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A portable instrument with disposable cells for in-situ measurements of viscosity in liquids

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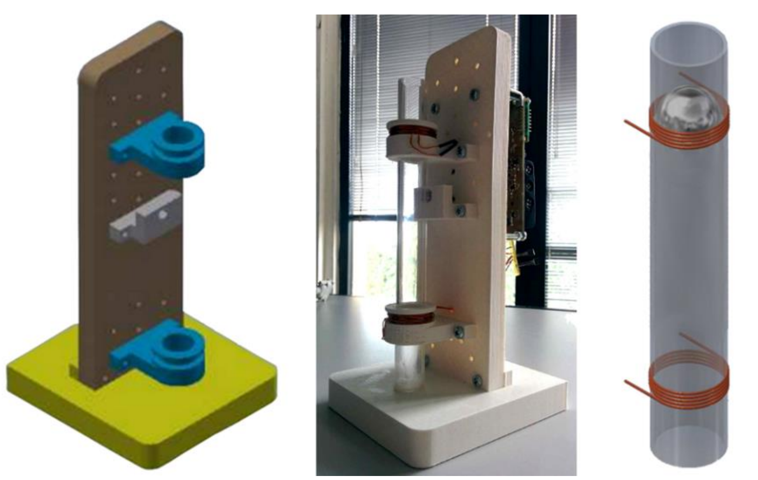
Abstract:

Viscosity is a very important property of liquids and its measure is mandatory for quality analysis in different industrial fields, such as food, paints, petroleum based products and cosmetics. Different types of viscometers exist that can measure fluids' viscosity with high accuracy exploiting different physical principles, however these instruments are generally laboratory based and not suitable for quick in-situ measurements by untrained personnel.
In this paper a portable instrument for in-situ measurement of liquids' viscosity is presented. The instrument is based on the falling ball principle and features a battery operated electronic board, an LCD display and a disposable cell for measurements on samples for which cleaning would be difficult and time consuming.
The instrument has been successfully tested by measuring the viscosity of tap water in the temperature range 15° - 45 °C and the viscosity of metalworking fluids in order to estimate oil concentration.



Keywords: viscosity, electronic instrument, embedded system, microcontroller, disposable, measurement

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1. INTRODUCTION

Viscosity is an important property of fluids and is related to internal friction mechanisms. To create a fluid motion, some energy must be provided to break bonds between atoms and molecules and to make the fluid layers to move relative to one another (Secco, Kostic, & de Bruyn, 2014).

The concept of viscosity can be explained with the 2D system model of Figure 1 (a), composed two parallel plates of area A and a fluid between them. A force of magnitude F is applied to the top plate making it move at a constant velocity, while the bottom plate is fixed. The top plate motion is transmitted to the underlying fluid with a velocity V_x that depends on the distance from the top plate (the fluid velocity is maximum for the layer near the top plate and zero for the layer near the bottom plate). In the case of laminar flow the following equation is valid:

$$\frac{F}{A} = \mu \frac{\partial V_x}{\partial y}, \quad (1)$$

where μ is the fluid dynamic viscosity, measured in Pascal–seconds (Pa·s) in the International System (SI). In the case of Newtonian fluids the dynamic viscosity is independent of $\partial V_x/\partial y$.
Indicating with ρ the fluid density (mass per unit of volume), the kinematic viscosity ν, measured in m^2/s, can be defined:

$$\nu = \frac{\mu}{\rho}, \quad (2)$$

In the case of liquids, viscosity is a very important parameter in different fields of application. In the petroleum industry, for example, the ability to pump the oil out of the ground is related to its viscosity (Shu, 1984). In the food industry, the viscosity of different products is strictly related with their organoleptic properties (De Wijk, Zijlstra, Mars, De Graaf, & Prinz 2008; Hernandez, Chen, Johnson, & Carter, 1995; Zijlstra et al., 2009). In the case of paints, the paint thickness depends on its viscosity, so different types of paints (for artistic paintings, indoor house painting, car painting,…) must feature different viscosities (Osterhold, 2000; Overbeek, Bückmann, Martin, Steenwinkel, & Annable, 2003). In cosmetics the product viscosity determines its consistency and the feel on the user skin (Brummer, 2006; Chiari, de Almeida, Corrêa, & Isaac, 2012; Gallegos & Franco, 1999).

Thus, viscosity measurements are necessary in various fields and steps within industrial production and a number of instruments, based on different working principles, exist that provide suitable accuracy. In rotational viscometers, for example, the system is composed of two parts with the liquid sample between them: the head unit is driven by a motor and maintained at constant velocity while the torque transferred to the other part (the spindle) is measured to estimate viscosity (Powell, 1993). Different implementations exist featuring different geometries for the head and the spindle such as concentric cylinders, cone and plate as well as parallel disks. In falling body viscometers, a body (usually a sphere, although cylinders and needles have also been used) is left to fall inside the sample and the viscosity is estimated from the time needed for the body to fall between two fixed points (Gui & Irvine Jr., 1994). In viscometers using the ultrasonic principle, a train of ultrasonic waves is generated inside the sample and the decay rate of the waves detected by a receiver is used to estimate viscosity (Nasch, Manghnani, & Secco, 1994). All these instruments make accurate measurements but are expensive and suitable for use within laboratory environment. On the other hand, low-cost, easy-to-use instruments for in-situ measurements are desirable in many different applications. Some recent examples in this sense are: a chemical sensor network for pH monitoring (Manjarres et al., 2016); a portable biosensor for bacterial concentration measurement in liquid and semi-liquid media (Grossi et al., 2011; Grossi, Lanzoni, Lazzarini, & Riccò 2012a; Grossi, Riccò, Parolin, & Vitali, 2017); a hydrogen gas detector card based on PIC12F1572 microcontroller (Nino & De Anda Salazar, 2016); a system for ice-cream characterization (Grossi, Lazzarini, Lanzoni, & Riccò, 2011, 2012b); a non-contact structural health monitoring system for machine tools (Goyal & Pabla, 2016); a portable sensor system for quality analysis in olive oil (Grossi, Di Lecce, Gallina Toschi, & Riccò, 2014; Grossi, et al., 2015; Valli et al., 2016); a mobile medical QR-code authentication system (Chang et al., 2015); an electronic portable device for non-destructive prediction of date moisture content (Mireei, Bagheri, Sadeghi, & Shahraki, 2016); an automatic titration system to measure oil concentration in metalworking fluids (Grossi & Riccò, 2017); a low cost portable pressure measurement system (Li, Liu, Wang, Shi, & He, 2012).

This work presents a portable electronic system to measure viscosity in liquid samples based on the falling sphere principle, where the sample viscosity is estimated by the time needed by a chrome steel ball to fall inside the liquid between two fixed points. With respect to a previous one, developed to measure the oil concentration in metalworking fluids (Grossi & Riccò, 2016), the new instrument presents substantial improvements. In fact the channel where the chrome steel ball falls has been made disposable, to treat also materials (such as paints and petroleum products) for which cleaning after use would be difficult and time consuming. Moreover the system hardware has been re-designed to reduce the system cost and power consumption: the PT100 temperature sensor of the former implementation has been replaced with a low cost NTC temperature sensor; the commercial proximity sensors used to detect the presence of the sphere have been replaced with two ad hoc designed inductive sensors with benefits in terms of reduction of cost and power supply voltage.

2. EXPERIMENTAL APPROACH

The designed instrument is based on the falling sphere principle. Thus, a chrome steel ball (diameter 15.85 mm, density 7.85 $g \cdot cm^{-3}$) is allowed to fall inside a 200 mm long polypropylene tube with internal diameter of 16 mm. As shown in Figure 1 (b), the sphere is subjected to three forces: gravity (F_G), buoyancy (F_B) and viscosity (F_V). The equation of the three forces are:

$$F_G = \frac{4}{3}\pi r^3 \rho_2 g , \tag{3}$$

$$F_B = \frac{4}{3}\pi r^3 \rho_1 g , \tag{4}$$

$$F_V = 6\pi \mu r v , \tag{5}$$

where ρ_2 is the sphere density, ρ_1 the sample density, r the sphere radius, g the gravity acceleration, μ the sample dynamic viscosity and v the sphere velocity.

Since the sphere falls with constant velocity, the total force acting on the sphere must be zero:

$$F_G = F_B + F_V , \tag{6}$$

thus, denoting with L the length of the sphere fall (120 mm):

$$\mu = \frac{2}{9}\frac{r^2}{L} g (\rho_2 - \rho_1) t_{fall} , \tag{7}$$

and

$$\mu = k (\rho_2 - \rho_1) t_{fall} , \tag{8}$$

where t_{fall} is the sphere falling time between the two fixed points and k is a constant depending on the geometry of the system (accounting also for the tube wall effects) (Viswanath, Ghosh, Prasad, Dutt, & Rani, 2007). Equation 8 shows how the sample dynamic viscosity μ can be estimated from the sphere falling time if the sample density is known.

The instrument of this work is based on an ad-hoc designed electronic board, featuring the microcontroller STM32F103R6 (by ST Microelectronics), responsible for all the operations (detection of the sphere passage at the two target points, measurement of temperature and t_{fall}). The results are displayed using a monochromatic 2 lines x 8 columns text LCD and user interaction is achieved by means of four buttons connected to digital input pins of the microcontroller. The whole system is powered with four 1.5V AAA alkaline batteries.

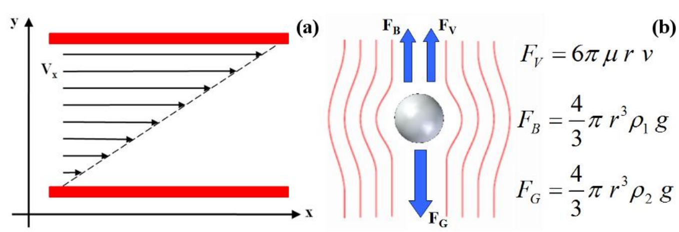

Fig. 1. System model used to describe the internal friction of a liquid (a) and physical model of a sphere falling inside a liquid (b).

The structure of the system, depicted in Figure 2 (a), has been realized using a Makerbot Z18 3D printer with all the parts designed using the CAD software Inventor. A NTC temperature sensor (B57045K produced by TDK) is placed in close proximity of the tube. The sample temperature, essential to compensate for viscosity variations due to temperature (T), is estimated from the measured ambient temperature. Thus, to achieve good accuracy, the sample must be in thermal equilibrium with the ambient. A photograph of the system is presented in Figure 2 (b).

Both top and bottom detection sensor are implemented by two 30 windings copper wires of diameter 0.8 mm (Figure 2 c). Since the inductance of the sensor increases with the relative magnetic permittivity of the material inside the coil and for the chrome steel ball is about 100 times higher than the permittivity of air, the passage of the sphere at the two target points can be detected by measuring the inductance variation of the sensor. In particular, in our case the measured values of the inductance is 33 μH and 38 μH in the absence and presence of the sphere respectively.

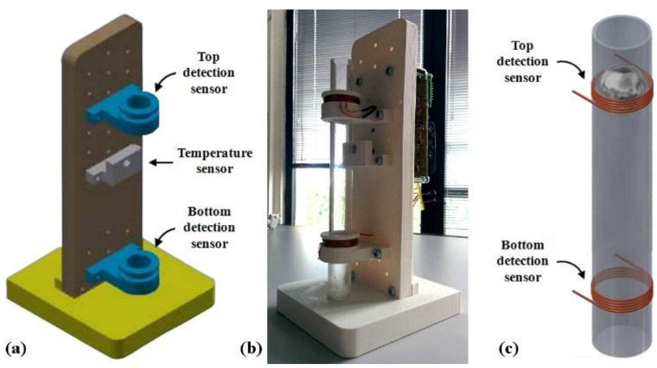

Fig. 2. Schematic (a) and photograph (b) of the designed portable system to measure viscosity in liquids. Sensors used to detect the presence of the sphere at the two target points (c).

The passage of the sphere at the two target points is detected by means of the circuit shown in Figure 3. The top and bottom detection sensor inductances are connected in parallel between the nodes A and B, and together with the capacitances C_1 and C_2 represent the main element of a Colpitts oscillator, whose output provides a sine-wave voltage or no oscillation in absence or presence of the sphere, respectively.

A high impedance stage is used to decouple the output from the rest of the circuit and a RC filter generates a DC voltage from the AC input (a DC value of 2.18V and 0V in absence and presence of the sphere, respectively). Finally an inverting Schmitt trigger (realized with a MCP601OT rail-to-rail operational amplifier) is used to generate a digital signal (high in presence of the sphere) that is acquired by the microcontroller.

The designed system works as follows: first, the tube is filled with the sample under test, then the temperature (T) is measured and the ball is allowed to fall inside the tube. When the sphere enters the top detection sensor, a microcontroller timer is enabled and counts the time elapsed until the sphere enters the bottom detection sensor. At this time, the sample viscosity is calculated from the measured values of t_{fall} and T.

A video of the instrument performing a measure is presented in the Supplementary Video Material.

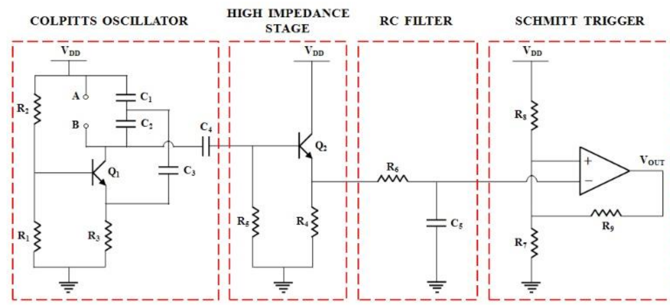

Fig. 3. Electronic circuit used to detect the sphere transit at the two target points.

3. RESULTS AND DISCUSSION

The instrument presented in Section 2 has been tested with two different types of samples: tap water and metalworking fluids featuring different values of oil concentration.

The measurements with tap water have been carried out inside a thermal incubator (Binder APT KB 53) at four different temperatures: T = 15, 25, 35 and 45 °C.

The measured t_{fall} vs T is shown in Figure 4 (a). As T increases t_{fall} decreases because of decrease of water viscosity. A simple empirical model, adequate within a limited range of temperature, was proposed by Reynolds (1886), that models the liquid viscosity as a negative exponential of the temperature:

$$\mu = \mu_0 \, e^{-b(T-T_0)}, \tag{9}$$

where μ_0 is the viscosity measured at temperature T_0 and b is an empirical parameter.

Since, according to equation 8, there is a correlation between the viscosity and t_{fall}, equation 9 can be rewritten as:

$$t_{fall} = t_{fall,T0} \, e^{-b(T-T_0)}, \tag{10}$$

where, $t_{fall,T0}$ is the measured t_{fall} at temperature T_0.

Equation 10 has been used to best fit the measured data of Figure 4 (a). The parameters obtained from the fitting procedure with T_0 = 25 °C are $t_{fall,T0}$ = 11.452 s and b = 0.023598 °C^{-1}. The corresponding determination coefficient R^2 is very high (0.995), thus validating the proposed model for t_{fall} variation with temperature.

Figure 4 (b) shows t_{fall} vs. water viscosity (values obtained from literature) for all the tested temperatures. The data have been fitted with a linear regression line with zero offset (in accordance with the proposed model of Equation 8) and the achieved regression line is

$$t_{fall} = 12.662\ \mu \tag{11}$$

with $R^2 = 0.9946$.

As T varies from 15°C to 45°C, t_{fall} goes from 14.5 s and 7.14 s (corresponding to a variation of 50.75%), while the variation of the water viscosity is between 1.1375 and 0.5958 mPa·s (corresponding to 47.62%) .

Since the chrome steel sphere density is $\rho_2 = 7.85$ g·cm^{-3} and the water density ρ_1 varies from 0.9993 to 0.9912 g·cm^{-3} in the tested temperature range, the corresponding variation of $\rho_2 - \rho_1$ is only 0.1182%, thus almost all variation of t_{fall} are due to variations of water viscosity μ, while in the modeling the water density can be approximated as a constant ($\rho_1 = 0.997$ g·cm^{-3}). Using Equation 8, the geometrical constant k can be calculated as:

$$k = \frac{\mu}{(\rho_2 - \rho_1)t_{fall}} = 11.524 \times 10^{-3}. \tag{12}$$

Water viscosity has been estimated for all the tested temperatures using the developed model and the results are presented in Table 1.

As already mentioned, the designed system has also been tested with a set of three metalworking fluids (liquids used in the metalworking industry for cooling and lubrication).

The samples have been prepared by mixing a soluble oil product (“Spirit MS 8200” by Total) with tap water in different ratios to obtain samples featuring different values of oil concentration (C_{oil} = 2%, 6% and 10%). Each sample has been tested in triplicate (the maximum deviation on the same sample is 0.3 s) and t_{fall} has been calculated as the average of the three measurements. These tests have been carried out at T = 27°C.

The measured t_{fall} vs C_{oil} is shown in Fig. 5 (a). A good linear correlation ($R^2 = 0.9694$) exists in the investigated C_{oil} range (2% – 10%) and the corresponding linear regression line is

$$t_{fall} = 0.325\, C_{oil} + 11.717\,, \tag{13}$$

Using equation 13, the sample C_{oil} can be estimated as presented in Figure 5 (b). The corresponding linear regression line has slope of 1 and offset of 0.0205, with a coefficient of determination of 0.9694. The error in the estimated C_{oil} is lower than 1%.

Using the value of k previously determined (11.524·10^{-3}) and assuming that the sample density ρ_1 varies with C_{oil} according to the function taken from literature (Grossi & Riccò, 2016)

$$\rho_1 = -554.74 \times 10^{-6}\, C_{oil} + 0.9926\,, \tag{14}$$

the samples viscosity can be calculated from equation 8. The results are μ = 0.9879, 1.0594 and 1.1942 mPa·s for C_{oil} = 2%, 6% and 10%, respectively.

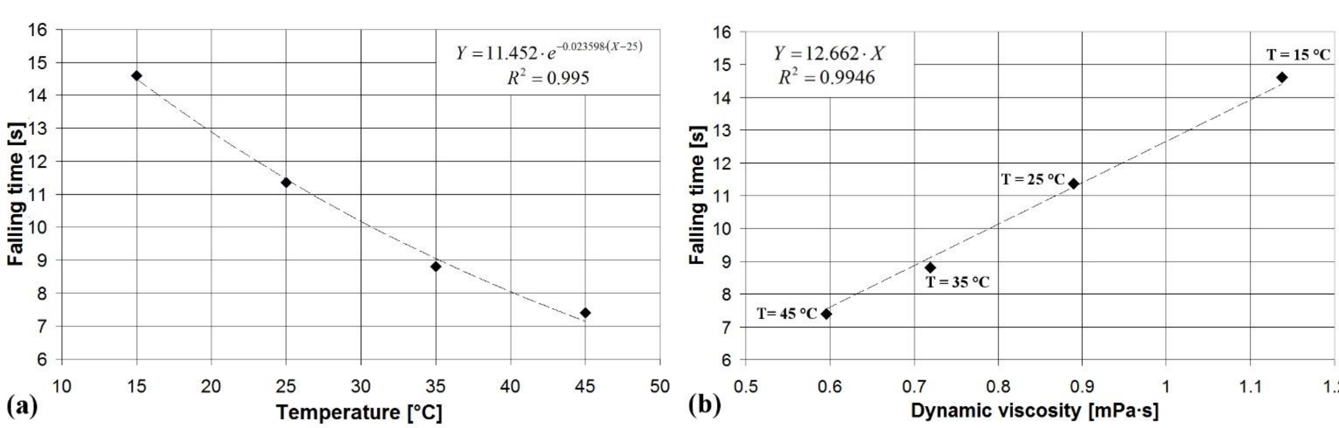

Fig. 4. Measured sphere falling time in tap water vs. temperature (a). Measured falling time vs. dynamic viscosity at 15 °C, 25 °C, 35 °C and 45 °C (b).

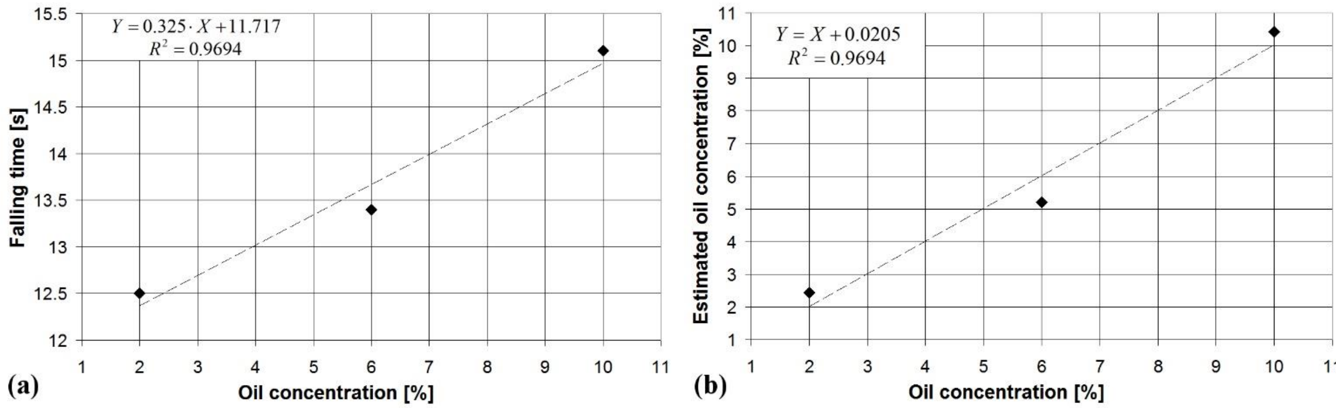

Fig. 5. Measured sphere falling time in metalworking fluids vs. sample oil concentration (a). Estimated vs. real oil concentration for metalworking fluids samples (b).

Table 1. Water dynamic viscosity and estimated viscosity for the tested temperatures 15, 25, 35 and 45 °C.

Temperature (°C)	*Viscosity (mPa·s)*	*Estimated viscosity (mPa·s)*
15	1.137	1.153
25	0.89	0.897
35	0.719	0.695
45	0.596	0.584

4. CONCLUSIONS

A portable electronic system with disposable cells for in-situ measurements of liquids' viscosity has been presented. The system is based on the falling sphere principle, features the microcontroller STM32F103R6 by ST Microelectronics and detects the sphere passage by measuring the inductance of two copper wire coils, thus enabling measures also with opaque samples and/or opaque fall tube.

The system has been successfully tested with measurements of water viscosity in the temperature range 15 °C – 45 °C as well as measurements of viscosity of metalworking fluids (allowing the estimates of sample oil concentration).

The use of disposable cells allows simple measurements also on particular types of samples, such as paints and petroleum based products, for which cleaning after use would be difficult and time consuming.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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