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Fluid Flow Visualization using an Improvised Reynolds' Apparatus

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ABSTRACT

In studying fluid mechanics, the Reynolds' apparatus is a fundamental tool for demonstrating how fluid flow in pipes transitions from laminar to turbulent regimes. However, commercial units can be prohibitively expensive for many institutions, limiting practical, hands-on experiences. In this work, a low-cost Reynolds apparatus was designed and constructed using locally available materials at a total cost of approximately Php 4,010 (about 70 USD). The system was validated by comparing observed flow regimes—ranging from laminar to turbulent—with those predicted by computed Reynolds numbers, and a strong correspondence between theory and observation was found. Further investigations were conducted on the effects of fluid velocity and temperature (and thus kinematic viscosity) on the Reynolds number. As expected, the Reynolds number is raised by increasing the flow velocity, while raising the fluid temperature lowers its viscosity and thus further elevates the Reynolds number. Notably, with tap water used as the working fluid and a test pipe of 2.2 cm inner diameter, Reynolds numbers as high as 67,715 can be achieved, allowing the study of highly turbulent flows. Given its affordability and demonstrated accuracy, this improvised Reynolds' apparatus is deemed well-suited for instructional and research applications, particularly in settings constrained by limited budgets.

Keywords: *improvisation, flow characteristics, laminar, turbulent, Reynolds apparatus*

INTRODUCTION

Fluid dynamics, the branch of physics concerned with the behavior of fluids (liquids and gases) in motion, underpins countless natural phenomena and engineering applications. From the complex patterns of atmospheric circulation and ocean currents to the design of aerodynamic vehicles and water distribution in cities, understanding fluid flows is essential across scientific and industrial domains (Addis, 2020; Batchelor, 2000; Kundu, 2015; Guilmineau, 2008; Sedagat. 2020). A fundamental aspect of fluid motion is characterizing how fluids move through conduits such as pipes, channels, and tubes, where parameters like velocity, viscosity, and temperature influence the flow's nature and stability.

Within confined geometries like pipes, fluid flows can be broadly classified into three major regimes: laminar, transitional, and turbulent. Laminar flow is characterized by smooth, orderly layers of fluid sliding past one another with minimal mixing, while turbulent flow is marked by eddies, swirls, and chaotic fluctuations (White, 2003). Flow in the transitional regime displays characteristics of both extremes, as localized perturbations begin to disrupt

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the orderly motion yet have not fully developed into sustained turbulence. Identifying when a flow transitions from laminar to turbulent—or vice versa—is critical for practical systems.

Central to characterizing flow regime is the concept of the Reynolds number—a dimensionless quantity representing the ratio of inertial to viscous forces. The Reynolds number enables the prediction of flow behavior by comparing a fluid's velocity, characteristic length scale (such as pipe diameter), and kinematic viscosity (Reynolds, 1883; Pritchard, 2011). Flow is generally considered laminar for Reynolds numbers below a critical threshold (approximately 2,100 in pipe flows) and turbulent for values above 4000. Between these regimes lies a transitional region, where small disturbances can grow and push the system into turbulence (Young, 2004).

Over a century ago, Osborne Reynolds pioneered the apparatus that allowed for the direct observation of these flow regimes. The classic Reynolds experiment involves injecting a dye stream into fluid moving through a clear-walled pipe, enabling a visual distinction between laminar and turbulent flow patterns (Reynolds, 1883). While standard Reynolds apparatus setups are widely available in well-funded laboratories, they may be less accessible in regions with limited educational resources.

Objectives of the Study

This study aimed to develop and evaluate the performance of an improvised Reynolds' apparatus designed for a resource-constrained educational environment, especially for a third-world country like the Philippines. The influence of fluid velocity and temperature on the computed Reynolds number and the observed fluid flow phenomena were also examined. By introducing this low-cost, effective experimental tool, we hope to enhance understanding and foster deeper engagement in learning fluid dynamics.

Theoretical Framework

Fluid flow refers to the movement of a liquid or gas under the influence of various driving forces, including pressure gradients, gravitational fields, or external constraints. When a fluid passes through a channel, pipe, or conduit, its behavior depends heavily on characteristics such as velocity, fluid viscosity, density, and the system's geometry. Understanding the nature of fluid flow and categorizing it into distinct regimes is fundamental to predicting flow patterns, mixing processes, and energy losses (Batchelor, 2000; Sunaris, 2019).

A key parameter in flow characterization is the Reynolds number, a dimensionless quantity introduced by Osborne Reynolds in the late 19th century. The Reynolds number (Re) is generally defined as:

$$Re = \frac{vD}{\mu} \quad (1)$$

where v is the characteristic flow velocity, D is the pipe diameter, and μ is the kinematic viscosity of the fluid (Reynolds, 1883). This dimensionless ratio succinctly compares inertial forces to viscous forces within the flow.

For flow in cylindrical pipes, velocity can be expressed in terms of volumetric flow rate Q:

$$v = \frac{4Q}{\pi D^2}. \quad (2)$$

The volumetric flow rate (Q) itself represents the volume of fluid passing through a pipe per unit time:

$$Q = \frac{V}{t} \quad (3)$$

where V is the volume of the fluid, and t is time.

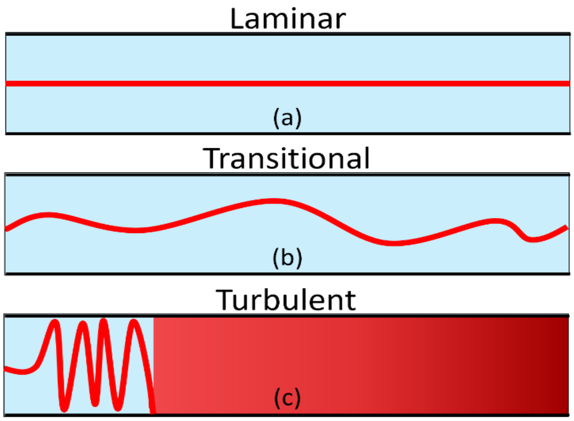

Figure 1

Illustration of dye behavior under different flow regimes in a cylindrical pipe

In (a) laminar flow, the dye travels smoothly in a straight line along the center of the pipe. During (b) transitional flow, occasional velocity fluctuations cause the dye to oscillate slightly, though it remains largely separated from the surrounding fluid. Under (c) turbulent flow, the dye rapidly mixes and disperses throughout the fluid due to persistent, chaotic velocity fluctuations.

The Reynolds number is central to understanding flow regimes in pipe flow. At low Reynolds numbers ($Re < \sim 2{,}100$), the flow is dominated by viscous forces, resulting in a laminar flow regime in which fluid layers slide smoothly past one another (see Figure 1). As the Reynolds number increases beyond a critical threshold, known as the critical Reynolds number (Re_{cr}), inertial forces begin to dominate. For internal flow in a circular pipe, this critical value is generally accepted to be around $Re_{cr} = 2{,}100$ (Novopashin, 2002). Once the flow passes this threshold, it enters a transitional regime, exhibiting increasing fluctuations and perturbations; eventually, at sufficiently high Reynolds numbers ($Re > \sim 4{,}000$), inertial forces overwhelm viscous damping, and the flow becomes turbulent. Turbulent flow is characterized by chaotic, eddying motions, rapid mixing, and increased energy dissipation (Munson, 1995; Kundu, 2015). Although laminar flow can occur in cases where highly viscous fluids, such as oil, move through small pipes or narrow passages, most flows encountered in engineering practice are turbulent (Kundu, 2015; Nur, 2019).

The exploration and validation of these flow regimes were famously pioneered by Osborne Reynolds in the late 19th century through experiments using dyed fluids in cylindrical pipes—a setup now commonly referred to as the Reynolds' apparatus (Reynolds, 1883). In its classic form, the Reynolds' apparatus consists of a transparent tube, a fluid reservoir, and a dye injection system that enables the visualization of flow patterns as the fluid moves through a controlled conduit. By adjusting flow rates, Reynolds demonstrated distinct changes in flow behavior and linked them to the dimensionless parameter that now bears his name. Over the years, modern iterations of the Reynolds' apparatus have maintained the core principles of Reynolds' original experiment while incorporating advanced materials, instrumentation, and visualization techniques (Yang, 2018; Yusoff, 2016).

METHODOLOGY

This section outlines the experimental design, construction process, and procedures implemented in the study.

Design and Construction

Many students find physics intimidating due to its abstract concepts and complex mathematical foundations (Cadorna, 2019; Cadorna, 2023). This difficulty can lead to fear and disengagement, particularly when the real-world relevance of theoretical principles is not immediately clear. In light of these concerns, the Reynolds' apparatus serves as a fundamental educational tool for visualizing different fluid flow regimes—ranging from laminar to turbulent—within pipes. By offering a direct, real-time demonstration of fluid behavior, this apparatus transforms abstract ideas into tangible observations, thereby enhancing students' grasp of core fluid dynamics concepts. Moreover, making the Reynolds' apparatus more accessible and cost-effective is especially beneficial for educational institutions with limited resources, as it provides a hands-on learning experience that can significantly improve students' engagement and understanding of physics.

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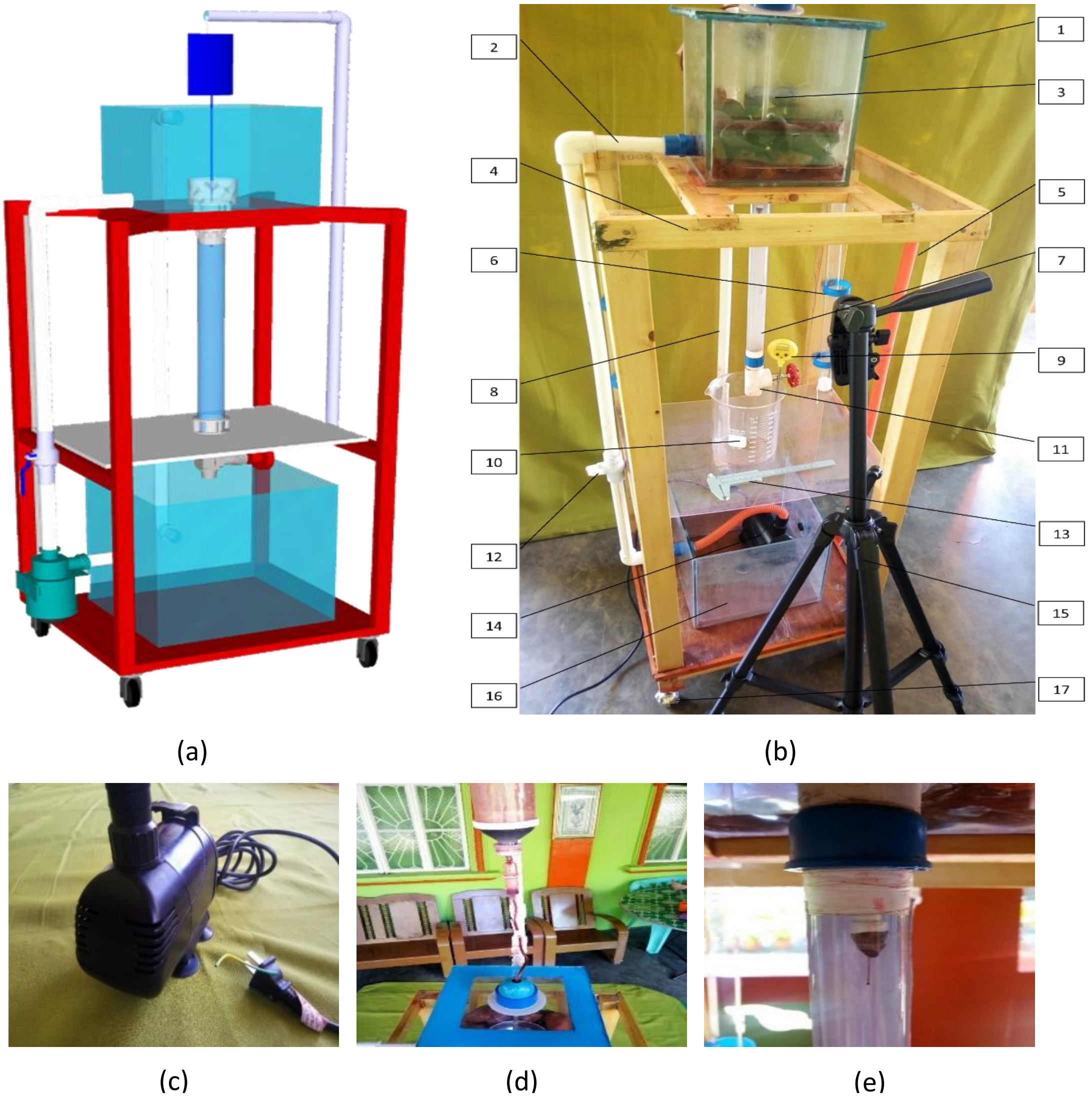

Figure 2

Low-cost Reynolds' Apparatus

(a) Design and (b) the finished product of the improvised Reynolds' apparatus. (c) A locally sourced submersible water pump drives the fluid up to the head tank. (d) A dye injector—made from a discarded dextrose and a (d) needle tip—enables fluid flow visualization.

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Table 1
Features and cost of each component of the improvised Reynolds' apparatus

S/N	Equipment/Materials	Features	Cost
1	Head Tank	$0.5cm$ thick clear glass plates $15cm\ x\ 15cm\ x\ 17cm$	290
2	Inlet Pipe	PPR pipe: 2 cm diameter	250
3	Dye/Dye Injector	Bromophenol red Dextrose container Stainless steel tip	90
4	Wooden Base	$2cm\ x\ 2cm$ thick pine wood $42cm\ x\ 42cm\ x\ 110cm$	455
5	Discharge Pipe	PPR pipe: $2cm$ diameter	150
6	Test Pipe Holder	Teflon tape container	40
7	Test Pipe	$2.2cm$ inner diameter acrylic glass tubes $52cm$ long	350
8	Overflow Pipe	PPR pipe: 2 cm diameter	130
9	Thermometer	Digital	-
10	Graduated Cylinder	Volume: $1L$	-
11	Outlet Valve	Gate valve	120
12	Inlet Valve	PVC ball valve	50
13	Vernier Caliper	-	-
14	Submersible Pump	$Q_{max} = 3050\ L/h$ $T_{max} = 35℃$	1300
15	Tripod with Camera	-	-
16	Fluid Tank	$0.5\ cm$ thick clear glass plates $25cm\ x\ 25cm\ x\ 25cm$	625
17	Rollers	Soft rubber	160
		Total	**4010**

Figure 2 shows (a) the design concept and (b) the completed, improvised Reynolds' apparatus. This system is floor-mounted, featuring a precision-bore glass test pipe oriented vertically so that the fluid flows downward. Mounting the apparatus vertically helps compensate for any slight differences in the density of the dye relative to the working fluid. A Resun® Submarine Water Pump (Figure 2(c)) propels the fluid from a cuboidal reservoir to a head tank. Inside the head tank, a stilling bed minimizes large velocity variations, while an overflow pipe at the rear maintains a uniform, low-velocity flow feeding into the vertically

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mounted test section. The fluid then enters this test section through a profiled bell mouth funnel, designed to accelerate the fluid uniformly without introducing unwanted inertial effects. An acrylic glass tube with a 2.2 cm inner diameter serves as the test pipe, providing a clear view of the fluid flow. The dye solution is introduced through a discarded dextrose container, as in Figures 2(d)-(e), with a flow rate controlled by a roller clamp near the container outlet. Meanwhile, the working fluid's flow rate is regulated by an outlet valve and measured volumetrically.

Table 1 summarizes the features and costs of each component of the improvised system, showing how careful material selection and cost-effective choices can keep overall expenses low. Remarkably, the entire apparatus can be built for just Php 4,010, making it a practical and affordable option for educational institutions seeking a hands-on, visually engaging way to demonstrate fluid flow in pipes.

Experimental Procedures

In this section, the step-by-step process for setting up and operating the low-cost Reynolds' apparatus is detailed, ensuring accurate data collection and clear visualization of fluid flow regimes.

1. Initial Setup

The apparatus was set up, and the pipe diameter and fluid temperature were measured. These parameters were essential for the calculation of the Reynolds number.

2. Filling the Fluid Tank

The water pump is switched on, and the inlet valve is opened while the outlet valve is kept closed to fill the fluid tank with water. This ensures that the head tank is filled to a constant water level. The inlet valve is adjusted as necessary to maintain that constant level. After some time, it is ensured that the test pipe section is filled with water.

3. Preparing the Dye Reservoir

The dye container is filled with dye, and the roller (or valve) on the dye container is ensured to be fully closed. This prevents accidental dye release into the system.

4. Establishing Low Flow

The outlet valve is slightly opened to introduce a low flow rate into the test pipe section. Initial conditions suitable for observing the dye flow pattern at lower velocities are thus provided.

5. Introducing the Dye

The roller on the dye container is opened, allowing the dye to flow from the nozzle at the entrance of the channel. A visible colored stream in the test pipe section is observed, indicating that the dye is consistently mixed with the main flow.

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6. Achieving Laminar Flow

The outlet valve is carefully adjusted until a laminar flow pattern is observed, characterized by a thin, straight dye line (streamline) extending along the entire test pipe section (see Figure 1). Markings are created on the outlet valve, as shown in Figure 3, to correlate specific valve positions with approximate flow rates for repeatability.

7. Measuring Flow Rate

Once stable laminar flow is achieved, the time (in seconds) required to collect a known volume of colored wastewater from the outlet valve is recorded. Equation 3 is used to calculate the volumetric flow rate (Q) from this measurement. The fluid velocity (v) is then computed by dividing the volumetric flow rate by the cross-sectional area of the glass pipe (Equation 2). Three trials are conducted at each flow rate for consistency. Finally, the Reynolds number is calculated using Equation 1, based on the fluid velocity. This step allows a direct comparison between the observed flow regime (laminar, transitional, or turbulent) and the regime predicted by theory.

8. Transitioning to Higher Flow Rates

Steps 6 and 7 are repeated while the flow rate is gradually increased by further opening the flow control valve. At each step, the flow pattern is monitored and documented as it shifts from laminar to transitional and eventually to turbulent flow.

9. Cleanup

After all measurements and observations are completed, the entire apparatus is thoroughly cleaned to remove any residual dye or debris. This ensures that the system is prepared for future experiments.

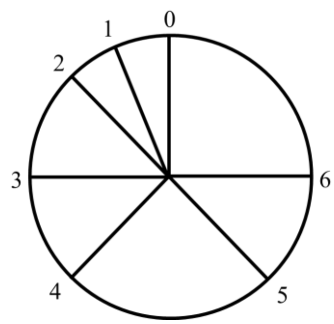

Figure 3

Graduation is placed at the outlet valve to ensure repeatability of fluid flow data.

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RESULTS AND DISCUSSIONS

Performance Evaluation

Having successfully constructed the improvised Reynolds' apparatus, its effectiveness was then assessed by comparing the visually observed flow regime of the injected dye with the regime predicted by the Reynolds number (Equation 1). This involves photographing or recording the dye's behavior at different flow rates and then computing the Reynolds number based on the measured velocity, fluid properties, and pipe dimensions. Insights into the apparatus's accuracy and its suitability for educational or experimental purposes are gained by evaluating whether the dye's observed motion (i.e., laminar, transitional, or turbulent) aligns with the theoretical predictions from the Reynolds number. This step is crucial to confirm that the expected flow transitions are reliably reproduced by the apparatus before further experiments or classroom demonstrations are conducted.

The primary purpose of a Reynolds' apparatus is to visually illustrate different fluid flow regimes in pipes. By injecting a thin filament of dye parallel to the main flow, one can easily identify whether the flow is laminar, transitional, or turbulent—even without calculating the Reynolds number. This direct visual approach simplifies the understanding of how fluid behavior varies with changes in flow conditions. Here, tap water at $25.10\ °C$ was used as the working fluid. At this temperature, its kinematic viscosity is approximately$8.90 \times 10^{-7}\ m^2/s$. The inner diameter of the test pipe is measured to be$2.2\ cm$. Following the experimental procedures described earlier, we recorded the flow characteristics at different outlet valve graduations.

Table 2 compares the flow regimes observed through visualization with those predicted by Reynolds numbers computed from measured flow velocities. As shown, the observed flow regimes perfectly match the theoretical predictions across all output valve settings. This agreement indicates that the improvised Reynolds apparatus effectively demonstrates how fluid flow transitions from laminar to turbulent, thus supporting theoretical predictions derived from the Reynolds number.

Factors Affecting Fluid Flow

Effect of Changing Fluid Velocity

Table 2 also highlights the impact of flow velocity on the Reynolds number. Increasing the outlet valve graduation proportionally increases the flow velocity, which in turn raises the Reynolds number, confirming the direct relationship between these two parameters. The dye remains in a thin, stable line, indicative of laminar flow at lower valve graduations (1–4). As the valve is opened further (graduation 5), the dye becomes visibly wavy, reflecting partial mixing and fluctuating behavior—a clear sign of transitional flow. Finally, the dye fully

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disperses throughout the pipe at the highest valve setting (graduation 6), signifying the chaotic, turbulent flow regime.

These observations agree with the theoretical understanding that increasing velocity (and thus inertial forces) eventually overcomes viscous damping, prompting the transition to turbulence (Munson, 1995; Kundu, 2015). This consistency further validates the effectiveness of the improvised apparatus for both educational demonstrations and practical investigations of flow behavior.

Comparison between Fluid Flow Regimes Based on Computed Reynolds Number and Flow Visualization

Table 2

Computed Reynolds Number versus Flow Visualization

Grad	Flow Rate (m^3/s)	Flow Velocity (m/s)	Reynolds number	Dye Condition	Observed Regime	Remarks
1	1.79E-07	4.71E-04	11.65		Laminar	Match
2	1.30E-06	3.43E-03	84.79		Laminar	Match
3	1.06E-05	2.79E-02	689.16		Laminar	Match
4	2.42E-05	6.36E-02	1573.52		Laminar	Match
5	4.65E-05	1.22E-01	3026.40		Transitional	Match
6	6.47E-05	1.70E-01	4208.69		Turbulent	Match

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Effect of Changing the Kinematic Viscosity of the Fluid

Reynolds number and the fluid's kinematic viscosity are theoretically inversely proportional—meaning that decreasing the viscosity increases the Reynolds number, and vice versa. In practical terms, raising the fluid temperature reduces viscosity, leading to higher Reynolds numbers (White, 2003; Munson, 1995; Boda, 2015). In this study, we examined the effect of changing the kinematic viscosity by varying the tap water temperature supplied throughout the system. Specifically, we tested three water temperatures—25.10°C, 29.20 °C, and 35 °C at the graduation 3 of the outlet valve—assuming that the flow remained adiabatic and isothermal.

Figure 4

Increasing the water temperature from 25.10 °C (blue) to 35 °C (green) reduces the fluid's kinematic viscosity, which in turn elevates the Reynolds number.

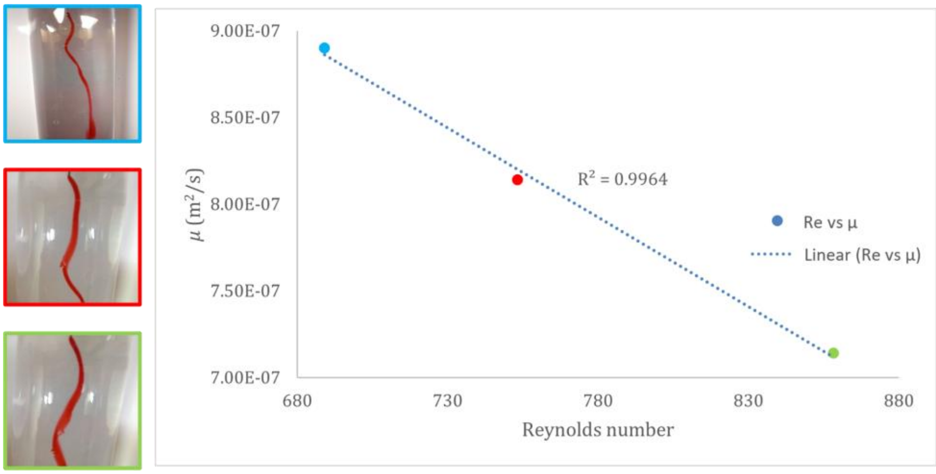

Figure 4 confirms that the Reynolds number is inversely proportional to the kinematic viscosity of the fluid. The plot shows a high coefficient of determination($R^2 = 0.9964$), indicating a strong correlation between these two parameters. From a practical standpoint, this confirms that water temperature is a key variable affecting fluid properties and, thus must be controlled or accounted for when predicting or analyzing flow conditions (Yusoff, 2016).

It was also observed that increasing the fluid temperature produces a thicker dye streak in the flow visualization. One possible explanation is that, at higher temperatures (and therefore lower viscosity), velocity fluctuations and local mixing may alter how the dye disperses. Additionally, a slight change in fluid density could also affect the buoyancy and mixing properties of the dye (Schlichting, 2016).

Maximum Reynolds Number Using the Improvised Reynolds' Apparatus

The maximum Reynolds number achievable with this improvised apparatus can be determined by combining the highest possible flow rate and the maximum allowable fluid temperature specified for the submersible pump. According to the pump's specifications (see Table 1), the maximum volumetric flow rate Q_{max} and the highest permitted fluid temperature T_{max} are as follows: $3{,}050\ L/h$ and $35\ °C$. At this temperature, the kinematic viscosity of tap water is approximately$7.241E-7\ \frac{m^2}{s}$. Given the pipe's inner diameter of $2.2\ cm$ and using tap water as the working fluid, one can calculate the maximum Reynolds number under these conditions.

Table 3
Maximum Reynolds Number

$Q_{max}\left(\frac{m^3}{s}\right)$	$v\left(\frac{m}{s}\right)$	$Re_{(max)}$
8.47E-04	2.23	67715

As shown in Table 3, the calculation yields a maximum Reynolds number of approximately $67{,}715$. This value is well above the typical turbulent flow threshold$Re > \sim 4{,}000$, allowing comprehensive investigations into turbulent flow phenomena using the improvised apparatus (Kundu et al., 2016; Munson et al., 2013). Such versatility underscores the apparatus's value for educational demonstrations and more advanced fluid mechanics research, as it provides a practical means to study a broad range of flow regimes.

CONCLUSIONS

The Reynolds' apparatus is considered essential for visualizing different fluid flow regimes in pipes. A low-cost version of this apparatus—costing only 4,010 Philippine pesos (approximately 70 USD) and made from locally available, inexpensive materials—was constructed to provide an economical solution for educational institutions operating with limited budgets. To confirm the efficacy of the design, observed flow regimes were compared with those predicted by computed Reynolds numbers. A strong correspondence between

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observed and theoretical flow behavior was demonstrated, confirming that flow transitions from laminar to turbulent are accurately captured by the apparatus. Having established its reliability, further exploration was conducted into how changes in fluid velocity and temperature—and consequently kinematic viscosity—affect the Reynolds number. The theoretical direct relationship between flow velocity and the Reynolds number and the inverse relationship between viscosity and the Reynolds number were reinforced by the results. Moreover, it was determined that this improvised setup can achieve a Reynolds number as high as 67,715, indicating its capability to investigate even highly turbulent flows.

RECOMMENDATIONS

Based on the findings of this study, it is recommended that educational institutions, particularly those with limited budgets, adopt this low-cost Reynolds' apparatus to enhance practical learning and teaching in fluid mechanics. Training sessions or workshops should be organized to familiarize instructors and students with its use. Researchers are encouraged to utilize the apparatus for investigating the complex behaviors of turbulent flow at high Reynolds numbers, focusing on turbulence modeling, energy dissipation, and chaotic dynamics. Further exploration of alternative working fluids with varying viscosities and densities is also recommended to validate the versatility of the apparatus. To improve functionality, design modifications such as integrating digital sensors for real-time flow rate and velocity measurements could be implemented, making the apparatus even more valuable for advanced research applications. Additionally, a systematic study on the durability and maintenance of the apparatus over extended periods of use is suggested to ensure its sustainability in various operational environments. Finally, incorporating modern visualization techniques, such as laser-based flow tracking or high-speed cameras, could provide more detailed insights into flow patterns and transitions, further expanding the potential applications of this improvised setup. These recommendations aim to maximize the utility of the apparatus and encourage advancements in fluid mechanics education and research.

ETHICAL STATEMENT

This study adhered to the ethical principles of research integrity, ensuring accuracy, transparency, and honesty in data collection and analysis. No human or animal subjects were involved, and all experimental procedures were conducted in compliance with relevant safety and environmental regulations.

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