes the system with minimal mass flow of water. The mechanical pressure booster device was designed, and the various components of the system were sourced locally and assembled. The toilet seat was molded using locally sourced fiber materials. The design of the pressure boosting device and the general flow dynamics of the system follow Continuity, Bernoulli's, Hagen-Poiseuille's and Torricelli's Laws. Both experimental and theoretical results show a significant pressure increase of about 186% in the system. This pressure boost ensured that water is forced through the inlet of the system with adequate force to maintain a steady and consistent flow. The evaluation also showed a higher momentum than the average quantity required for an effective cleaning action at the bowl of the water system. Generally, the eco-friendly and water-efficient toilet system showed a significant relative reduction in water consumption, with a 50% cost savings, thus highlighting the economic benefits of adopting the smart and sustainable design.**

Keywords—Pressure-Boosting, Water Closet System, sanitation practices, public health, Bernoulli's, Hagen-Poiseuille's, Torricelli's Laws

1.0 Introduction

A water closet, often abbreviated as WC, is a fixture commonly found in bathrooms and restrooms for the disposal of human waste. Water closet originally came from the use of water to flush away waste, distinguishing it from the more primitive and unsanitary methods of waste disposal (George, 2008).

Figure 1: A water closet

The system provides a hygienic and convenient way for individuals to relieve themselves (Parker, 2019). Unlike traditional pit latrines or open-air facilities, water closets utilize a water-based system to flush away waste, ensuring cleanliness and proper sanitation. The water closet consists of a toilet bowl, a seat, and a flushing mechanism. The toilet bowl is designed to collect waste, while the seat provides a comfortable seating surface for users. The flushing mechanism, usually operated by a lever or button, releases water into the bowl to wash away waste. The key distinguishing factor of a water closet is its ability to flush waste using a water-based system. This mechanism helps maintain proper hygiene and cleanliness by efficiently removing waste and minimizing odour. The waste is then transported through the plumbing system to a sewage network or septic tank for appropriate treatment and disposal.

Modern water closets come in various designs and styles, ranging from wall-mounted to floor-standing models. They can be found in both residential and commercial settings, catering to the needs of individuals and the public. Proper sanitation practices in water closets play a crucial role in maintaining public health, (Serrato, 2018). Furthermore, modern advances in water closet design have introduced features like bidets and self-cleaning mechanisms. These additions enhance personal hygiene and further reduce the potential for the spread of diseases. Bidets, for example, provide a gentle and thorough cleansing experience, eliminating the need for excessive toilet paper usage. Self-cleaning mechanisms, on the other hand, ensure that the water closet is sanitized after each use. The evolution of the water closet has experienced notable advances in recent times thanks to the integration of smart technology. What was once a conventional toilet was transformed into a sophisticated and efficient system, incorporating intelligent features for enhanced user experience. Smart water closet systems typically boast a range of state-of-the-art components that underpin their intelligent functionality. These components commonly include sensors, actuators, connectivity modules, and user interfaces. Sensors play a crucial role in detecting user presence, monitoring water usage, and assessing system cleanliness. Actuators enable automated functions such as flushing, lid operation, and other mechanical tasks.

Traditional WC models use more than 12 liters of water per flush (Koeller & Gauley, 2003). With increasing awareness of water scarcity, there is a compelling need to reduce water consumption in toilets. Innovations such as dual-flush mechanisms, and pressure-assisted flushing demonstrate significant advancements in reducing water usage. Dual-flush toilets offer two flushing options: a low-volume flush for liquid waste and a higher-volume flush for solid waste. This innovation significantly reduces water usage to about 6 liters of water per flush (Gauley & Koeller, 2005). Low-flow toilets are designed to use less water per flush without compromising performance. Pressure-assisted toilets use compressed air to enhance flushing power, allowing them to use less water while maintaining effective waste removal. This technology is particularly effective in commercial settings where high performance is required (U.S. Environmental Protection Agency, 2013).

Moreover, concerns regarding hygiene persist due to manual operation, which increases the risk of germ transmission and cross-contamination, particularly for individuals with mobility impairments, who physically interact with potentially contaminated surfaces. Also, modern toilets are designed with ergonomics in mind, offering features such as comfortable seat heights, elongated bowls, and easy-to-use flush mechanisms to enhance user comfort (Pogue, 2018; Chui & Thompson, 2017).

However, these innovations are only popular in developed nations of the world and are only exported to the developing ones. Consequently, the trade deficits of such countries are further raised, resulting in inflation with its catastrophic economic consequences. Thus, there is a compelling need for local designs and production of such systems, with locally sourced materials. Therefore, this work designs and produces a pedal pressure-booster water closet system to reduce water consumption. The design also minimizes contact with germs and bacteria with hand-free operation of the system.

2.0 Materials and method

The water is pressurized so that the resulting momentum flushes the system with minimal mass flow of water. The mechanical pressure booster device was designed, and the various components of the system were sourced locally and assembled. Same was also the mechanical lever and cable system which opens and closes the toilet lid. The pressure booster follows the fundamental thermo-fluids equations. With the right design dimensions, the toilet seat was molded using locally sourced fiber materials. The seat was attached to a wooden wall where many other features for effective and optimal performance of the system were attached.

2.1 Pressure Booster Device

The pressure booster (figures 2 and 3) was designed to enhance the inherent hydrostatic pressure of water supplied from the overhead tank. Water enters the pressure booster from the overhead tank, and remains stored until the flushing mechanism is activated. When the flush button (or lever handle) is engaged, the device activates the integrated mechanisms that amplify the pressure of the stored water. Thus, the gravitational pressure of the elevated water is enhanced.

2.2 Mathematical Approach

The design of the pressure boosting device and the general flow dynamics of the system follow these equations:

(i) Bernoulli's Equation: The total mechanical energy of the fluid remains constant along a streamline, provided the flow is incompressible and there are no friction losses, mathematically expressed as:

$$\frac{P}{\ell g} + \frac{u^2}{2g} + z = constant \qquad - \qquad Eqn.\ i$$

This principle balances the pressure and velocity of the system to ensure effective flushing (White, 2016).

(ii) Continuity Equation: The mass flow rate remains constant from one cross-section of the pipe to another, mathematically expressed as:

$A_1V_1 = A_2V_2$ - *Eqn. ii*

This principle was crucial in designing the geometry of the inlet and outlet sections of the WC system to ensure a consistent and adequate flow rate (Streeter & Wylie, 1998).

(iii) Hagen-Poiseuille Law: The Hagen-Poiseuille law applies to laminar flow in narrow pipes and was used to determine the volumetric flow rate of the system, expressed as:

$\Delta P = \frac{8\mu uL}{R^2}$ - *Eqn. iii*

This principle was particularly useful for designing the flow through narrow sections like flush valves and nozzles (Perry & Green, 1997).

(iv) Torricelli's Law: Torricelli's law describes the speed of efflux of a fluid through an orifice under gravity, given by:

$v=(2gh)^2$ - *Eqn. iv*

The principle estimates the water tank height for sufficient flushing velocity (Fox et al., 2011).

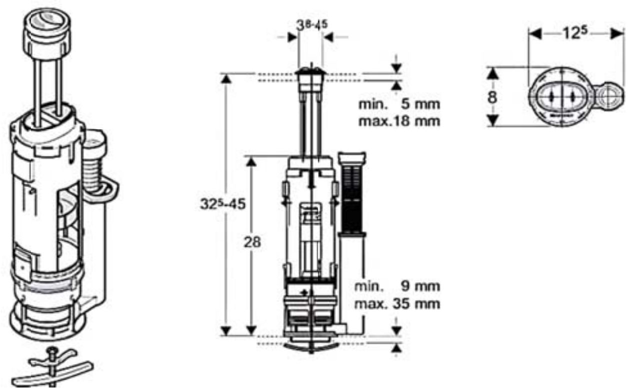

Figure 2: Schematic views of the internal components of the pressure boosting device.

2.3 Hydraulics Analysis

Required volume flow rate = 1.5L/s = 0.0015m^3/s

Volume of water per flush = 0.003m^3

ASME Standard diameter of pipe = 0.051m

Area of pipe (A) = $\frac{1}{4}\pi D^2 = \frac{1}{4}\pi(0.051)^2$

A = 0.002m^2

Volume flow rate (V) is given as: V = $A \times u$ - *Eqn. v*

where u is the velocity of flow.

Therefore, the required velocity of flow u = 1.5m/s

As the velocity of flow at the outlet of the WC is known, the pressure developed in the line is then assessed. From the Poiseuille flow equation, pressure change is given as:

$\Delta P = \frac{8\mu uL}{R^2}$ - *Eqn. vi*

where u is the flow velocity,
μ = fluid viscosity (water in this case = 0.001 pa.s)
L = length of the pipe
R = radius of the pipe

Therefore,

$\Delta P = \frac{8x20x0.001x1.5}{0.0255^2}$

ΔP = 369.088 kpa

But,

$\Delta P = P_3 - P_1$ - Eqn. vii

Where:

P_1 = hydrostatic pressure

P_3 = final pressure at the WC

$P_1 = \ell \times g \times Z$

where;

Z = height of the tank
g = acceleration due to gravity
ℓ= density of water = 1000 kg/m^3

P_1= 1000 x 9.81 x 20

P_1 = 196.2 kpa

The required pressure at the inlet of the WC for a flow velocity of 0.75m/s is:

$\Delta P = P_2 - P_1$ - Eqn. (i)

$P_2 = \Delta P + P_1$ = 369.088 + 196.2

P_2= 562.288 kpa

So that:

$P_3 = P_2 - (P_f + P_m)$ Eqn.(ii)

P_2 = Pressure at the outlet of the mechanical pressure system.

P_f = pressure loss due to frictions along the entire length of the pipe.

P_m = minor pressure loses due to fittings, valves and bends in the pipe connection

Press. loss due to frict. $(P_f) = f\, x\, \frac{L}{D}\, x \frac{u^2}{g}$ Eqn. (iii)

where f is the frictional constant given as:

$$f = \frac{0.25}{\left[\log\left(\frac{\frac{\varepsilon}{D}}{3.7}+\frac{5.74}{Re^2}\right)\right]^2}$$

According to work of Jamil, (2019), for a PVC pipe of diameter 0.051m, Ɛ/D = 0.00007

Reynolds number (Re) for the flow is given as:

$$Re = \frac{\ell u D}{\mu} = \frac{1000x0.75x0.051}{0.001}$$

Re = 38250, (the flow is turbulent)

Thus:

$$f = \frac{0.25}{\left[\log\left(\frac{0.0007}{3.7}+\frac{5.74}{(38250)^2}\right)\right]^2}$$

$$f = \frac{0.25}{[\log(0.0000189)]^2} = \frac{0.25}{[-4.723]^2} = \frac{0.25}{22.306}$$

f = 0.0112

From eqn. (iii)

$$P_f = 0.0112\, x\, \frac{20}{0.051}\, x \frac{0.75^2}{9.81}$$

P_f = 0.251 kpa

Also, Minor pressure loses due to valves, fittings and bends is given as:

$$P_m = K\left(\frac{u^2}{2g}\right) \quad - \quad \text{Eqn. (iv)}$$

where K is a constant of proportionality.

According to Crane, 2016, K is given as 0.8

thus:

$$P_m = 0.8\left(\frac{0.75^2}{2x9.81}\right)$$

P_m = 0.0229 kpa

P_3 = 562.288 – (0.251+ 0.0229)

The pressure boosting mechanism uses the gravitational potential energy from the elevated tank, together with the spring-loaded valve to compress the water, thereby increasing the pressure of the water at discharge. This enhanced water flow enables the system to use a minimal volume of water thus ensuring its conservation and sustainability.

2.4 Pressure Boosting Materials

Below are components and materials of the mechanical pressure device, whose contributions to the system's sustainability and efficiency are highlighted.

(i) Push Buttons which serve as the user interface for activating flushes. When pressed, the boosting device increases pressure for efficient waste removal, requiring minimal water usage.

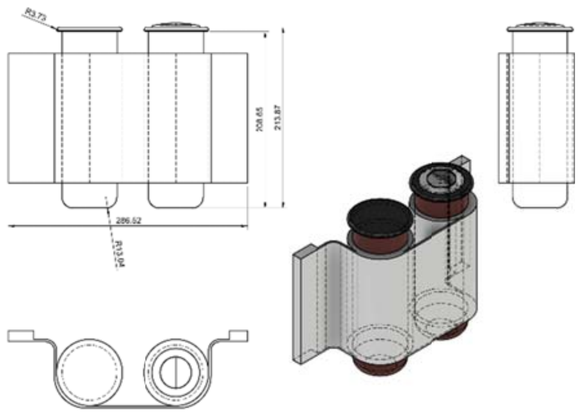

Figure 3: Outer view of the pressure booster.

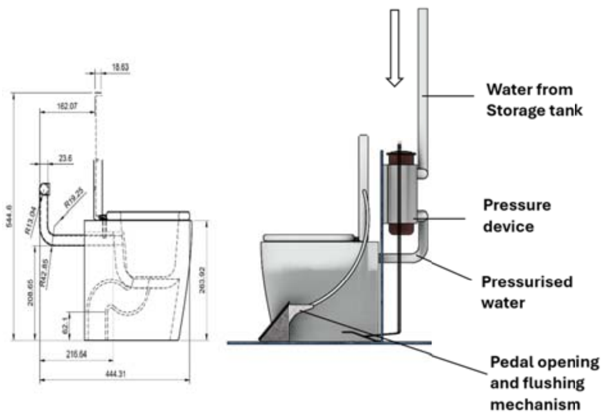

Figure 4: A view of a complete assembly of the WC system.

(ii) Lever Handle provided an alternative manual flushing option, mechanically linked to the boosting device.

(iii) Stainless steel known for its corrosion resistance, durability, and high tensile strength, was used for the primary components of the mechanical pressure device, including valves and fittings. Its corrosion resistance ensures longevity and reduced maintenance needs, making it ideal for handling water over extended periods.

(iv) Rubber Seals are Flexible, durable, and water-resistant as such, they were used to prevent water leakage at connection points. Their flexibility allowed for a watertight seal, which was essential for maintaining pressure within the system and preventing water leakages.

(v) Polyethylene has a light weight, it is highly resistant to chemical corrosion, and highly durable. Polyethylene was used for certain internal components and housings of the mechanical pressure device. Its resistance to chemical corrosion ensured it remained intact and functional, even with prolonged exposure to water and other substances.

(vi) Teflon tapes are non-reactive with low friction, and high resistant to high temperatures. Teflon tape was used to ensure airtight and watertight seals on threaded connections within the mechanical pressure device. Its properties prevented leaks and ensured efficient operation of the pressure device.

(vii) A dual flush button was constructed from stainless steel and plastic. These materials were chosen for their durability, corrosion resistance, and smooth operation. These materials ensured that the flushing mechanism withstood repeated use with efficient performance.

(viii) Valves and fittings were polyvinyl chloride material. These valves and fittings are known for their chemical resistance, leak-tight, durability, and ease of installation. They resist corrosion and degradation from water and other chemicals, thus ensuring a constant flow of water without compromising their performance.

(ix) Levers and cables were used for the opening and closing of the toilet lid. This mechanism was designed to facilitate the smooth operation of the toilet lid, reducing the need for direct manual contact. The pedal made of aluminum was designed to be stepped on to open and close the seat cover. The levers, made of aluminum, converted the rotational motion of the pedal to a 0 – 90 Degree movement of the seat cover, thus, opening and closing it. The cables, made of stainless steel, connect the levers to the dual flushing mechanism. The pedal and lever materials were chosen for their durability, reliability, and smooth operation.

(x) Inlet and Outlet Pipes from the storage tank remain critical components of the system, thus playing a vital role in maintaining high water pressure.

3.0 Results and Discussion

The system was produced using locally sourced materials and many experimental runs were conducted to assess its performance. The eco-friendly and water-efficient toilet system showed a significant relative reduction in water consumption. Also, the hand-free operation allowed users to control the flushing and seat opening with foot pedals, with enhanced hygiene and convenience. The seat was attached to a wooden wall to incorporate other features for effective and optimal performance of the system.

Figure 5: 3D views of the produced system.

3.1 Experimental Runs

Experimental runs using the WC system were carried out and the results compared with theoretical values. The experiment focused on flow dynamics of the system, specifically volume per flush and momentum of the flow.

The results showed that the theoretical volume flow per flush of the system remains constant at 0.003 m^3 across all tests, suggesting a well-defined design system. The values of the experimental runs of the system fluctuate slightly from 0.00294 m^3 to 0.00304 m^3, (table 1). These variabilities could be attributed to minor flow differences in the flush mechanism or pressure dynamics during each trial.

Table 1: Volume flow assessment per experimental runs.

Exp. Runs	Momentum (*kgm/s*) *[Theo.]*	Density (kg/m³)	Volume per flush (m³)
1	4.5	1000	0.003
2	4.5	1000	0.00294
3	4.5	1000	0.00302
4	4.5	1000	0.00296
5	4.5	1000	0.00298
6	4.5	1000	0.00304
7	4.5	1000	0.00302

Table 2: Momentum assessment per experimental runs in reference to the theorical value.

Exp. Runs	Velocity (m/s)	Momentum *(kgm/s) [Exp.]*	Momentum (kgm/s) [Theo.]
1	1.5	4.5	4.5
2	1.47	4.3218	4.5
3	1.51	4.5602	4.5
4	1.48	4.3808	4.5
5	1.49	4.4402	4.5
6	1.52	4.6208	4.5
7	1.51	4.5602	4.5

The momentum analysis indicates that while the theoretical momentum remains constant at 4.5 kgm/s, the experimental values showed minor variations between 4.3218 kgm/s and 4.6208 kgm/s. Although these differences exist, they are within a reasonable range, thus showing the system consistent performance in each experimental run.

The minor differences observed between the theoretical and experimental results could be attributed to factors like changes in water pressure, actuation, mechanism response, resistance encountered in the piping system, etc. Despite the deviations, the experimental values closely align with theoretical predictions, thus underscoring the robustness of the design. Also, some experimental momentum values were slightly lower than theoretical values, attributed to energy losses due to friction in the system, inefficiencies in the flush mechanism, or air resistance. However, the differences are minimal, showing the optimal efficiency of the system.

Generally, the experimental results showed that the WC system operates efficiently, exhibiting minimal deviations from theoretical expectations. The small fluctuations in volume per flush, flow velocity, and momentum are consistent with the variations expected in practical systems.

3.2 System Performance

Pressure measurements were a critical part of our evaluation. The initial pressure from the overhead tank (P1) was 196.2 kPa, the pressure within the pressure casing (P2) was 562.288 kPa, and the final pressure entering the water closet (P3) was 562.01 kPa after losses due to friction and valve fittings and valves. These values were verified using strategically placed pressure gauges, which showed that the pressures matched the calculated values, demonstrating the effectiveness of the pressure casing and the mechanical pressure system in amplifying the pressure as designed. Pressure ensures that water is forced through the water inlet system with adequate force in order to maintain a steady and consistent flow, while momentum ensures that this force translates into effective cleaning action at the bowl of the water closet system.

Momentum is given as:

$$M = \dot{m}.\ u$$

where:
$\dot{m}$ = mass flow rate
$\dot{m}$ = density x volume of water per flush

$\dot{m} = \ell\ x\ V$
Recall that $V = A.u$
$\dot{m} = \ell.A.u$
So that momentum,
$M = \ell.A.u.u = \ell.A.u^2 \quad = 4.5$ kgm/s

According to Rose C. Parker (Rose et al., 2015), the average daily mass of human feces ranges from 0.1 to 0.2kg per day. Multiplying 0.2kg by a factor of safety of 5, the maximum human feces by day becomes 1kg. This means that the impact of the incoming stream of water will have enough force to move the waste quickly and effectively out of the bowl.

3.3 System Economic Assessment

The economic evaluation of both the novel and traditional WCs was carried out. The assessment compares the economic gains of the smart water closet (WC) with the traditional WC for a 1,000-liter overhead storage tank.

Smart Water Closet:

Volume per flush: 3 liters
Number of flushes per day: 5
Daily water usage: $3\,L \times 5 = 15\,L$
Days until next refill:

$$\frac{1000L}{15L} \approx 66$$

Traditional Water Closet:
Volume per flush: 6 liters
Number of flushes per day: 5
Daily water usage: $6\,L \times 5 = 30\,L$

Days until next refill:

$$\frac{1000L}{30L} \approx 33$$

Cost Analysis

Assuming a refill cost of ₦2,000 per tank:

Smart Water Closet:

With a refill every 66 days, the total cost for refills within this period is:

Cost = ₦2,000

Traditional Water Closet:

With a refill every 33 days, the total cost for refills within 66 days is:

$$\text{Cost} = \frac{66\ days}{33\ days} x\ ₦2,000$$

$$= ₦4,000$$

From the forgoing, it is clear that the smart water closet design demonstrates a clear economic advantage over traditional water closets. The cost of refilling the overhead tank for the smart WC is ₦2,000 over 66 days, while the traditional WC incurs a cost of ₦4,000 within the same timeframe. This represents a 50% cost savings, highlighting the economic benefits of adopting the smart and sustainable WC design.

4. 0 Conclusion

The design and production of a sustainable water closet system aimed at developing a water closet that optimizes water usage through high-pressure application. The design features a hand-free mechanism where flushing and seat operations are controlled via foot pedals, leveraging the principles of lever mechanics and tension strings. The AutoCAD model presented a sleek and smooth design, which was integral to the project's conceptualization. The project on the design and fabrication of a sustainable water closet system has shown promising results. By the use of pedal-operated mechanism and minimal water, a system that is accessible, efficient, and environmentally friendly was created. While, this project has successfully demonstrated the core principles and functionality of the system, challenges remain in achieving the design's full potential. Addressing these challenges through design refinement, alternative pressure enhancement methods, and rigorous testing will be crucial for the successful realization and implementation of the water closet system. Future work will build upon these findings to enhance the design's effectiveness and practicality, paving the way for innovative solutions in water-efficient sanitation technology.

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