Science and Engineering Connect, ISSN 3027-7914 (Online)
Vol. 48 No. 1 pp. 69-90 (2025)

Research Article

Flow Measurement Using Bypass Flow Meters for Smart Farming Applications

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Received 24 January 2025; Revised 5 March 2025; Accepted 17 March 2025

Abstract

Background and Objectives: Accurate flow measurement is essential in order to improve water efficiency and productivity in any irrigation system. Precision irrigation is a technique that optimizes water usage by utilizing technology to deliver the right amount of water according to crop requirement. In smart farming, this approach relies on precise water monitoring and control. However, traditional flow meters often pose significant challenges due to their high installation costs, particularly for large-diameter pipes. Bypass flow meter (BPF meter) offers a cost-effective alternative resolution for flow measurement. BPF meter measures flow in large-diameter pipes by diverting a portion of the flow through a smaller bypass pipe mounted with a flow meter. Although the BPF technique has been around for some time, its application and performance in flow measurement are still underexplored. Therefore, this study sought to fill the gap by presenting the concept, performance, and practical implementation of BPF meter as a cost-effective and accessible alternative for water flow measurement in smart farming applications.

Methodology: Experiments were conducted using BPF meters with different main pipe to bypass pipe diameter ratios (D/d = 2:1, 2.5:1, 3:1, and 4:1). To ensure consistency across experimental settings, the lengths of all pipes were fixed to focus on the examination of the effect of the diameter ratio on BPF meter performance. The bypass flow rate (Q_{BP}) and the total flow rate (Q) were quantified under regulated experimental settings. Each pipe diameter configuration was tested at different flow rates, with each flow rate subjected

to a minimum of three tests to verify dependability and to reduce experimental errors. The relationship between Q_{BP} and Q was then analyzed and is expressed by the equation $Q=KQ_{BP}$, where K is the loss coefficient, which is dependent on pipe configuration. Statistical parameters, including the coefficient of determination (R^2), root mean square error (RMSE), and mean percentage error (MPE) were employed to evaluate the accuracy and reliability of the model for each configuration.

Main Results: The main findings reveal that the total flow rate (Q) is directly proportional to the bypass flow rate (Q_{BP}), and this relationship is influenced by the pipe diameter ratio (D/d). The findings indicate a robust linear relationship between Q and Q_{BP} ($R^2 > 0.99$), with minor errors across all configurations. Larger D/d ratios demonstrate higher K values, indicating increased sensitivity to bypass flow measurement. The consistency of the K values across pipe configurations supports the robustness of the proposed calibrated model and illustrates the adaptability of the BPF meter for varying pipe diameters. While the BPF meter maintains accuracy across all pipe configurations, larger pipe diameters are correlated with minor increase in the measurement variability. Therefore, the selection of a suitable pipe diameter ratio (D/d) is essential for maintaining the accuracy of BPF meter. By considering these design aspects, BPF meter could be accurately calibrated to meet the different demands.

Conclusions: The study validated the suitability of BPF meters for accurate water flow measurement in smart farming applications. The variation of the K coefficient across different D/d ratios illustrates the flexibility in adapting the BPF meter for different applications. The results also show that the choice of pipe diameter (D/d ratio) significantly affects the accuracy and applicability of BPF meter. Smaller D/d ratios are more suitable for systems with lower flow rates, while larger ratios are more suitable for higher flow rate systems. Nevertheless, the calibration equation ensures that BPF meter can be effectively used in various irrigation applications.

Practical Application: This study provides a practical framework for the implementation of BPF meter as a viable and cost-efficient alternative to conventional flow measurement devices. BPF meter can be practically applied to enhance water management in smart farming or any irrigation applications. Farmers would be able to monitor and regulate water usage in real-time through the use of BPF meter. Integrating BPF meter with IoT systems would allow precision irrigation to be implemented, optimizing water allocation to crops according to plant water requirements, hence improving productivity, conserving water resources, and providing significant benefits to agricultural systems with limited resources.

Keywords: Bypass System, Flow Meter, Flow Rate, Smart Farming, Flow Measurement

Introduction

Precision farming, also referred to as smart agriculture, is the application that emphasizes the use of various information and communication technologies in the management of physical farms to improve productivity [1-2]. In smart farming settings, water measurement and quantification are essential for optimizing water usage and enhancing water efficiency [3]. The efficacy of smart farm irrigation relies on accurate irrigation scheduling and the assessment of the appropriate quantity of water applied depending on plants and soil conditions [4-5]. Thus, the ability to measure water flow is essential for the efficacy and sustainability of irrigation systems in precision farming.

Irrigation technology has evolved significantly and led to the development of various methods such as sprinkler irrigation, drip irrigation, and micro-irrigation [6]. An efficient irrigation system required that the operator have complete control of the water with the ability to measure it at various points throughout the system [7]. Flow measurement is crucial for effective water management; without it, managing water resources is not possible and can cause waterlogging or wasting resources [7-8]. Flow measurement typically relies on the principle of continuity [9]. There are various flow measuring devices available, and common methods for measuring pipeline flow in agricultural irrigation include turbine, vortex, differential pressure, ultrasonic measurements, and electromagnetic flow meters [8, 10-13].

Flow measurement systems operate based on two fundamental methods, namely weighing and volumetric methods [14-16]. In the weighting method, water is passed through the flow meter under test for a predetermined time. The flow rate is determined by measuring the weight of water collected during this period and averaging it with the flow rate indicated by the meter during the collection interval [16]. Whereas the volumetric method determines the flow rate by measuring the volume of water that passes through the meter over a specific time. This is achieved using calibrated containers or tanks with known capacities [17]. The flow rate is then calculated by dividing the measured volume by the elapsed time. Alternatively, flow rate can be obtained through flow sampling or bypassing flow from main pipelines [18].

Bypass flow meters have demonstrated high effectiveness in various water applications. There is limited research available in this field, despite the flow meter appearing in literature in the early 20th century [19]. Studies have investigated their design and implementation, such as those conducted by Torigoe [20] proposed flowmeter measures total flow by dividing it between a main conduit and a bypass conduit. The total flow rate is calculated using the flow rate in the bypass conduit and the bypass rate, obtained from the pressure differential in the main conduit using Bernoulli's equation. Samani [21] introduced a cost-effective and energy-efficient bypass system for flow measurement, outlining two calibration methods to ensure accuracy in relating the bypass flow rate to the total flow. Chu-wen, et al. [22] examined bypass flow meters for measuring flow in large-scale pipes by analyzing parallel pipe flow and conducting experiments with a modified centrifugal pump test system. Kumar, et al. [23] investigated alternative bypass flow meters for sloped pipelines, demonstrating their efficacy in minimizing head loss and enhancing operational cycles while addressing site-specific limitations and operational difficulties.

Despite these contributions, research on bypass flow meters remains underexplored in the field of flow measurement technology. It seems that in the pursuit of new technologies, the focus on fundamental innovations, such as bypass flow meters, has been somewhat overlooked. While advanced systems dominate current research, revisiting and refining fundamental technologies could address practical challenges and enhance their applicability in modern contexts. This highlights the significance of integrating foundational techniques with modern advancements. Current flow measurement techniques are often expensive, energy-intensive, and not always suited to the needs of small-scale farming systems. This presents a significant opportunity to develop low-cost, efficient, and accurate water flow measurement tools. To address these challenges, this study proposes a bypass flow meter as a potential cost-effective alternative tool for monitoring water usage in a smart farm setting.

Principle of Bypass Flow Meters

Bypass flow meter, referred to as the BPF meter, is a device used to measure the flow rate of water in large pipes. It involves installing a flow meter on a smaller bypass pipe instead of installing a meter directly on the main pipe. It operates by diverting a small portion of the main flow through the bypass pipe (Figure 1), where the flow rate is measured. This design allows for the measurement of the bypass flow, which can then be used to estimate the total flow rate in the main pipe.

The fundamental principles of fluid dynamics serve as the foundation for the BPF meter's design. First, the continuity equation, also known as the principle of mass conservation, states that the total flow rate entering a system must equal the total flow rate leaving it [24-25]. Second, the principle of energy conservation states that the total energy (pressure and velocity) remains constant along a streamline as long as no additional force is added and energy losses are taken into consideration [26].

In order to estimate the total flow correctly, it is necessary to know the bypass rate, the exact ratio between the total flow and the bypass flow. Since the conditions generally differ between the main conduit and the bypass conduit, the bypass rate usually changes with the variations in the total flow.

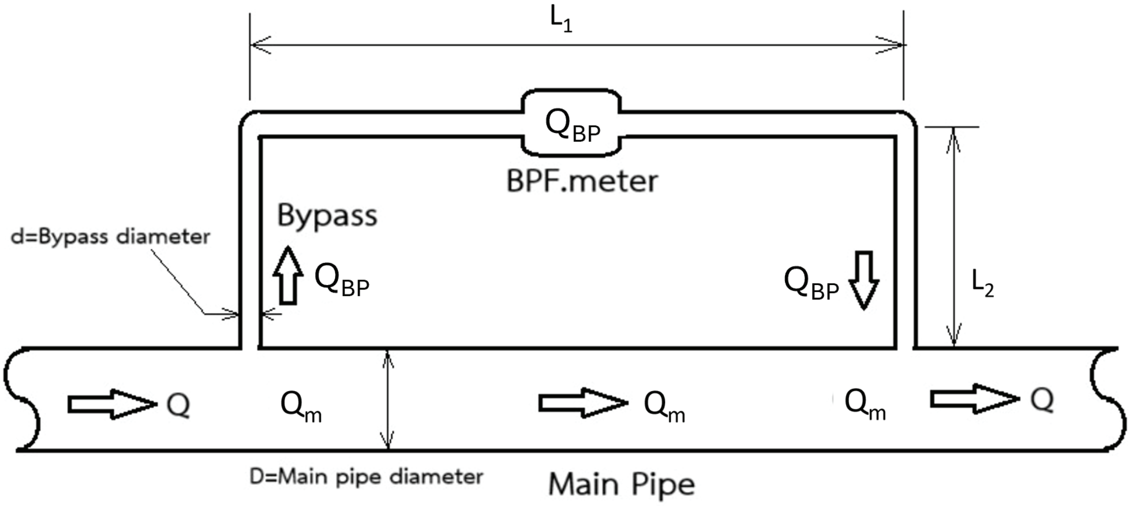

Figure 1 Top view of a conceptual diagram of the proposed bypass flow meter (BPF meter) system

In the BPF system, the experiment is conducted to establish a relationship between the flow rate through the bypass pipe (Q_{BP}) and the total flow rate (Q). The main pipe, which has a diameter of D, is connected to a bypass pipe with a diameter of d. The total length of the bypass pipe is $L_1 + 2L_2$ meters, where L_1 is the length of the main pipe and L_2 is the length of the bypass pipe.

Mass Conservation (Continuity Equation)

As water with a flow rate of Q reached the bypass section, it is separated into two streams;

1. Q_m: the portion of water that continues through the main pipe
2. Q_{BP}: the portion of water that flows through the bypass pipe and is monitored by the BPF meter.

After passing through the bypass pipe, the flow then returns to the main downstream, as shown in Figure 1. From fluid dynamics principles, the total flow rate through the system is the sum of the flow rate in the main and bypass pipes. As determined by the continuity equation:

$$Q = Q_m + Q_{BP} \quad (1)$$

Where

Q = total flow rate in the system (m^3/ s).

Q_m = Flow rate through the main pipe (m^3/ s).

Q_{BP} = flow rate through the bypass pipe (m^3/ s).

This equation assumes that no water is lost or added during the flow split, ensuring the conservation of mass.

Head Loss in Main and Bypass Pipes

Head loss in the main pipe uses the Darcy-Weisbach formula to calculate head loss due to friction in the main pipe [27].

$$\text{Head loss (main)} = f_m * \frac{L_1}{D} * \frac{V_m^2}{2g} \quad (2)$$

For the bypass pipe, the head loss is extending the Darcy-Weisbach equation to include additional minor losses in the bypass pipe. When water flows through the bypass route, the pressure head is then:

$$\text{Head loss (Bypass)} = \left(f_{BP} * \frac{L_1 + 2 * L_2}{d} + \sum k\right) * \frac{V_{BP}^2}{2g} \quad (3)$$

Where

V_m = mean flow velocity in the main pipe (m/ s)

V_{BP} = mean flow velocity in the bypass pipe (m/s).

D = diameter of the main pipe (m).

d = diameter of the bypass pipe (m).

f_m = Darcy's friction factor of the main pipe.

f_{BP} = Darcy's friction factor of the bypass pipe.

L_1 = length of the main pipe (m).

L_2 = length of the bypass pipe (m).

$\sum k$ = the sum of minor loss coefficients in bypass pipes.

Energy (Head) Conservation

From equations (1) - (3), we assumed the water that flows into the main and bypass pipes experience the same amount of energy loss (head loss), therefore, the relationship between velocity in the main pipe (V_m) and velocity in the bypass pipe (V_{BP}) is expressed as:

$$\frac{V_m}{V_{BP}} = \sqrt{\frac{\left(f_{BP}*\frac{L_1+2*L_2}{d}+\sum k\right)}{f_m*\frac{L_1}{D}}} \quad \textbf{(4)}$$

From equations (1) – (4), the total flow rate (Q) can be obtained using the fluid dynamics principle [28].

$$Q = V_m * A \quad \textbf{(5)}$$

Where

A = cross-sectional area of flow (m^2), calculated as:

$$A = \pi\left(\frac{D^2}{4}\right) \quad \textbf{(6)}$$

By substituting the expression for A into the equation, the total flow rate (Q) is the sum of the flow rate through the main pipe based on its velocity, cross-sectional area, and the bypass flow rate (Q_{BP}).

$$Q = V_m \pi \left(\frac{D^2}{4}\right) + Q_{BP} \qquad (7)$$

This expression combines the flow rates from the main and bypass pipes to find the total flow rate of the system. Then we substitute expressions for V_m and V_{BP} into Q (total flow rate). Therefore,

$$Q = \left(\sqrt{\frac{\left(f_{BP} * \frac{L_1 + 2*L_2}{d} + \sum k\right)}{f_m * \frac{L1}{D}}} V_{BP}\right) \pi \left(\frac{D^2}{4}\right) + Q_{BP} \qquad (8)$$

$$Q = \left(\sqrt{\frac{\left(f_{BP} * \frac{L_1 + 2*L_2}{d} + \sum k\right)}{f_m * \frac{L1}{D}}}\right) \left(\frac{D}{d}\right)^2 Q_{BP} + Q_{BP} \qquad (9)$$

Further simplification leads to,

$$Q = \left\{1 + \left(\sqrt{\frac{\left(f_{BP} * \frac{L_1 + 2*L_2}{d} + \sum k\right)}{f_m * \frac{L1}{D}}}\right) \left(\frac{D^2}{d^2}\right)\right\} Q_{BP} \qquad (10)$$

1.1. Coefficient K

Finally, defining the proportionality constant K, Q can be expressed as:

$$Q = K * Q_{BP} \qquad (11)$$

Where

K = a coefficient factor for converting Q_{BP} (bypass flow rate) to Q (total flow rate).

The coefficient K is a crucial factor in bypass flow meter (BPF) design, used to relate the bypass flow (Q_{BP}) to the total flow (Q) in the system. Its value depends on various factors related to the configuration and hydraulic properties of the BPF system, such as diameter ratio (D/d), length of pipe (L_1, L_1+2*L_2), and loss coefficients, which the geometric structure determined. Therefore, equation 11 shows that the total flow rate (Q) is directly proportional to the bypass flow rate (Q_{BP}), with K capturing the system resistance characteristics.

Methodology

Experimental Setup

The experimental system was designed and set up as illustrated and the conceptual diagram of the proposed bypass flow meter (BPF meter) are shown in Figure 2 and Figure 3. The step-by-step process for its operation to determine the K-factor of the bypass flow meter (BPF meter) is explained below.

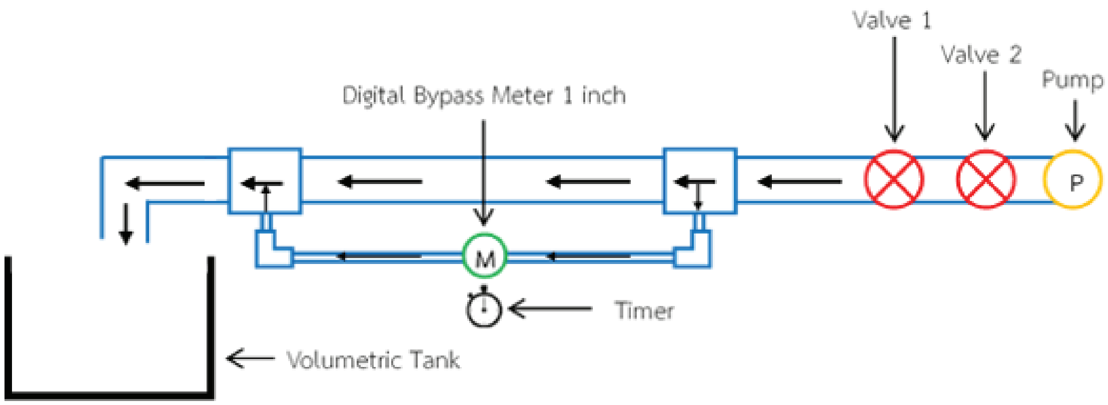

Figure 2 A conceptual drawing of the proposed bypass flow meter showing the main pipe, the bypass pipe, the control valves, the water meter, the volumetric tank, and the timer, which are integrated into the flow measurement process

In our experiments, we tested four main pipe diameters (D) of 2, 2.5, 3, and 4 inches, while the diameter of the bypass pipe was kept at 1 inch. The experiment aimed to evaluate the relationship between total flow rate (Q) and the bypass flow rate (Q_{BP}), which may differ due to the diameter ratios (D/d). The BPF meters were tested in four configurations based on the diameter ratio D/d, including 2:1, 2.5:1, 3:1, and 4:1, where

D: Diameter of the main pipe (in inches).

d: Diameter of the bypass pipe (in inches).

Additionally, for all configurations, the pipe lengths were fixed as follows:

L_1 = 1.0 m (length of the main pipe segment).

L_2 = 0.155 m (length of the bypass pipe segment).

These fixed lengths allowed for consistency in the experimental setup of the impact of the diameter ratio (D/d) on the bypass flow meter's performance.

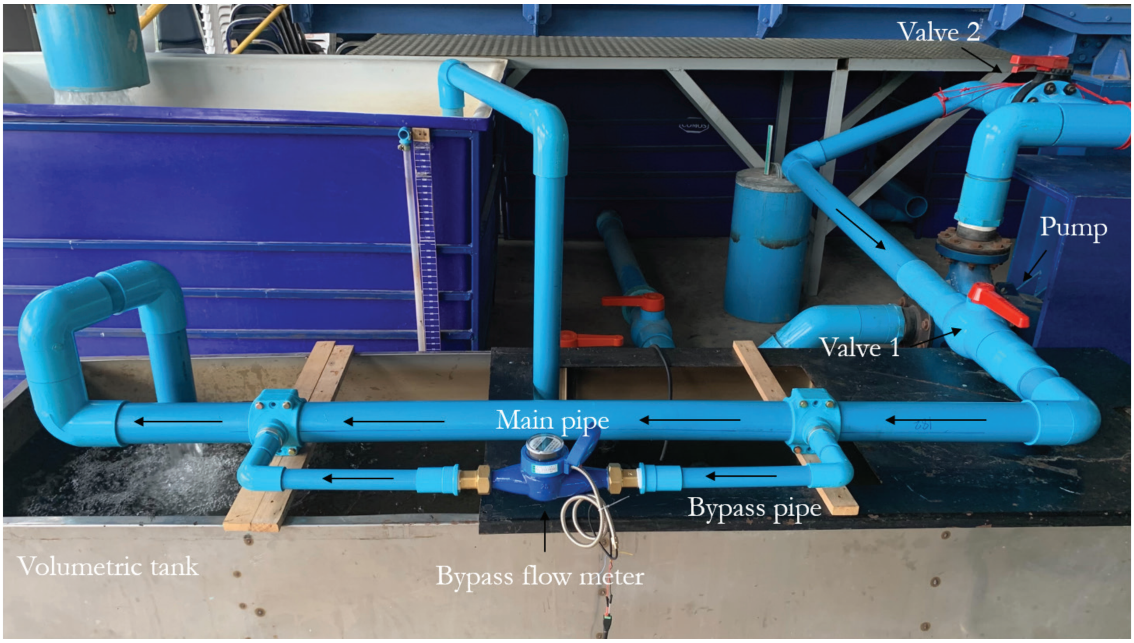

Figure 3 A flow measurement system setup using a bypass flow meter in a controlled water environment. The system consists of PVC pipes connected in a closed-loop setup, with an inline flow meter installed in the bypass line

Experimental Procedures

To determine the flow rates of the main and bypass pipes under different pipe configurations, the experiment proceeds with the detailed procedure as follows: First, valve 1 was adjusted to regulate the total flow rate (Q), extending from Q_{min} to Q_{max}, which aligns with the operational range of the pipeline system. Valve 2 was then opened, and the timer was started to monitor the flow duration. Valve 2 was also used to control the start and stop of water flow for measurement purposes.

The initial bypass flow meter (BPF meter) reading in the bypass line was recorded, and as the water meter reading changed, the starting volume was recorded. Upon the specified water level in the volumetric tank being reached, the water meter reading was re-evaluated, and any variation in volume was noted prior to stopping the timer. The second valve is subsequently closed.

The volumetric tank's water capacity was measured and divided by the elapsed time to determine the flow rate of the main pipe (Q). Similarly, the flow rate through the bypass pipe (Q_{BP}) was determined by dividing the water volume reported from BPF meter by the corresponding elapsed time. In order to ensure thorough data collection under various flow conditions, valve 1 was recalibrated to obtain a range of main pipe flow rates (Q) during the repetitions. This procedure is conducted for various flow rates with a minimum of three repetitions for each configuration to verify dependability and reduce experimental error.

Data Analysis

The data analysis aimed to explore how total flow rate (Q) and the bypass flow rate (Q_{BP}) were related for various bypass flow meter configurations, which were defined by the ration of the main pipe diameter (D) to the bypass pipe diameter (d). Additionally, the calibration coefficient (K) was determined for each configuration.

The relationship between Q and Q_{BP} was analyzed using a linear regression model with zero intercept to derive a correlation equation for each D/d ratio (as described by Equation 9). The slope of the regression line determined the calibration coefficient (K) for every D/d ratio. The sensitivity of the BPF meter performance to the pipe configuration was evaluated by analyzing the variations of K with different D/d ratios.

The coefficient of determination (R^2) was performed to measure the proportion of total variance explained by the model, value ranging from 0 to 1, with values closer to 1 indicating a perfect fit. The root mean squared error (RMSE) measures the differences between predicted and observed values, with smaller values suggest better model accuracy. Similarly, mean percentage error (MPE) was calculated to evaluate the accuracy and reliability of the derived equations by representing the forecast error as aa percentage of the observed values. Nevertheless, data visualization was performed using correlation graphs to illustrate key trends.

Results and Discussion

The relationship between the total flow rate (Q) and the bypass flow rate (Q_{BP}) varied depending on the pipe ratios (D/d) as detailed in Table 1. The linear equation Q = K*Q_{BP} represents the linear relationship with zero intercept for each configuration, where K is the calibrated coefficient obtained from experimental data for each configuration. The results show a high coefficient of determination (R^2) value across all configurations, indicating a very strong linear relationship. Additionally, the Root Mean Square Error (RMSE) and Mean Percentage Error (MPE) values provide insights into the precision of each equation.

Table 1 Statistical evaluation of the linear model with zero intercept for different D/d ratios, including R^2, RMSE, and MPE

D/d ratio	Equation: $Q=K*Q_{BP}$	R^2	RMSE	MPE
2	$Q = 56.1387*Q_{BP}$	0.9959	0.399	3.7
2.5	$Q = 108.9310*Q_{BP}$	0.9933	0.607	4.8
3	$Q= 139.3483*Q_{BP}$	0.9941	0.707	5.4
4	$Q= 319.3949*Q_{BP}$	0.9938	0.999	6.5

For each D/d ratio, the relationship between Q (total flow) and Q_{BP} (bypass flow) assumes that there is no intercept, meaning the total flow rate is directly proportional to the bypass flow (Figure 3). These relationships allow us to predict the total flow (Q) based on the bypass flow rate (Q_{BP}) for each specific configuration.

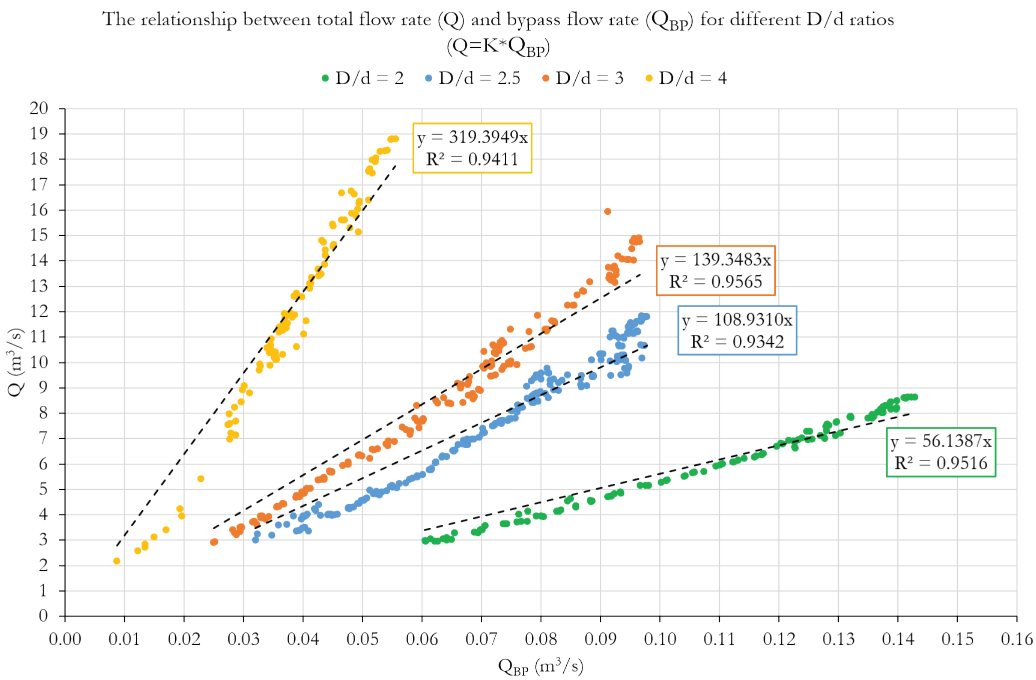

Figure 4 Test results for determining the K factor of the BPF meter at four D/d ratios

The high R-squared value indicates strong linear correlation for each configuration.

Variation in the Calibration Factor (K)

The calibrated coefficient (K) is essential in determining the precision of flow measurement for a specific D/d configuration. From table 1, the slope (K), which serves as the calibration coefficient, varies significantly across the different D/d ratios. For larger D/d ratios (e.g., 3:1 and 4:1), they tended to have a higher value of K (139.3483 and 319.3949, respectively). This suggests that in these configurations, the bypass flow captures a larger proportion of the total flow related to the total flow in these configurations. Whereas a smaller D/d ratio (e.g., 2:1) has a lower value of K (56.1387), indicating that the bypass flow represents a smaller proportion of the total flow.

When the relationship between K and D/d is analyzed, as shown in Figure 4, a strong linear relation is observed. The relationship between K and D/d can be expressed in the following equation:

$$K = 131.09*\frac{D}{d} -220.94 \; ; R^2=0.9599 \quad (12)$$

Where

K = a calibration constant

D = diameter of the main pipe (m).

d = diameter of the bypass pipe (m).

According to the coefficient of determination (R^2) values, which exceed 0.99 in all configurations, Figure 4 illustrates a strong linear relationship between Q and Q_{BP} for each configuration. The consistency in trends supports the robustness of the proposed calibration model and highlights the versatility of the BPF meter across varying pipe diameters.

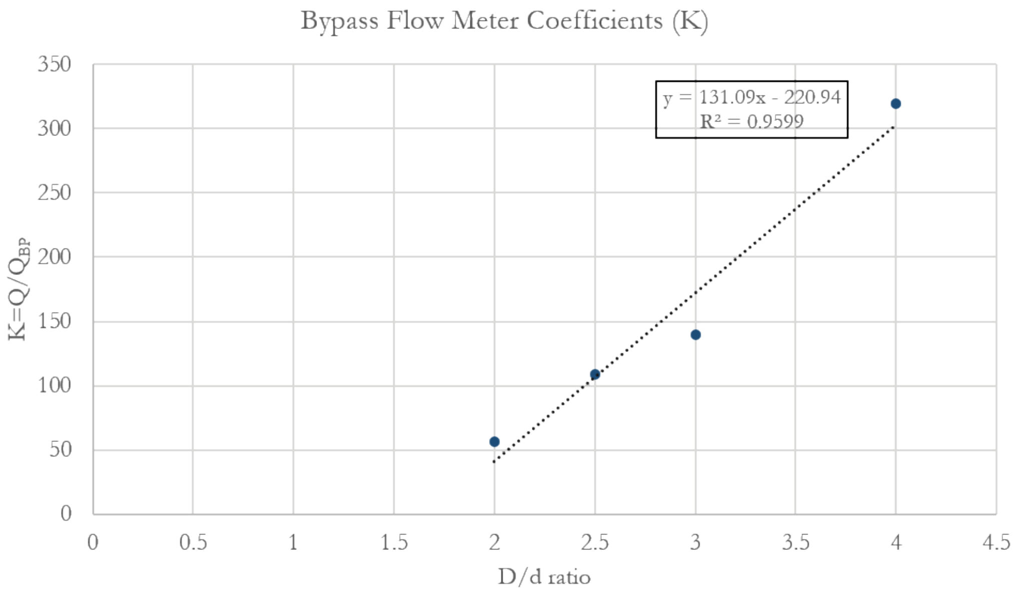

Figure 5 The relationship between BPF meter coefficient (K) and D/d ratio.

Figure 5 shows that the calibration coefficient (K) increases as the ratio of D/d increases. The relationship between K and D/d ratio was modeled using a linear model to fit for practical implementation in smart farm irrigation systems. Although a non-linear trend may be covering a broader range. The high R^2 value of 0.9599 indicates a strong and reliable linear relationship between K and the D/d ratio. The results suggest that the calibration coefficient can be effectively predicted based on the diameter ratio. This present pattern corresponds with the conceptual assumptions, where larger pipe diameters required greater bypass flow rates to maintain equivalent flow.

Precision and Accuracy

Although the coefficient of determination (R^2) values indicate great model fit, the root mean square error (RMSE) and mean percentage error (MPE) provide additional support for the accuracy measurement of each configuration. The RMSE values vary from 0.399 to 0.999, while the MPE values range from 3.7 to 6.5 percent.

The RMSE and MPE values slightly rise as the D/d ratio increases, but the R^2 value continuously elevates. This indicates that the bypass flow measuring technique works reliably across all configurations.

The result indicates that the choice of D/d ratio significantly affects the accuracy and applicability of the BPF meter. Smaller ratios are suitable for systems with lower flow rates, while larger ratios are preferable for higher flow rate systems. The calibration equations ensure that the BPF meter can be used in various applications effectively.

Nonetheless, we acknowledge the possibility of a non-linear relationship over an extended range of pipe diameter ratios (D/d). The decision to use a linear model is based on a practical engineering consideration to reduce the computational complexity. In our application, an error margin below 10 is accepted.

Considerations for Practical Design of BPF Meter

Accurate flow measurement is essential for enhancing water efficiency and economics in any irrigation system. For achieving precision in flow control, the calibrated coefficient (K) must be precisely determined for different D/d ratios to ensure accuracy in flow regulation.

The data indicate that while BPF meter is able to maintain uniform precision across different configurations, larger main pipe diameter results in somewhat greater variation. This is probably due to increased hydraulic complexity in larger systems. Nonetheless, the BPF meter offers a practical and versatile option for precision farming, especially in contexts where economic development is crucial. On the other hand, our BPF meter utilizes the linear equation $Q=KQ_{BP}$, facilitating precise water volume regulation (as V=K) in a smart farming environment. The application of a linear model simplifies flow measurement and irrigation control, offering effective water management. Whereas, a non-linear model would require handling supplementary factors, so augmenting computational complexities and affecting real-time processing performance, especially in regulating pump operation and stopping water flow. This feature enables improved irrigation schedules, hence increasing water-use efficiency.

The selection of pipe diameter ratios (D/d) significantly impacts the accuracy and applicability of the BPF meter. Where smaller D/d ratios are more suitable for systems with lower flow rates, larger ratios are preferable for higher flow rate systems. By addressing these design considerations, the BPF meter can be effectively calibrated to meet the different demands of irrigation systems, offering reliability and adaptability.

Challenges and Limitations of BPF Meter in Smart Farming

In the context of smart farming, smart irrigation focuses on delivering water at the precise time, amount, and location, thereby enhancing resource efficiency and productivity [29]. Efficient water management relies on the use of monitoring and control strategies to optimize irrigation practices, improve resource use, and enhance productivity. A key aspect of water management is the ability to accurately measure water flow through irrigation systems, which enables farmers to estimate water usage and calculate water use efficiency [30]. However, for small-scale farms, the cost of conventional flow meters, particularly those designed for larger pipes, can be expensive. This cost includes not only the price of the meter itself but also the associated installation and maintenance expenses.

Selecting the appropriate flow meter type for a specific application is an essential step in reducing measurement uncertainties [9]. Nonetheless, the meter's limitations must be recognized along with its advantageous features in order to make the best selection. Numerous innovative smart irrigation technologies, despite their technical sophistication, are either not practical for commercial use or too expensive for small-scale farmers, especially in developing countries [31]. This highlights the urgent need to develop affordable and accessible smart irrigation solutions.

While the bypass flow meter (BPF meter) offers an alternative solution for small-scale applications, such as simpler installation and lower costs, they are also subject to some limitations. A primary limitation of the bypassing technique is the low flow rate through the bypass pipe. This is because only a small portion of the flow is being measured. This potentially leads to a decrease in sensitivity to flow fluctuations [18]. Moreover, the BPF meter may be susceptible to inaccuracy when dealing with multiphase flows and is particularly designed for flow rate measurements in large-diameter pipes [22]. As the applicability of the linear model in this study is validated within the tested pipe diameter ratio (D/d), where R^2 values exceed 0.99 and mean percentage errors (MPE) are below 10%. Within this range, the linear assumption simplifies calibration and real-time water control. However, beyond this range, measurement accuracy may decline and future research require alternative model to increase the accuracy.

Despite these challenges, the adaptability of BPF meters has been demonstrated across various applications to improve water management. For instance, Samani [21] research demonstrated that although the bypass rate fluctuates with flow condition, the total flow rate remains accurate regardless of these variations. Similarly, Chu-wen, et al. [22] found that pipe geometry and flow conditions have an impact on the flow rate ratio between main and bypass pipes, with connecting a bypass pipe reducing head loss by 7.64% to 9.34%. The bypass techniques have also been explored in the field of thermal mass flowmetry. Dasgupta, et al. [18] reported that alternations to bypass designs enhanced thermal signal strength by as much as 38% compared to the baseline bypass design. These findings emphasize the versatility and adaptability of BPF meters across various applications, including irrigation systems.

All water meters, regardless of their types, have inherent measurement limitations that may result in either under-registration or over-registration of water usage [32-33]. Both scenarios highlight the critical role of meter inaccuracies as a significant component of apparent water losses. Consequently, it becomes essential to quantify and understand the magnitude of these errors to ensure the accuracy of water management practices [32].

Within application constraints, the primary objective is to optimize the overall mechanical stability and fit in order to achieve good repeatability performance. While the accuracy of a small bypass flow meter may be slightly lower compared to larger, more expensive models, it provides a practical solution for small-scale farms. The significant benefits of obtaining water usage data, which allow farmers to make informed decisions that improve water efficiency and crop yields, justify the trade-off between cost and precision. The BPF meter methodology effectively addresses the special needs of small-scale smart farming, where cost-effective solutions and efficient water management are essential for sustainable, cost-effective, and long-term operation.

Currently, a growing trend is the incorporation of the internet of things (IoT) into smart water applications. However, the integration of different technologies for practical application remains a challenge [34]. The emergence of affordable IoT-based sensors presents a significant possibility to enhance irrigation monitoring at the farm scale [35]. Therefore, BPF meter could be used in integration with IoT devices to monitor real-time water usage. This integration offers a viable approach toward optimizing irrigation schedules, improving water efficiency, and reducing operational costs for farmers.

Conclusion

Although the bypass flow meter (BPF meter) has been around for many years, it has been reexamined in this work as a practical solution to the challenges of water flow measurementin smart farming applications. This study explores the feasibility and accuracy of the BPF meter, offering information that could help to improve water management practices and promote sustainable agricultural production.

The experiment demonstrates the impact of the BPF meter's geometry on its flow measuring performance. The results show a strong relationship between the main flow rate (Q_m) and the bypass flow rate (Q_{BP}) for all examined diameter ratio of the main pipe to the bypass pipe (D/d = 2:1, 2.5:1, 3:1, and 4:1). This relationship is expressed by the equation $Q = KQ_{BP}$, where K is the calibration coefficient. Further analysis indicates that higher D/d ratios correspond to larger K-values, suggesting that the main flow rate (Q) increases with the bypass flow rate as the pipe diameter ratio increases.

In summary, the proposed BPF meter offers a practical and economical solution for small-scale farmers to monitor water usage effectively. The strong linear relationship between Q and Q_{BP}, along with the established calibration equations validates the BPF meter as reliable and cost-effective device for flow measurement in smart farming applications. This approach aligns with the goals of smart farming by promoting sustainable agricultural practices through accessible and efficient technology.

Acknowledgements

This research was supported by the Agricultural Research Development Agency (ARDA) (Public Organization). The authors would like to acknowledge their financial support, which made this work possible.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Walter, A., Finger, R. Huber, R. and Buchmann, N., 2017, "Smart Farming Is Key to Developing Sustainable Agriculture," *Proceedings of the National Academy of Sciences*, USA, pp. 6148-6150.
2. Hsu, W.L., Wang, W.K., Fan, W.H., Shiau, Y.C., Yang, M.L. and Lopez, D.J.D., 2021, "Application of Internet of Things in Smart Farm Watering System," *Sensors and Materials*, 33 (1), pp. 269-283.
3. Vallejo-Gómez, D., Osorio, M. and Hincapié, C.A., 2023, "Smart Irrigation Systems in Agriculture: A Systematic Review," *Agronomy*, 13 (2), p. 342.
4. Dhanaraju, M., Chenniappan, P., Ramalingam, K., Pazhanivelan, S. and Kaliaperumal, R., 2022, "Smart Farming: Internet of Things (Iot)-Based Sustainable Agriculture," *Agriculture*, 12 (10), p. 1745.
5. Bwambale, E., Abagale, F.K. and Anornu, G.K., 2023, "Model-Based Smart Irrigation Control Strategy and Its Effect on Water Use Efficiency in Tomato Production," *Cogent Engineering*, 10 (2), pp. 1-17.
6. Velasco-Muñoz, J.F., Aznar-Sánchez, J.A., Batlles-delaFuente, A. and Fidelibus, M.D., 2019, "Sustainable Irrigation in Agriculture: An Analysis of Global Research," *Water*, 11 (9), p. 1758.
7. Gamal, Y., Soltan, A., Said, L.A., Madian, A.H. and Radwan, A.G., 2023, "Smart Irrigation Systems: Overview," *IEEE Access*, 4 (1), pp. 1-13.
8. Eisenhauer, D.E., Martin, D.L., Heeren, D.M. and Hoffman, G.J., 2021, "Chapter 3: Measuring Water Applications," pp. 35-47, in D.E. Eisenhauer, D.L. Martin, D.M. Heeren and G.J. Hoffman, (Eds.) *Irrigation Systems Management*, American Society of Agricultural and Biological Engineers, St. Joseph, Michigan.

9. LaNasa, P.J. and Upp, E.L., 2014, "2 - Basic Flow Measurement Laws," pp. 19-29, in P.J. LaNasa and E.L. Upp (Eds.) *Fluid Flow Measurement*, 3rd ed., Butterworth-Heinemann, Oxford.

10. Johnson, A., Benham, B.L., Eisenhauer, D. and Hotchkiss, R., 2001, "Ultrasonic Water Measurement in Irrigation Pipelines with Disturbed Flow," *Transactions of the ASAE*, 44 (4), p. 899.

11. Garmabdari, R., Shafie, S. and Isa, M.M., 2012, "Sensory System for the Electronic Water Meter," *2012 IEEE International Conference on Circuits and Systems (ICCAS)*, Kuala Lumpur, Malaysia, pp. 223-226.

12. Lee, C.H., Jeon, H.K. and Hong, Y.S., 2017, "An Implementation of Ultrasonic Water Meter Using Dtof Measurement," *Cogent Engineering*, 4 (1), p. 1371577.

13. Whiting, P.J., 2016, "Flow Measurement and Characterization," pp. 260-277, in G.M. Kondolf and H. Piégay (Eds.) *Tools in Fluvial Geomorphology*, Wiley Blackwell, Oxford.

14. Jaiswal, S.K., Yadav, S. and Agarwal, R., 2017, "Design and Development of a Novel Water Flow Measurement System," *Measurement*, 105, pp. 120-129.

15. Pöschel, W., Engel, R., Dopheide, D., Baade, H.J., Kecke, H.J., Praetor, R., Weist, N. and Kurras, E., 2000, "A Unique Fluid Diverter Design for Water Flow Calibration Facilities," *10th International Conference on Flow Measurement FLOMEKO,* Salvador, Brazil.

16. Jaiswal, S.K., Yadav, S., Bandyopadhyay, A.K. and Agarwal, R., 2012, "Global Water Flow Measurement and Calibration Facilities: Review of Methods and Instrumentations," *MAPAN*, 27 (2), pp. 63-76.

17. Aibe, V.Y., Aquino, M.H.G., Farias, E.C.C. and Gabriel, P.C., 2015, "Flow Meter Calibration by Volumetric Method and by Weighing Method Using an Innovative System," *Journal of Physics: Conference Series*, 648 (1), p. 012016.

18. Dasgupta, S., Radhakrishnan, A. and Gandigudi, N., 2022, "Improving Effectiveness of Flow Measurement by Bypass Method: A Technique Applied to Thermal Mass Flowmeter," *Journal of Heat Transfer*, 144 (9), p. 092901.

19. Yuan, B.Z., Nishiyama, S., Fukada, M. and Kanamori, H., 2003, "Hydraulic Design Procedure for Bypass Flow Meters Using a Pipe Bend," *Transactions of the ASAE*, 46 (2), pp. 279-285.
20. Torigoe, I., 2005, "Bypassing Flowmeter Capable of Detecting Bypass Rate," *Transactions of the Society of Instrument and Control Engineers*, 41 (9), pp. 724-728.
21. Samani, Z.A., 2009, Parallel Flow Meter Device for Measuring Flow Rate in Pipes, U.S. Patent Application No. 12/456, 673.
22. Chu-wen, G., Nan-nan, W. and Shuang, X., 2009, "Flowmeter for Large-Scale Pipes," *Procedia Earth and Planetary Science*, 1 (1), pp. 1498-1502.
23. Kumar, K., Farande, K.U., Ajai, S., Sahu, T.K., Raut, A., Farande, S. and Tichkule, Y., 2020, "By-Pass Flow Meter for Sloped Pipelines," *Trends in Manufacturing Processes: Select Proceedings of ICFTMM 2018*, Singapore, pp. 83-92.
24. Craik, A.D.D., 2013, "“Continuity and Change”: Representing Mass Conservation in Fluid Mechanics," *Archive for History of Exact Sciences*, 67 (1), pp. 43-80.
25. Hafeez, H.Y. and Ndikilar, C.E., 2020, "Boundary Layer Equations in Fluid Dynamics," pp. 67-94, in R. Fagbenle, O.M. Amoo, A. Falana and S. Aliu (Eds.) *Applications of Heat, Mass and Fluid Boundary Layers*, Brian Romer, United Kingdom.
26. Schnick, J., 2008, "Chapter 11 Resistivity, Power," pp. 84-89, in J.W. Schnick (Ed.) Calculus-Based Physics II, Manchester, New Hampshire.
27. Haktanır, T. and Ardıçlıoğlu, M., 2004, "Numerical Modeling of Darcy-Weisbach Friction Factor and Branching Pipes Problem," *Advances in Engineering Software*, 35 (12), pp. 773-779.
28. Kundu, P.K., Cohen, I.M. and Dowling, D.R., 2016, "Chapter 7 - Ideal Flow," pp. 293-347, in P.K. Kundu, I.M. Cohen and D.R. Dowling (Eds.) *Fluid Mechanics,* 6th ed., Academic Press, Boston.
29. Bwambale, E., Abagale, F.K. and Anornu, G.K., 2022, "Smart Irrigation Monitoring and Control Strategies for Improving Water Use Efficiency in Precision Agriculture: A Review," *Agricultural Water Management*, 260, p. 107324.

30. Adeyemi, O., Grove, I., Peets, S. and Norton, T., 2017, "Advanced Monitoring and Management Systems for Improving Sustainability in Precision Irrigation," *Sustainability*, 9 (3), p. 353.
31. Bazaluk, O., Havrysh, V., Nitsenko, V., Mazur, Y. and Lavrenko, S., 2022, "Low-Cost Smart Farm Irrigation Systems in Kherson Province: Feasibility Study," *Agronomy*, 12 (5), p. 1013.
32. Arregui, F., Cabrera, E., Cobacho, R. and García-Serra, J., 2005, "Key Factors Affecting Water Meter Accuracy," *IWA Water Loss Conference*, Halifax, Canada, pp. 1-10.
33. Criminisi, A., Fontanazza, C., Freni, G. and Loggia, G.L., 2009, "Evaluation of the Apparent Losses Caused by Water Meter under-Registration in Intermittent Water Supply," *Water Science and Technology*, 60 (9), pp. 2373-2382.
34. Kamienski, C., Soininen, J.P., Taumberger, M., Dantas, R., Toscano, A., Salmon Cinotti, T., Filev Maia, R. and Torre Neto, A., 2019, "Smart Water Management Platform: Iot-Based Precision Irrigation for Agriculture," *Sensors*, 19 (2), p. 276.
35. Cáceres, G., Millán, P., Pereira, M. and Lozano, D., 2021, "Smart Farm Irrigation: Model Predictive Control for Economic Optimal Irrigation in Agriculture," *Agronomy*, 11 (9), p. 1810.