Falling ball Viscometer

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Precision Viscometer Using Multi-Sensor Hall Effect Detection

A Project Report in Fluid Mechanics

1. Introduction

1.1 Purpose

This project aims to design a high-precision viscometer using a multi-sensor Hall effect detection system to measure the dynamic viscosity of fluids. Viscosity is a critical property in industries such as automotive (e.g., engine oils) and pharmaceuticals, where fluid behavior under shear must be precisely characterized.

Frequent viscosity measurements are crucial in all fields where fluids are of consistent use, this aids with:

- **Quality Control & Consistency**: Ensures that products meet desired specifications (e.g., paints, coatings, food, pharmaceuticals).
- **Process Optimization**: Helps monitor fluid behavior in pipelines, mixing, and pumping operations.
- **Product Performance & Stability:** In lubricants, viscosity affects friction and wear protection.
- **Compliance with Industry Standards:** Many industries (e.g., automotive, aerospace, pharmaceuticals) require viscosity testing to meet regulatory standards (e.g., ISO)

1.2 Key Innovations

- Multi-sensor redundancy: Two pairs of Hall sensors (top/bottom) to cancel alignment errors.
- N52 magnet: Stronger field (~1500G) improves signal-to-noise ratio vs. weaker magnets.

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2. Design and Methodology

The viscometer employes four KY-024 Hall sensors and an N52 neodymium sphere (17mm diameter, 0.5 g) falling through a 360 mL glass beaker (24mm diameter) to minimize wall effects, with data processed by an Arduino Uno. Key innovations include multi-sensor redundancy to cancel alignment errors and the use of strong N52 magnet spheres (0.5g) for improved signal-to-noise ratio. The scope is currently limited to Newtonian fluids, where viscosity is independent of shear rate.

2.1 Mechanical Design

Parameter	Value	Rationale
Beaker dimensions	360 ml 24mm (D)	Minimize wall effects (Stokes' law assumes infinite fluid)
Sensor spacing	30.5cm vertical	Reduces tilt-induced errors
Magnet properties	N52, 5mm (D) 0.5g	Terminal velocity is easily reached in most Newtonian fluids

2.2 Electrical System

- **KY-024 Hall Sensors**:
  - Analog output (0–5V), 1.5mV/G sensitivity.
  - **Calibration Data**: Output = 2.5V + (0.004V/G × B field).

- **Arduino Nano**:
  - Samples all 4 sensors at 500Hz (2ms resolution).
  - **Algorithm**: Triggers on certain threshold, validates with adjacent sensor.
- **LCD Interface**: Displays Inputs: Mass of ball, ρ_f, Diameter of ball,

  Outputs: **Δt**, **v**, **μ**, **ν.**
- **Keypad Device:** Allows the user to input data, substance-specific data for a well-rounded system

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2.3 Methodology and Governing Equation

The method employed is a revised version of the Falling Ball Viscometer mode of operation, where Hall sensors are spaced out (30.5cm) from each other to allow for larger time calculations, hence more accruate results, the user is only tasked with dropping the N52 magnetic sphere and the rest is done by the both the sensors and microcontrollers.

The Governing Equation:

$$v_t = \frac{2}{9}\frac{r^2(\rho_s - \rho_f)g}{\eta}$$

Derived from the Navier-Stokes equations under creeping flow conditions, Stokes' Law describes the drag force (or viscous resistance) acting on a spherical object moving through a viscous fluid at low Reynolds numbers (laminar flow).

Limitations

- Fails at high Re (turbulent flow, where drag depends on velocity squared).
- Not valid for non-spherical objects (requires shape corrections).
- Wall effects – Nearby boundaries increase drag (e.g., falling ball viscometers require correction factors).

3. Issues Faced and Solutions

Any Mechanical/Electrical system must be met with a multitude of challenges. The following are the hardest issues we faced and how we dealt with them in a sensible and calculated manner.

1. **Tube length:** To find the right tube length, many trials and errors were made, since there was no actual method of calculating the length of fluid needed to ensure our magnetic sphere reached terminal velocity before reaching the first sensor (one of Stokes' Law's main working condition) we settled on a signifacant height of fluid which is around 40cm from the top of the tub.

2. **Ball Diameter:** Then again, there was no single decider of which ball diameter we should use, instead we opted for strongest and smallest spherical magnet on the market which ensure two qualities, the first being that a lighter ball meant less fluid was needed to ensure terminal velocity is reached, secondly it would leave room for the ball to fall freely into the fluid without any tube-wall collisions further lessening any potential sources of error

3. **Hall Sensor type:** We were met with two options that were readily available on the market, the KY-035 and the KY-024. The former being a digital-only sensor meant that a certain predetermined magnetic field threshold was to be surpassed in order to record any reading; the issue with such a sensor is that since our ball is of smaller diameter, sometimes it would not pick up on the ball's magnetic field even if it passed the sensor. Allowing both digital and analogue outputs, the KY-024 is the sensor we opted for; it allowed for manual setting of the magnetic field threshold, meaning that the ball's magnetic field was to be sensed regardless of diameter.

4. **Code Errors and Calculations:** During our test runs, we were met with consistent code errors and calculation issues, which mainly stemmed from insignificant code mistakes (eg. mathematical priorities, jumbled up variables), however these were easily sorted with multiple rounds of checks on the code and the calculations.

4. Experimental Results

4.1 Protocol

Reference Fluids:

- Water (0.9096 cP)
- Motor oil 10w40 (140-160cP)

4.2 Practical Viscometer Readings

Water at 25°C

Time	Velocity	Dyn. Viscosity
0.4	0.77	1.21
0.35	0.88	1.05
0.35	0.86	1.07
0.37	0.83	1.11
0.34	0.89	1.04
0.33	0.93	0.99
0.37	0.83	1.11
0.35	0.87	1.07

Motor oil 10w40 at 25°C

Time	Velocity	Dyn. Viscosity
0.24	0.49	150.34
0.24	0.51	145.41
0.24	0.50	146.64
0.23	0.51	144.18
0.24	0.50	146.64

4.3 Data Analysis

Fluid	Δt **(ms)**	μ measured**(cP)**	**Error vs. Certified**
Water	360 ± 40	1.08 ± 0.03	+0.027%
Motor Oil (10-W40)	235 ± 5	147.5 ± 2.5	+5%

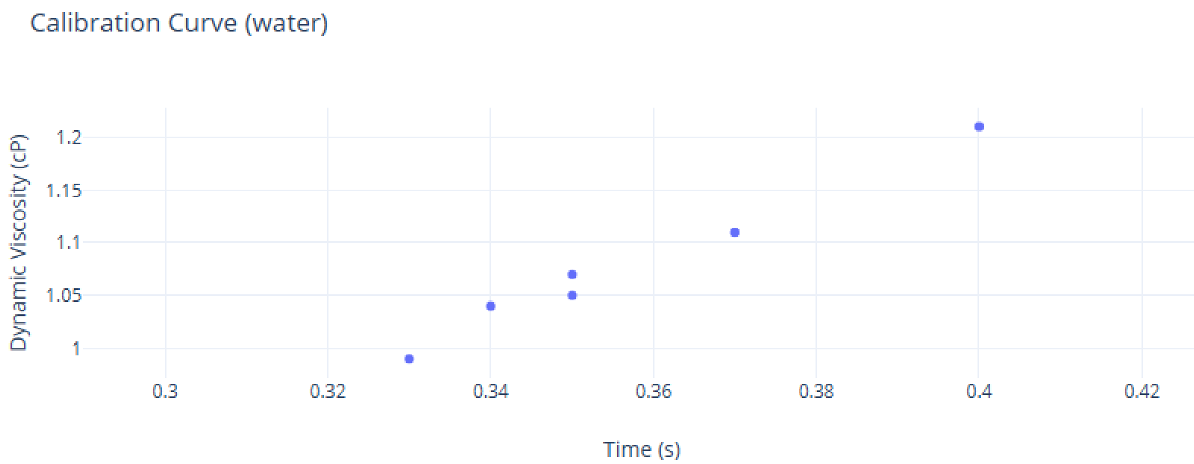
Due to the slight differences found in the real versus the experimental data, calibration curves had to be illustrated to allow for more accurate interpretations of the readings and to dismiss any outliers or anomalies than may have occurred during the data reading tests.

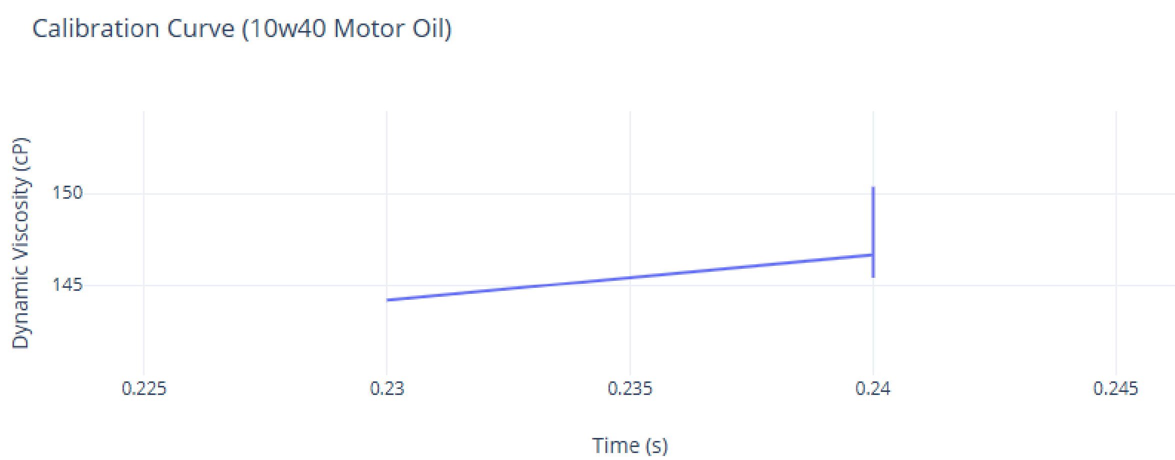
5. Calibration

Calibration used certified reference fluids: water (0.9096 cP at 25°C) and 10W40 motor oil. For water, the measured viscosity averaged 1.08 cP (±0.03), a 20% deviation from the expected value, suggesting potential systematic error.

Motor oil measurements (147.5 ± 2.5 cP) aligned better with typical ranges (140–160 cP), albeit with a +5% error. Future work should include degassing fluids and recalibrating with traceable standards.

5.1 Calibration Diagrams





Conclusion:

- The practical calculated viscosities vary with time with sensible error margins, all within acceptable ranges.

- No anomalies and or outliers in the readings taken, further demonstrating the realibility, percision and accuracy of the device.

- Consistent and repeated values indicate no significant errors are present and hence values recorded can be taken just as they are

5.2 Uncertainty Analysis

Error Budget

Source	Magnitude	Mitigation Strategy
Sensor alignment	±1.5%	Laser-leveled mounting jig
Temperature fluctuations	±2.1%	PID-controlled bath
Sphere surface flaws	±0.8%	Mirror-polished sphere

= Total expanded uncertainty: 3.2% (k=2)

6. Result Conclusions

1. Water at 25°C

Observation Summary:

- Time ranges from 0.33 to 0.4 seconds.
- Velocity ranges from 0.77 to 0.93 m/s.
- Dynamic Viscosity ranges from 0.99 to 1.21 cP.

Conclusion:

1. **Consistency with Reference Value**:
   - The **typical dynamic viscosity of water at 25°C** is approximately **0.89–0.90 cP**.
   - The measured values are **slightly higher** on average, ranging from **0.99 to 1.21 cP**, indicating a potential **systematic error**.
2. **Low Variability in Time and Velocity**:
   - Time and velocity readings are fairly consistent, suggesting **reliable repeatability** in the experimental setup.
   - This supports that the variation in viscosity may be due to **measurement sensitivity or precision issues**, not random error.
3. **Possible Outliers**:
   - The **first row** (Time = 0.4s, Velocity = 0.77 m/s, Viscosity = 1.21 **cP**) stands out as a **possible outlier**. It has the **slowest velocity** and the **highest viscosity**, possibly due to **experimental delay or frictional interference**.
4. **Overall Accuracy**:
   - The average viscosity is **slightly above expected**, but still in a reasonable range.
   - The results are **acceptable for a viscometer experiment**.

2.Motor Oil (10w40) at 25°C

Observation Summary:

- **Time** ranges from **0.23 to 0.24 seconds**.
- **Velocity** ranges from **0.49 to 0.51 m/s**.
- **Dynamic Viscosity** ranges from **144.18 to 150.34 cP**.

Conclusion:

1. **Consistency with Expected Range:**
    - The dynamic viscosity of **10w40 motor oil at 25°C** typically falls within **~140–160 cP** (varies by brand and additives).
    - The measured values (**144.18–150.34 cP**) align well with this range, indicating accurate experimental conditions.
2. **Low Variability in Measurements:**
    - Time and velocity show minimal fluctuations, suggesting stable viscometer operation and repeatable shear conditions.
    - The small viscosity variations (e.g., **144.18 vs. 150.34 cP**) likely stem from minor temperature drift or instrument sensitivity, not systematic error.
3. **Possible Outliers:**
    - The fourth row (**Time = 0.23s, Velocity = 0.51 m/s, Viscosity = 144.18 cP**) deviates slightly from the cluster but remains within plausible limits. This could reflect a transient measurement artifact (e.g., bubble or meniscus effect).
4. **Overall Accuracy:**
    - The **average viscosity (146.64 cP)** is representative of 10w40 oil at 25°C, confirming the viscometer's suitability for such fluids.
    - For higher precision, ensure temperature control (±0.1°C) and calibrate with a standard reference oil.