DE GRUYTER Applied Rheology 2024; 34: 20240021

Research Article

Isabel Diañez*, Inmaculada Martínez*, Abel Jerez, and José M. Franco

Low-cost rolling ball viscometer for the evaluation of Newtonian and shear-thinning fluids

https://doi.org/10.1515/arh-2024-0021
received September 12, 2024; accepted October 16, 2024

Abstract: This article describes the design and testing of a low-cost automatic rolling-ball viscometer. The device has been manufactured from three-dimensional printed parts and conventional and affordable mechanical and electronic components. It is controlled by an Arduino MEGA with a custom code that includes manual and automatic measuring modes. Both the type of viscometer and the models used are, in principle, valid for Newtonian and power-law fluids. However, measurement and calculation procedures have been developed that also makes it possible to determine the viscosity of Herschel–Bulkley fluids that might exhibit a yield stress behaviour within the range studied. By these procedures, viscosity values have been obtained for model fluids – Newtonian, power-law, and Herschel–Bulkley fluids – and compared to those obtained with a commercial rotational rheometer. The proposed setup and measuring method have thus proven to provide very reasonably accurate viscosity values for a low-cost device.

Keywords: viscometer, rolling-ball, low-cost, automatic, power-law, Herschel–Bulkley

*** Corresponding author: Isabel Diañez,** Pro2TecS – Chemical Process and Product Technology Center, Dpto. Ingeniería Química, ETSI, Campus de “El Carmen”, Universidad de Huelva, 21071, Huelva, Spain, e-mail: isabel.dianez@diq.uhu.es

*** Corresponding author: Inmaculada Martínez,** Pro2TecS – Chemical Process and Product Technology Center, Dpto. Ingeniería Química, ETSI, Campus de “El Carmen”, Universidad de Huelva, 21071, Huelva, Spain, e-mail: imgarcia@diq.uhu.es

Abel Jerez: Brussels Innovation Center, Procter and Gamble Services Company NV, 1853, Strombeek Bever, Belgium

José M. Franco: Pro2TecS – Chemical Process and Product Technology Center, Dpto. Ingeniería Química, ETSI, Campus de “El Carmen”, Universidad de Huelva, 21071, Huelva, Spain

1 Introduction

Three-dimensional (3D) printing has become a powerful ally for low-cost hardware manufacturing. It is a fast, inexpensive, and, above all, extremely versatile manufacturing technique. As a result, it is possible to create parts and structures that adapt perfectly to their purpose, offering total freedom for innovation and autonomous manufacturing. Thus, there are many examples of device and tool manufacturing projects in which 3D printing has played a relevant role [1–6]. Moreover, apart from 3D printing, there has been another element that has been of enormous relevance in the expansion of low-cost hardware (and software): open-source electronics creation platforms, such as Arduino or Raspberry [7]. The 3D printing/open-source electronics tandem has also found the perfect ecosystem to develop in communities such as RepRap, Instructables, or Thingiverse, among many others [8]. In these communities, all kinds of users, of all levels of expertise and knowledge, share designs, codes, and ideas. This has brought the manufacture of devices and equipment within the reach of researchers, teachers, students, and any hobbyist. In short, technological development has been placed in the hands of end users from a wide range of fields, which has led to a massive boom in creativity.

Long before this, over a 100 years ago, Flowers patented a device in which a ball was allowed to roll down an inclined tube filled with a fluid to determine its viscosity [9]. This type of viscometer has been used for so long mainly because of its simplicity and low cost, and because it can be built as an enclosed system, as well as requiring a small sample volume [10,11]. Initially, equations describing the rolling ball viscometer (RBV) only considered Newtonian fluids, i.e., a single non-shear-dependent viscosity value [9,10,12]. However, it was only a matter of time before its application for non-Newtonian fluids was also studied [13]. Several works on viscosity measurement of non-Newtonian fluids by means of RBVs can be found in the literature. Among them, it is worth highlighting those of Šesták and

Ambros [14], Stastna and De Kee [15], Bagchi and Chhabra [16], Briscoe et al. [17], and Tang [18], whose mathematical expressions and design considerations are still fully valid today. Nevertheless, their equations are focused only on measurements carried out on power-law and Bingham plastic fluids [14]. However, more complex rheological behaviours, such as that of Herschel–Bulkley fluids, cannot be predicted by the same models or, at least, not without being aware of certain considerations.

Part of the previous work on this kind of device has also consisted of the determination of the shear rate in RBV measurements. In this type of inclined tube viscometer, the ball rolls on the wall of the tube so that the gap between them is variable: from zero, at the point of contact, to the maximum, at its vertical. For this reason, there is no one unique shear rate, and it is necessary to estimate an average or representative value. In addition, the shear rate will depend on the speed that the ball reaches in each case. Thus, even if the same tilt angle and diameters of the tube and ball are maintained, the shear rate will be different for fluids with different rheological behaviours. It is of course possible to compensate for this to some extent by measuring at different angles and with balls of different diameters. But, in any case, the range of shear rates available will inevitably depend on the fluid to be measured. This is obviously a limitation compared to other viscosity-measuring devices. However, it also has advantages. For example, as the sample is introduced into a closed, hermetic system, problems of drying or other changes that may occur in the sample due to its exposure to the environment are avoided. This allows measurements to be taken for as long as desired without fear of the results being influenced by unwanted changes in the sample, making it possible, for example, to monitor the rheological behaviour of the same aqueous sample for hours, days, or even months. Something that would be impossible with other viscometers.

Moreover, its essential configuration is quite simple: a tube, a ball, a support that can be set at different inclinations, and a way to determine the falling time of the ball (in the most basic version, an observer with a stopwatch). This makes it a great candidate for a project in STEM education [18–21], as a way for students to acquire a variety of skills, both through its design and building, and subsequent use. It is also, for the same reason, an affordable way to routinely check viscosities in companies and laboratories. However, in most cases, more accurate time control and less reliance on human intervention would be required for this application, especially to take advantage of its suitability for long-term measurement. In this scenario, a detection system is of key importance. Electrodes [22], X-ray [23], light sensors [24,25], and cameras [26,27] are commonly used for this purpose in research viscometers. The Lovis 2000 M/ME, a high-performance RBV from Anton Paar, uses inductive sensors for ball detection. However, their cost may be excessive for many small or developing areas laboratories. Commercial equipment, moreover, while having obvious advantages, is often not so useful in educational applications, being less intuitive and giving less access to the intricacies of both hardware and software.

In this work, an RBV has been designed and built from 3D printed parts and low-cost components, controlled by an Arduino MEGA board, and tested for a variety of Newtonian and non-Newtonian shear-thinning fluids. A code has been developed for its operation, both in manual and automatic mode, which also includes an algorithm for the calculation of the viscosity of Newtonian and non-Newtonian fluids.

2 Methods

2.1 Materials

Different fluids have been used for the calibration and validation of RBV. 20 BW (Zentrum für Messen und Kalibrieren & ANALYTIK GmbH, Germany), soybean oil (Heuschen & Schrouff Oriental Foods, Netherlands), E200 (Thermo Scientific HAAKE, Germany), HT75 (CANNON Instrument Company, USA), and piston oil 150 (Josval S.L., Spain) were used as Newtonian model fluids. Fresubin Clear Thickener® (Fresenius Kabi Deutschland GmbH, Germany) was mixed with distilled water at different concentrations (0.25, 0.5, 0.75, 1, 1.25, and 1.5 wt%) to obtain power-law shear-thinning fluids. In addition, fabric softener formulations (Procter & Gamble, USA) exhibiting Herschel–Bulkley behaviour have been characterised by both RBV and rotational rheometry to evaluate the application of the technique to these fluids.

Mechanical non-printable parts were purchased from HTA3D (Spain), and electronic components were acquired at the same place and at Electrónica Odiel, S.L. (Spain).

2.2 3D printing

Printable parts have been designed specifically for this work and modelled with SolidWorks software. STL files have been sliced using Cura Ultimaker and printed in PLA with a BQ Hephestos (BQ, Spain) FDM 3D printer.

2.3 Validation of rheological measurements

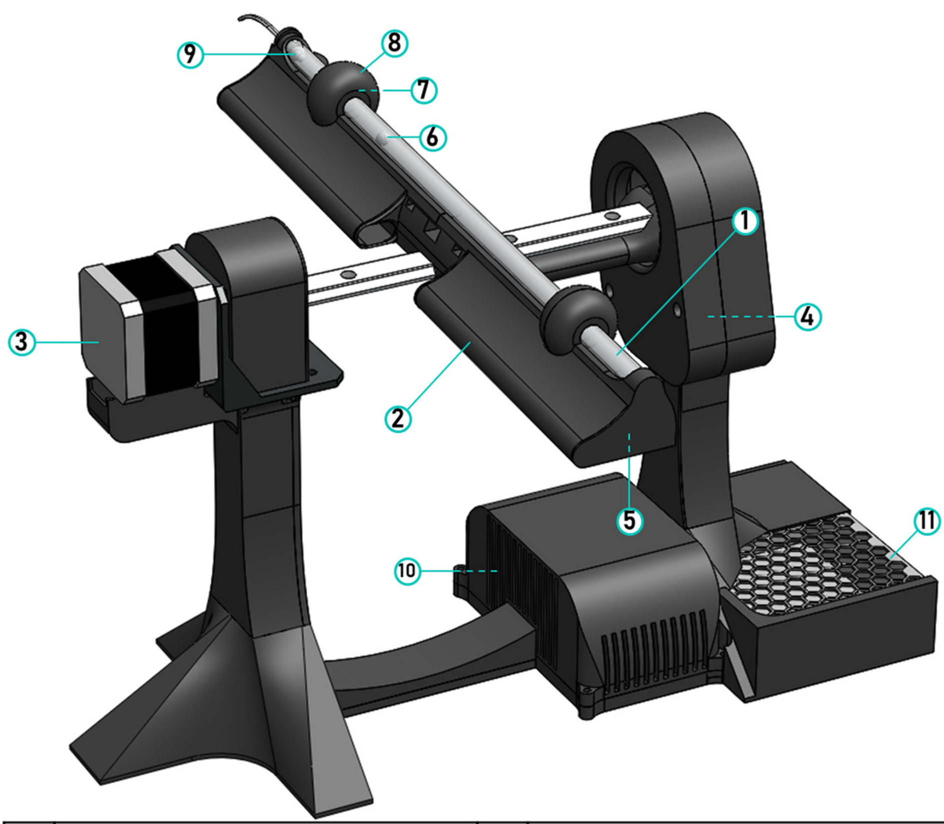
RBV-measured viscosities were compared for validation with those obtained by means of an MCR-301 rotational rheometer (Anton Paar, Austria). Viscosity vs shear rate curves were obtained in a range between 0.1 and 1,000 s^{-1} at 25°C with a 50 mm cone-and-plate geometry.

2.4 Device

2.4.1 Main components

The device was designed and manufactured in PLA with the aid of a 3D printer (Figure 1).

The designed device consists of a (1) glass tube (9 mm outer diameter, 6 mm inner diameter and 30 cm long) placed in a (2) 3D printed holder, whose tilt angle can be adjusted by means of a (3) NEMA 17 stepper motor. The zero tilt with respect to the horizontal plane is established by means of an (4) optocoupler speed sensor. At both ends of the tube, there is an (5) electromagnet which, when activated, holds a (6) 4/5 mm diameter steel ball (or other size as required). When the magnets are deactivated, the ball rolls freely inside the tube, its passage being detected by two (7) inductive sensors placed at 20 cm from each other, symmetrically to the axis of rotation of the tube, and covered by respective (8) interference suppressors. A (9) thermistor, also located at one end of the tube, measures the temperature inside the sample tube. All electronic components are controlled by an (10) Arduino



1	Glass tube	7	Inductive sensor
2	3D printed holder	8	Interference suppressors
3	NEMA 17 stepper motor	9	Thermistor
4	Optocoupler speed sensor	10	Arduino MEGA
5	Electromagnet	11	12V DC power supply
6	Steel ball		

Figure 1: Rolling-ball viscometer components.

MEGA 2560 microcontroller board. A (11) DC power supply provides 12 V to the stepper motor.

The core of the device's electronics is the Arduino MEGA board. However, an additional board has also been used. This custom PCB can be attached as a shield to the Arduino MEGA, allowing easy connection of all the electronic components and comprising all extra circuits needed for their proper functioning.

The firmware that enables operation and communication with the device has been specially developed for this project. This includes all the codes required for the operation of the stepper motor and electromagnets, as well as thermistor, detection, and zero sensor readings.

The device has been tested with Newtonian, power-law, and Herschel–Bulkley fluids, obtaining reasonably accurate results (see Section 3), within the following operating ranges:

- Recommended viscosities (10 s^{-1}): 0.02–0.50 Pa s.
- Recommended measurement time range: 3–60 s.
- Tilt angle: 1°–75° (recommended 10°–60°).
- Ball: 4 or 5 mm diameter, 420 stainless steel to avoid corrosion.

2.4.2 Building cost

Obviously, better accuracy in viscosity measurement can be obtained with other devices and equipment. However, this device allows measurement of Newtonian and non-Newtonian viscosities with reasonable accuracy at a cost well below that of most alternatives.

The components listed in Table 1 can be easily found in local or online stores. The one that may vary the most will most likely be the custom PCB. However, this can also be manufactured with a 3D printer [28], so its cost would be further reduced. In any case, the cost of all the components required for the construction of the device should be less than 200€. Considering that the price of commercial models can run into thousands of euros, the savings are obvious.

2.4.3 Inductive sensors

Ball detection was the main challenge in the development of this device. Commercial high-tech sensors were not an option for a low-cost setup, and the detection range of hobby components (inductive and capacitive sensors) was not wide enough to register the pass of the ball through the glass wall. Thus, it was decided to manufacture a custom-made sensor, which would better adapt to the geometry of the device. For this purpose, the design of a metal detector for Arduino [29] was taken as a basis and adapted. It simply consists of a copper wire 0.2 mm in diameter and wrapped (100 windings) around a supporting part, which in turn fits the glass tube (Figure 2, left).

This sensor is then enclosed in a protective cover (Figure 2, right) with an aluminium foil inside, acting as interference suppressor and protecting the sensor from possible spills and minimising electromagnetic interference from the environment.

The two ends of the wire are connected to the Arduino board, which feeds the circuit with current pulses and detects the variation in inductance caused by the ball passing through the coil [29].

Another essential aspect to consider during the design stage is the terminal speed. As will be detailed below, all the equations used for viscosity calculation consider a constant, terminal velocity. Therefore, it is necessary to set enough distance between the release of the ball and its passage through the first sensor for it to be reached. The

Table 1: Approximate cost of components for building of RBV

Component	Price (€)
PLA filament (1 kg)	13.75[a]
Arduino MEGA	12.75[a]
Custom PCB	80 (approx.)
12 V DC power supply	17.49[b]
NEMA 17 stepper motor	9.35[a]
Electromagnets (×2)	22.56[b]
Optocoupler	7.17[b]
Generic electronic components	10 (approx.)
Glass tube	1 (approx.)
Non-printable mechanical components	10 (approx.)
Total	184.07

[a]Price on HTA3D website as of 10/30/2023.
[b]Price at Electrónica Odiel (Huelva, Spain) at the time of purchase.

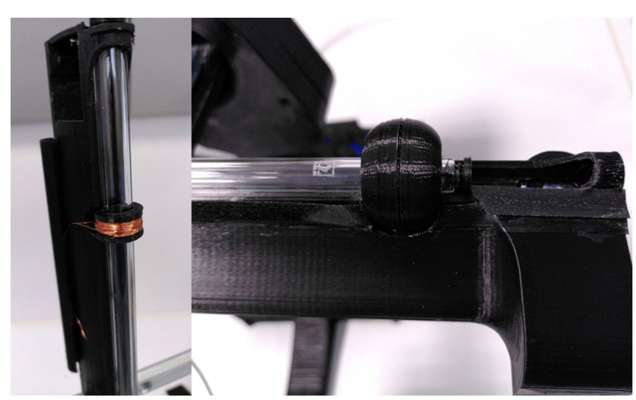


Figure 2: Custom made inductive sensor, with (right) and without (left) protective cover.

evolution of speed with time for a sphere in a fluid, with respect to the terminal speed, V, can be calculated as [18]

$$v = V(1 - e^{-s/\tau}), \tag{1}$$

where

$$\tau = \frac{m}{6\pi\eta r}, \tag{2}$$

here v is the speed at a time "s" (m/s), s is the time since ball release (s), m is the ball mass (kg), η is the apparent viscosity (Pa s), and r is the ball radius (m).

Giving values to time, s, it is possible to predict the evolution of ball speed for a certain fluid. Once the speed of the ball is known, also its position can be calculated. For example, in the case of a fluid with a viscosity of 0.02 Pa s at 10 s^{-1}, the lowest recommended viscosity (the worst-case scenario, as terminal speed is reached later in low viscosity fluids), the predicted evolution of speed with distance is as shown in Figure 3.

Conceptually, the speeds would only equal at infinite time. However, only 3 cm after release, the ball speed is above 98% of the value of the terminal speed. After 5 cm, it is 99.8%, so it can be considered that the terminal speed has already been reached. Thus, sensors are located at 5 cm from each tube end.

2.5 Calculation of flow and consistency indices

It is possible to calculate the flow (n) and consistency (k) indices of a power-law fluid from the geometry of the setup and the speed of the ball. For this, it is necessary to determine the speed of the ball at two different tilt angles. From the time-lapse measured between the detection of the two sensors and knowing the distance between them, n can be calculated as follows [14]:

$$n = \frac{\log(\sin\beta_1/\sin\beta_2)}{\log(V_1/V_2)}, \tag{3}$$

where n is the flow index, β_1, β_2 are tilt angles (rad), and V_1, V_2 denote speed at corresponding tilt angle (m/s).

Once n has been calculated, k is obtained by the following expression [14]:

$$k = \frac{(g/3)d(\rho_s - \rho)\sin\beta\, D^n}{\left(\frac{2n+1}{n}\pi V\right)^n J_n}\left(\frac{D-d}{D}\right)^{2n+\frac{1}{2}}, \tag{4}$$

where k is the consistency index (Pa s^n), g is the gravity acceleration (m/s^2), d is the ball diameter (m), ρ_s is the ball density (kg/m^3), ρ is the sample density (kg/m^3), β is the tilt angle (rad), D is the inner diameter of the tube (m), n is the flow index, V is the speed (m/s), and J_n is the n-depending parameter.

J_n values were tabulated by Šesták and Ambros [14]. However, to facilitate automatic calculation, these values can be fitted to a fifth-degree polynomial in the range between n = 0.15 and n = 1 (R^2 = 1):

$$J_n = -1.9099n^5 + 7.5424n^4 - 12.614n^3 + 11.97n^2 - 7.423n + 2.9654. \tag{5}$$

For the determination of the viscosity of a fluid, the glass tube is filled completely with the sample, the desired angle of inclination is selected, and the ball is released to roll through the fluid to record the time lapse between passing through the two sensors. From the selected angle and the measured time, the viscosity is calculated as detailed below in Section 3.

Two measuring modes are available: manual and automatic measurement. Manual measurement mode allows

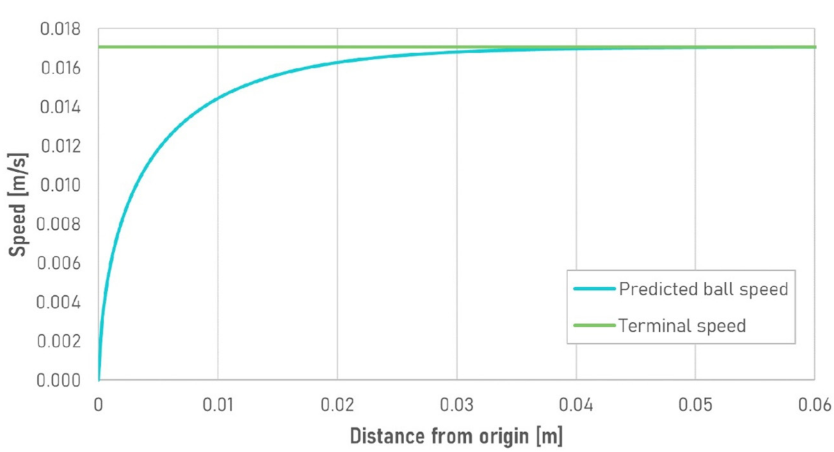


Figure 3: Predicted ball speed for a fluid with a viscosity of 0.02 Pa s (n = 0.845, k = 0.035 Pa s^n, L = 20 cm, D = 6 mm, d = 5 mm, β = 10°, ρ_s = 7,880 kg/m^3, ρ = 995 kg/m^3).

all elements to be controlled manually and independently, a flexible way of use during the development and validation stages. In this mode, commands are inputted through the Arduino IDE terminal and sent via serial port communication protocol, being time (in microseconds) and temperature, the only information returned by the device after measurement.

In automatic mode, operation becomes somewhat more "user-friendly," guiding the operator through communication via the serial monitor. At the appropriate moment, the firmware requests the parameters according to which the measurement is to be carried out. With this information, the device automatically performs two measurements at different tilt angles. When valid results have been obtained, with an error below a user-defined tolerance, the program returns the measured times, the angles at which they were obtained, and the results of the entire calculation sequence (Figure 4).

3 Results

3.1 Calibration factor

Rolling ball viscometers must be calibrated in order to find their characteristic instrument constant [14,17,18]. For this, values obtained from the measurement of fluids of known viscosity and density must be compared to those obtained with another viscometer/rheometer. This procedure must be carried out for each ball diameter to be used, since the calibration factor depends on the geometry of the setup.

20 BW, soybean oil, E200, HT75, and piston oil were used as Newtonian model fluids. Figure 5 shows the viscosity values obtained for these fluids with the RBV (μ_{RBV}), plotted against rotational rheometer-measured values (μ_{rheo}).

As can be seen, there is a linear relationship between μ_{RBV} and μ_{rheo}.

The same happens when measuring power-law shear thinning fluids (Fresubin Clear Thickener® at 0.25, 0.5, 0.75, 1, 1.25, and 1.5 wt% in distilled water). Both k and n power-law parameter values calculated from RBV measurements are proportional to those obtained from power-law fitting of viscosity curves obtained by means of the rotational rheometer (Figure 6).

Again, k_{RBV}/k_{rheo} shows a linear trend. However, the proportionality constant obtained in this case differs from μ_{RBV}/μ_{rheo} obtained for Newtonian fluids.

In the case of Herschel–Bulkley fluids, n and k parameters obtained from equations (3) and (4) are not comparable to those obtained by fitting rheometer viscosity curves.

Figure 4: Results obtained with RBV in automatic mode.

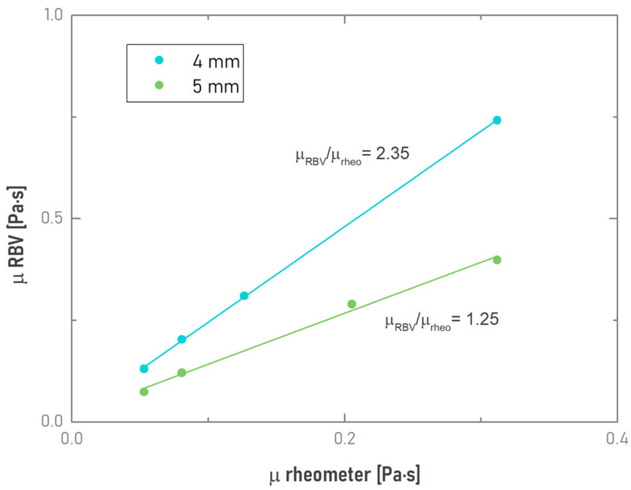


Figure 5: RBV vs rheometer viscosity values for Newtonian fluids.

However, if these k and n values, obtained from RBV measurements by means of equations (3) and (4), are used to calculate a viscosity value at a certain shear rate using a power-law expression (also in the case of Herschel–Bulkley fluids), $\mu_{\text{RBV}}/\mu_{\text{rheo}}$ and $\eta_{\text{RBV}}/\eta_{\text{rheo}}$ ratios take quite similar values (Table 2).

By taking these ratios as starting points, a correction factor has been found for which the sum of relative errors for all samples is minimum. Thus, viscosity can be calculated by using a constant (1/1.41 for 5 mm balls and 1/2.30 for 4 mm balls), which minimises RBV-rheometer deviations and is valid for all types of fluids, only depending on the diameter of the ball. Thus, once k and n are known,

Table 2: RBV vs rheometer μ and η values at 10 s^{-1}: resulting ratios

	$\mu_{\text{RBV}}/\mu_{\text{rheo}}$		$\eta_{\text{RBV}}/\eta_{\text{rheo}}$	
	4 mm	**5 mm**	**4 mm**	**5 mm**
Newtonian	2.35	1.25		
Power-law			2.02	1.36
Herschel–Bulkley			2.40	1.40

viscosity values must always be (regardless of the type of fluid measured) calculated by means of a modified power-law expression:

$$\eta = 0.7092k\dot{\gamma}^{n-1}, \quad (6)$$

where η is the viscosity (Pa s), k is the consistency index (Pa s^n), $\dot{\gamma}$ is the desired shear rate (s^{-1}), and n is the flow index.

Empirical factor in equation (6) is only valid for measurements with 5 mm balls. For measurements with 4 mm, its value should be changed to 0.4348.

3.2 Measurement procedure for Herschel–Bulkley fluids

Equations (3) and (4) allow k and n to be calculated for power-law fluids from data obtained with an RBV. Of course, this includes Newtonian fluids, where $n = 1$ and $k = \mu$. However, these equations for RBV do not consider

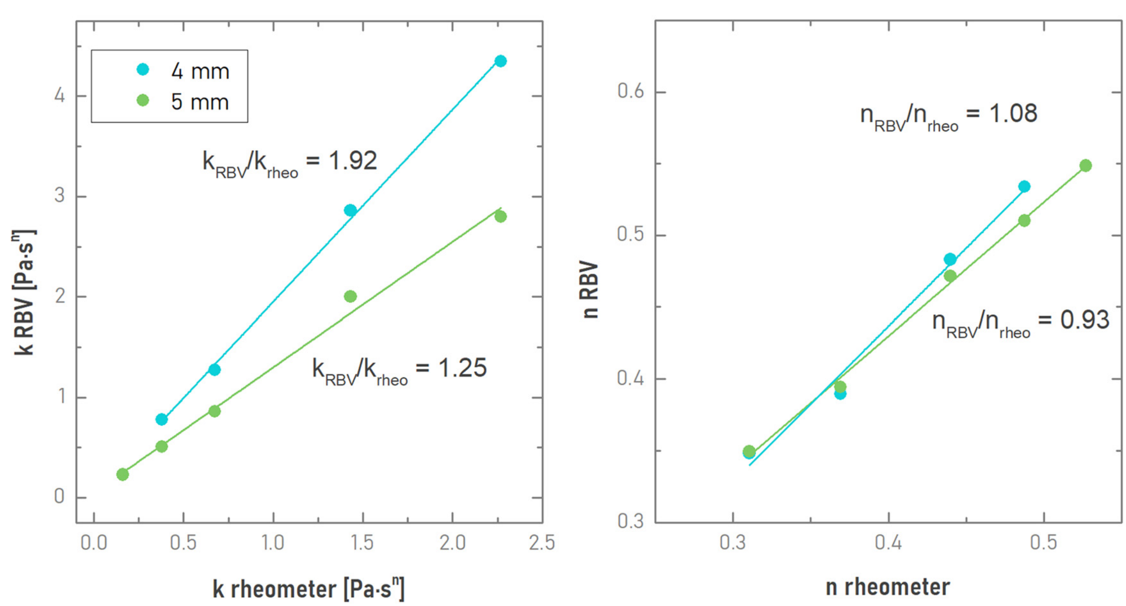


Figure 6: RBV vs rheometer k and n values for power-law fluids.

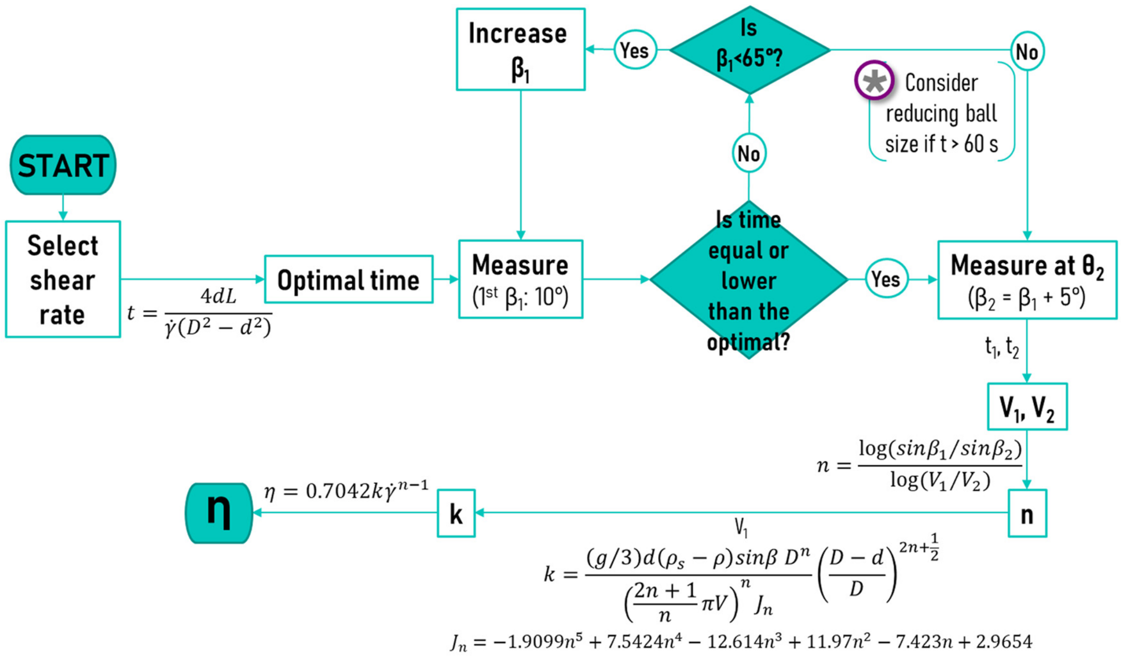


Figure 7: Measuring flow diagram.

the possible existence of yield stress. Obviously, fitting Herschel–Bulkley fluids to a power-law expression is an approximation, in which a viscosity vs shear rate plot is fitted to a line (in a log–log plot). However, this approximation can be applicable if the Herschel–Bulkley viscosity–shear rate curve is divided into short power-law segments. This is, if the considered shear rate range is narrow enough (i.e. small increment between two tilt angles used for the calculation of n) and the measurement is performed at a shear rate close to that at which the viscosity value is to be determined.

For this device, the shear rate cannot be imposed, but it can be sought, within a range that depends on the measured fluid. According to Briscoe et al. [17], an average (as the ball-tube gap is not constant) shear rate value can be calculated as follows:

$$\dot{\gamma} = \frac{4dV}{D^2 - d^2}. \quad (7)$$

Optimal measured time can be calculated as follows:

$$t = \frac{4dL}{\dot{\gamma}(D^2 - d^2)}, \quad (8)$$

where t is the measured time-lapse (s), d is the ball diameter (m), L is the distance between sensors (m), $\dot{\gamma}$ is the desired shear rate (s^{-1}), D is the inner diameter of the tube (m).

Then, the tilt angle can be modified to approach the desired measurement time and/or shear rate. In case the optimal shear rate cannot be reached by modifying measuring parameters, it will always be preferable to measure at shear rates above than below the optimal. This is because, at low shear rates, the influence of the yield stress is obviously more pronounced, so the viscosity of the Herschel–Bulkley fluid deviates further from the power-law behaviour.

3.3 Proposed measurement protocol

The case of Herschel–Bulkley is analysed separately because the existing equations for RBV do not consider the possible existence of yield stress. In this sense, it is only with these fluids that the proposed measurement procedure must be followed (search for the shear rate as close as possible to the desired one and with a small increment between angles), while power-law and Newtonian fluids could, theoretically, be characterised by any pair of angles. However, the Herschel–Bulkley procedure is established as the general one, so that it is not necessary to know in advance the type of fluid to be measured.

Thus, the measurement process can be summarised as shown in Figure 7.

All the steps detailed in this flow chart can be followed by the operator in manual mode and will be performed by the device in automatic mode, with little or no intervention from the user.

Following data (Tables 3 and 4 and Figure 8) are some viscosity values (at a shear rate of 10 s^{-1}) resulting from the

Table 3: Comparison between rolling-ball and rheometer viscosities, for 5 mm ball

Newtonian fluids			Power-law fluids			Herschel–Bulkley fluids		
Rheometer (Pa s)	Rolling-ball viscometer (Pa s)	Error (%)	Rheometer (Pa s)	Rolling-ball viscometer (Pa s)	Error (%)	Rheometer (Pa s)	Rolling-ball viscometer (Pa s)	Error (%)
0.0530	0.0525	0.9	0.0544	0.0575	5.6	0.0464	0.0450	3.0
0.0806	0.0857	6.3	0.1150	0.1161	1.0	0.0648	0.0612	5.5
0.2053	0.2052	0.0	0.1835	0.1806	1.6	0.0996	0.1064	6.8
0.3119	0.2825	9.4	0.3330	0.3518	5.6	0.1440	0.1629	13.1
			0.4665	0.4439	4.8	0.1890	0.1768	6.5

Table 4: Comparison between rolling-ball and rheometer viscosities, for 4 mm ball

Newtonian fluids			Power-law fluids			Herschel–Bulkley fluids		
Rheometer (Pa s)	Rolling-ball viscometer (Pa s)	Error (%)	Rheometer (Pa s)	Rolling-ball viscometer (Pa s)	Error (%)	Rheometer (Pa s)	Rolling-ball viscometer (Pa s)	Error (%)
0.0530	0.0566	6.9	0.1150	0.1157	0.6	0.1080	0.1001	7.3
0.0806	0.0881	9.3	0.1835	0.1684	8.2	0.1770	0.1612	8.9
0.1265	0.1348	6.6	0.3330	0.3050	8.4	0.2040	0.1997	2.1
0.3119	0.3226	3.5	0.4665	0.4214	9.7	0.1890	0.1894	0.2

application of the proposed setup and calculation procedures to the measurement of different fluids.

As can be seen in Tables 3 and 4 and Figure 8, good accordance between a conventional rotational rheometer and RBV is achieved for measurements with both 4 and 5 mm balls.

4 Discussion

The proposed setup has proven to be capable of measuring the viscosity of Newtonian, power-law, and Herschel–Bulkley fluids with reasonable accuracy. Moreover, n and k values can also be obtained for power-law fluids. For Herschel–Bulkley fluids, although it is not possible to obtain the model parameters, it is possible to obtain accurate viscosity values at specific shear rates. In both cases (especially for Herschel–Bulkley fluids), determination of valid viscosity values involves difficult and laborious calculations, an iterative measurement process, and very accurate time measurements. This device and its automatic mode simplify and reduce the time needed for this. In this way, technological and human resources are economised, as, apart from having a very low cost, it allows for viscosity determination without prior knowledge in rheology or intensive training. This makes the RBV useful for certain applications such as quality control [30,31] or STEM education.

In industry, in quality control of non-Newtonian fluids, it can serve as a quick method of routine viscosity testing. As shown above, the accuracy of the device is reasonably good for this, and its precision is even better, e.g., five repetitions on the same load for a given shear-thinning fluid of 0.4228 Pa s, measured at 10 s^{-1}, have a maximum relative standard deviation (RSD) of 0.82%, and the overall RSD value for five different sample loads (five repetitions

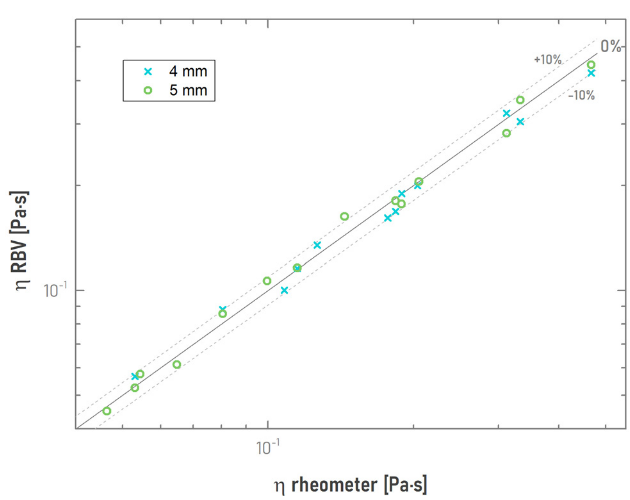


Figure 8: Rolling-ball viscosities vs rheometer viscosities and corresponding linear fittings: influence of ball diameter.

each) is 0.95%. The results obtained for different non-Newtonian fluids, in addition to broadening the range of applicability of this type of viscometers, have the advantage of making it possible to obtain viscosity values for different types of fluids without the need to previously know which model their rheological behaviour fits to [32]. Moreover, due to automatic operation, the measurement can be replicated as many times as desired without human intervention. Likewise, it can be programmed to follow the evolution of a sample during long time periods.

Conversely, in STEM education, building of this device could help students with learning of mechanics, electronics, mathematics, programming, CAD design, and 3D printing. After this, by measuring and analysing results, it can be a good way to understand the physics and rheology of Newtonian and non-Newtonian fluids.

Funding information: Authors state no funding involved.

Author contributions: I.D. – conceptualisation, data curation, formal analysis, investigation, methodology, software, validation, visualisation, writing – original draft; I.M. – conceptualisation, formal analysis, funding acquisition, methodology, project administration, resources, supervision, writing – review & editing; A.J. – conceptualisation, data curation, formal analysis, funding acquisition, investigation, methodology, resources, software, supervision, validation, writing – review & editing; J.M.F. – conceptualisation, formal analysis, methodology, resources, supervision, writing – review & editing.

Conflict of interest: Authors state no conflict of interest.

Ethical approval: The conducted research is not related to either human or animal use.

Data availability statement: Some of the data that support the findings of this study are available from the authors but restrictions apply to the availability of these data which were used under IP agreement for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of Procter and Gamble Services Company.

References

[1] Hendrich N, Wasserfall F, Zhang J. 3D printed low-cost force-torque sensors. IEEE Access. 2020;8:140569–85.

[2] Telegenov K, Tlegenov Y, Shintemirov A. A low-cost open-source 3-D-printed three-finger gripper platform for research and educational purposes. IEEE Access. 2015;3:638–47, https://ieeexplore.ieee.org/document/7109102.

[3] Bernard P, Mendez JD. Low-cost 3D-printed polarimeter. J Chem Educ. 2020 Apr;97(4):1162–6, https://pubs.acs.org/doi/full/10.1021/acs.jchemed.9b01083.

[4] Bicer MB. Design of an octagonal-shaped curved sensor antenna for dielectric characterization of liquids. Measurement. 2023 Feb;207:112389.

[5] Zhou Y, Duan C, Doh IJ, Bae E. Exploring the utility of 3-D-printed laboratory equipment. Appl Sci. 2019 Mar;9(5):937, https://www.mdpi.com/2076-3417/9/5/937/htm.

[6] Mitra S, Basak M, Biswas S, Gooh Pattader PS. Digital electronic based portable device for colorimetric quantification of ketones and glucose level in human urine. Measurement. 2023 Jun;214:112848.

[7] Ngo TD. Open-source electronics platforms: Development and applications. Electronics. 2019 Apr;8(4):428, https://www.mdpi.com/2079-9292/8/4/428/htm.

[8] Camburn B, Wood K. Principles of maker and DIY fabrication: Enabling design prototypes at low cost. Des Stud. 2018 Sep;58:63–88.

[9] Flowers AE. Method and machine for determining viscosity, US Pat., 1247523A, 1913.

[10] Hubbard RM, Brown GG. Rolling ball viscometer. Ind Eng Chem Anal Ed. 1943 Mar 1;15(3):212–8, https://cir.nii.ac.jp/crid/1363388843431678976.

[11] Barnett CH. A rolling-ball viscometer for clinical use. Physics in medicine and biology. Vol. 1. Bristol, UK: IOP Publishing; 1957. p. 380–2. https://iopscience.iop.org/article/10.1088/0031-9155/1/4/407.

[12] Lewis HW. Calibration of rolling ball viscometer. Anal Chem. 1953 Mar;25(3):507–8, https://cir.nii.ac.jp/crid/1362262945334587136.

[13] Bird RB. Communication non-newtonian flow in a rolling-ball viscometer. Ind Eng Chem Fundam. 1964 Feb;3(1):87, https://pubs.acs.org/doi/abs/10.1021/i160009a017.

[14] Šesták J, Ambros F. On the use of the rolling-ball viscometer for the measurement of rheological parameters of power law fluids. Rheol Acta. 1973 Mar;12(1):70–6, https://link.springer.com/article/10.1007/BF01526902.

[15] Stastna J, De Kee D. The rolling-ball viscometer and non-Newtonian fluids. Int J Math Educ Sci Technol. 2006 Jul 1;18(4):527–34. doi: 101080/0020739870180404, https://www.tandfonline.com/doi/abs/10.1080/0020739870180404.

[16] Bagchi A, Chhabra RP. Rolling ball viscometry for Newtonian and power law liquids. Chem Eng Process Process Intensif. 1991 Jul;30(1):11–3.

[17] Briscoe BJ, Luckham PF, Ren SR. An assessment of a rolling-ball viscometer for studying non-Newtonian fluids. Colloids and Surf. 1992 Jan;62(1–2):153–62.

[18] Tang JX. Measurements of fluid viscosity using a miniature ball drop device. Rev Sci Instrum. 2016 May;87(5):054301, https://aip.scitation.org/doi/abs/10.1063/1.4948314.

[19] Simon J, Gogolák L. Development of an IoT based 3D printed Mobile Robot Platform for training of Mechatronics Engineering Students. Anal Tech Szeged. 2024 May;18(1):18–30, https://www.analecta.hu/index.php/analecta/article/view/45430.

[20] Shah J, Thareja P. Design Your Experiment (DYE) – Project based learning in Fluid Mechanics Laboratory. Asean J Eng Educ. 2021 Nov;5(1):51–7, https://ajee.utm.my/index.php/ajee/article/view/60.

[21] Wang S, Jiang L, Meng J, Xie Y, Ding H. Training for smart manufacturing using a mobile robot-based production line. Front Mech Eng. 2021 Jun;16(2):249–70, https://link.springer.com/article/10.1007/s11465-020-0625-z.
[22] Srinivasan A, Sharavanee DP, Shwetha MP, Surendran S, Suryaprakash S, Hans JW. Arduino based automated viscometer for oil health monitoring. Proceedings of the 4th International Conference IoT in Social, Mobile, Analytics and Cloud, ISMAC 2020. 2020 Oct. p. 1069–73.
[23] Rose PB, B Ezell ND, Gallagher RC, Martin AJ. Radiographic rolling ball viscometer. In Transactions of the American Nuclear Society. Conference at 2021 ANS Annual Meeting – Virtual, Tennessee, United States of America, United States, 2021.
[24] Newkirk MS. Design and development of a high-temperature high-pressure rolling ball viscometer/densimeter and evaluation of star polymer-solvent mixtures. [Thesis dissertation]. Virginia Commonwealth University (VCU University Archives); 2016 Jan. https://scholarscompass.vcu.edu/etd/4654.
[25] Gamwo IK, Burgess W, Tapriyal D. High temperature, high pressure equation of state: Solidification of hydrocarbons and measurement of krytox oil using rolling-ball viscometer validation. Technical Report from the Department of Energy of the United States; 2014 Oct, https://www.osti.gov/servlets/purl/1350962/.
[26] Birri A, Termini N, Rose P, Chapel S, Andrews H, Bull Ezell ND. Development and demonstration of a rolling ball viscometer for molten salts with near-minimum liquidus NaCl–KCl. Therm Sci Eng Prog. 2023 Sep;44:102029.
[27] Sato Y, Baba H, Yoneyama C, Inomata H. Development of a rolling ball viscometer for simultaneous measurement of viscosity, density, bubble-point pressure of CO2-expanded liquids. Fluid Phase Equilib. 2019 May;487:71–5.
[28] Espera AH, Dizon JRC, Chen Q, Advincula RC. 3D-printing and advanced manufacturing for electronics. Prog Addit Manuf. 2019 Sep;4(3):245–67, https://link.springer.com/article/10.1007/s40964-019-00077-7.
[29] Simple Arduino metal detector: 8 steps (with Pictures) – Instructables [Internet]. Rgco. https://www.instructables.com/Simple-Arduino-Metal-Detector/.
[30] Zheng P, wang H, Sang Z, Zhong RY, Liu Y, Liu C, et al. Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives. Front Mech Eng. 2018 Jun;13(2):137–50, https://link.springer.com/article/10.1007/s11465-018-0499-5.
[31] Sui D, Vidaur JCM. Automated characterization of non-Newtonian fluids using laboratory setup. Appl Rheol. 2020 Jan;30(1):39–53, https://www.degruyter.com/document/doi/10.1515/arh-2020-0101/html.
[32] Barnes HA. An examination of the use of rotational viscometers for the quality control on non-newtonian liquid products in factories. Appl Rheol. 2001 Apr;11(2):89–101, https://www.degruyter.com/document/doi/10.1515/arh-2001-0006/html.