26th International Congress of Mechanical Engineering
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-0354
DEVELOPMENT OF AN AUTOMATED HOPPLER VISCOMETER

José Victor Passos Santiago.
Luís Henrique Simões Leite.
Gustavo Fonseca de Freitas Maia.
Pontifícia Universidade Católica de Minas Gerais. Departamento de Engenharia mecânica. Av. Dom josé Gaspar, 500 CEP:30535-901.
jose.passos@sga.pucminas.br
luis.simoes@sga.pucminas.br
gustavomaia@pucminas.br

Abstract. *Viscosity is one of or perhaps the main property of a liquid, several equipment and standards have been developed in order to determine and classify viscosity. And with time new technologies have emerged and enabled a better evaluation of the fluids to be used in various industrial procedures. Technological innovations in this area have a great relevance, since in the current competitive world, the quality and precision of equipment is gradually becoming an extremely important point when it comes to customer choice and reliability. A point to be highlighted is that these procedures, even though they present reliable results, are usually subject to errors, whether due to environmental conditions, such as pressure and temperature, equipment technicians, or even human error, which can lead to false results. In view of this, this project aims to minimize some of these inaccuracies as well as the time of these experiments with the automation of one of the viscosity measurements processes, the Höppler viscometer. The automation of the equipment was developed through the Arduino, a microcontroller capable of performing several tasks through an electrical circuit composed of several electronic components, including operating a viscometer.*

Keywords: *Keywords: Viscometer, automated, efficient, Höppler, validation.*

1. INTRODUCTION

During the flow of a fluid, its molecules present relative motion among themselves and consequently frictional forces arise generating a resistance to the natural flow of the substance. (Mezger, 2006). This opposition to flow is called viscosity.

Especially for lubricants, but also for fluids in general, viscosity is the most important property (Fitch, 2020) and consequently several studies are conducted around this property. Today it is known that temperature is the determining factor in the choice of lubricant, since it has a major influence on viscosity. Given this, a dimensionless value was created in order to describe this behavior of temperature as a function of viscosity, the viscosity index (IV), which is calculated based on the kinematic viscosity at 40° C and 100° C. (Hackländer, 2012). Fluids that have low IV are characterized by being highly susceptible to temperature change, thus, with decreasing temperature, they become thick (extremely viscous) and with increasing temperature they become highly thin (fluids with very low viscosity).

Understanding the viscosity index proves to be very useful since, even though some fluids have the same viscosity at a given temperature, the value of the property changes with the increase or decrease in temperature by means of the viscosity index. Hence the need to analyze and understand this property in order to be able to use the most appropriate fluid for a given application.

According to a survey conducted by Machinery Lubrication magazine (Fitch, 2020), 89% of lubrication professionals use the IR as the main parameter when selecting a lubricant. That said, IR improvers are becoming a focus of study as well as synthetic oils that can achieve IRs much higher than the standard ceiling of 100.

Knowing that viscosity is one of or perhaps the main property of a liquid, various equipment and standards have been developed in order to determine and classify viscosity. Today there are several types of viscosimeters, which, according to their physical shape and the operation of the equipment, cover a wide variety of viscosities. These include rotation viscosimeters, those that work based on an external pressure (or even gravity) that forces the liquid to pass through a slit, capillary tube or orifice, falling sphere viscosimeter, among others. (Leblanc, 1999)

These instruments are easy to handle, have very good accuracy and a relatively simple method of operation. Basically, these equipments measure the stress and shear rate that occur inside the fluid during the experiment and the experimental result is usually determined as a function of time, pressure or temperature. (Mezger, 2006)

The Höppler viscometer is a variation of the bead drop viscometer, it has a slope of 80º. This viscometer can also present other working angles, but with a small variation in the formula, since the change in angle directly influences the resulting force on the sphere. An example of this apparatus is represented in figure 6. The viscosity in a Höppler viscometer is given by Stokes' equation. (Anton Paar, 2020)

The equipment proposed in this project has a very simple operation and is based on the Höppler viscometer. By measuring the time, a sphere falls inside an inclined tube containing the fluid to be analyzed, it is possible to find the viscosity value using Höppler's equation, as shown in Eq. 1 below.

$$\mu = K\,(\rho_s - \rho_f)\,t \qquad (1)$$

Where μ is the dynamic viscosity, K is a constant that depends on the sphere and tube, ρ_s is the density of the sphere, ρ_f is the fluid and t is the measured ball fall time.

2. METHODS

The viscometer defined in this work named Höppler or ball bearing viscometer is an instrument basically composed of three main components: a glass tube, a steel ball and a fluid to be studied. This triad, as the name of the instrument already says, has as its objective the quantification of a physical property of a fluid called viscosity.

The Höppler viscometer requires an operator to measure the time it will take for a sphere to pass two previously established points and, using equation 15 previously seen, and also knowing the values of the sphere density, the fluid density, and the sphere coefficient "K", define the viscosity of the fluid that is inserted in the tube.

This project aims to simplify and reduce the operator's interactions with the viscosity result, leaving to him only the insertion and removal of the tube and the microcontroller processing settings using an electronic interface.

For this, a system of lasers was defined, allied to a microcontroller, capable of defining specific triggers that will serve to indicate the ball drop time.

2.1 Viscometer design

The viscometer project is fundamentally divided into two different parts. The first part was defined as the idealization of the instrument itself, that is, the structural part of it, and the second part was defined as the idealization of the control center where the positions of the Arduino microcontroller and the input and output commands were determined, which will be named as console.

First it is essential to define some points about design concepts so that the instrument presents the characteristics so much sought, being the first major focus a complete automation during the measurement of the viscosity of the fluid that is being studied. The main points are: the instrument must have a firm structure and, for being in direct contact with fluids, a certain impermeability; the instrument must be able to perform several measurements in sequence after its calibration; it must have a structure in which it is possible to correctly position the laser sensors.

To meet the above requirements, the following design was chosen to be built. It is represented in Figure 1 below.

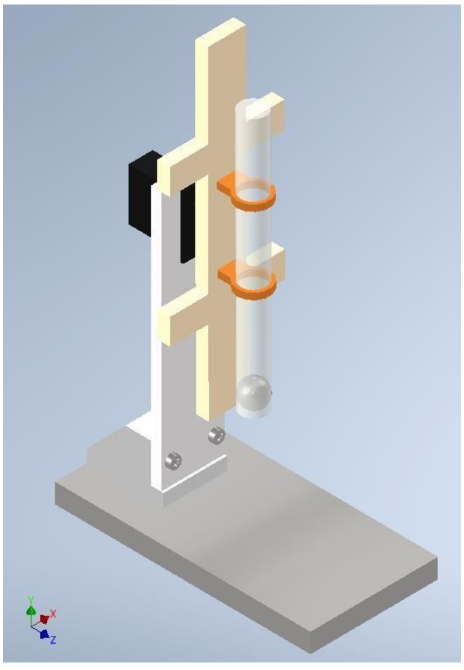

Figure 1. Representation of the prototype isometric view.

As previously shown, the microcontroller chosen for this viscometer was the Arduino Uno R3. As it is a microcontroller of even domestic use, the Arduino Uno R3, even keeping an excellent data storage capacity, proves to be easy to handle and use, thus meeting the main requirements to be used in the process as a whole.

In addition, because it is a microcontroller widely spread and used worldwide, Arduino has numerous peripherals created to make it a powerful automation tool. The so-called peripherals are a set of devices capable of performing various functions developed to have a communication sending or receiving data from Arduino. This communication allows almost infinite possibilities in the use of an Arduino Uno R3 board, from simply turning on a LED when pressing a button to measuring the ambient temperature or controlling the pitch and angle of a servo motor.

The peripherals used in this project, besides the previously mentioned sensors and laser emitters, will be fundamental to guarantee the communication between the operator and the viscometer, and to measure the ambient temperature in order to have a minimum control on the temperature in which the fluid is exposed. In this work, then, the ambient temperature will be considered as the current temperature of the fluid, and it will be measured in each test individually.

The communication between the operator and the viscometer will be through a 16x2 Display Lcd screen with Blue Backlight, where all the information necessary for the operator to perform the viscosity measurements will be shown on the display, such as menus, values and properties inputs, ball drop time and results obtained.

Tubes and sphere chosen for the instrument were: the smaller tube of 20.5mm internal diameter as well as for the larger tube of 22mm internal diameter and a sphere with 20mm diameter.

2.2 Calibration Tests

The calibration of the viscometer can be essentially treated as the capacity of the instrument to have in its internal memory, previously established data both of standard fluids at a certain study temperature and also specific characteristics of standard spheres, thus ensuring a set of spheres ready for use at any time. All calibration will be based on the quantities necessary to obtain the viscosity by the Höppler method.

The "K" coefficient of the sphere, as previously explained, can be obtained in a theoretical way using Eq (2). Thus, enabling the operator to calculate the "K" of the sphere on the instrument itself by providing all the necessary inputs is an excellent possibility to ensure the best use of the instrument. For this purpose, a special subroutine for the calibration of the viscometer was provided on the instrument itself.

The second way of calculating "K" is to allow a real test using Höppler's equation, that is, with a fluid with the previously known viscosity, densities of the sphere and the fluid, and the drop time of the sphere, it is possible to quantify the value of this relationship as shown in Eq. (2) bellow. This second method of calibration of the constant "K of the sphere" was chosen to continue with the other tests

$$K = \frac{\mu}{(\rho_S - \rho_f)\, t} \quad (1)$$

Where μ is the dynamic viscosity, K is a constant that depends on the sphere and tube, ρ_S is the density of the sphere, ρ_f is the fluid and t is the measured ball fall time.

REPSOL 5W40 oil at 40°C was used. Thus, by means of the known kinematic viscosity of the oil, it was possible to find the ball constants for both pipes.

2.3 Experimental Tests

Experimental tests were divided into two procedures, the first aiming to compare the results of the automated viscometer with those of the Höppler and a second to check the results against the literature.

First, the viscosities of a given detergent were measured using a calibrated Höppler viscosimeter (HAKE), available in the laboratories in PUC MINAS. These detergent viscosity results w
ill be used to compare the viscosity measured by the prototype. Thus, if the results are similar, it means that the calibration of the viscosimeter was successful. This step will be directed to checking the pipe with the largest diameter, i.e., the 22 mm pipe.

The second step is to verify the calibration of the smaller, 20.5 mm tube. For this, water will be used as the fluid to be studied. Water, being one of the most standard fluids to be studied, presents a high range of revisions of its previously known viscosity.

For the experimental tests of both tubes, the constant "K of the ball" found previously in the calibration test and the fluid properties at T=20°C will be used.

3. RESULTS

3.1 Viscometer design

This prototype was built in the cutting and drilling laboratory of PUC MINAS according to the technical drawings presented, which are attached at the end of this work. The materials chosen for the instrument were defined to meet the demands of use and through the stock of the workshop at PUC MINAS.

As for the assembly, the first support is attached to the base by screws. The servo motor was attached to this same support by interference and the servo motor support was screwed to the second support. The lasers, LDR sensors and the tube were attached to the acrylic frame. Finally, the wires were adjusted so as not to hinder the movement of the equipment and the Arduino and the LCD screen were put in a special case. Figure 2 below shows the final result of this step.

Figure 2. First assembly of the prototype.

3.2 Calibration Tests

First, a three-test procedure was performed on the automated viscometer prototype using the smaller 20.5mm inner diameter tube and REPSOL 5W40 oil at 40°C. For this oil, the viscosity at 40°C is 84 cSt, this value will be used for calibration of the "K of the ball" using Eq. (2). The results are shown in Table 1 below.

Table 1. Automated viscometer calibration test with 5W40 oil for the smaller tube.

Test number	**Fall time (s)**
1 (1)	754
2 (1)	743
3 (1)	751
Average	749,3 ± 5,7

(1) Test temperature 40°C

Next, 25 tests were performed on the automated viscometer and this time with the larger inner diameter tube of 22mm and again the REPSOL 5W40 oil at 40ºC. The results are shown in Figure 3.

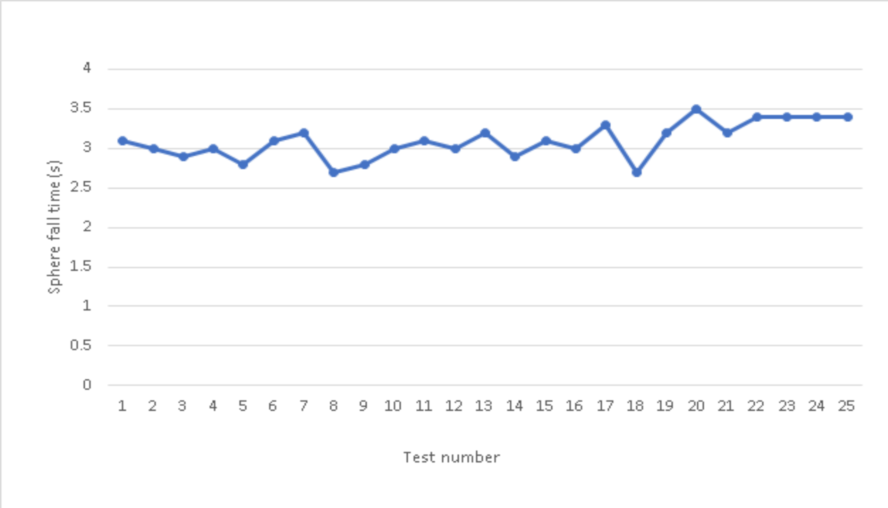

Figure 3. Graphic of the ball fall times in the larger tube.

The results of the K of the sphere for the larger and smaller tube are shown in Table 2 below. Thus, with these calibration values, it is possible to start the experimental tests.

Table 2. Values of the sphere's constant K for both tubes.

	Smaller tube	**Larger tube**
Average time (s)	749,3 ± 5,70	3,1 ± 0.23
Constant K (cSt*cm³)/(g*s)	0,014 ± 0.001	3,499 ± 0.392

As expected, for the smaller tube with an internal diameter of 20.5mm, the value of the constant K is a value much smaller than zero, i.e., this tube is able to measure lower viscosity values than the larger tube with an internal diameter of 22mm. This difference between the K values ensures that the automated viscometer measures a wide range of viscosities, being able to measure small viscosities, such as that of water, or very viscous fluids, such as detergent.

3.3 Experimental Tests

3.3.4 Comparative test with the standard Höppler viscometer

This experiment consists in comparing the results obtained by the Höppler viscometer itself and the viscometer presented in this paper. For this, tests were performed with the Höppler using the neutral detergent LIMPOL. Thus, according to Eq. 1, the dynamic viscosity (cP) of the detergent was found, and then transformed into kinematic (cSt) for comparison purposes with the automated viscometer. The results of the ball drop time are shown in Table 3 and the viscosities (cP and cSt) are in the Table 4.

Table 3. Experiment with the neutral detergent LIMPOL using the Höppler viscometer.

Test number	**Fall time (s)**
1(1)	341
2(1)	343
3(1)	353
4(1)	358
Average	348,75 ± 8,10

(1) Test temperature 20°C

Table 4. Results of viscosities founded on the Höppler experiment with neutral detergent LIMPOL

	Neutral LIMPOL
Dynamic viscosity	343,20 ± 35,49 cP
Kinematic viscosity	336,48 ± 34,80 cSt

Next, tests were performed with the same neutral detergent LIMPOL, but this time using the automated viscometer. The results found for viscosity are shown in the graph in Figure 4 below.

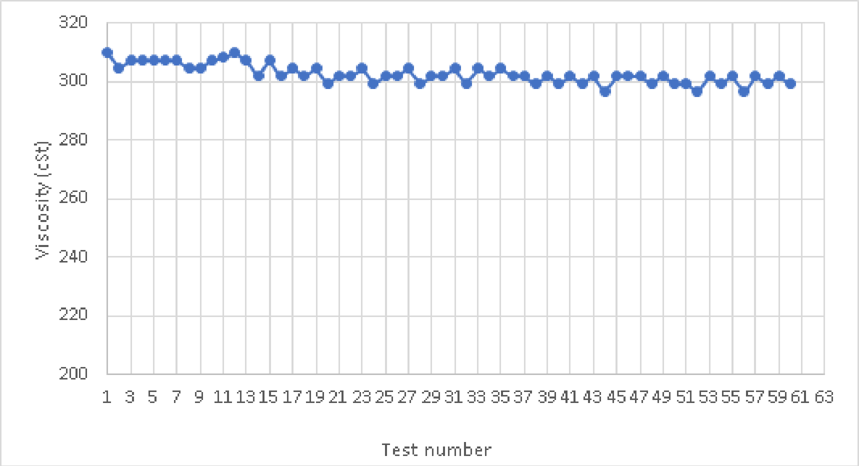

Figure 4. Graphic of the viscosity test for LIMPOL detergent with the automated viscometer.

The physical properties used in the test were defined as shown in Table 5 below.

Table 5. Physical properties of the fluid and sphere used in the automated viscometer experiment with the neutral detergent LIMPOL.

Properties	**Fall time (s)**
Constant K (($cm^5/(g*s^2)$)	3,499 ± 0,392
Density of the sphere ($g.cm^3$)	8,59 ± 0,32
Density of fluid ($g.cm^3$)	1,02
Number of repetitions	60

The average viscosity value found in the tests is shown in table 6 below.

Table 6. Viscosity test for LIMPOL detergent with the automated viscometer and Höppler viscometer.

Average experimental viscosity (cSt)	**Expected viscosity (cSt)**	**Percentage error (%)**
302,64 ± 3,22	336,48 ± 34,80	10,1

By looking at table 4 and table 6, it can be seen that there was a discrepancy between the results, a percentage error of 10.1%. This divergence is due to the difference in temperature at which the Höppler and automated viscometer tests were performed. Following the same reasoning, the drop in viscosity shown in Figure 4 was caused by the increase in temperature that the fluid suffered during the test, since a larger number of tests were performed compared to the Höppler procedure and, consequently, a much longer time interval, which allowed a more significant temperature variation of the fluid.

3.3.4 Literature comparison test

For this test, water was used as the test fluid, the "K" ($cm^5/(g*s^2)$) of the sphere obtained in the first test for the smaller tube, and the densities (g/cm^3) of the tube and sphere. The physical properties used in the test were defined according to Table 7 below.

Table 7. Physical properties of the ball and water used in the experiment with the automated viscometer.

Properties	**Fall time (s)**
Constant K (($cm^5/(g*s^2)$)	0,014 ± 0,00063
Density of the sphere ($g.cm^3$)	8,59 ± 0,32
Density of fluid ($g.cm^3$)	1,00
Number of repetitions	100

The results obtained for the kinematic viscosity of water are shown in the graph in Figure 5 below.

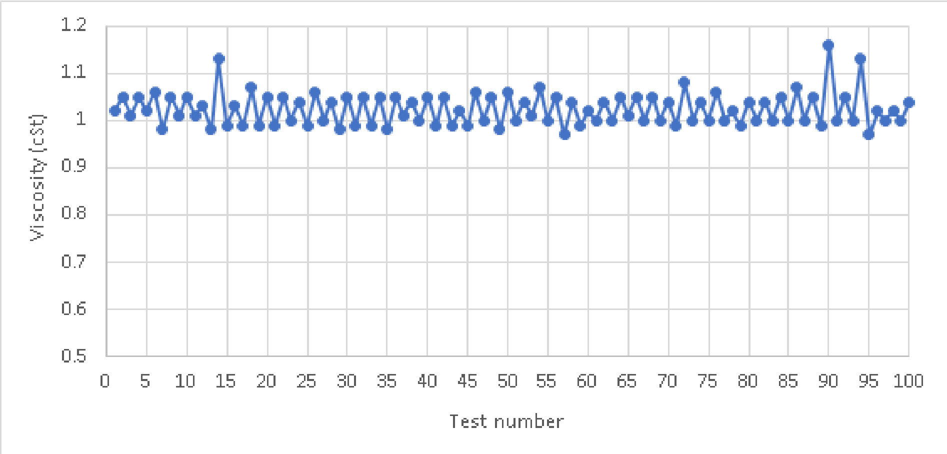

Figure 5. Graphic of the viscosity test for water with the automated viscometer.

Finally, these results were compared with the literature by the graph in Figure 6.

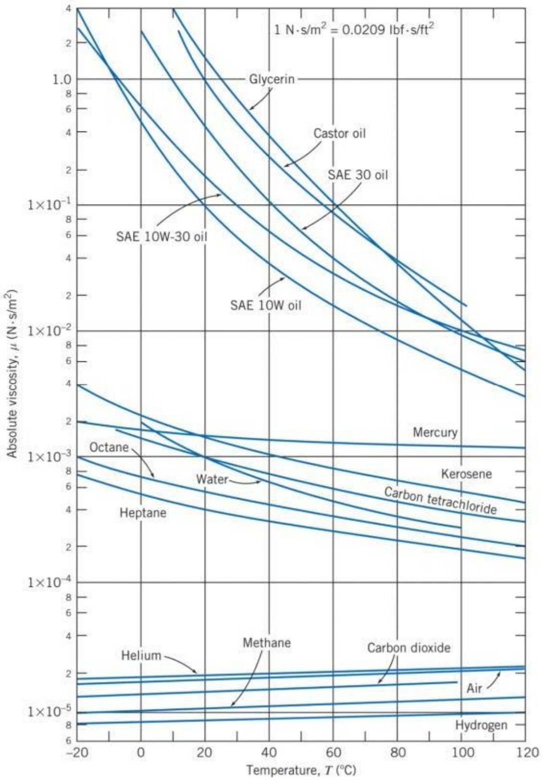

Figure 6. Graphic viscosity vs temperature for water and other fluids and gases. (Fox, McDonald, Pritchard, 2014)

Using the graph in Figure 6 and some unit conversions, the kinematic viscosity of water at 20ºC is defined as 1.02 cSt. The average viscosity value obtained in the 100 tests is shown in table 8 below.

Table 8. Physical properties of the ball and water used in the experiment with the automated viscometer.

Average experimental viscosity (cSt)	**Expected viscosity (cSt)**	**Percentage error (%)**
1,03 ± 0,03	1,02	-0,98

According to Table 8 above, the percentage error found in this test presents a value below 1%, presenting a great proximity of the theoretical values when compared to the experimental values. This confirms the calibration performed in the smaller tube, i.e., ensuring the calibration of the K of the sphere found with the value of K=0.014 $cm^5/g*s^2$.

4. CONCLUSION

According to what was presented in the experiments, it can be said that the equipment, as well as the code embedded in it, is able to perform the necessary tests and calculations and satisfactorily present the viscosity of the fluid under analysis. In addition, the automated viscometer is able to validate and deliver the values of the K constants of any spheres to be used in the experiments.

When comparing the result obtained by Höppler for the viscosity of the neutral detergent LIMPOL with that presented by the automated viscometer, it is noted that there is a small divergence in the results. As there is no accurate temperature control of the fluid, the ambient temperature is adopted as the temperature of the liquid. Thus, it can be said that the difference of approximately 10% is due to the difference in temperature at which the tests were performed. The automated viscometer test was performed on a day or at a place where the average ambient temperature was higher, and therefore the viscosity found was a little lower than expected. The same applies to the difference in viscosity during the test itself. As the procedure consists of several tests, there was an increase in the average temperature of the site, which caused the fluid viscosity to drop during the measurement procedure.

Regarding the comparative experiment with the literature, it is observed that the result obtained is in accordance with what was really expected, with a difference of 0.78% to the theoretical value.

It can be seen in the graphs of the initial experiments of the automated viscometer that there are some points that differ from the others. It is believed that these are due to electrical or mechanical failures of the equipment. However, it is notable that these singularities do not significantly affect the final results, which proved satisfactory with the theoretical data.

5. REFERENCES

Anton Paar. *How to measure viscosity: The principles introduced in this section represent a cross-section from traditional to technically advanced methods*. [S.l. : s. n.], [2020]. Available at: https://wiki.anton-paar.com/en/how-to-measure-viscosity/Access in: 18 Nov. 2020.

Fitch, Jim. *Don't Ignore Viscosity Index When Selecting a Lubricant. Machinery Lubrication*, United States of America, n.? p. 1, jun. 2020.

Fox, R.W., McDonald, A.T., Pritchard, P.J., 2014. Introduction to Fluid Mechanics. (in Portuguese). Editora LTC, Rio de Janeiro.

Hackländer, Astrid. *Viscosity - the single most important physical characteristic of any oil*. ÖL CHECKER - OEL Check., Germany, 2012 p. 5-7. 2012.

Leblanc, G.E; Secco, R.A.; Kostic, M. *Viscosity Measurement. Shear Viscosity*. McMaster, n.?, 1999.

Mezeger, Thomas G. The Rheology Handbook: *For users of rotational and oscillatory rheometers*. 2. ed. Germany: Vincentz, 2006.

6. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.