Experimental Investigation of Turbulent Manipulation in Pipe Flow

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ABSTRACT

For over six decades, the phenomenon of reducing friction between fluids and pipe walls by adding high-molecular-weight polymer solutions during turbulent flow known as polymer drag reduction has been extensively studied. Research has shown its effectiveness in applications such as industrial processes and crude oil transport. Recent studies suggest that this phenomenon can also be applied to improve drainage efficiency in flood-prone areas, such as communities, airports, and railways, where heavy rainfall often causes inadequate water drainage and flooding. This study aimed to investigate how polymer solutions affect water flow in drainage systems. An experimental setup was designed using a 65-liter acrylic tank and a 20 mm transparent acrylic pipe to simulate water storage and flow. Polyacrylamide FLOJET SW26 (molecular weight 20×10^6 g/mol) was injected into the system at 500 cc volumes in concentrations of 10, 20, 30, 50, and 70 ppm. Flow conditions with and without polymer addition were compared. The results showed that at 70 ppm, the maximum reduction in the friction factor was 11.5%, and the flow rate increased by 13%. Dye visualization revealed that the polymer temporarily suppresses turbulence, altering the flow structure within the pipe. These findings highlight the potential of polymer drag reduction for improving drainage systems. The author hopes to extend this research to real-world drainage networks, particularly in urban flood-prone areas in Thailand. With further development, this approach may contribute to effective flood mitigation in the future.

1. INTRODUCTION

It is well-known that adding a high molecular mass polymer solution to a fluid during turbulent flow can reduce friction between the fluid and the pipe wall, resulting in an increased flow rate. This phenomenon, known as the drag reduction effect or the Tom effect, was discovered by Tom in 1949 [1]. Lumley [2] was among the earliest to propose that the stretching of polymer molecules in water could influence flow dynamics. This concept aligns with later models introduced by Bird et al. [3] and Den Toonder et al. [4], which describe polymers as dashpot-spring systems capable of absorbing kinetic energy fluctuations from the surrounding turbulent flow.

Christopher M., White [5] also shared a similar view, suggesting that the interaction between polymer solutions and turbulent flow contributes significantly to drag reduction. While it is commonly understood that polymer solutions primarily influence the flow in the turbulent regime, their effects may in fact begin during the transition phase. In the context of pipe flow, Avila et al. [6] identified that the onset of transition occurs at Reynolds numbers starting from approximately Re = 2040. Nevertheless, the mechanisms governing polymer–flow interactions in this regime remain complex and are not yet fully understood.

Unexpected or conflicting outcomes are frequently observed in this field. For example, Choueiri et al. [7] investigated the influence of polymer additives on the transition regime in pipe flow using polyacrylamide (PAM) and polyethylene oxide (POE). Their results showed that PAM at Re = 3150 produced drag reduction beyond Virk's maximum drag reduction (MDR) asymptote [8]. In contrast, Chandra et al. [9] reported that skin friction asymptotically approached the MDR curve but did not exceed it, highlighting inconsistencies in the observed effects.

After the discovery of the friction reduction phenomenon achieved by adding polymer solutions to turbulent flow, the precise nature and underlying causes of this behavior are still unclear, despite numerous applications. Subsequently, this innovation has found diverse applications such as the pipe

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systems in industries and crude oil transportation for example in high-profile experiments such as the TransAlaska project conducted by Burger et al. [10]. In this project, a polymer solution was introduced to reduce friction within pipelines spanning 1,287 km in length. This application resulted in a remarkable reduction in the number of pump stations, from twelve down to just four, because of a flowrate increase of up to 14.4% achieved by injecting a 10 ppm polymer solution into the pipelines.

Furthermore, it has been employed to enhance flow rates in drainage systems, as demonstrated in an experiment conducted by Marksimovic in 1978 [1], a polymer solution was added to the drainage system during periods of water overload flow. The findings revealed that when the water overload condition was reached, the water level increased, but it was observed that the drainage rate could be increased by up to 20%

In a recent study conducted by Walid et al. in 2021 [11], a polymer solution known as Polyacrylamide (PAM) with a molecular weight of 20×106 g/mol was injected into large irrigation canals, spanning up to 27 km in length. The findings demonstrated a significant reduction in water depth, with decreases of 10% and 3% observed at distances 10 and 20 km downstream from the injection point, respectively. Moreover, the bulk velocity increased by over 15% near the location where the polymer solution was injected. These compelling results, along with the prior experimental work of Marksimovic and Walid [1], [11], highlight the potential for enhancing drainage systems to address issues like flooding in various settings, including communities, railway transportation systems, airports, and more.

In this research, experiments were conducted to simulate the receiving water area and drainage system, comparing cases involving pure water and the injection of a high molecular weight polymer solution into the system under turbulent flow conditions. The analysis focused on changes in flow rate, friction factor in the pipe, and flow pattern. The detailed relationship between these variables is presented in Section 3 of the experimental results. Section 4 discusses changes in flow patterns and characteristics observed from flow visualization results, while Section 5 provides a summary of the experiment.

2. EXPERIMENTAL SETUP

In this study, we aimed to simulate a scenario in which a substantial volume of water flows into a specific area and is subsequently drained by a drainpipe. From the Figure. 1 The experimental setup consisted of a 65-liter acrylic tank (No. 2) with scale and a transparent acrylic pipe with a 20 mm diameter (No. 3) to mimic water storage and drainage (slope 1:200).

The experiment commenced with pure water, during the experiment water from a 100-liter water tank (No. 1) was filled into tank 2 to keep the water level constant. We conducted the experiment at seven different water level heights, ranging from 20 to 80 cm with 10 cm increments. This systematic approach enabled us to compare flow rates at varying water levels, with the flow rates being directly proportional to the water level's height within the system.

When the water level in Tank 2 reached the designated testing point, a valve was opened to allow the water to flow through the acrylic pipe into water storage (No. 7), and the mass of water was measured using a scale (No. 6). Meticulously, we recorded the timing between opening and closing the valve, observed and recorded the pressure within the pipe using a manometer (No. 5), and accurately measured the weight of the water using a dedicated scale. These measurements provided the necessary data for calculating the mass flow rate and friction factor within the pipe.

After obtaining data from the pure water case, the second experiment was initiated. We introduced Polyacrylamide FLOJET SW26, a white opaque powder with a molecular weight of 20×10^6 g/mol, in volumes of 500 cc (cubic centimeters) at concentrations of 10, 20, 30, 50, and 70 ppm (parts per million by weight) into the system using the Polymer Injection Tank (No. 4). The purpose was to compare the flow conditions with and without the polymer solution.

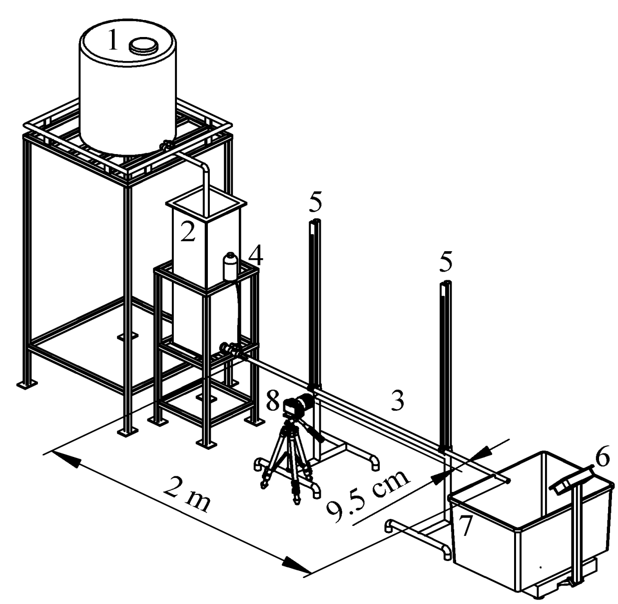


Fig. 1. Experimental setup

In this experiment, we utilized a dye visualization technique employing high-resolution cameras (No. 8), specifically the Canon EOS M50 Mark II for images and the Sony Rx100 II for high-speed videos to observe how the flow behavior changes when the polymer is introduced into the system. As a tracer medium, we used a low molecular weight fabric dye to generate streak lines in alignment with the flow direction, capturing the evolving flow patterns through photographs and videos with image resolutions of

6000×4000 pixels (dimensions: 180×100 mm) and 1920×1080 pixels (dimensions: 170×90 mm) at the center of the acrylic pipe at a distance of 9.5 centimeters, using an 18-watt LED light, 8 units serve as the light source. All experiments were conducted with the water temperature maintained at 30 ± 1 ℃.

3. EXPERIMENT RESULT

3.1 Friction Factor Effect of Polymer

To understand alterations in system flow following the introduction of the polymer solution during turbulent conditions, the analysis begins by calculating relevant parameters, starting with the flow rate by volume $Q\ (m^3/s)$. This is determined from the mass flow rate of water $\dot{m}\ (kg/s)$ through the pipe, measured by weighing the water and precisely timing valve openings and closings in the experiment. The relationship is expressed as:

$$Q = \frac{\dot{m}}{\rho} = Av \qquad (1)$$

where, ρ represents the density of water (kg/m^3) at a temperature of 30 Celsius, v is the velocity of water (m/s), and A is the cross-section area of a pipe (m^2). Subsequently, we substitute the volumetric flow rate into the Hazen-Williams Equation [12], following the format employed by Simpson et al. (1994) [12] for SI units. This step assists in determining the coefficient of friction within the pipe or the value of water head loss (h_f), as defined by the equation:

$$h_f = 10.675 \cdot \frac{L}{D^{4.8704}} \cdot \left(\frac{Q}{C}\right)^{1.852} \qquad (2)$$

In this case, L is the length of the pipe (m), D is the inside diameter of the pipe (m), C is the roughness coefficient of water movement in the acrylic pipe (set at 150) [13]. With the water head loss inside the pipe calculated, the next step involves determining the coefficient of friction (f). within the pipe through the Darcy-Weisbach equation [5]:

$$hf = f \cdot \frac{L}{D} \cdot \frac{v^2}{2g} \qquad (3)$$

Figure 2 illustrates the relationship between the friction factor (f) inside the pipe and the Reynolds number. Based on the experimental results, the parameters for the pure water case are represented by solid blue circles, the first experiment starting at a water level in the acrylic tank of 20 cm. The Reynolds number for this scenario is calculated to be 24710, indicating turbulent flow. To ensure data accuracy, we present the Blasius equation for the friction factor in turbulent flow through pipes $f = 0.184/Re^{1/5}$ [14], widely recognized as an international standard, and compare it with the experimental result, depicted as a solid black line.

The results demonstrate a consistency with the theoretical expectation as the Reynolds number increases, the frictional force inside the pipe tends to decrease with a rise in the water level in the tank.

Subsequently, an equation is derived to describe the relationship between the friction factor and the Reynolds number. Through the analysis of all seven experiments, it becomes evident that the linear equation converges towards the Blasius equation [1], [14], as shown by the solid blue line.

The experiment of a polymer solution injected to a turbulent flow regime at varying concentrations 10, 20, 30, 50, and 70 ppm. These concentrations are represented by blue inverted triangles, black triangles, red circles, black inverted triangles, and blue hexagrams, respectively. Remarkably, even the addition of a small volume of a high-molecular-weight polymer solution consistently resulted in reduced friction. The friction factor decreased proportionally with higher solution concentrations, reaching its peak at a concentration of 70 ppm. This led to a significant Drag Reduction Percentage $(DR\%)$ of up to 11.5%. $(DR\%)$ is calculated using Equation 4,

$$DR\% = \left(\frac{f_w - f_p}{f_w}\right) \qquad (4)$$

In this context, f_w and f_p denote the friction coefficients with and without the polymer solution, respectively. After a comprehensive analysis of the data and fitting it with mathematical models for various concentrations of friction force, it is evident that the trend line declines as the friction value decreases. However, as the Reynolds number increases, a subtle upward trend emerges. This phenomenon can be attributed to the data's rightward skew with each escalation in the solution's intensity. The injection of the polymer exhibits a significant effect, leading to an increase in the Reynolds number compared to the baseline of pure water. The equations of the relationship between friction factor (f) and Reynolds number (Re) for each experiment are presented in Table 1.

Table 1. Equations of friction factor (f) and Reynolds number (Re), with coefficients of the equation

Experiment case	Equation form: $f = A \cdot Re + B$	
	A	B
water	-9.03918×10^8	0.02607
10 ppm	-8.67342×10^8	0.02602
20 ppm	-8.52098×10^8	0.02596
30 ppm	-8.31492×10^8	0.02588
50 ppm	-8.02197×10^8	0.02576
70 ppm	-7.95718×10^8	0.02573

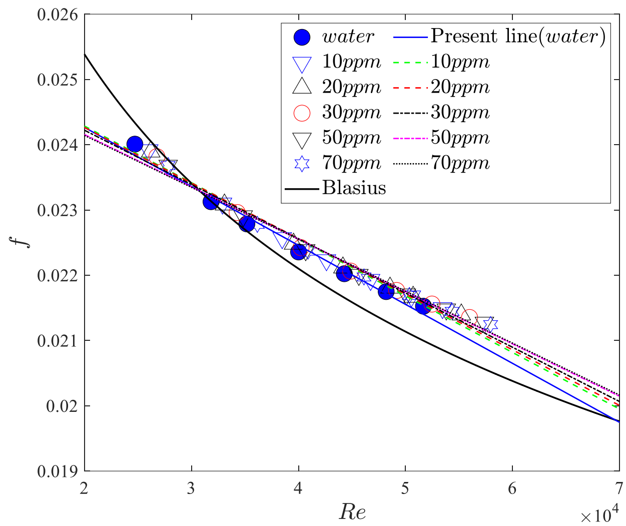


Fig. 2. Friction (*f*) vs. Reynolds number (*Re*)

3.2 Mass Flow Rate Effect of Polymer

The relationship between water height on the Y-axis and changes in mass flow rates on the X-axis is illustrated by Figure 3, which depicts the variation in water drainage rates. For the pure water experiment, represented by solid blue circles, a proportional increase in flow rate was observed with increasing height. Mathematical calculations, shown by the solid blue line, confirmed the linear relationship between water height in the acrylic tank and the flow rate.

In the initial analysis of data, where 500 cc of polymer solution was injected at a concentration of 10 ppm, an immediate 3.3% increase in flow rate was observed compared to measurements at the same water level with pure water. In subsequent experiments revealed a linear increase in flow rate with escalating solution concentrations of 10, 20, 30, 50, and 70 ppm, respectively.

A thorough data analysis, categorized by concentration, was conducted to elucidate mathematical relationships and formulate equations for each concentration. The resulting relationships, provided in Table 2, exhibit a linear increase in flow rate, akin to the behavior observed with water. However, a distinctive observation emerges, indicating that the slope of the equation line decreases as the water height extends further, with this trend becoming particularly evident at heights ranging from 70 to 80 cm. This phenomenon may be attributed to the broader range of data values. Figure 2 serves to reinforce these data characteristics, particularly within the region characterized by the highest Reynolds numbers at heights of 70 and 80 cm.

This observation is consistent with the principle of polymer friction reduction, where an increase in flow velocity results in a substantial decrease in the friction factor. This reduction, influenced by the polymer's characteristics and Reynolds number, can persist until it reaches the maximum line representing the polymer's maximum effect, known as Maximum Drag Reduction (MDR) as proposed by Virk [8]

In this study, increasing the water tank's height led to an increase in flow velocity, ultimately resulting in a maximum flow rate increase of 13.26% at a polymer concentration of 70 ppm.

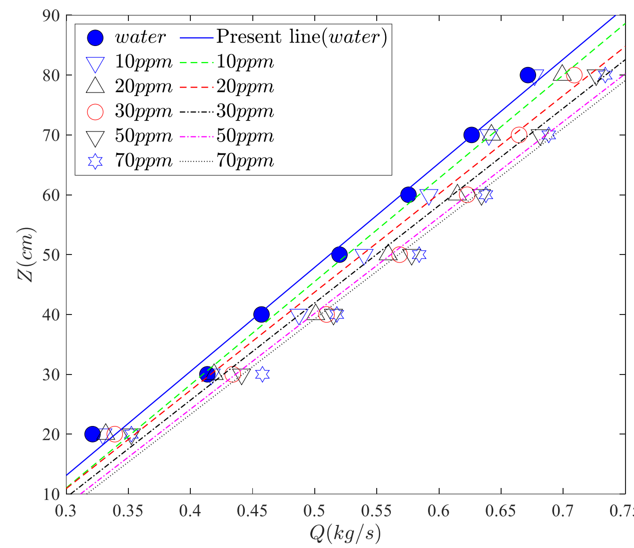


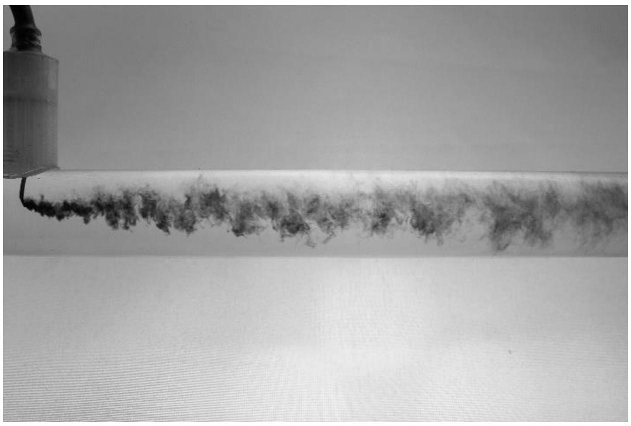
Fig. 3. Water level (*Z*) vs. Mass Flowrate (*Q*).

Table 2. Equations of water height (Z) and mass flow rates (Q), with coefficients of the equation

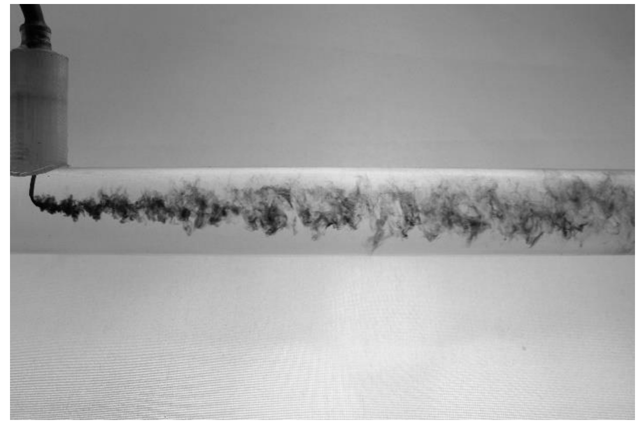
Experiment case	Equation form: $Z = a \cdot Q + b$	
	a	b
water	173.86	-39.05
10 ppm	172.44	-40.71
20 ppm	164.15	-38.34
30 ppm	162.54	-39.33
50 ppm	160.11	-39.87
70 ppm	159.37	-40.44

3.3 Flow Visualization

After a comprehensive review of the flow photographs, Figure 4a presents an image of pure water in an acrylic tank with a water level of 30 cm, resulting in a Reynolds number of approximately 31,000. The flow direction is from left to right. The image illustrates that the flow within the tube is entirely turbulent, evident from the distribution of flow streaks throughout the inside of the pipe. Furthermore, the fading color of the dye ink as it moves away from the release point indicates the instability of the small-scale turbulent flow inside the pipe, primarily visible on the right side of the pipe. The turbulent small scale [8], also known as a turbulent eddy, is a distinctive feature of the swirling masses during turbulent flow. Its characteristics change with increasing Reynolds number (Re), and it can only be clearly observed through dye or particle flow visualization techniques. This observation is crucial for understanding the behavior of the system.



a) Water

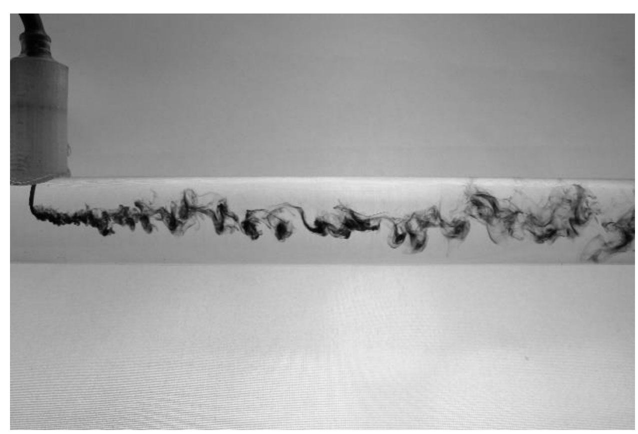


b) C = 10 ppm

c) C = 20 ppm

d) C = 30 ppm

e) C = 50 ppm



f) C = 70 ppm.

Fig.4. Flow visualization at water level (Z) = 30 cm.

At the same height, when the polymer solution was introduced into the system at concentrations of 10, 20, 30, 50, and 70, the results were depicted in Figures 4b to 4f, respectively. Starting at a concentration of 10 ppm in Figure 4b, it's evident that the intensity of the streak lines near the dye release point increases, while the appearance of small-scale turbulence becomes more concentrated. Upon inspecting the additional images, it became evident that with higher polymer concentrations, the streak length increased while turbulence decreased proportionally with the substance concentration, ultimately leading to the acquisition of the clearest image in Figure 4f, it depicts the effect of a polymer solution with a concentration of 70 ppm on the system. A comparison with the experimental results obtained from pure water reveals notable differences. In the presence of the polymer solution, the intensity of the dye ink remains consistent, and the streamwise direction lines do not disperse throughout the pipeline. This clear observation indicates that the polymer solution has a temporary suppressing effect on the intensity of turbulent flow, effectively reducing the dispersion of small-scale turbulence. In other words, it promotes a shift toward a more robust flow pattern compared to the same Reynolds number. The results of this experiment are consistent with the experiments of Sattaya and Matsubara [15], who proposed that polymer solutions influence flow patterns and lead to delays in transitioning to the turbulent flow phase.

4. CONCLUSIONS

From the results of the present study, it can be concluded that the injection of a high molecular weight polymer solution into the system in a small amount can nevertheless affect the flow by increasing the flow rate of the system as the friction factor between the fluid and the pipe wall decreases. And the polymer solution also directly affects the structure of the flow inside the pipe. In the future project, the authors hope that the technique for reducing friction in pipes can be tested on a larger scale, such as in real sewer systems to observe how much it can reduce friction and increase the flow rate of the system, which can be beneficial and reduce energy consumption significantly if it is used in a real drainage system in places such as community drainage systems or the train station system, etc.

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