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CP - 301

Dep Project Report

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Submitted by

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Weissenberg Effect (Rod Climbing Effect)

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AIM

The primary aim of this project is to design, develop, and validate a high-precision experimental setup for quantitative investigation of the Weissenberg effect (rodclimbing phenomenon) using polymeric solutions under controlled rotational conditions. The setup employs a NEMA stepper motor controlled by a TB6600 driver interfaced with an Arduino microcontroller and potentiometer-based RPM regulation to facilitate precise variation of angular velocity for examining the elastic response of viscoelastic fluids across multiple concentration parameters.

OBJECTIVE

- To design and construct a precise experimental setup using a NEMA stepper motor, TB6600 driver, Arduino, and potentiometer for controlled rotation of a rod to study the Weissenberg effect.
- To systematically investigate the rod-climbing behaviour of polymer solutions at different concentrations and rotational speeds.
- To enable fine adjustment and real-time control of RPM for accurate experimentation and repeatability.
- To capture and analyse the dynamic behaviour of the fluid using a high-speed camera for quantitative assessment.
- To establish the relationship between solution properties, rotational speed, and the magnitude of the Weissenberg effect observed in the experimental setup.

INTRODUCTION

The Weissenberg effect, named after Austrian physicist Karl Weissenberg, is a fascinating phenomenon observed in non-Newtonian fluids, particularly those with viscoelastic properties. Unlike Newtonian fluids, which follow simple shear flow behavior and spread outward when subjected to rotation, viscoelastic fluids can climb a rotating rod or shaft. This counterintuitive behavior is prominently seen in polymer solutions, molten polymers, and other complex fluids where elasticity plays a significant role.

This effect arises due to the inequality of normal stresses in shear flow, which results in a force that pulls the fluid inward and upward. Understanding this phenomenon is critical in the field of **rheology**, as it helps in predicting the behaviour of non-Newtonian fluids in industrial and natural applications. Several experimental, analytical, and numerical studies have been conducted to explain the mechanism behind this effect and its implications in fluid dynamics

This effect highlights the interplay between viscosity and elasticity, a defining characteristic of many non-Newtonian fluids. It challenges our conventional understanding of fluid dynamics and has practical implications in industries involving polymers, food processing, and rheological measurements.

Non–Newtonian fluids :

Unlike Newtonian fluids, where viscosity remains constant irrespective of applied stress, non-Newtonian fluids exhibit complex flow behaviors. These fluids can be classified into:

- **Shear-thinning fluids**: Viscosity decreases with increasing shear rate (e.g., paint, blood, ketchup).
- **Shear-thickening fluids**: Viscosity increases with shear rate (e.g., cornstarch in water, wet sand).
- **Viscoelastic fluids**: Exhibit both viscous and elastic properties (e.g., slime, glue with borax).

MECHANISM OF WEISSENBERG EFFECT

The Weissenberg effect arises due to the development of normal stress differences in viscoelastic fluids under shear. Unlike Newtonian fluids, which primarily exhibit shear stress, viscoelastic fluids also develop significant normal stress components when subjected to rotational forces. This phenomenon leads to the characteristic rod climbing behavior when a rotating rod is immersed in such a fluid.

According to Weissenberg (1947), the primary cause of the Weissenberg effect is the fluid's ability to store elastic energy under shear. When a viscoelastic fluid is exposed to a rotating rod, the polymer chains in the fluid become aligned in the direction of rotation. This alignment causes the chains to stretch, creating elastic tension. As the rotation continues, the fluid experiences both viscous and elastic responses, with the elastic component causing the fluid to be pulled inward rather than pushed outward as in typical Newtonian flows.

The elastic nature of these fluids allows for the buildup of normal stresses, which act perpendicular to the shear plane. These stresses push the fluid toward the axis of rotation and subsequently upward along the rod. This combination of forces causes the fluid to climb the rod instead of being flung outward by centrifugal forces.

1. **Primary Normal Stress Difference ($N_1 = \sigma_1 - \sigma_2$)**
    - σ_1 (Tangential Normal Stress) > σ_2 (Radial Normal Stress)
    - This imbalance pulls the fluid inward toward the rod rather than moving outward, as would be expected in Newtonian behavior.

2. **Secondary Normal Stress Difference ($N_2 = \sigma_2 - \sigma_3$)**
    - σ_2 (Radial Normal Stress) > σ_3 (Axial Normal Stress)
    - This stress difference causes the fluid to be squeezed upward, leading to the rod-climbing phenomenon.

Why Does the Fluid Climb?

- The fluid's elasticity allows it to store energy under shear conditions. The stored ey is released as an inward and upward movement, causing the fluid to climb the rod.
- As described by Debbaut and Hocq (1998), numerical simulations of rod climbing indicate that increasing fluid elasticity and rotational speed enhances the climbing height up to a critical point.

BACKGROUND & LITERATURE

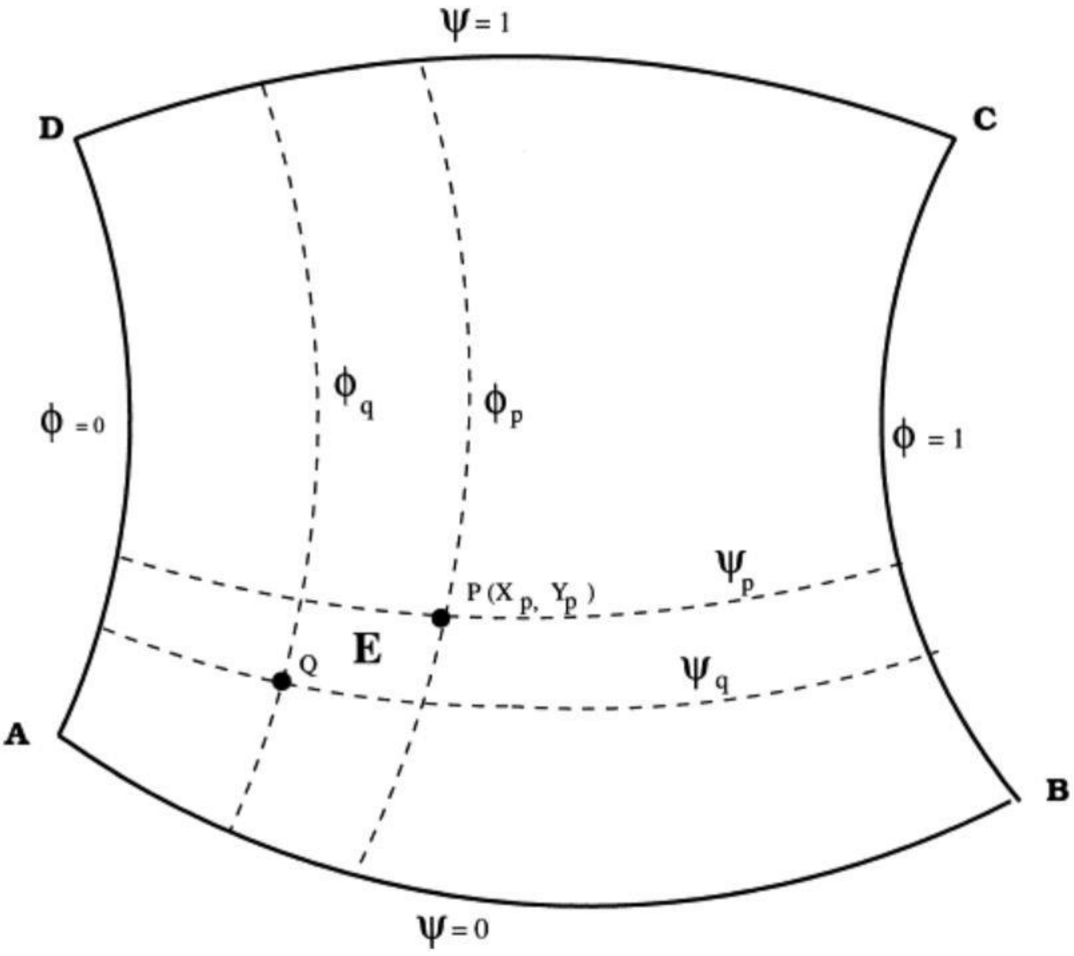


Fig : Mathematical Model of Weissenberg effect

In the above image two functions (Ψ and Φ) that are harmonic and orthogonal. The orthogonality condition is given by:

$\nabla\Psi\cdot\nabla\Phi=0$

This implies that the gradient vectors of these functions are perpendicular everywhere within the domain, forming an orthogonal trajectory mesh.

The functions Ψ and Φ represent potential functions whose level curves intersect orthogonally. This is useful in many applications, such as fluid dynamics and potential theory, where orthogonal coordinate systems simplify problem-solving.

Physical Interpretation:

- Ψ can represent a stream function, where contours of Ψ are streamlines (lines along which the fluid particles move).
- Φ can represent a velocity potential, where the gradient of Φ gives the fluid velocity.
- Since the streamlines (Ψ) and equipotential lines (Φ) are orthogonal, they form a curvilinear orthogonal grid.

Mathematical Properties:

- The pair (Ψ, Φ) satisfies the Cauchy-Riemann equations if they are solutions of the Laplace equation. This means they are conjugate harmonic functions.
- The orthogonality condition ($\nabla\Psi\cdot\nabla\Phi=0$) ensures that the level curves of Ψ and Φ intersect at right angles.

Equation (1):

$\Delta\Psi=0$, $\Psi=0$ on AB, $\Psi=1$ on DC, $\nabla\Psi\cdot n=0$ on AD and BC

Equation (2):

$\Delta\Phi=0$, $\Phi=0$ on AD, $\Phi=1$ on BC, $\nabla\Phi\cdot n=0$ on AB and DC

The equations (1) and (2) shown in the image deal with finding orthogonal functions that satisfy the Laplace equation with specific boundary conditions. These equations arise when constructing orthogonal trajectories, which are curves that intersect other curves at right angles.

In mathematical physics and potential theory, the orthogonal trajectories are often obtained from two scalar potential functions (Ψ and Φ) that satisfy the Laplace equation.

The equations (1) and (12) deal with finding orthogonal functions that satisfy the Laplace equation with specific boundary conditions. These equations arise when constructing orthogonal trajectories, which are curves that intersect other curves at right angles.

In mathematical physics and potential theory, orthogonal trajectories are often obtained from two scalar potential functions (Ψ and Φ) that satisfy the Laplace equation.

Equation (1):

$\Delta\Psi=0$, $\Psi=0$ on AB, $\Psi=1$ on DC, $\nabla\Psi\cdot n=0$ on AD and BC

Explanation: The symbol Δ denotes the Laplace operator ($\Delta=\nabla\cdot\nabla$), which ensures that the function Ψ is harmonic (satisfies Laplace's equation).

Boundary Conditions:

- $\Psi=0$ on side AB (Dirichlet condition).
- $\Psi=1$ on side DC (Dirichlet condition).
- The normal derivative ($\nabla\Psi\cdot n=0$) on sides AD and BC implies that there is no flux across these boundaries (Neumann condition).

Equation (2):

$\Delta\Phi=0$, $\Phi=0$ on AD, $\Phi=1$ on BC, $\nabla\Phi\cdot n=0$ on AB and DC

Explanation: This equation also represents a harmonic function (Φ) with the Laplace operator.

Boundary Conditions:

- $\Phi=0$ on side AD (Dirichlet condition).
- $\Phi=1$ on side BC (Dirichlet condition).
- The normal derivative ($\nabla\Phi\cdot n=0$) on sides AB and DC indicates no flux across these boundaries (Neumann condition).

Orthogonality Concept

The primary goal here is to find two functions (Ψ and Φ) that are harmonic and orthogonal. The orthogonality condition is given by:

$\nabla\Psi\cdot\nabla\Phi=0$

This implies that the gradient vectors of these functions are perpendicular everywhere within the domain, forming an orthogonal trajectory mesh.

The functions Ψ and Φ represent potential functions whose level curves intersect orthogonally. This is useful in many applications, such as fluid dynamics and potential theory, where orthogonal coordinate systems simplify problem-solving.

APPARATUS REQUIRED:

- **A base frame** that holds the entire setup stable.

Fig1 : Steel Base (50x50 cm2)

- **Two threaded rods** attached to the base, supporting the stepper motor and ensuring rigidity.

Fig 2 : Threaded rods (2pcs) (30cm each)

- **A stepper motor** mounted at the top, which rotates the rod submerged in a beaker containing viscoelastic fluid.

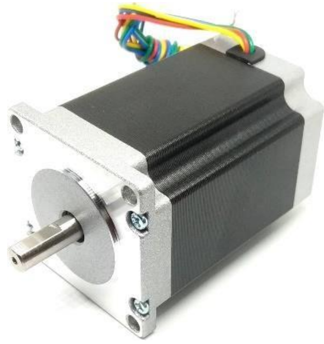


Fig 3 : Nema Stepper motor

- **TB6600 motor driver** to control the steps of stepper motor and to control the rpm of motor.

Fig 4 : TB6600 Stepper motor driver

- **The Arduino microcontroller** connected to the stepper motor, allowing precise control over rotation speed.

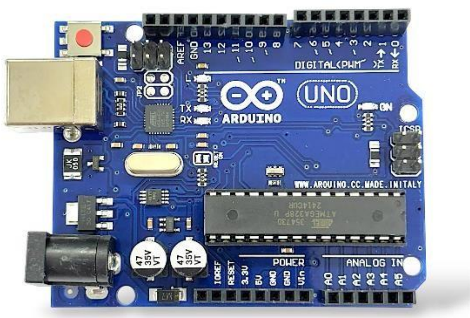


Fig 5 : Arduino uno •

A potentiometer for manual speed adjustments.

Fig 6 : Potentiometer (10k ohm)

- **A beaker placed** at the center, containing the test fluid.

Fig 7 : Beaker for fluid storage (500ml)

- **A high-speed camera** for data collection, Slow motion videos and analysis.

Fig 8 : High Speed Camera

- **Fedus 12V – 5A AC-DC adapter** : To power the driver as it require DC power and at least 9 Volts to operate.

- **Working Fluid :** Viscoelastic fluid in which we have used PAM (Polyacrylamide) , These are water-soluble synthetic linear polymers.

  ○ 400mg of Polyacrylamide (PAM) in 80g water = 5000 ppm solution ○ 800mg of Polyacrylamide (PAM) in 80g water = 10000 ppm solution ○ 1200mg of Polyacrylamide (PAM) in 80g of water = 15000 ppm solution

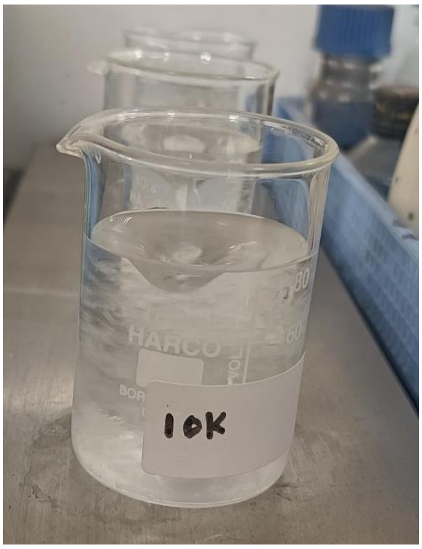


Fig 9 : PAM solution

- Magnetic Stirrer : A **magnetic stirrer** or **magnetic mixer** is a laboratory device that employs a rotating magnetic field to cause a stir bar (or *flea*) immersed in a liquid to spin very quickly, thus stirring it

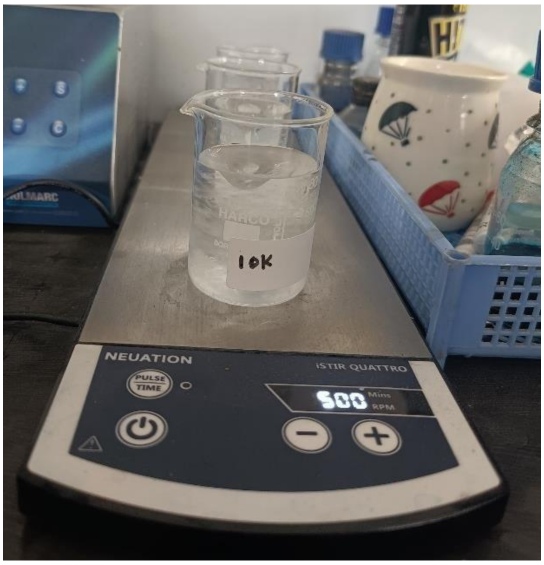


Fig 10 : Neuation Magnetic stirrer

- **Mild Steel rod** : A mild steel rod is used to for the rod climbing effect.

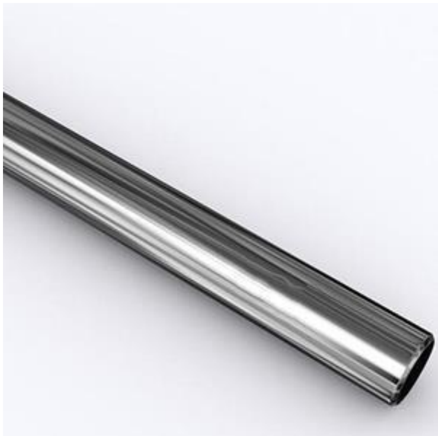


Fig 11 : Mild steel rod (15 cm)

- **M16 nuts** for manually changing the height of the motor.

Fig 12 : M16 Hexagonal Nut (4 pcs)

EXPERIMENTATION

✞ <u>Preparation of PAM Solutions</u>

1. Prepared three different concentrations of Polyacrylamide (PAM) solutions:
    - 5000 ppm solution: Precisely measured 400 mg of PAM powder and dissolved it in 80 g of distilled water
    - 10000 ppm solution: Mixed 800 mg of PAM powder with 80 g of distilled water
    - 15000 ppm solution: Combined 1200 mg of PAM powder with 80 g of distilled water
2. Added a small amount of blue dye to each solution to enhance visibility and facilitate better observation of the fluid climbing behavior during experimentation.
3. Used a Neuation magnetic stirrer to ensure complete dissolution of the PAM powder in water. Maintained gentle stirring to avoid introducing air bubbles while ensuring homogeneous solutions.

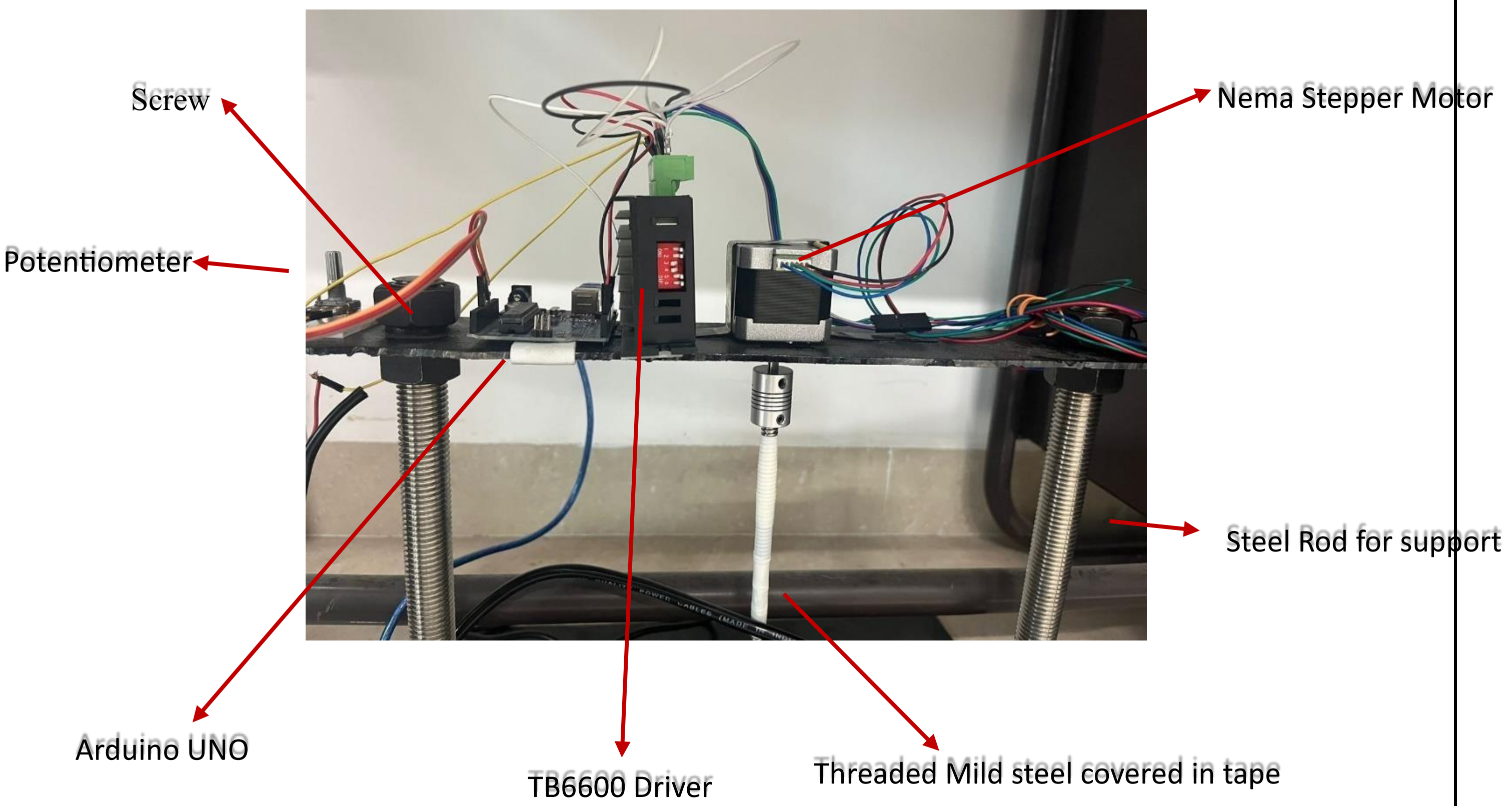
✞ <u>Experimental Setup Configuration</u>

1. Assembled the experimental apparatus by mounting the NEMA stepper motor on the steel base (50×50 cm^2) using two threaded rods (30 cm each).
2. Connected the TB6600 stepper motor driver to the NEMA motor following the manufacturer's wiring guidelines.

3. Interfaced the Arduino Uno microcontroller with the TB6600 driver and connected a 10K ohm potentiometer to allow for precise RPM control.
4. Programmed the Arduino with custom code to:
    - Control the stepper motor rotation speed
    - Enable real-time RPM adjustments via the potentiometer
    - Maintain consistent rotation speeds throughout each test cycle
5. Attached a mild steel rod (15 cm length) to the motor shaft, ensuring it was perfectly vertical and properly secured.
6. Positioned a 500 ml beaker directly beneath the rod to contain the test fluids.
7. Set up the high-speed camera at an optimal position to record the fluid behavior, with particular focus on capturing the rod-climbing effect.

✞ <u>Testing Procedure</u>

- First conducted a control test using water (a Newtonian fluid) to establish baseline behavior and verify that no rod climbing occurs with a Newtonian fluid at any motor speed.
- For each PAM solution concentration (5000 ppm, 10000 ppm, and 15000 ppm):
    - Filled the beaker with the prepared solution to a consistent fill level
    - Lowered the rod into the solution, maintaining a consistent immersion depth across all tests



- Adjusted the height of the motor using M16 nuts on the threaded rods as needed

- Started with the lowest concentration (5000 ppm) and conducted tests at multiple preset RPM values, maintaining identical speed settings across all concentration tests.
- Repeated the testing procedure for the 10000 ppm and 15000 ppm solutions, ensuring consistent experimental conditions.
- For each test:
  - Gradually increased the motor speed using the potentiometer o Allowed the

    system to reach steady state at each speed setting
  - Recorded the climbing behavior using high-speed camera in both normal speed and slow-motion modes
  - Documented the maximum climbing height achieved at each speed

Between each test, thoroughly cleaned the rod to prevent cross-contamination of solutions and allowed sufficient time for the system to reset.

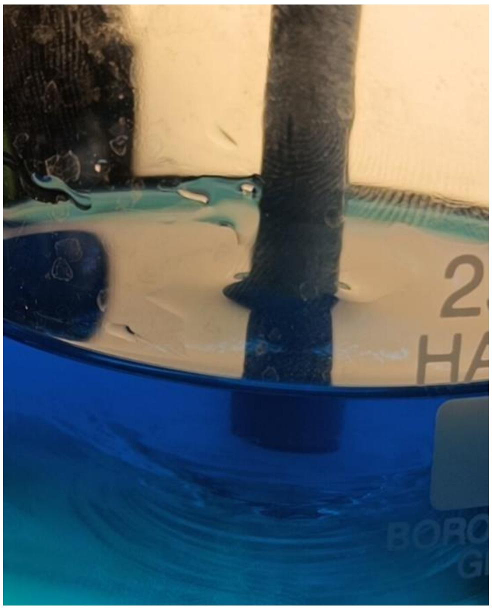


Fig 14 : experiment with 15k ppm solution

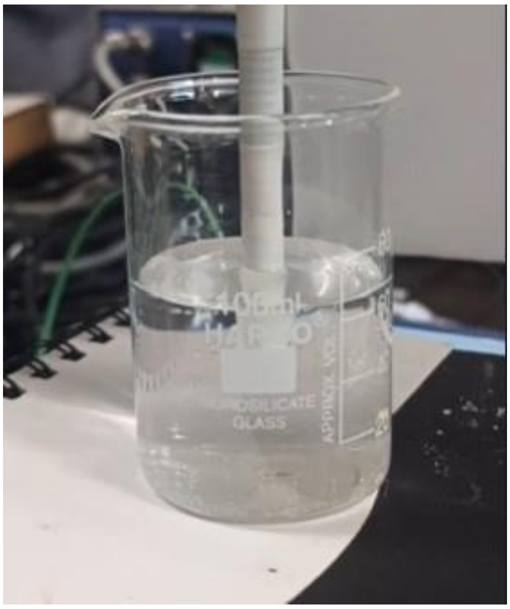


Fig 15 : experiment with water

✞ Data Collection and Analysis

- Recorded the following parameters for each test:
  - o PAM concentration o Motor rotation speed (RPM)
  - o Maximum climbing height achieved by the fluid o Time taken to reach steady-state climbing
- Analyzed the high-speed camera footage to:
  - o Measure precise climbing heights at different rotation speeds
  - o Observe the dynamic behavior of the fluid during acceleration and deceleration phases
  - o Compare the climbing behavior between different concentrations
- Based on the experimental results, the 15000 ppm solution demonstrated the maximum climbing height at equivalent rotation speeds due to its higher elasticity, which produces greater normal stress differences when subjected to shear forces.
- Identified the threshold rotation speed for each concentration, below which no climbing effect was observed, as explained by the contact line pinning and de-pinning phenomenon described in rheological literature.

This systematic procedure allowed for quantitative analysis of the Weissenberg effect and clear demonstration of the differences between Newtonian and non-Newtonian fluid behavior under rotational forces.

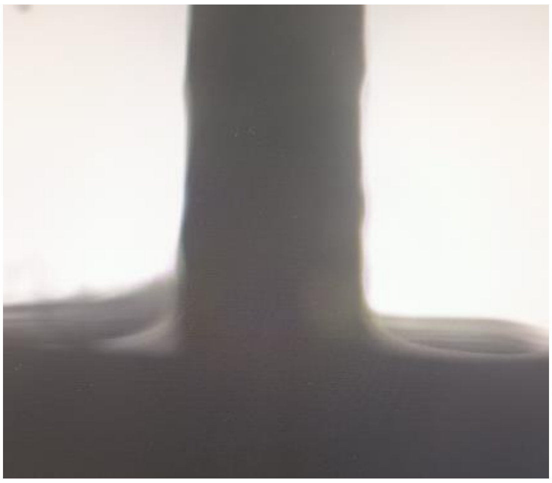


Fig 16 : Camera view of the experiment

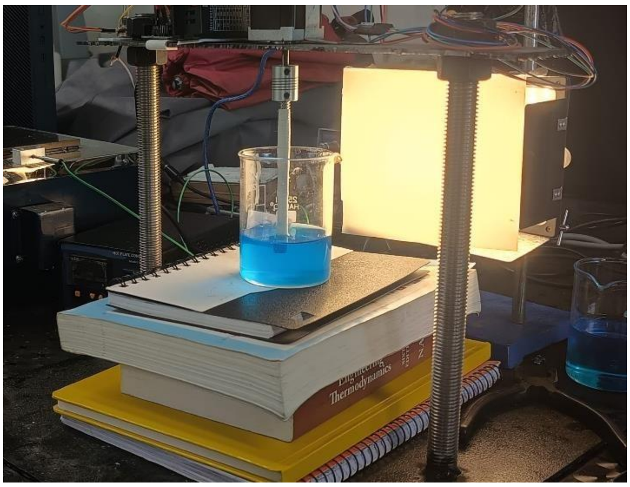


Fig 17 : Experimentation of 15k ppm solution

Code for the motor :

```
int potPin = A0;  // Potentiometer connected to A0
int stepPin = 3;  // Stepper motor PUL pin
int dirPin = 2;   // Stepper motor DIR pin
int speedValue;   // Variable to store potentiometervalue

void setup() {
pinMode(stepPin, OUTPUT);
pinMode(dirPin, OUTPUT);
digitalWrite(dirPin, LOW);  // Set direction
}
void loop() {
 speedValue = analogRead(potPin);  // Read potentiometer value (0-1023)
int delayTime = map(speedValue, 0, 1023, 2000, 50);  // Map to delay range

 digitalWrite(stepPin, HIGH);
delayMicroseconds(delayTime);
digitalWrite(stepPin, LOW);
delayMicroseconds(delayTime);
}
```

Industrial Applications

1. Polymer Processing & Advanced Manufacturing

- **Fiber Spinning Optimization**: Controls die swell in synthetic fiber production by managing normal stress differences through rotational parameters.
- **Micropattern Writing**: Enables precise deposition of polymer melts for microfluidic device fabrication using controlled rod-climbing dynamics observed in 15,000 ppm PAM solutions.
- **3D Printing**: Mitigates nozzle clogging in direct ink writing by countering elastic recoil through rotational shear modulation.

2. Pharmaceutical Engineering

- **Tablet Coating Systems**: Utilizes contact line pinning/de-pinning behavior (observed in bare vs oil-coated rods) to achieve uniform drug layer deposition.
- **Viscoelastic Gel Production**: Applies concentration-dependent climbing height relationships (5000-15000 ppm data) to design reactor impellers that prevent elastic climb.

3. Energy & Automotive

- **Torsional Vibration Dampers**: Implements rod-climbing dynamics in silicone oilfilled dampers for drivetrain systems, using threshold RPM concepts from the study.
- **Enhanced Oil Recovery**: Guides polymer flood design using PAM solution elasticity profiles to improve oil displacement efficiency.

4. Biomedical Technologies

- **Lab-on-Chip Devices**: Leverages micro-scale Weissenberg effects observed in highspeed camera footage to manipulate biological fluids (e.g., synovial fluid) in diagnostic cartridges.
- **Artificial Mucus Production**: Uses 10,000 ppm PAM solution's shear-thinning behavior to replicate respiratory tract fluid dynamics.

5. Advanced Materials Development

- **Smart Adhesives**: Engineers pressure-sensitive adhesives using the inverse relationship between polymer concentration and threshold rotation speed.
- **Liquid Crystal Displays**: Applies rod-climbing principles to align liquid crystal molecules during panel manufacturing.

CONCLUSION

The experiments conducted with three concentrations of Polyacrylamide (PAM) solutions5000 ppm, 10,000 ppm, and 15,000 ppm-demonstrated clear differences in rod-climbing behavior under identical rotational speeds. The 5000 ppm solution exhibited minimal or no climbing, likely due to its low elasticity and insufficient generation of normal stress differences required to overcome surface tension and initiate climbing. The 10,000 ppm solution showed a slight improvement, with some climbing observed at higher RPMs, but the effect remained modest. The 15,000 ppm solution displayed the most pronounced rod climbing among the three, confirming that higher polymer concentration enhances elasticity and thus the Weissenberg effect.

However, even at this highest concentration, the overall climbing heights were lower than expected from theoretical predictions. This is due to less Weissenberg number which suggest that fluid elasticity is low, which ultimately results in lower rod climbing effect.

This can be attributed to factors such as contact **line pinning at the rod-fluid interface**, where the fluid stuck at one place which creates a threshold rotational speed below which climbing does not occur, as well as the influence of **surface tension**. PAM solutions exhibit **shear-thinning characteristics** at higher shear rates, potentially reducing effective viscosity near the rod surface and limiting climbing height.

These findings are consistent with recent research, which highlights that both the viscoelastic properties of the fluid and the interfacial conditions of the rod play crucial roles in determining the magnitude of the Weissenberg effect. Overall, the study successfully demonstrates the concentration dependence of rod climbing in viscoelastic fluids and underscores the importance of both fluid formulation and experimental design in such investigation.

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