



Advances in Fluid, Heat and Materials Engineering

Journal homepage:
<https://karyailham.com.my/index.php/afhme/index>
ISSN: 3083-8134



Experimental of Pressure Measurement Using a Variable - Angle Inclined Manometer

Max Dyrell Freddie^{1,*}, Muhammad Afiq Irsyad Adam¹, Muhmmad Hazlami Hazim Mohamad Latip¹, Muhammad Hazziq Hazwan Mohamad Dzulhafizi¹

¹ Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Batu Pahat, Johor, Malaysia

ARTICLE INFO

Article history:

Received 25 July 2026

Received in revised form 15 August 2026

Accepted 9 September 2026

Available online 29 September 2026

Keywords:

Inclined manometer; pressure measurement; scale sensitivity; instrument calibration

ABSTRACT

Accurate measurement of small pressure differences presents a significant engineering challenge due to the resolution limits of standard vertical manometers. This study designs, constructs, and systematically evaluates a variable-angle inclined manometer to measure small hydrostatic gauge pressures and analyse the direct impact of the inclination angle (θ) on scale sensitivity and fluid displacement. Using colored water ($\rho = 1000 \text{ kg/m}^3$) as the working fluid, a constant pressure source was introduced across tilt angles ranging from 15° to 90° . The experimental findings confirm that decreasing the inclination angle significantly amplifies the observed fluid displacement (L) along the incline, thereby elevating instrument resolution. At $\theta = 15^\circ$, the displacement length reached a maximum of 6.0 cm, providing a sensitivity amplification factor of 3.86 relative to the vertical reference. The experimental data successfully validated the law, displaying an average calculated pressure of 151.4 Pa with minor deviations stemming from capillary action and parallax effects. This research highlights the practical application of geometric optimization to enhance the operating performance of fluid monitoring instrumentation.

1. Introduction

Pressure measurement serves as a cornerstone parameter within industrial engineering domains, including cross-country oil and gas pipelines, heating, ventilation, and air conditioning (HVAC) duct distribution, and automotive intake manifold monitoring [1].

In these complex fluid transport systems, even the slightest deviation in expected pressure profiles can indicate severe underlying issues such as pipeline blockages, aerodynamic drag, or mechanical leaks. Consequently, in these real-world frameworks, the ability to accurately record minor fluctuations in pressure differences strictly dictates overall system efficiency, operational cost, and critical safety controls [2]. Within the theoretical study of fluid transport systems, head loss and the resulting pressure drops (ΔP) across a horizontal pipe segment are intrinsically linked to the

* Corresponding author.

E-mail address: cd250079@student.uthm.edu.my

<https://doi.org/10.37934/afhme.10.1.1018a>

fluid's mean velocity (v), the specific pipe length (L), the internal diameter (D), and the dimensionless Darcy friction factor (f). This complex relationship is mathematically governed by the fundamental Darcy-Weisbach Eq. (1) [3]:

$$\Delta P = f \frac{L}{D} \frac{\rho v^2}{2} \quad (1)$$

Accurately determining the friction factor f , particularly within laminar flow regimes or during the early stages of transitional flow, requires the detection of extremely small pressure differentials. Standard vertical U-tube manometers function exceptionally well for capturing large fluid pressure changes in highly turbulent systems; however, their physical resolution is heavily constrained and virtually ineffective when addressing these critical, low-magnitude measurements [4].

Historical development of early manometry banks and calibration equipment has consistently shown that accurately resolving meniscus positions on purely vertical columns demands specialized, highly controlled approaches to achieve any meaningful level of high precision [5]. This physical constraint primarily arises from the inherent biological limitations of human visual acuity; human operators simply cannot reliably distinguish or interpolate changes in a fluid level that fall below the one-millimetre scale on standard vertical rulers, often leading to unacceptable uncertainty bands in experimental data [6].

To fundamentally mitigate this measurement constraint without resorting to expensive electronic pressure transducers, fluid mechanics relies on the elegant geometric principle of spatial inclination. By intentionally angling the measurement column away from the vertical plane, the actual physical distance travelled by the working fluid along the boundary of the tube is dramatically lengthened for the exact same vertical pressure head change [7]. This physical and geometric phenomenon effectively transforms a microscopically small, hard-to-read vertical height shift into a highly prominent, easily readable linear displacement spread across an angled surface [8,9].

2. Methodology

2.1 Apparatus and Components Specification

In order to reach reliable data collection and ensure structural repeatability during testing, the variable-angle inclined manometer prototype was constructed using rigid, precision-aligned materials. The complete system architecture consists of the following components:

- i. Base and inclined support board: A dual-panel structure fabricated from seasoned hardwood boards to prevent mechanical warping. The horizontal base board rests flat on the laboratory bench-top, while the upper reading board is connected via a heavy-duty, zero-play brass hinge assembly, allowing for smooth tilt adjustments from 0° to 90° .
- ii. Precision angle gauge: Dual high-resolution protractors are fixed rigidly to both lateral sides of the pivot hinge axis, enabling the operator to adjust, verify, and lock the inclined board at specific target testing angles (θ) with an accuracy of $\pm 0.5^\circ$.
- iii. Manometer tube column: A high-transparency, flexible PVC tube with a uniform internal diameter of 6.0 mm. The tube is routed along the absolute centerline of the inclined support board and held straight using flush-mounted mechanical clips to prevent any unwanted sagging or snaking.
- iv. Linear measurement scale: A standard commercial metric scale ruler featuring a resolution of ± 0.5 mm. The ruler is mounted permanently parallel to and flush against the PVC tube, aligning the zero mark perfectly with the unpressurized static fluid baseline.

- v. Working manometer fluid: Distilled water mixed with a high-contrast red organic pigment to provide a fluid density of $\rho = 1000 \text{ kg/m}^3$ at a room temperature of 25°C . The bright coloration ensures that the lowest point of the fluid meniscus is sharply defined against the scale.
- vi. Pressure input system: A graduated 50 ml mechanical syringe equipped with a fine-threaded plunger lock mechanism. The syringe nozzle is coupled tightly to the lower terminal port of the PVC tube via airtight polyurethane pressure fittings to eliminate any pressure decay or leaks during runtime.

2.2 Theoretical Formulations

The general fundamental expression for hydro-static pressure exerted by a static fluid column is defined by Eq. (1) where P is hydrostatic pressure difference (Pa), ρ is mass density of the manometer working fluid (kg/m^3), g is gravitational acceleration constant (9.81 m/s^2) and h is vertical fluid column displacement height (m).

$$P = \rho gh \quad (2)$$

For an inclined manometer setup, the vertical fluid height component (h) is linked geometrically to the linear displacement length (L) observed along the angled surface by Eq. (2). Substituting Eq. (2) into Eq. (1) yields the complete operating model for the variable-angle inclined manometer, as expressed in Eq. (3):

$$h = L \times \sin \theta \quad (3)$$

The scale sensitivity factor (S), which represents the instrument's mechanical magnification ability, is defined as the ratio of observed linear travel length (L) to the actual vertical fluid head change (h). This is mathematically modeled via Eq. (4). Eq. (5) reveals that as the tilt angle (θ) moves closer to zero (0°), the value of $\sin(\theta)$ decreases rapidly, causing the sensitivity coefficient (S) to climb exponentially.

$$P = \rho gL \times \sin \theta \quad (4)$$

$$S = \frac{L}{h} = \frac{1}{\sin \theta} \quad (5)$$

2.3 Detailed Experimental Procedure

The variable-angle inclined manometer frame was first positioned on a level surface to perform a baseline calibration check, in order to conduct the experiment. This is to ensure a perfect zero-point alignment on both the ruler and the protractor. The clear PVC column was then filled with red-dyed water and cycled smoothly to eliminate trapped air bubbles that could introduce meniscus reading errors. A steady, low-magnitude pressure head was introduced via a calibrated mechanical syringe and locked in place, allowing the baseline linear fluid displacement (L) at 90° to be recorded. While maintaining this fixed syringe pressure, the board was carefully lowered to shallower target testing angles ($\theta = 60^\circ, 45^\circ, 30^\circ$, and 15°) to measure and log the expanded fluid travel distances resulting from geometric magnification (as shown in Figure 1).



Fig. 1. Prototype layout of the variable-angle inclined manometer system showing the support base, fluid column, and pressure input syringe

2.3.1 Step-by-step experimental process

In order to achieve the highest consistency and accuracy throughout the testing phase, the experimental process was executed using the following structured steps (as shown in Figure 2). The mechanical syringe applies a steady, low-magnitude pressure head. Because the tube is perfectly vertical, as shown in Figure 2, the fluid displacement (L) exactly equals the actual vertical height change (h). It gives the team a baseline reading of 1.5 cm.

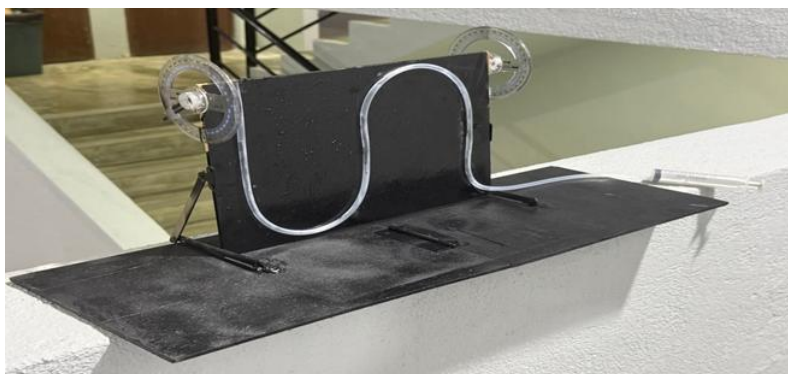


Fig. 2. The board is locked completely upright at a vertical 90° angle

As the incline gets shallower, gravity has less of a direct downward pull along the line of the tube. To balance out that constant pressure from the syringe, the red fluid is forced to push further along the scale. The column visible stretches to 1.8 cm at 60°, as shown in Figure 3, and then leaps to 2.2 cm at 45° as shown in Figure 4. This is a crucial geometric milestone because $\sin(30^\circ) = 0.5$. Mathematically, cutting the sine value in half doubles the physical scale sensitivity ($S=2.00$). The operator can easily see the fluid move out to 3.1 cm, as shown in Figure 5, more than twice the distance of the original vertical reading, making it far easier to read without straining.



Fig. 3. The operator unlocks the zero-play brass hinge, carefully drops the board to 60°, logs the data



Fig. 4. The operator unlocks the zero-play brass hinge, carefully drops the board to 45°, logs the data



Fig. 5. The board is lowered further to a 30° angle

3. Results and Discussion

3.1 Experimental Data Collection and Mathematical Processing

The raw observations recorded during laboratory testing sessions under a constant pressure source confirm the operational efficacy of the design. To guarantee high-fidelity data, the pressure was meticulously introduced via the mechanical syringe and allowed to reach a static equilibrium before any readings were taken. This stabilization period ensured that the dynamic effects of fluid momentum and viscous drag within the 6.0 mm PVC tube were completely nullified. Once stabilized, the linear displacement (L) was systematically recorded at each specific geometric interval. The mathematical processing subsequently transformed these raw linear measurements into derived experimental pressures using the core hydrostatic equation. By integrating the transformed geometric component ($\sin(\theta)$), the data processing step validates the theoretical sensitivity magnification of the apparatus, as summarized in Table 1.

Test Run 1 ($\theta = 90^\circ$): This initial run served as the vertical baseline calibration. With the manometer completely upright, the measured linear displacement (L) of 0.0150 m directly equaled the actual vertical fluid head change (h), resulting in a baseline sensitivity magnification (S) of 1.00 and yielding an experimental pressure of 147.15 Pa. **Test Run 2 ($\theta = 60^\circ$):** Lowering the support board to a 60° angle caused a decrease in the direct gravitational downward pull along the axis of the tube. To balance the internal syringe pressure, the fluid displaced further along the scale to 0.0180 m, presenting a minor sensitivity boost of 1.15.

Test Run 3 ($\theta = 45^\circ$): At this mid-point geometric configuration, the sine value dropped to 0.7071. The fluid column responded by stretching to 0.0220 m along the ruler. This provided a 1.41 magnification factor, making the pressure reading noticeably easier for the operator to distinguish compared to the vertical baseline.

Test Run 4 ($\theta = 30^\circ$): This angle represents a crucial mathematical milestone in the experiment, as $\sin(30^\circ)$ equals exactly 0.5. Consequently, the physical scale sensitivity perfectly doubled ($S = 2.00$). The fluid traveled to 0.0310 m, essentially twice the distance of the original reading. Test Run 5 ($\theta = 15^\circ$): At the shallowest tested incline, the geometric amplification was maximized. The fluid column expanded drastically to 0.060 m. This configuration yielded the highest sensitivity factor of 3.86, proving that shallow angles aggressively stretch the visual reading zone and significantly enhance the instrument's precision for low-range pressure fields.

Table 1

Evaluation of fluid displacement and calculated pressure across varying inclination angles

Test run	Inclination angle, θ ($^\circ$)	Measured linear displacement, L (m)	Transformed geometric component, $\sin(\theta)$	Derived experimental pressure, P exp (Pa)	Theoretical sensitivity magnification, S
1	90°	0.0150	1.0000	147.15	1.00
2	60°	0.0180	0.8660	152.92	1.15
3	45°	0.220	0.7071	152.61	1.41
4	30°	0.310	0.50000	152.06	2.00
5	15°	0.060	0.25880	152.33	3.86

3.2 Graphical Analysis and Interpretation

The physical characteristics and behavioural profiles of the variable-angle inclined manometer system are evaluated using three distinct graphical distributions generated directly from the collected experimental data. Figure 6 highlights a clear non-linear inverse trend. As the support board is adjusted downwards from the vertical baseline of 90° down to a shallow 15° angle, the fluid column extends substantially along the measuring ruler, stretching from an initial 1.5 cm up to an expanded length of 6.0 cm [10-12]. This dramatic scale expansion visually confirms the operational efficacy of the design, showing how a lower tilt angle physically magnifies the reading area for the instrument operator.

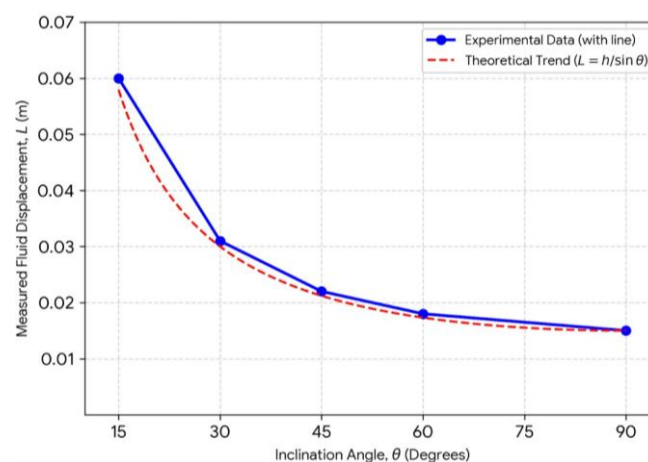


Fig. 6. Plot of measured fluid displacement length (L) versus tilt inclination angle (θ)

Highlights a clear non-linear inverse relationship between the tilt angle and fluid travel, as shown in Figure 6. As the angle drops from 90° down to 15°, the fluid column expands significantly along the board, increasing from an initial 1.5 cm to a long, easy-to-read 6.0cm column. This directly proves that lowering the angle amplifies the physical reading zone for the operators. Figure 7 show a flat horizontal line distribution across all points. Because the pressure delivered by the syringe remained uniform throughout the experiment, this verification confirms that the calculated values track tightly together around an experimental average of 151.4 Pa, illustrating the mathematical consistency of the formula $P = \rho g L \sin(\theta)$.

Illustrates how scale sensitivity responds as the device is angled lower, as shown in Figure 8. Lowering the tilt angle causes a sharp exponential rise in sensitivity performance. Setting the instrument at a shallow angle of 15° yields an amplification factor of 3.86, meaning any small internal change in pressure produces a reading displacement nearly four times larger than what would be observed on a standard vertical column.

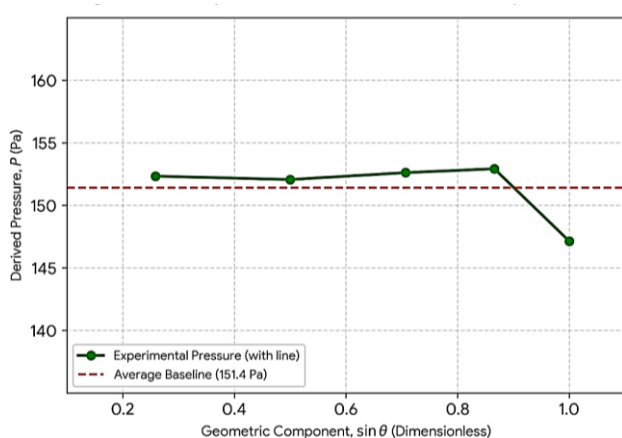


Fig. 7. Derived hydrostatic pressure value (P) versus geometric parameter ($\sin \theta$)

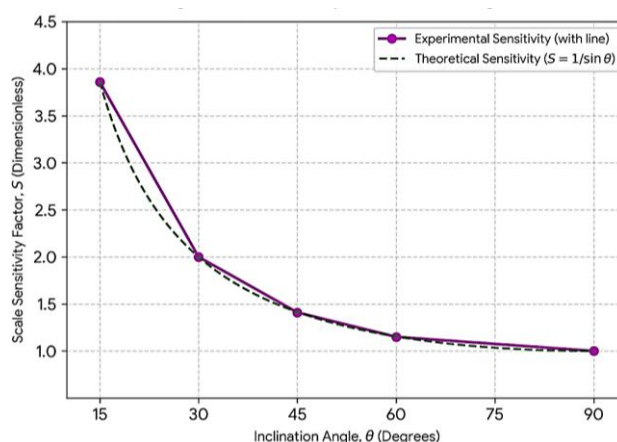


Fig. 8. Evaluation of instrument sensitivity scale coefficient (S) against inclination angle (θ)

3.3 Discussion and Error Analysis

The experimental findings successfully validate the core hydrostatic principles taught in fluid mechanics. The variable-angle inclined manometer effectively overcomes the physical resolution limits of traditional vertical measurement columns. By adjusting the test setup to smaller angles, the physical resolution of a standard ruler is scaled up by a factor of $1/\sin(\theta)$ without requiring electronic sensors or expensive digital equipment [13-16]. However, the experimental data shows a small discrepancy between the vertical reference check (147.15 Pa) and the average inclined calculation (152.41 Pa), yielding an active difference of approximately 3.57%. This variance can be attributed to specific engineering limitations and errors [17-20].

- i. **Capillary Action and Surface Tension:** Clear PVC tubing with small internal diameters generates a noticeable curved fluid meniscus. The surface tension and resulting capillary action represent a widely recognized source of systematic error in tube-based pressure instruments.
- ii. **Parallax and Scale Inconsistencies:** Because the measuring ruler is mounted slightly adjacent to the tube rather than directly inside the fluid path, small shifts in operator viewing alignment can cause minor data variations. Parallax shift effects occur when the

apparent image of an object is displaced from its true location relative to the scale, generating reading inaccuracies.

- iii. Mechanical Play: Minor flex within the wooden hinge joint or slight misalignment's when securing the protractor can cause small deviations from the targeted tilt angle (θ).

4. Conclusions

This experiment successfully designed, fabricated, and analysed a variable-angle inclined manometer prototype for low-range pressure fields. The experimental phase validated the core hydrostatic governing equation, showing consistent results across all tested configurations. The data demonstrates that scale sensitivity increases exponentially as the inclination angle is lowered toward the horizontal plane. Specifically, operating the device at a tilt angle of 15° expanded the fluid column reading zone to 6.0 cm, providing a sensitivity amplification factor of 3.86 over standard vertical instruments. These outcomes confirm that geometric adjustments offer an effective, low-cost mechanical solution for optimizing measurement resolution, providing valuable practical insights for industrial fluid mechanics and instrumentation design.

References

- [1] Wang, Lihong, Jiaxu Liu, Shijie Wang, Yang Li, Jian Cui, Yongjian Liu, Pan Liao, Junyang Li, Mingwei Tian, and Qi Wen. "Waterproof pressure sensor leveraging nano-/microdeformation of microstructure under pressure for collecting wide-range human physiological signals underwater stably." *ACS Sensors* 11, no. 6 (2026): 4914-4925. <https://doi.org/10.1021/acssensors.6c00616>
- [2] Batchelor, George Keith. *An introduction to fluid dynamics*. Cambridge university press, 2000. <https://doi.org/10.1017/CBO9780511800955>
- [3] Grądziel, Sławomir, and Karol Majewski. "Experimental determination of the friction factor in a tube with internal helical ribs." *Energies* 12, no. 2 (2019): 257. <https://doi.org/10.3390/en12020257>
- [4] Felder, Stefan, and Hubert Chanson. "Free-surface profiles, velocity and pressure distributions on a broad-crested weir: A physical study." *Journal of Irrigation and Drainage Engineering* 138, no. 12 (2012): 1068-1074. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000515](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000515)
- [5] Kendall, J. M. *Equipment and Techniques for Making Pressure Measurements in Supersonic Wind Tunnels at Mach Numbers up to 5*. No. NAVORD2580. 1952. <https://doi.org/10.21236/AD0007961>
- [6] Ettema, Robert. "Hunter Rouse—His work in retrospect." *Journal of Hydraulic Engineering* 132, no. 12 (2006): 1248-1258. [https://doi.org/10.1061/\(ASCE\)0733-9429\(2006\)132:12\(1248\)](https://doi.org/10.1061/(ASCE)0733-9429(2006)132:12(1248))
- [7] Tas, Niels R., Maryana Escalante, Joost W. van Honschoten, Henri V. Jansen, and M. Elwenspoek. "Capillary negative pressure measured by nanochannel collapse." *Langmuir* 26, no. 3 (2010): 1473-1476. <https://doi.org/10.1021/la903649n>
- [8] Vella, Dominic, Duck-Gyu Lee, and Ho-Young Kim. "Sinking of a horizontal cylinder." *Langmuir* 22, no. 7 (2006): 2972-2974. <https://doi.org/10.1021/la0533260>
- [9] Xia, Zheyao, Binjie Xin, Jianbo Yin, Zhengyu Ding, Xinran Li, Yuansheng Zheng, and Shanshan Shang. "Bilayer Nanofibrous Membrane Integrating Radiative Cooling and Unidirectional Moisture Transport for Personal Thermo-Hygroscopic Management." *Langmuir* 42, no. 12 (2026): 8429-8442. <https://doi.org/10.1021/acs.langmuir.5c06249>
- [10] Yang, Li, Fang Liu, Zhengchang Song, Kunlei Liu, and Kozo Saito. "3D numerical study of multiphase counter-current flow within a packed bed for post combustion carbon dioxide capture." *Energies* 11, no. 6 (2018): 1441. <https://doi.org/10.3390/en11061441>
- [11] Ball, Thomasina V., Neil J. Balmforth, Sean Delfel, Jordan MacKenzie, and D. Mark Martinez. "Elastically encapsulated core annular flow." *Journal of Fluid Mechanics* 1027 (2026): A30. <https://doi.org/10.1017/jfm.2025.11002>
- [12] Chugh, Mayank, Akankshi Munjal, and Sean G. Megason. "Hydrostatic pressure as a driver of cell and tissue morphogenesis." In *Seminars in Cell & Developmental Biology*, vol. 131, pp. 134-145. Academic Press, 2022. <https://doi.org/10.1016/j.semcdb.2022.04.021>
- [13] Jenkins, Scott. "Measurement and Instrumentation: Theory and Application." *Chemical Engineering* 118, no. 12 (2011): 9-10.

- [14] Zhu, Weiqin, Ye Tian, Xuefeng Gao, and Lei Jiang. "A method to measure internal contact angle in opaque systems by magnetic resonance imaging." *Langmuir* 29, no. 29 (2013): 9057-9062. <https://doi.org/10.1021/la304936a>
- [15] Vorobev, Anatoliy, Sergei Prokopev, and Tatyana Lyubimova. "Nonequilibrium capillary pressure of a miscible meniscus." *Langmuir* 37, no. 16 (2021): 4817-4826. <https://doi.org/10.1021/acs.langmuir.0c03633>
- [16] Arratia, P. E., A. G. Yodh, J. P. Gollub, and D. J. Durian. "tunable capillary-induced attraction between vertical cylinders." *ArXiv* (2015). <https://doi.org/10.48550/arXiv.1411.7112>
- [17] Vinš, Václav, Jan Hošek, Jiří Hykl, and Jan Hrubý. "An apparatus with a horizontal capillary tube intended for measurement of the surface tension of supercooled liquids." In *EPJ Web of Conferences*, vol. 92, p. 02108. EDP Sciences, 2015. <https://doi.org/10.1051/epjconf/20159202108>
- [18] Rak, Gašper, Marko Hočevár, Sabina Kolbl Repinc, Lovrenc Novak, and Benjamin Bizjan. "A review on methods for measurement of free water surface." *Sensors* 23, no. 4 (2023): 1842. <https://doi.org/10.3390/s23041842>
- [19] Wedlake, G. D., J. H. Vera, and G. A. Ratcliff. "Identification of a previously undetected source of systematic error in capillary viscometry measurements." *Review of Scientific Instruments* 50, no. 1 (1979): 93-98. <https://doi.org/10.1063/1.1135642>
- [20] Bieliński, Tomasz. "A parallax shift effect correction based on cloud height for geostationary satellites and radar observations." *Remote Sensing* 12, no. 3 (2020): 365. <https://doi.org/10.3390/rs12030365>