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Development of In-Pipe Water Pollution Detection System Focusing on pH Contaminant

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ABSTRACT

Developing an in-pipe water pollution detection system ensures that the contaminated water will not enter the system in the event of water pollution, hence reducing the possibility of a water crisis. In this research, the design of the system was completed using SOLIDWORKS. ANSYS software was used for the deformation simulation analysis of the pH sensor and the ball valve installed in the system due to water pressure. The maximum deformation of the ball valve occurred at the edges of the ball valve for a fully-closed valve and the middle tip of the ball valve when the valve was opened 45°. The deformation is similar in these conditions due to the small area at the edges; thus, the pressure at the location is higher. For the pH sensor, the deformation of the body is approximately 5.7138×10^{-4} mm. The maximum stress is below the limit, proving that the sensor is suitable for operating in that position. Overall, the experimental results proved that the system is able to detect if the water is polluted by sensing the pH level changes in the water and managing the flow of the water pipe. In the future, by complementing this system with the Internet of Things (IoT), it can assist and alert workers in water treatment plants to detect water pollution in their treatment facility at the earliest stage. Thus, reducing operational costs and the closure of water treatment plants can be prevented in the future.

Keywords: pH contaminants, sensor, simulation, valve, wastewater, water pollution

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INTRODUCTION

Water pollution in Malaysia is generally caused by point and non-point sources. The point source is from sewage treatment plants, agro-based industries, and animal farms, whereas non-point sources are from diffused, such as agricultural activities and surface runoffs. Human activities, such as dumping illegal waste into the river or human residence near the river without a proper sewage system, can also contribute to this disaster (Dalun & Abdullah, 2021).

Providing clean and safe water to the community is a basic requirement in life. Efficient water quality monitoring is essential for water management and water pollution prevention as water pollution problems significantly affect our daily lives (Yuan et al., 2018). Furthermore, the demand for clean and safe water increases as the increasing human population depletes more water resources every year. Therefore, improving water resource management technology is essential to ensure that the water environment is managed correctly. In recent studies, the use of Internet of Things (IoT) technology has been highly considered for monitoring water quality in real-time to guarantee safety (Abdulwahid, 2020). According to another study, a low-cost and innovative water monitoring system can be developed, utilising the IoT to monitor water's real-time quality and quantity (Madhavireddy & Koteswarrao, 2018). However, the analysis of the working system components has been under-reported.

Budiman et al. (2019) developed a monitoring and control system of ammonia and pH levels for fish cultivation using Raspberry Pi 3B. The results revealed that the system could be controlled automatically or manually, where the monitoring system was connected through a mobile phone application to inform if there is an increase of pH or ammonia levels in the water (Budiman et al., 2019). The Arduino UNO microcontroller will send the impulse to the ESP32 microcontroller to connect the water detection system with people miles away through messages or make a direct call to the phone. In another study, the real-time data and decision-making generated using fuzzy logic were developed to check water contamination levels (Priya et al., 2019). However, none of these works evaluated the effect of water pressure on the deformation of the added components, such as sensors and valves, into water pipes.

A water pollution detection system in the pipe can potentially be the first barrier to prevent polluted water from affecting clean water sources and water treatment plant operations. In this research, the system is expected to detect any chemical changes from the difference in pH level in the water through a sensor detection system. A motorised ball valve was also added to prevent the polluted water from entering the treatment facility in the water treatment plant. The simulation analysis focused on the deformation effect of running water on the added pH sensor and the ball valve. A simplified system prototype was developed and tested to prove the concept mentioned in this study.

METHODS

Design of the System in Solidworks

The in-pipe water pollution detection system was designed using SOLIDWORKS 2018. The design includes a motorised ball valve and a sensor. Then, the detection system was simulated by Arduino. The coding represents a response for the motorised valve to open or close. The coding also shows the reaction by an alarm when the pH level in the water is lower than 5.5. Figure 1 shows the design of the in-pipe water pollution detection system.

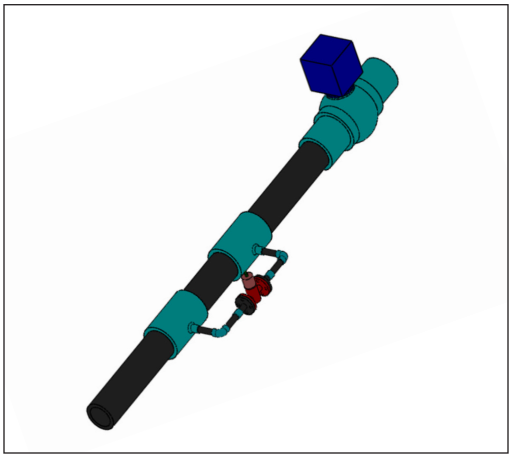


Figure 1. In-pipe water pollution detection system

Proof of Concept Using ANSYS

The system is proposed to be installed in a water treatment plant and located at the inlet where water from the river will enter the plant. Thus, the water flowing through the pipe will exert pressure on the valve when the system detects the polluted water through the pH sensor. Therefore, the analysis focused on two critical parts: the pH sensor and the motorised ball valve. The study of stress and deformation was conducted on these two components. From the analysis, suitable materials and dimensions for the pH sensor and valve were proposed.

Proof of Concept of Sensor and Valve

Several sensors were used in a study by Meghana et al. (2019), such as temperature, pH, water level, and turbidity sensors. The results showed that sensors play a crucial role to monitor and detecting the quality of water. An automated system was designed by Supriadi et al. (2019) to monitor the pH level of an aquaponic plants system utilising Arduino and Raspberry Pi microcontrollers, and the results revealed that the pH sensor worked properly, and the information about pH could be observed clearly through the LCD. Based on these findings, a pH level sensor was attached to Arduino. The sensor will detect any changes in the pH level of water.

The whole concept in this study works based on the setting that when the pH level in the water is within 5.5–9.0, no changes will occur to the system. However, when the pH level is less than 5.5 or higher than 9.0, the sensor will send an impulse to the Arduino UNO microcontroller. After receiving the impulse from the sensor, it will signal the motor to move, which will close the valve in the pipe. The microcontroller will also send the signal to activate the alarm as an indicator that the pH level in the water is increasing or decreasing and send the impulse to the ESP32 microcontroller to connect the water detection system with people miles away through messages or make a call to their mobile phone. Once the sensor detects that the pH level falls within the acceptable range (5.5–9.0), the Arduino UNO microcontroller will signal the motor to open the valve again and allow the water to flow normally into the water treatment plant. Figure 2 shows the flow chart for the proposed water pollution detection system.

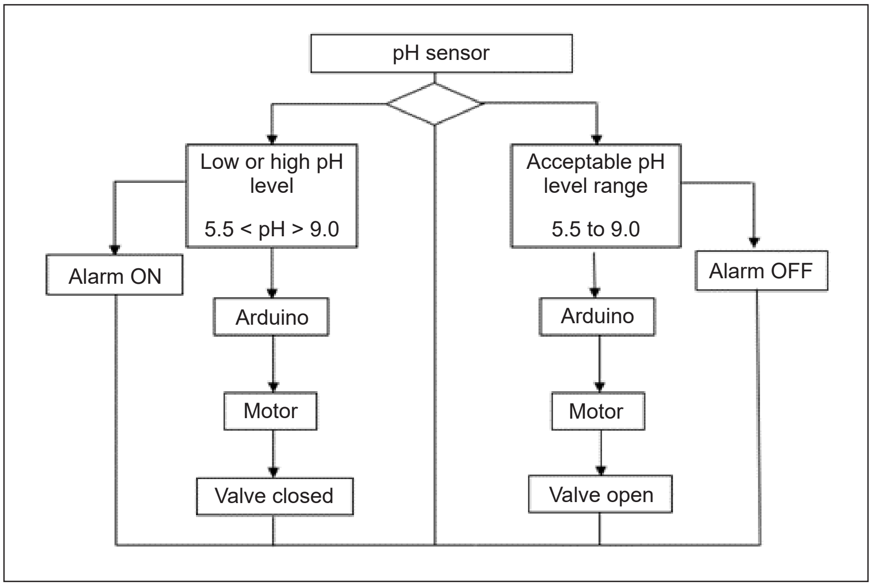


Figure 2. The flow chart for the water pollution detection system

Computational Setup

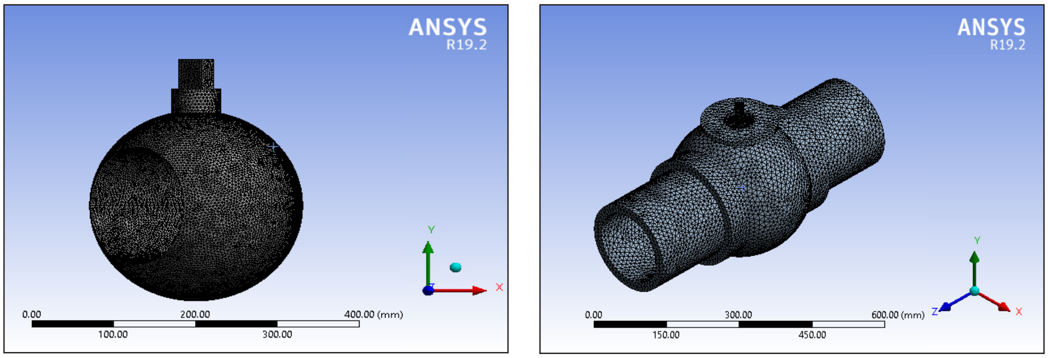
The simulation of the critical part (i.e., the ball valve) was done using ANSYS 19.2. The ball valve was chosen as a vital part to be analysed because the valve will close the channel once the sensor detects any pH changes in the water. The ball valve will experience pressure load from the flowing water in the pipe when the valve is moved to close the channel. Thus, the analysis of the ball valve was performed to analyse structural deformation and stress that may occur on the valve.

Boundary Condition. In the static structural system analysis, the initial pressure condition of the flowing water in the pipe was assumed to be 1.2937×10^5 Pa based on the theoretical calculation. The fixed support was applied on both ends of the pipe.

Material Data. The material used in the simulation of the ball valve was stainless steel, while the material for the pH sensor was Epoxy S-glass UD. The material data were obtained from the ANSYS software.

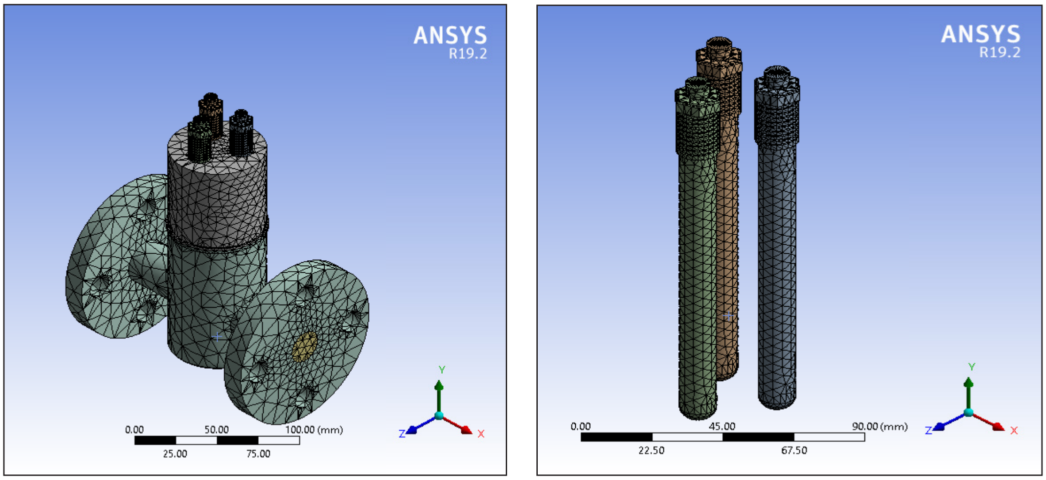
Grid Generation. The fine tetrahedral mesh method and body sizing were employed in both ball valve and pipe for mesh generation. Figures 3 and 4 show the final computational mesh used for the numerical analysis.

Mesh Independence Test. Before proceeding with the final solution, a mesh independence test must be carried out to verify the grid independence of the numerical solution. A mesh independence test was conducted to minimise the solution's numerical uncertainty and obtain mesh convergence. Five sets of meshing schemes with the element size of 4–7 mm and three different mesh generation methods (i.e., coarse, medium, and fine tetrahedral) were tested. By increasing the number of elements, mesh independence was examined by comparing the equivalent stress. Figure 4 illustrates the dependence of equal stress on the number of elements. According to Figure 5, the total number of elements of 713,257 fine tetrahedral was taken for the numerical solution.



(a) (b)

Figure 3. Generated mesh: (a) ball valve and (b) pipe



(a) (b)

Figure 4. Generated mesh: (a) sensor and (b) sensor holder

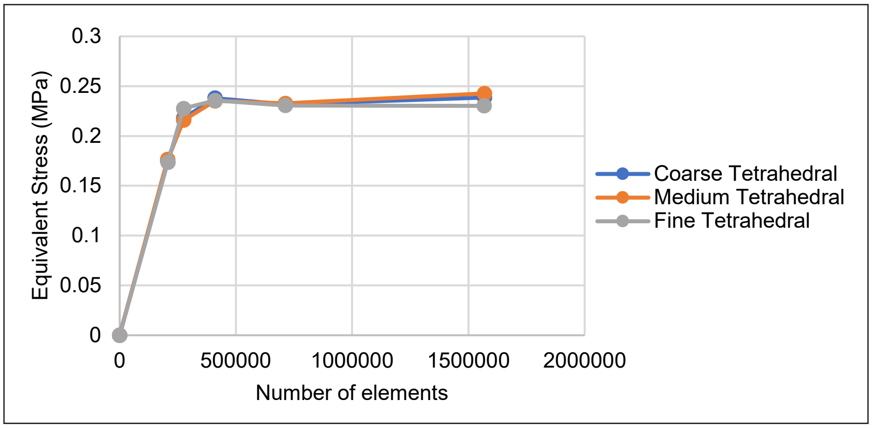


Figure 5. The dependence of equivalent stress on the number of elements

RESULTS AND DISCUSSION

Valve-Static Structural Analysis

For the valve analysis, the simulation was done for two positions of the ball valve. The first position is a half-open valve with a 45° opening, and the second is a fully closed valve. The simulation was done for these positions to observe the structural change occurring on the valve during the closing process. As the valve could not be simulated while moving like the actual process, the simulation was conducted individually at different angles to observe whether structural changes might occur during the closing of the channel in the pipe. The load that acts on the valve comes from the hydraulic pressure of the flowing water. Based on the theoretical calculation for the water, the pressure exerted on the valve is approximately 1.2937×10^5 Pa. The load focuses on the valve's front face in contact with the water while closing the pipe. Figures 6 and 7 show the equivalent stress of the ball valve for two different positions (45° and 180°). Figures 8 and 9 show the total deformation of the ball valve for two different positions (45° and 180°). Table 1 presents the simulation results for the ball valve at 45^O opening and fully closed conditions.

Table 1

Simulation results for ball valve of 45^O opening and fully closed conditions

Ball valve (45^O opening)	
Maximum Equivalent Stress	0.23059 MPa
Maximum Total Deformation	5.5773×10^{-5} mm
Minimum Equivalent Stress	7.4604×10^{-6} MPa
Minimum Total Deformation	3.5102×10^{-10} mm
Ball valve (fully closed)	
Maximum Equivalent Stress	0.97885 MPa
Maximum Total Deformation	0.00022243 mm
Minimum Equivalent Stress	8.2291×10^{-6} MPa
Minimum Total Deformation	5.4661×10^{-10} mm

Based on Figure 6, the maximum stress at the position for 45° occurred at the top and bottom edges of the ball valve, while the minimum stress occurred at the middle edges of the ball valve. The stress is distributed to the top and bottom of the valve. Based on Figure 8, the maximum

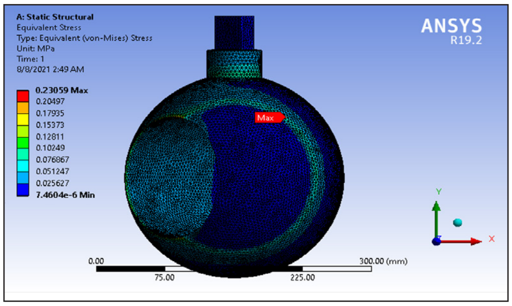


Figure 6. Equivalent stress of ball valve (45°)

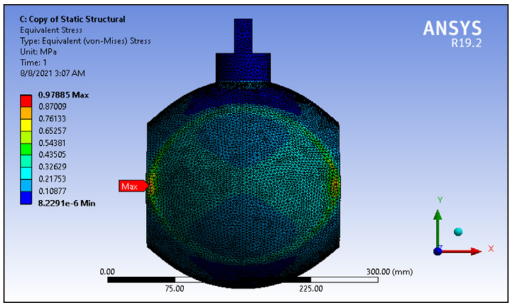


Figure 7. Equivalent stress of ball valve (fully closed)

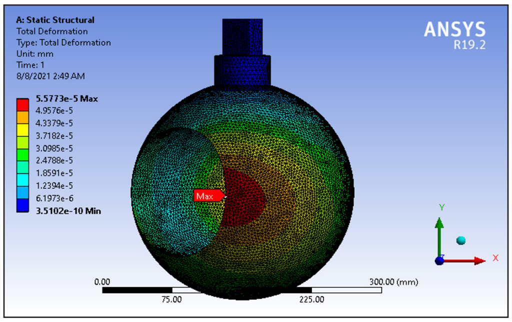


Figure 8. Total deformation of the ball valve (45°)

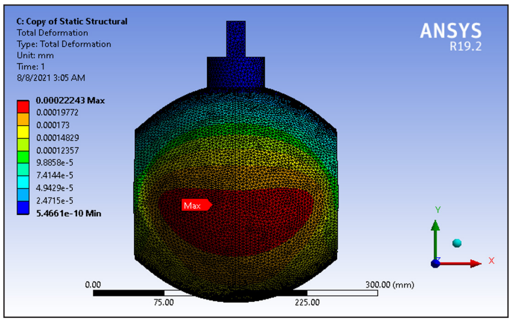


Figure 9. Total deformation of the ball valve (fully closed)

deformation occurred at the middle tip of the ball valve. In this condition, it is easier to deform under pressure from the turbulent flow in the pipe. Therefore, deformation will quickly occur at that location. Sharp edges also tend to have high-stress concentrations due to the small area at the edges. Nevertheless, the total deformation is minimal, 5.5773×10^{-5} mm, making no significant changes to the ball valve. Thus, this ball valve design is accepted to be used in the project.

Based on Figure 7, the maximum stress for the ball valve for the fully closed position is at the end of the ball valve edges. The stress is distributed around the side body of the ball valve. The stress was higher at the end of the edges compared to the middle of the ball valve. Based on Figure 9, the ball valve's maximum deformation also occurred along the middle body to the bottom of the ball valve. It is because of the pressure distributed load. As the shape of the ball valve is a sphere, higher deformation occurs at the bottom of the valve due to gravitational forces. However, the total deformation is minimal, 2.2243×10^{-4} mm. The amount of the deformation will not break the ball valve structure due to the high thickness at the sides. Thus, this ball valve design is accepted to be used in the project.

Sensor-Static Structural Analysis

The sensor is the main component to detect any pH changes in the water along the pipe. The analysis of the sensor was conducted to observe the equivalent stress and total deformation occurring on the sensor. The assigned material of the sensor in this simulation is Epoxy S-Glass. Even though this material is the most suitable material for the pipeline industry, it is also necessary to observe the static structural changes on the sensor due to water pressure in the pipe. Table 2 shows the simulation result for the sensor.

Table 2
Simulation results for the sensor

pH Sensor	
Parameter	Value
Maximum Equivalent Stress	0.20432 MPa
Maximum Total Deformation	0.00057138 mm
Minimum Equivalent Stress	8.897e^{-8} MPa
Minimum Total Deformation	3.1027e^{-7} mm

The maximum stress and deformation occurred on different parts of the sensor. From Figure 10, it can be seen that the maximum equivalent stress occurred at the middle region of the electrode with the value of 0.20432 MPa. The continuous turbulent flow in the pipe may cause the sensor to be exposed to the high pressure of the water. Thus, the design of the sensor holder in the pipe may be helpful as a protective cover for the electrode to overcome the high-stress region occurring on the sensor. Meanwhile, the maximum deformation of the sensor occurred at the end component with a value of 5.7138 × 10^{-4} mm. The deformation may appear in this region when this sensor is used in real-life applications because the sensor's electrode is made of glass. As the stress and deformation value that occurred on the sensor is minimal, it will not affect the structure of this sensor when placed in the pipe because this sensor is placed in the bypass line. Furthermore, the sensor is specifically designed to be used in the pipe. Figures 10 and 11 illustrate the equivalent stress and total deformation of the sensor.

Experimental Analysis

In the proof-of-concept study, a simplified prototype was developed and tested. Three solutions were used to represent the acid, neutral, and alkaline pH range. The pH level

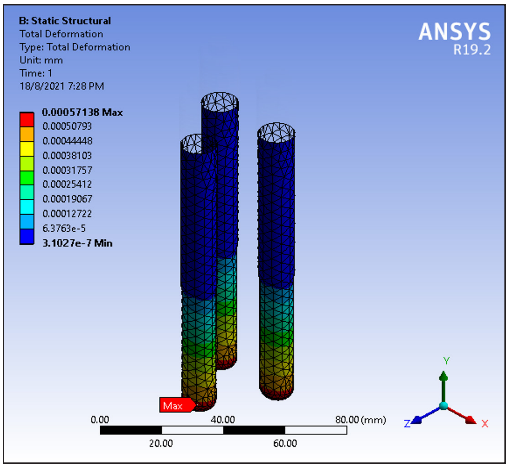


Figure 10. Sensor equivalent stress

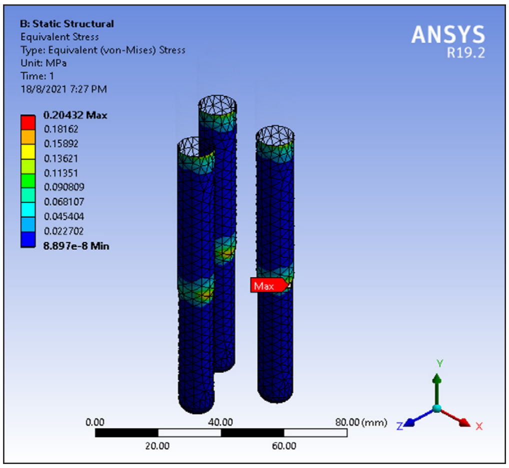


Figure 11. Sensor total deformation

of the solutions was determined using litmus paper. The ranges of pH levels obtained for Coca-Cola, tap water, and liquid body wash are between 3 and 4, between 5 and 6, and between 7 and 8, respectively. The experimental value of the pH was obtained using the Arduino pH sensor. From Table 3, the pH level of the solution detected by the pH sensor for Coca-Cola is marginal for every reading. All the experimental values of the pH for Coca-Cola are below the actual pH level tested using litmus paper. For tap water, the experimental values detected by the pH sensor range between 5 and 6, which agrees with the actual pH level. The reading pattern for the experimental values increased slightly from the first reading until the third reading, with a small margin between each experimental value obtained. Finally, the reading for the liquid body washes detected by the pH sensor has a more significant margin than tap water and Coca-Cola. The reading increased significantly from the first reading until the third reading. Moreover, the experimental values for the second and third readings of the liquid body wash are above the actual pH level.

Based on the results and observation obtained, the factor influencing the reading of experimental value using a pH sensor depends on the accuracy and sensitivity of the sensor. The pH sensor used in this project has moderate accuracy and high sensitivity with the surrounding solutions. The pH sensor should be of high quality and accuracy to increase the accuracy of the result in future studies or its application. Another limitation of the pH sensor used in this study is its ability to accurately detect the pH range only when the water flow is almost stagnant.

Due to high velocity and pressure inside the pipe during operation, the pH sensor used in this study can determine the pH level of the solutions, but the reading is less accurate. Thus, a bypass pipe was designed and installed along the water distribution line because the sensor can give a more accurate pH reading with lower velocity and pressure of water. Other than that, the viscosity of the liquid body wash influenced the pH reading, where the liquid body wash coated the pH electrode. Therefore, the electrode needs to be cleaned thoroughly before being tested with different solutions to avoid errors in the experimental data obtained. Another consideration for installing the sensor is scheduled maintenance or cleaning to ensure accurate sensor reading. Figure 12 shows the prototype of the in-pipe water pollution detection system consisting of a water tank, polyvinyl chloride (PVC) pipe, a pH sensor, and a motorised ball valve. During the prototype test, the system functioned

Table 3
Experimental pH reading

Test	Type of solution	pH level	Experimental value			Average reading
			1st reading	2nd reading	3rd reading	
1	Coca-cola	3-4	2.21	2.22	2.25	2.23
2	Tap water	5-6	5.34	5.52	5.92	5.59
3	Body wash liquid	7-8	7.03	8.54	8.93	8.17

as expected. When the pH level falls out of the range, the ball valve closes the water flow. Once the pH returned to the acceptable range, the ball valve opened, and the water flow continued in the pipe.

Figure 12. Actual prototype of in-pipe water pollution detection system

CONCLUSION

In conclusion, developing an in-pipe water pollution detection system requires the examination of various parameters. In this study, finite element analysis has become a core process in completing this work because it predicts possible failure within the structure. The analysis of deformation and stress inside the material allows designers to observe the theoretical results when the parts are in working order. Thus, from the design analysis on the valve assembly at different opening positions, the maximum stress on the valve with 50% opening is 0.23059 MPa and 0.97885 MPa for a fully closed valve. The value is below the yield of stress for stainless steel, which is 215 MPa. The maximum deformation is 5.5773×10^{-5} mm for 50% valve opening and 2.2243×10^{-4} mm for a fully closed valve. Therefore, the boundary condition applied in the ball valve is within the limit, and the part is safe to be used in this application. For the pH sensor, the deformation of the body is approximately 5.7138×10^{-4} mm. The maximum stress is also below the limit, proving that the sensor is suitable for operating in that position. In the proof-of-concept study, the prototype developed and the experiment conducted show that the system can function properly. Some limitations that need to be considered are also highlighted to improve the system. Hence, it can be concluded that this concept has a bright future to be implemented in the water treatment industry, and it can be complemented with the implementation of IoT. Nevertheless, more aspects of water contamination other than pH, such as nitrate level, dissolved oxygen in water, free residual chlorine, ammonia level, and others, have to be assessed as they also contribute to the aspect of water pollution (Varsha et al., 2021). Thus, this added feature will increase the capability and the efficiency of the water management system in the country.

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