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Experimental Study for Enhancement of Water Flow in Horizontal Pipelines by Using Nanoparticles of Zinc Oxide and Poly Acrylic Acid

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Keywords:

Drag reduction; Friction factor; Poly acrylic acid; Zinc oxide nanoparticles; Nanofluid.

Highlights:

- *The pipeline system achieved maximum drag reduction by mixing Poly Acrylic acid (PAA) and Zinc Oxide (ZnO) nanofluids.*
- *Decrease frictional resistance and conserve pumping power for turbulent pipe flow.*
- *DRAs are most effective in high-velocity flows with low to moderate viscosities.*

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Abstract: Process industries need to move fluid over long distances in pipes of various capacities, consuming a lot of energy and raising the cost of establishing and maintaining pumping stations. Therefore, additives were used to reduce such costs and overcome fluid resistance. This work used Poly Acrylic acid (PAA) added to the water at different concentrations of 100, 200, 300, 400, and 500 ppm. This work used rough pipes (P.V.C. covered in sand) of different diameters, i.e., 17, 23, and 26.5 mm, to experiment. After that, the 500 ppm of (PAA+ water) solution was mixed with 0.3% and 0.6% Zinc Oxide Nanoparticles (ZnO) at different flow rates, i.e., 44.2, 40, 35.9, 31, 26.2, and 20.8) l/min at 25 °C The effect of polymer, nanoparticle concentrations, flow rate, and diameter on percentage drag reduction (%Dr) and friction factor was investigated. The results showed an increase of percentage drag reduction % Dr was observed as NP concentration and bulk velocity increased. The drag reduction enhancement was 47% at 0.6% ZnO NP concentration with 500 ppm of PAA solution at a 44.2 l/min flow rate and a diameter of 17mm. The experimental data were also used to calculate the friction factors. The results showed a decrease in friction factors when using a 500 PAA solution: 37% and 54% for 0.6% ZnO NP with the solution.

دراسة تجريبية لجسيمات حمض بولي أكريليك وأكسيد الزنك النانوية لتعزيز تدفق المياه في نظام تدفق خطوط الأنابيب الأفقية

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الخلاصة

تحتاج الصناعات العملية إلى نقل السوائل لمسافات طويلة في أنابيب بسعات مختلفة، مما يستهلك الكثير من الطاقة ويرفع تكلفة إنشاء محطات الضخ وصيانتها. بحيث تم استخدام المواد المضافة لتقليل هذه التكاليف والتغلب على مقاومة السوائل. استخدم هذا العمل حمض بولي أكريليك (PAA)، الذي تمت إضافته إلى الماء بتركيزات مختلفة من ١٠٠ و٢٠٠ و٣٠٠ و٤٠٠ و٥٠٠ جزء في المليون. خلال هذا العمل، تم استخدام أنابيب خشنة (P.V.C. مغطاة بالرمل) بأقطار مختلفة، مثل ١٧ و٢٣ و٢٦,٥ مم، لإجراء التجربة. بعد ذلك، تم خلط ٥٠٠ جزء في المليون من محلول PAA + المائي مع ٠,٣٪ و٠,٦٪ من جزيئات أكسيد الزنك النانوية (ZnO) بمعدلات تدفق مختلفة لتر/دقيقة.(44.2, 40,35.9, 31, 26.2 and 20.8) تم دراسة تأثير تركيزات البوليمر والجسيمات النانوية، وكذلك معدل التدفق والقطر، على نسبة تقليل السحب (٪ Dr) وعامل الاحتكاك، أظهرت النتائج زيادة بنسبة ٪ Dr لوحظت مع زيادة تركيز NP وسرعة الكتلة. كان تعزيز تقليل السحب ٤٧٪ عند تركيز ZnO NP بنسبة ٠,٦٪ مع ٥٠٠ جزء في المليون من محلول PAA بمعدل تدفق ٤٤,٢ لتر / دقيقة وقطر ١٧ مم. كما تم استخدام البيانات التجريبية لحساب عوامل الاحتكاك، وأظهرت النتائج انخفاضا في عوامل الاحتكاك عند استخدام محلول ٥٠٠ :PAA٣٧٪ و٥٤٪ ل ٠,٦٪ ZnO NP مع المحلول.

الكلمات الدالة: تقليل الاعاقة، تقليل الاحتكاك، حمض البولي أكريليك، جزيئات أكسيد الزنك النانوية، السوائل النانوية.

1.INTRODUCTION

In practical life and engineering applications, important observations of how turbulence in fluid flow affects wall shear stress rate need to be made and explained clearly. The mechanism of turbulent fluid flow is very complex in dedicated pipelines, and in theory—scientific research is still ongoing in the field of turbulent fluid flow understanding these fluctuations is insufficient [1]. The movement of liquid particles randomly and in transverse directions is the practical description of the turbulent liquid flow heading toward the main liquid flow. The liquid flow is generally unsettled, which is the real description of the turbulent liquid [2]. It occurs in swirling regions of fluids, called eddies, where fast, turbulent flows of water flow. These perturbations provide an additional mechanism for energy and momentum transfer. The liquid particles flow orderly along the path relative to the laminar liquid flow via molecular diffusion and across streamlines, energy, and momentum are transferred. The liquid particles flow in an orderly manner along the path relative to the laminar liquid flow via molecular diffusion and across streamlines, energy and momentum are transferred, and the process of turbulent transfer of mass, energy, and momentum to the regions of flow is faster than molecular diffusion in the case of turbulent fluid flow. Mass transfer and momentum plus operation greatly improve the process of heat transfer; therefore, the values of friction factors are mainly determined by the purpose of the flow of the turbulent fluid [3]. There is frictional force or drag in a turbulent fluid flow inside a pipeline. Although it may cost more, employing pumps to enhance the fluid's pressure is an option. As a result, the problem has been addressed using the drag reduction technique. By simply adding additives known as drag-reducing agents (DRA), the pressure loss is reduced, and the flow performance is boosted (DRA) [4]. Since its discovery decades ago, the issue of polymer-induced drag reduction has received constant study because polymer drag reducers may significantly reduce pressure drop and drag with a relatively small amount of material; however, they are still commonly employed [5]. It is a synthetic polymer polymerized from acrylic acid monomers. It has good solubility in water and is characterized by its molecular weight. It is used in making polymeric mixtures and nanocomposites. In this research, the goal is to determine the ability of poly (acrylic acid) to interact with the formation of nanocomposites with high performance and effectiveness [6]. Nanofluids, which are fluid suspensions of nanoparticles, have a variety of intriguing qualities, and their one-of-a-kind capabilities provide unparalleled potential for a wide range of applications. Because of their large surface area and nanoscale size, NPs have unique physical and chemical characteristics. According to reports, their optical properties are size-dependent, which imparts distinct hues due to absorption in the visible spectrum. Their distinctive size, shape, and structure also affect their reactivity, toughness, and other qualities. Because of these nanoparticles' good properties, many researchers have studied nanofluids using different nanomaterials and volume fractions, such as Omar used Al_2O_3, CuO, SiO_2, and ZnO, with different volume fractions [7]. Farouk et al. examined how nano Ag addition affected composites' mechanical and physical characteristics [8]. Nanoparticles are classified as metals, oxides, or carbides, while base fluids can be water, ethylene glycol, or other ionic liquids [9,10]. Thamer and Abbass [11] examined the solution of water and titanium dioxide (TiO_2) nanoparticles at five distinct concentrations and flow rates via the pipe. The outcomes demonstrated the suggested nanoparticle solutions' effectiveness in reducing turbulent drag and that when their concentrations and flow velocities rise, so did their efficiencies. Higher Reynolds numbers and additive concentrations resulted in lower friction coefficients. Polymers are used to enhance cross-linking and more easily dispose of residual free bonds and are of great significance due to their numerous connections and movement impediments. Here, the diverse classes of polymers with different chemical structures, i.e., branched and block, and structures have been shown to favor cross-linking over ZnO NPs [12]. Escudier et al. [13] studied various aqueous polymer solutions' fully evolved turbulent pipe flow, including carboxymethylcellulose (CMC), a CMC/XG blend, and polyacrylamide (PAM). They discovered that, for the most part, the drag-reduction behavior was compatible with the behavior of viscoelastic and extensional viscosity at low shear. Xiaoping et al. [14] examined the impacts of drag reduction by adding SiO_2 nanoparticles to various polymer polyacrylamide (PAM) solutions. They observed that this could enhance the drag reduction performance of polymer drag reducers under higher Reynolds numbers and optimum nanoparticle concentration. Sajadi et al. [15] investigated the ZnO/water nanofluid flow's pressure drop behavior and heat transmission when the base fluid contained 1% and 2% volume percentages of nanoparticles in the turbulent regime. The measurements revealed that 1% and 2% nanofluids pressure drops were 45% and 145% higher than those of the basic fluid, respectively. Karuppasamy et al. [16] investigated increasing heat transfer while decreasing pumping loss using different mass flow rates and water nanofluids, such as Al_2O_3, SiO_2, CuO, and ZnO. The result showed that the mass flow rate and friction factor were inversely proportional. The friction factor will decrease as the turbulence increases. Various concentrations of nanoparticles (NPs) were evaluated with varying fluid flow rates to examine heat transfer efficiency and characteristics of pressure drop of ZnO/DIW (deionized water) in horizontal microtubes of diverse diameters. They demonstrated that the friction factor decreased as the volume flow rate increased. At a 12.0 ml/min flow rate of nanofluids NFs, for tubes with 1.0-2.0 mm diameters, the largest variation in friction factor was 28.85-12.72%, respectively [17]. The amount of drag reduction that can be accomplished depends largely on a fluid's viscosity. In general, fluids with higher viscosities encounter greater drag than those with lower viscosities because fluids with higher viscosities exhibit greater flow resistance, leading to elevated shear stress and turbulence. Fluids can have their viscosity decreased and flow efficiency increased using specific additives such as polymer, surfactant, and nanoparticles. Many new studies recently have investigated using hybrid nanofluid [18,19], produced by suspending various nanoparticle types in composite or mixed form. The innovative use of nanofluid is for potential improvements in heat transfer and pressure drop characteristics by balancing the benefits and drawbacks of each unique solution. Corcione [20] demonstrated that an empirical correlation was legitimate, as in Eqs. (1) and (2), to forecast the relative viscosity:

$$\frac{\mu_{nf}}{\mu} = \frac{1}{1-34.87\left(\frac{d_p}{d_f}\right)^{-3}\varphi^{1.03}} \quad (1)$$

$$d_f = 0.1\left(\frac{6M}{N\Pi\rho f_0}\right)^{\frac{1}{3}} \quad (2)$$

Where ρ_f is the base liquid mass density, estimated at T_o = 293K, N is the Avogadro number, the corresponding diameter of a base fluid molecule, d_f, d_p is the diameter of particles, φ is the volume fraction of nanoparticles, M is the macular weight, and μ_{nf}. is the viscosity of nanofluid. A novel association between temperature and solid concentration and the dynamic viscosity of the MWCNT-MgO (SAE50) hybrid nano-lubricant was proposed by Asadi et al. in Eq. (3) [21].

$$\mu_{nf} = 328201 * T^{-2.053} * \varphi^{0.09359} \quad (3)$$

This study aims to provide more information regarding investigating the impact of pipe diameter, flow rate, and concentration on drag reduction and friction factor in horizontal water flow systems using polyacrylic acid (PAA) and their mixture (PAA-ZnO nanoparticles).

2.EXPERIMENTAL PROGRAM

2.1.Materials

Water was used in this work as a flowing liquid, with the following properties at 25 °C: viscosity was 1 cP (centipoise), and density was 996 kg/m³. Polyacrylic acid (PAA) is an anionic polymer, a non-toxic, biocompatible, and biodegradable polymer that can be synthesized by the free radical polymerization of acrylic acid [22]. (PAA) was provided by RICHEST GROUP SUPPLIER. It has a swelling nature and tends to absorb and retain water, with an average molecular weight of 25000 g/mol. The zinc oxide nanoparticles (ZnO NPs) were provided by US Research Nanomaterials, Inc. with a diameter of 35–45 nm, 99.9% purity, an appearance of white powder, and a bulk density of 5700 kg/m³.

2.2.Preparation of the Samples and the Method

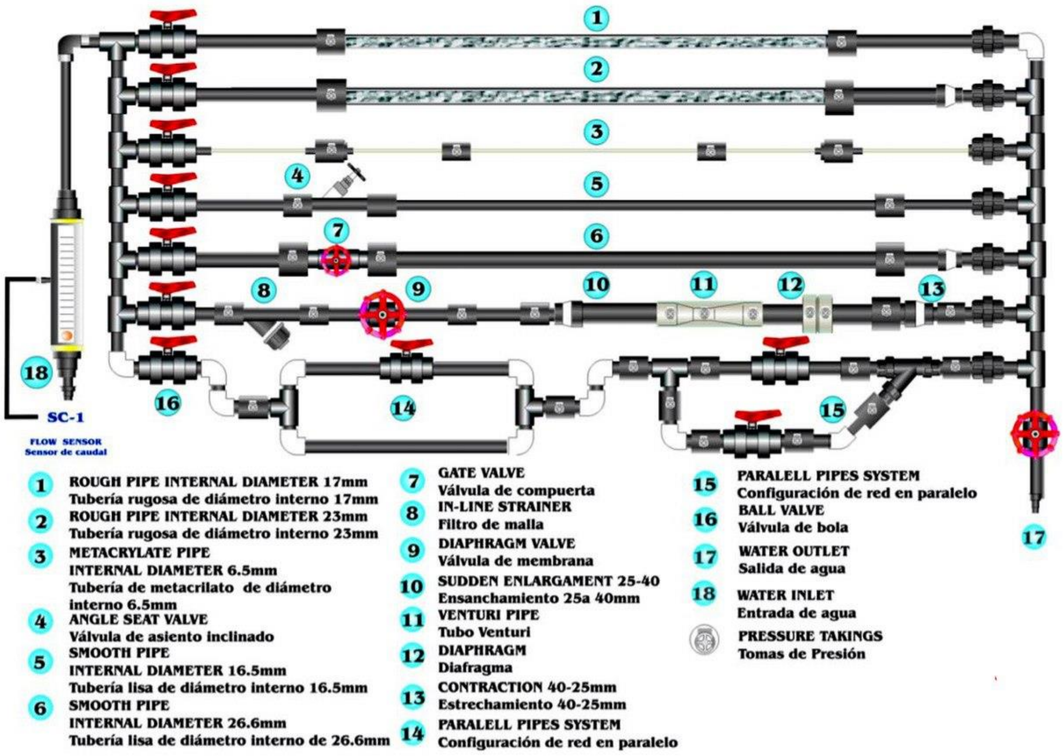
Weighing the sample using an electronic balance with high precision (TP-SERIES). Five concentrations, i.e., 100, 200, 300, 400, and 500 ppm (part per million) of PAA due to their unique properties and uses, were mixed with water by a magnetic stirrer for 30 minutes, required the mixture to be completely homogenized at a relatively low speed to avoid polymer breakdown. The stirred solution was allowed for 12 hours to ensure that the polymer particles were completely dissolved and released gas bubbles that had been trapped to create the master solution (Gimba et al., [23] and Edomwonyi-Otu and Adelakun [24]). The PAA and water solution was mixed with 0.3% and 0.6% ZnO nanoparticles; i.e., Based on the agents that reduce drag, these concentrations selected were efficient, readily available, and inexpensive; by a stirrer for 30 minutes, then with an ultrasonic homogenizer of 1200 W power for 20 minutes to overawed agglomerative and made the suspension more stable. All nanofluids were uniformly disseminated and maintained their stability even after one week, making them suitable for testing. FUNGILAB SMART devices were used to measure the viscosities. A spindle immersed in nanofluids was led by the viscometer. Using a calibrated spring deflection, the friction and viscosity of the solution next to the spindle were intended to be increased while the spindle was rotating. The measurement range for viscosity was between 1.5 and 30,000 mPas.

2.3.Experimental Procedure

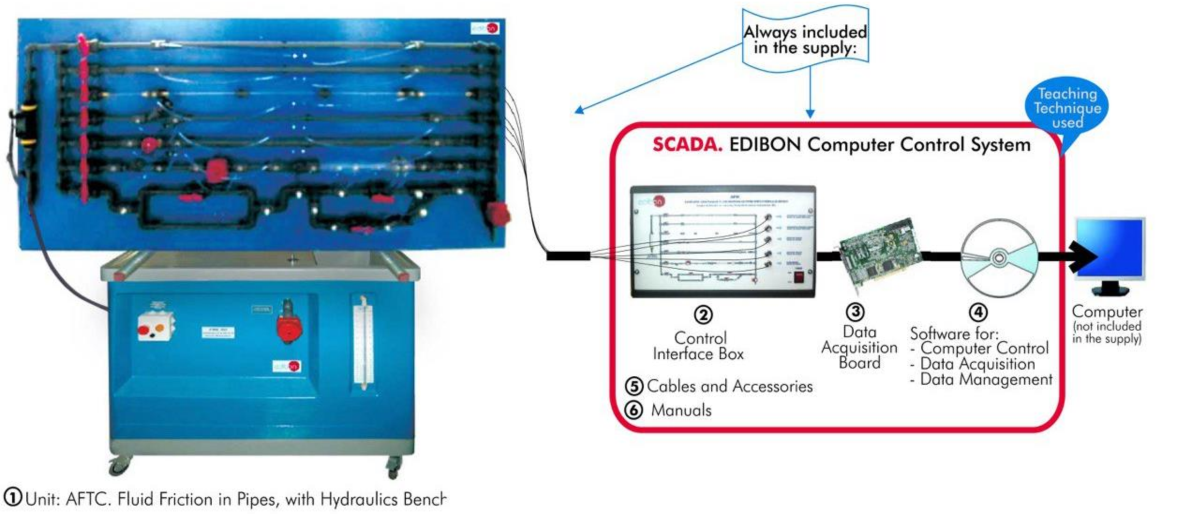
The experimental procedure is listed below:

Three pipe diameters—rough pipe, i.e., P.V.C. covered in sand, of 17, 23, and 26.5mm were used to experiment, as shown in Fig. 1. The experimental procedure included checking the hydraulic system well in terms of saving water in the device tank by venting and expelling air from the water pump, i.e., centrifugal pump, computer-controlled, 0.37 KW, single phase 220V, 50Hz, the runner made from stainless steel, opening the driver program from the computer and turning on the pump for the tube to be manual valves (Ball valve) and the rest of the accessories of the test device.

1) Opening the manual valves of the tube whose pressure drop was measured and connecting the rubber bushings between the two points (entry and exit) checked for a pressure drop.
2) Fixing the pump speed each time to change the volumetric amount flowing through the tube to be measured by the pressure drop on it.
3) Record the pressure drop and volumetric flow at each selected speed, i.e., five pump speeds (6, 7, 8, 9, and 10 l/min.). It means increasing the electric propulsion force of the pump that operates with variable electrical frequencies and according to the required height (head). Each pump speed corresponds to the fluid flow rate. The fluid speed was calculated according to flow rates, such as (44.2, 40,35.9, 31, 26.2, and 20.8 L/min), and the pipe diameter (17, 23, and 26.5mm). The residence time was 60 min for each experiment.
4) The same steps were performed for all tubes mentioned in the experiment for five PAA concentrations (100, 200, 300, 400, and 500 ppm) and repeated for the solution of (PAA + water), i.e., mixed with 0.3% and 0.6% ZnO nanoparticles in a pipe with a diameter of 17mm because it has a higher drag reduction than other diameters.



(a)



(b)

(c)

Fig. 1 (a, b, and c) The Experiment Device Showing the Working Stages.

2.4.Drag Reduction Calculation

In this work, Eqs. (3) - (7) are used to predict the drag reduction percentage (%DR), the flow Reynolds number (Re), the Darcy friction factor [25, 26], Power consumption, and density [27], respectively.

$$\%\mathrm{DR} = \frac{(\Delta P_b - \Delta P_a)}{\Delta P_b} \quad (4)$$

$$\mathrm{Re} = \frac{\rho v d}{\mu} \quad (5)$$

$$f = \frac{2 d \Delta P}{L \rho v^2} \quad (6)$$

$$p_E = Q.\Delta p \quad (7)$$

$$\rho_{nf} = \varphi\ \rho_p + (1 - \varphi)\ \rho_f \quad (8)$$

Where Pb and Pa are the pressure drop prior to and following the DRA, v is the linear velocity, ρ is the fluid density, ρ_{nf} is the nanoparticles density, ρ_p is particles density, φ is the volume fraction of nanoparticles, μ is the dynamic viscosity, d is the pipe diameter, and L is the pipe length. The measured results were compared to the theoretical predictions made by the Petukhov equation [28].

$$f = [0.79 \ln(\mathrm{Re}) - 1.64]^{-2} \quad (9)$$

3.RESULTS AND DISCUSSION

According to various research, polymers function as a drag-reducing material by suppressing producing Eddie current, greatly reducing turbulence. Additionally, it has been noted that several variables, including concentration, diameter, molecular weight, chain flexibility, and flow rate, impacted the polymers' performance. Figure 2 shows that DR increased from 23.1%, 13.37%, and 11.75% with a decrease in the pipe diameter, i.e., 17, 23, and 26.5 mm, respectively, at 500 ppm for the polymer-water solution compared to without polymer addition. Increasing the polymer increased the fluid's viscosity, reducing the drag reduction. The smaller pipe diameter caused a high-pressure drop, intensifying the turbulence. As a result of collisions between larger eddies, the smaller pipe's high degree of turbulence created numerous insignificant water phase eddies. Due to the smaller eddies' lower energy requirements than the bigger ones, the DRP readily overcame them. This behavior agrees with Gimba et al. [29].

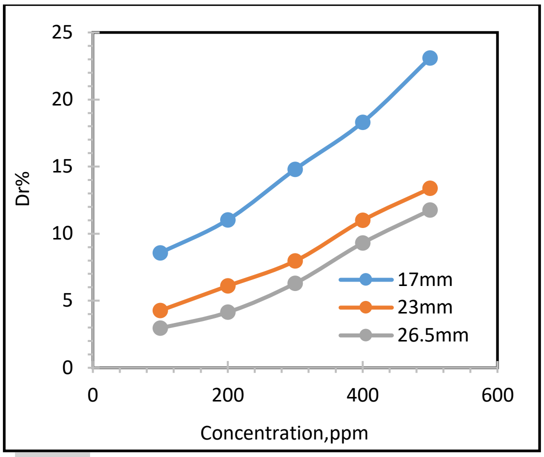


Fig. 2 Effect of Diameter on the Percentage Drag Reduction for PAA at 44.2 L/min.

Figure 3 shows that the drag reduction percentage varied with the velocity of the solution flowing into the pipes, i.e., polymer and (500 PPM polymer + 0.3% and 0.6% ZnO) nanofluid solutions. The drag reduction enhancement was 47% at 0.6% ZnO NP concentration with 500 ppm of PAA solution at a flow rate of 44.2 l/min. A larger margin of drag reduction can be produced by the drag reducer since increasing velocity causes more turbulence. This behavior agrees with Mucharam et al. [30]. Particles in nanofluid, as small as a nanometer in size, are present. These particles are colloidally suspended in the base fluid. Compared to polymers, nanofluids function differently as drag reducers. The technique through which nanofluid lowers drag inside the pipeline is known as surface modification due to the better changes in physical and chemical characteristics and the higher solubility. The greater surface area of nanoscale materials will make it easier for them to dissolve in solutions, boosting their effectiveness in reducing drag. The pipeline becomes a smoother conduit for fluid flow since the nanofluid's nanoparticles are in cracks throughout its length inside the wall. The nanomaterials' capacity to interact with water to lessen drag is also improved. The nanoparticles' high surface area efficiently reduces the bursting process caused by the turbulent flow. The most effective method to decrease frictional resistance and conserve pumping power for turbulent pipe flow is drag reduction, accomplished using a few polymeric additives and nanoparticles. Figure 4 shows the power consumption reduction from 28.8 watts at zero to 23.6 watts for 500 PPM of PAA. For the mixing (500 ppm PAA + 0.3% and 0.6% ZnO nanoparticles), the power consumption decreased by 20.7 and 19 watts, respectively, indicating significant power savings. The power consumption decreased gradually, so it was clear that adding nanoparticles has an important role in improving power consumption. This can be explained by forming an association complex between the polymer chains and nanoparticles, enhancing the polymer molecules' bonding force, and extending the polymer chains. Figure 5 demonstrates that the friction factor reduced with Re number and concentration. As concentration increased, the friction factor also decreased. The results showed a decrease in friction factors when using 500 PAA solution: 37% and 54% for 0.6% ZnO NP with the solution. Elongation effects are responsible for lowering the friction coefficient in the turbulent flow of highly diluted polymer solutions. This behavior agrees with Hinch [31]. Others claimed this may be connected to a strong resistance to molecule elongation caused by the strain and its impact on fluid extensional viscosity. As a result, the viscosity would be greater than it would be if these elongational deformations were not there. The polymer friction factor values lie near the Petukhov equation. Figure 5 also shows that lowering the friction factor even more using a PAA polymer solution with ZnO NP was possible due to using polymers with nanoparticles to further lower fluid resistance in pipelines.

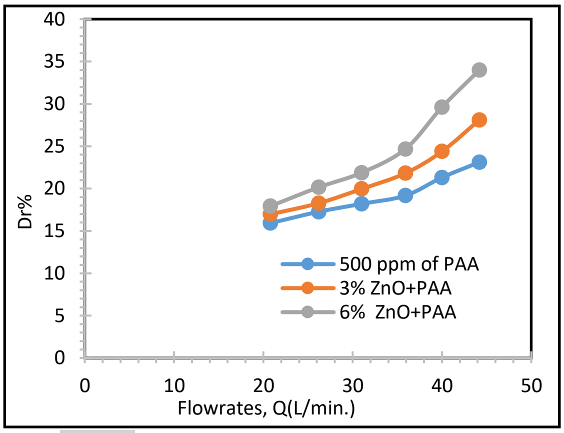


Fig. 3 Effect of Concentration on the Percentage Drag Reduction for PAA and (PAA+ ZnO) at Different Flowrates.

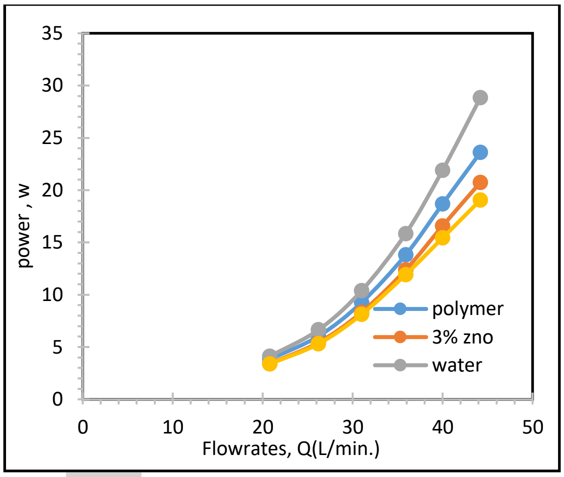


Fig. 4 Effect of PAA and PAA+ ZnO Concentration on Pumping Power Consumption.

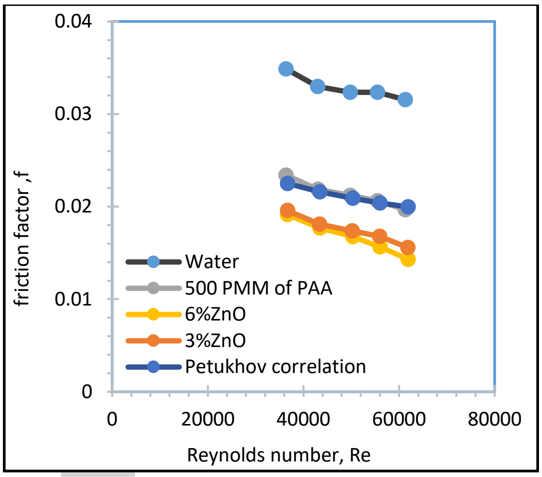


Fig. 5 Effect of PAA and PAA+ ZnO Concentration on Friction Factor at 6 m^3 /hr.

4.CONCLUSIONS

1) In a water flow loop, the effectiveness of PAA polymer at reducing drag was studied. The findings indicated that the additives under consideration reduced turbulent drag as their concentrations and flow velocities increased, and so did their efficiencies.
2) The drag reduction (DR) increased with reducing the three pipe diameters for the polymer-water solution, meaning that the polymer solution effectively reduced turbulence and drag in the smaller pipes than in the larger pipes. The fluid's inclusion of a polymer solution can reduce the turbulence and shear stresses by creating a layer of polymer molecules that acts as a lubricant between the fluid and the pipe wall. When the additive concentrations and Reynolds number were high, lower friction factors were obtained.
3) In addition, the experimental study of Poly Acrylic acid (PAA) and Zinc Oxide (ZnO) nanoparticles to enhance water flow in a horizontal pipeline flow system concluded that combining PAA polymer and ZnO nanoparticles enhanced the drag reduction effectiveness in water compared to PAA-water alone. It can be noticed that adding ZnO nanoparticles to the PAA solution increased the polymer molecules' stability and improved their ability to reduce turbulence and drag in the water flow. At a concentration of 500 ppm, PAA mixed with 0.3 and 0.6% ZnO nanoparticles, the maximum drag reduction was achieved, resulting in a reduction of up to 47% at a diameter of 17mm and a flow rate of 44.2 l/min in the pipeline.
4) The combination of PAA polymer and ZnO nanoparticles has the potential to be an effective method for reducing energy consumption in pipeline systems and reducing friction factors.

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NOMENCLATURE

DRA	Drag-reducing agents
NFs	Nanofluid
NPs	Nanoparticles
PAA	Poly Acrylic acid
ZnO	Zinc Oxide
CMC	carboxymethylcellulose
XG	Xanthan gum
SiO_2	Silica
PAM	Polyacrylamide
Al_2O_3	Aluminum oxide
CuO	Copper oxide
DIW	Deionized water
N	Avogadro number
MWCNT	Multi-walled carbon nanotube
Ppm	part per million
cP	centipoise
%DR	Drag reduction percentage
Re	Reynolds number
f	Darcy friction factor
P	Power consumption, W
D	diameter, m
M	Macular weight kg/kmol
Greek symbols	
Φ	Volume fraction of Nanoparticles.
ρ	Density, kg/m^3
μ	Viscosity, Pa.s
Subscripts	
bf	base fluid
nf	nanofluid

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