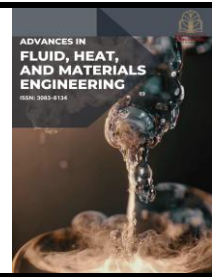




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Experimental Validation of a Custom Venturi Meter for Water Flowrate Measurement Based on Bernoulli's Equation

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ABSTRACT

Accurate water flow measurement is essential in fluid mechanics for designing and analyzing hydraulic systems, yet commercial Venturi meters remain cost-prohibitive for educational and low-cost laboratory applications. To address this, this study designed, fabricated, and experimentally validated a low-cost, transparent acrylic Venturi meter featuring a 25 mm upstream pipe, a 16mm throat, and two vertical piezometer tubes. Tested under steady, incompressible flow conditions, the actual volumetric flow rates were determined via the volume-time method by collecting 1000cm of water, while theoretical values were derived from Bernoulli's and Continuity equations. The results across three trials showed that pressure differentials increased with velocity, yielding actual flow rates of 228.3 cm³, 160.8 cm³, and 101.3 cm³ that closely matched the theoretical predictions of 240.3 cm³, 169.3 cm³, and 106.6 cm³. A consistent discharge coefficient of approximately 0.95 indicated minimal energy losses from friction and turbulence, confirming that this fabricated apparatus provides a reliable, accessible alternative for fluid mechanics instruction and research.

1. Introduction

Accurate measurement of fluid flow rate is a fundamental requirement in fluid mechanics because it directly influences the design, operation, and performance evaluation of hydraulic systems, water distribution networks, industrial processing equipment, and laboratory experiments [1-4]. Reliable flow-rate information is essential for monitoring energy consumption, ensuring efficient fluid transport, and optimizing system performance. Among the various differential-pressure flowmeters available, the Venturi meter has remained one of the most widely adopted devices because of its high accuracy, low permanent pressure loss, and relatively simple operating principle [1,3,5]. These characteristics make the Venturi meter suitable for both industrial applications and engineering education.

The operating principle of the Venturi meter is governed by the combined application of the Continuity Equation and Bernoulli's Equation. According to the Continuity Equation, a reduction in

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cross-sectional area causes an increase in fluid velocity in order to conserve mass flow rate [2,3]. Bernoulli's Equation further explains that this increase in velocity is accompanied by a decrease in static pressure under steady incompressible flow conditions [2]. Consequently, the pressure difference generated between the upstream section and the throat can be measured and used to determine the volumetric flow rate of the fluid [3,5,6]. Theoretical analyses of this relationship have been widely presented in classical fluid mechanics references such as previous researchers [3,6].

Numerous researchers have investigated the performance of Venturi meters under different flow conditions. Kambayashi *et al.*, [7] conducted theoretical, numerical, and experimental studies on unsteady Venturi flowmeters and demonstrated that pressure-difference measurements can provide reliable flow-rate predictions for incompressible flows. Zeghloul *et al.*, [8] performed experimental investigations on gas–liquid two-phase flow through a vertical Venturi meter and reported that the discharge coefficient is strongly influenced by flow regime and pressure distribution. Similarly, Messilem *et al.*, [9] analyzed pressure losses in vertical Venturi configurations and confirmed the importance of geometry and operating conditions on measurement accuracy. More recently, Zheng *et al.*, [10] optimized Venturi geometry for supercritical carbon dioxide flow measurement and showed that local pressure methods can significantly improve flow-rate determination.

Recent studies have also focused on validating numerical and computational approaches for Venturi flow analysis. Mihalić *et al.*, [11] verified computational fluid dynamics predictions against experimental Venturi data and reported good agreement between numerical and measured pressure distributions. Furthermore, a comprehensive experimental and computational analysis of circular eccentric Venturi meters demonstrated that discharge coefficients vary with flow regime and meter geometry, emphasizing the need for experimental calibration of non-standard designs [12]. These findings indicate that although the governing theory is well established, practical flow measurement performance depends strongly on fabrication quality, geometry, and operating conditions.

In industrial practice, Venturi meters are commonly manufactured according to standardized specifications such as ISO 5167-1:2022 [13] and ASME flow-meter standards [1]. Standardized fabrication ensures consistent discharge coefficients and reliable measurement performance. However, commercially manufactured Venturi meters are relatively expensive and may not be readily available for undergraduate laboratories or educational projects. As a result, there has been increasing interest in developing low-cost experimental apparatus using readily available materials while maintaining acceptable measurement accuracy [14,15]. Transparent acrylic is particularly attractive for educational applications because it provides excellent optical clarity, dimensional stability, and sufficient mechanical strength, allowing direct observation of pressure variations within the flowmeter.

Several engineering laboratory manuals have demonstrated the educational value of transparent Venturi apparatus for illustrating pressure-head differences and flow behaviour [14,15]. Experimental methods described by Madachy *et al.*, [16] emphasize that direct visual observation can improve students' understanding of fluid mechanics concepts and measurement uncertainty. In addition, Kumar [17], Kambayashi *et al.*, [7], Douglas [4], and Kundu *et al.*, [18] discuss the importance of experimental validation when applying theoretical fluid-flow equations to real systems.

Although the theoretical behaviour of Venturi meters has been extensively documented, relatively few studies have experimentally evaluated custom-built Venturi meters fabricated from inexpensive acrylic components for educational applications. Most previous investigations have focused on commercially manufactured devices with established calibration characteristics, whereas limited information is available regarding the discharge coefficient, pressure distribution, and measurement accuracy of self-fabricated acrylic Venturi meters [19,20]. This represents an important research gap because fabrication tolerances, assembly methods, surface finish, and minor leakage

may influence the pressure difference and overall flow-rate prediction. Experimental validation of a low-cost fabricated Venturi meter is therefore necessary to determine whether such a device can provide reliable measurements while serving as an effective teaching tool.

Therefore, this study aims to design, fabricate, and experimentally validate a custom Venturi meter constructed from transparent acrylic tubing for water flow-rate measurement. The specific objectives are to fabricate a functional and economical Venturi meter using readily available materials, determine the actual volumetric flow rate using the volume–time method, calculate the theoretical flow rate based on the Continuity Equation and Bernoulli's Equation, determine the discharge coefficient by comparing theoretical and experimental results, and evaluate the overall performance of the fabricated device. The findings of this study are expected to demonstrate that a low-cost acrylic Venturi meter can provide reliable flow-rate measurements while reinforcing the practical application of fundamental fluid mechanics principles in engineering education and laboratory experimentation.

2. Methodology

2.1 Experimental Design and Materials

An experimental investigation was conducted to evaluate the performance of a custom-built Venturi meter for measuring the volumetric flow rate of water based on the principles of the Continuity Equation and Bernoulli's Equation. The apparatus was designed and fabricated using low-cost, readily available materials to produce a functional flowmeter suitable for laboratory demonstrations while maintaining satisfactory measurement accuracy (Figure 1).

The Venturi meter was fabricated using transparent acrylic pipes because of their high optical clarity, dimensional stability, and sufficient mechanical strength. The transparent construction enabled direct observation of the water levels inside the piezometer tubes during the experiment. The flowmeter consisted of an upstream pipe with an internal diameter of 25 mm and a throat section with an internal diameter of 16 mm, as shown in Table 1. Two vertical piezometer tubes were connected at the upstream and throat sections to measure the static pressure heads generated during water flow. An inline PVC ball valve was installed to regulate the water supply, while all pipe joints were sealed using industrial adhesive and hot glue to prevent leakage throughout the experiment.

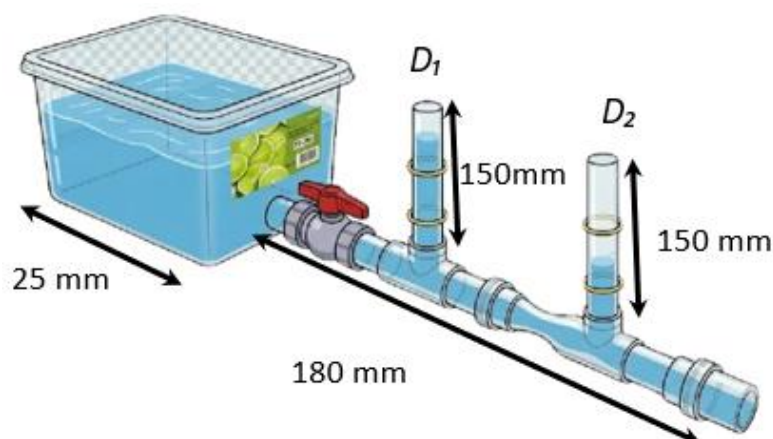


Fig. 1. The fabricated venturi meter and its principal components

Table 1

Geometrical dimensions of the fabricated venturi meter

Parameter (m)	Symbol	Value
Upstream diameter	D_1	25 mm (0.025 m)
Throat diameter	D_2	16 mm (0.016 m)
Upstream cross-sectional area	A_1	$4.91 \times 10^{-4} \text{ m}^2$
Throat cross-sectional area	A_2	$2.01 \times 10^{-4} \text{ m}^2$
Diameter ratio	$\beta = D_2/D_1$	0.64
β^4	-	0.1678

2.2 Experimental Setup

The experimental setup was designed to establish steady incompressible flow through the fabricated Venturi meter (Figure 2). Water stored in a reservoir flowed through the acrylic Venturi tube under gravity before being discharged into a measuring container. A constant water level inside the reservoir was maintained throughout each experiment to minimize fluctuations in inlet pressure and satisfy the assumptions of steady flow.

Static pressure at both the upstream and throat sections was measured using vertically mounted piezometer tubes. The difference between the two water levels represented the pressure head difference produced by the acceleration of water through the converging section of the Venturi meter. During data collection, the upstream PVC valve remained fully open to minimize turbulence near the pressure tapping locations, while different flow conditions were produced by adjusting the outlet restriction.



Fig. 2. Complete venturi meter experimental setup

2.3 Experimental Procedure

The experiment was conducted following a systematic procedure to ensure accurate and repeatable measurements. Initially, the reservoir was filled with clean water until the predetermined operating level was reached. The PVC ball valve was then opened fully to allow water to flow through the Venturi meter while simultaneously removing trapped air bubbles from the pipeline and piezometer tubes. The apparatus was allowed to operate until the water columns inside both piezometer tubes became stable as shown in Figure 3. After steady-flow conditions had been achieved, the upstream pressure head (h_1) and throat pressure head (h_2) were measured using a metric ruler positioned behind the transparent piezometer tubes. The pressure head difference, $\Delta h = h_1 - h_2$, was subsequently calculated for each experimental trial (Figure 4).

To determine the actual volumetric flow rate, 1000 cm³ of discharged water was collected in a calibrated container while the collection time was measured using a digital stopwatch. Three

independent trials were conducted by varying the outlet restriction to produce different flow rates while maintaining a constant upstream water head. This procedure enabled comparison between theoretical and experimental flow rates under different operating conditions.

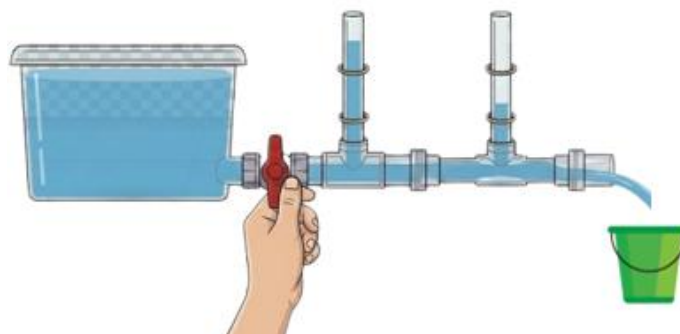


Fig. 3. Turn the red handle to your desired flow rate setting

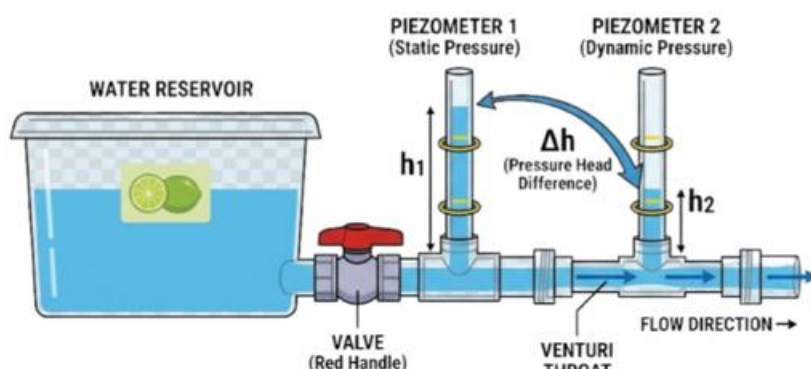


Fig. 4. Experimental venturi meter (Bernoulli principle)

2.4 Theoretical Analysis

The performance of the Venturi meter was analysed using the Continuity Equation and Bernoulli's Equation for steady, incompressible flow. The actual volumetric flow rate was determined experimentally using Eq. (1).

$$Q_{act} = V/t \quad (1)$$

where the Q_{act} is the actual volumetric flow rate (cm^3/s), V is the volume of water collected during the experiment (cm^3), and t is the time required to collect the specified volume of water (s). This equation was used to determine the flow rate for each experimental trial by measuring the time taken to collect 1000 cm^3 of water from the outlet of the Venturi meter.

According to the Continuity Equation, the volumetric flow rate remains constant throughout the flow passage, which means that the product of cross-sectional area and fluid velocity at one section must be equal to that at another section. This relationship is expressed by Eq. (2),

$$A_1 V_1 = A_2 V_2 \quad (2)$$

where A_1 and A_2 represent the cross-sectional areas of the upstream and throat sections, respectively, while V_1 and V_2 represent the corresponding fluid velocities. As the flow passes through the smaller throat section of the Venturi meter, the decrease in cross-sectional area causes the fluid velocity to increase to maintain continuity of flow.

Applying Bernoulli's Equation between the upstream section and the throat section gives Eq. (3).

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} \quad (3)$$

where P_1 and P_2 are the pressures at the upstream and throat sections, respectively, V_1 and V_2 are the fluid velocities at each section, ρ is the density of water, and g is the gravitational acceleration. This equation shows that when the velocity of the fluid increases, the pressure decreases. In the Venturi meter, the diameter is reduced at the throat section, causing the water velocity to increase and the pressure to drop. The pressure difference measured by the piezometer tubes is then used to calculate the theoretical flow rate.

By combining the Continuity Equation with Bernoulli's Equation, the theoretical volumetric flow rate can be expressed as Eq. (4).

$$Q_{Theo} = A_2 \sqrt{2g(h_1 - h_2)} / \sqrt{1 - \beta^4} \quad (4)$$

where Q_{Theo} is the theoretical volumetric flow rate (m^3/s), A_2 is the cross-sectional area of the throat section (m^2), g is the gravitational acceleration ($9.81 m/s^2$), h_1 is the pressure head at the upstream section (m), h_2 is the pressure head at the throat section (m), and β is the diameter ratio of the Venturi meter. This equation uses the pressure difference measured between the two piezometer tubes to estimate the flow rate assuming ideal flow conditions with no energy losses.

The diameter ratio, β , is defined as the ratio between the throat diameter and the upstream diameter, as shown in Eq. (5).

$$\beta = D_2 / D_1 \quad (5)$$

where D_2 is the throat diameter and D_1 is the upstream diameter. The diameter ratio is an important parameter in Venturi meter analysis because it influences the change in fluid velocity and pressure between the two sections.

In practice, fluid flow is affected by friction, viscosity, and minor turbulence, causing the actual flow rate to differ slightly from the theoretical value. To account for these losses, the discharge coefficient was calculated using Eq. (6).

$$C_d = V_{Act} / V_{Theo} \quad (6)$$

where C_d is the discharge coefficient, Q_{Act} is the experimentally measured flow rate, and Q_{Theo} is the theoretical flow rate calculated using Eq. (4). The discharge coefficient indicates how closely the actual performance of the Venturi meter matches the ideal theoretical prediction. A value close to 1.0 suggests that the flowmeter has relatively low energy losses and good measurement accuracy.

2.5 Experimental Precautions

Several precautions were implemented to improve the accuracy and repeatability of the experimental measurements. The reservoir water level was maintained at a constant height throughout each trial to ensure a stable inlet pressure. Air bubbles trapped inside the pipeline and piezometer tubes were removed before data collection because they could affect pressure readings. The upstream PVC valve remained fully open during all experiments to minimise turbulence near the

pressure tapping locations, while pressure measurements were recorded only after the water columns had completely stabilised. Finally, each experiment was repeated three times to verify the consistency and reliability of the measured results.

3. Results

3.1 Pressure Difference and Flow Behaviour

This section presents the results obtained from the pressure measurements in the custom-built Venturi meter. The pressure distribution along the flow passage was analysed by comparing the upstream pressure head (h_1) and the throat pressure head (h_2), which were measured using the vertical piezometer tubes.

3.1.1 Experimental measurements

The experimental measurements obtained from the Venturi meter are presented in Table 2, showing the variation of pressure head difference under different flow conditions. It includes the recorded flow time and corresponding pressure head values at both the upstream and throat sections. Table 2 presents the raw experimental measurements, indicating that the pressure head difference increases as the flow rate increases. This trend confirms that higher flow velocities produce a greater pressure drop at the throat section.

Table 2

Experimental measurements obtained from venturi meter test

Number of trial	Time, s	h_1 , cm	h_2 , cm
1	4.38	14.5	4.4
2	6.22	10.0	5.0
3	9.87	8.2	6.1

3.1.2 Pressure difference calculations

The calculated pressure head difference and its corresponding square root values are presented in Table 3. These values were obtained from the measured piezometer readings and are used to examine the relationship between pressure variation and flow conditions in the Venturi meter. The calculated pressure head difference and its square root derived from the experimental measurements. The values indicate that the pressure difference decreases as the flow rate decreases.

Table 3

Calculated pressure head difference and square root values

Number of Trial	$\Delta h = (h_1 - h_2)$, cm	Δh , $\text{cm}^{0.5}$
1	10.1	3.18
2	5.0	2.24
3	2.1	1.45

3.1.3 Flow rate calculations

The calculated flow rates based on the experimental data are presented in Table 4. The actual volumetric flow rate was determined using the volume–time method, while the theoretical flow rate was calculated using Bernoulli's equation. These values are used to evaluate the accuracy of the experimental measurements. The calculated actual and theoretical flow rates. The actual flow rate

was determined using the volume–time method, while the theoretical flow rate was calculated using Bernoulli’s equation. The results show good agreement between both values.

Table 4

Calculated pressure head difference and square root values

Number of trial	Q _{actual} , cm ³ /s	Q _{theoretical} , cm ³ /s
1	228.3	240.3
2	160.8	169.3
3	101.3	106.6

4. Conclusions

This study successfully achieved its objectives by designing, fabricating, and experimentally validating a custom Venturi meter constructed from transparent acrylic tubing for water flow-rate measurement. The fabricated apparatus demonstrated the practical application of the Continuity Equation and Bernoulli's Equation by producing a measurable pressure drop between the upstream and throat sections as the flow velocity increased. The experimental results showed that the actual volumetric flow rates were in close agreement with the corresponding theoretical values, confirming that the fabricated Venturi meter can provide reliable flow-rate measurements under steady incompressible flow conditions. The calculated discharge coefficient remained approximately 0.95 throughout the experimental trials, indicating that only minor energy losses due to friction and turbulence were present and that the performance of the fabricated device closely approached the theoretical model.

The findings demonstrate that a low-cost Venturi meter fabricated using transparent acrylic materials can serve as an effective flow measurement device for laboratory experiments and engineering education. The transparent construction also enables direct observation of pressure variations within the system, enhancing the understanding of fundamental fluid mechanics concepts. Overall, the developed Venturi meter provides an economical and practical alternative for demonstrating the relationship between pressure difference and volumetric flow rate while validating the theoretical principles of fluid flow.

Future work should include a greater number of experimental trials, investigation of different throat diameter ratios and flow conditions, and comparison of the fabricated Venturi meter with commercially manufactured flowmeters to further improve measurement accuracy and calibration.

References

- [1] American Society of Mechanical Engineers, Research Committee on Fluid Meters. *Fluid Meters: Their Theory and Application*. New York: American Society of Mechanical Engineers, 1971.
- [2] Bansal, R. K. *A textbook of fluid mechanics*. Firewall Media, 2005.
- [3] Cengel, Yunus A., John M. Cimbala, and Mehmet Kanoglu. *Fluid mechanics: fundamentals and applications*. Vol. 956. New York: McGraw-Hill, 2006.
- [4] Douglas, John F. *Fluid mechanics*. Pearson education, 2005.
- [5] Pritchard, Philip J., and John W. Mitchell. *Fox and McDonald's introduction to fluid mechanics*. John Wiley & Sons, 2016.
- [6] Murugesan, Krishnan. *Modeling and Simulation in Thermal and Fluids Engineering*. CRC Press, 2022. <https://doi.org/10.1201/9781003248071>
- [7] Kambayashi, Izuru, Donghyuk Kang, and Naoki Nishimura. "Theoretical, numerical, and experimental study on an unsteady venturi flowmeter for incompressible flows." *Journal of Fluids Engineering* 143, no. 2 (2021): 021308. <https://doi.org/10.1115/1.4048689>
- [8] Zeghloul, Ammar, Abdelkader Messilem, Nabil Ghendour, Abdelsalam Al-Sarkhi, Abdelwahid Azzi, and Abbas Hasan. "Theoretical study and experimental measurement of the gas liquid two-phase flow through a vertical

- Venturi meter." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 235, no. 9 (2021): 1567-1584. <https://doi.org/10.1177/0954406220947118>
- [9] Messilem, Abdelkader, Abdelwahid Azzi, Ammar Zeghloul, Faiza Saidj, Hiba Bouyahiaoui, and Al-Sarkhi Abdelsalam. "Single-and two-phase pressure drop through vertical Venturis." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 234, no. 12 (2020): 2349-2359. <https://doi.org/10.1177/0954406220906424>
- [10] Zheng, Chunfeng, Wanyou Yang, Dedong Xue, Lei Kou, Sheng Wang, Zhengyang Chen, Shijiao Jia, and Chao Yuan. "Venturi Optimization and Local Pressure Method for Measuring Supercritical CO₂ Flow in Downhole." *Energies* 18, no. 8 (2025): 1951. <https://doi.org/10.3390/en18081951>
- [11] Mihalić, Tihomir, Ante Zaninović, and Srđan Medić. "Verification and validation of student's cfd tool on the venturi flow case." *Journal of Energy Technology* 17, no. 3 (2024): 54-61. <https://doi.org/10.18690/jet.17.3.54-61.2024>
- [12] Karthik, M. S., P. Siva Kota Reddy, Tapankumar Trivedi, Asha Rajiv, Madhu Chennabasappa, and Fehmi Gamaoun. "Experimental and computational analysis of circular eccentric venturi meters: discharge coefficients and flow regimes." *Ain Shams Engineering Journal* 16, no. 11 (2025): 103727. <https://doi.org/10.1016/j.asej.2025.103727>
- [13] International Organization for Standardization. *Measurement of Fluid Flow by Means of Pressure Differential Devices Inserted in Circular Cross-section Conduits Running Full: Mesure de Débit Des Fluides Au Moyen D'appareils Déprimogènes. Inseres Dans Des Conduites en Charge de Section Criculaire. General Principles and Requirements*. International Organization for Standardization, 2003.
- [14] Hochstein, John I., and Andrew L. Gerhart. *Young, Munson and Okiishi's A Brief Introduction to Fluid Mechanics*. John Wiley & Sons, 2021.
- [15] Purnea College of Engineering. *Venturi Meter Laboratory Manual*. Purnea, India: Purnea College of Engineering, 2020.
- [16] Madachy, Raymond J., and Daniel Houston. *What every engineer should know about modeling and simulation*. CRC Press, 2017. <https://doi.org/10.1201/9781315268583>
- [17] Kumar, D. S. *Fluid mechanics and fluid power engineering*. Katson Publishing House, 1981.
- [18] Kundu, Pijush K., Ira M. Cohen, David R. Dowling, and Jesse Capecelatro. *Fluid mechanics*. Elsevier, 2024.
- [19] Miller, Richard W. "Flow measurement engineering handbook." (1983).
- [20] Babister, A. W. "Mechanics of Fluids. Irving H. Shames. McGraw-Hill, London. 1962. 555 pp. 69s. 6d." *The Aeronautical Journal* 66, no. 622 (1962): 658-659. <https://doi.org/10.1017/S000192400008948X>