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A portable electronic system for in-situ measurements of oil concentration in MetalWorking fluids

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ABSTRACT

MetalWorking fluids (MWFs) are widely used to cool and lubricate machines and tools. By far, the most common MWFs are oil-in-water emulsions with oil concentration (C_{oil}) in the range from 1% to 10%, depending on type of oil, material to be worked, etc. In order to optimize emulsion and machine performance, as well as for good waste policy, the right value of C_{oil} should be kept (approximately) constant during the MWF's lifecycle to compensate inevitable changes due to water evaporation, bacterial attack, oil adhesion to metal parts, etc. This, however, requires periodic measurements, often skipped because they require unhandy operations and produce inaccurate results. In this context, a new system is presented that is based on the falling ball principle, normally used for viscosity measurements, shown to be suitable also for accurate C_{oil} measurements. In our system, the transit time of the sphere within the instrument is determined by means of inductive proximity sensors, a PT100 sensor is used for temperature whose effects on C_{oil} are accounted for by means of an ad-hoc algorithm. A battery-operated electronic board has been designed that allows rapid and user-friendly "in-situ" measurements and a prototype of an whole portable and automatic instrument, suitable for in-situ measurements, has been fabricated.

1. Introduction

MetalWorking fluids (MWFs), widely used in industries for machine cooling and lubrication during different finishing processes [1], usually are mix of water and soluble oils with oil concentration (C_{oil}) in the range from 1% to 10%, depending on oil type, material to be worked etc. In addition, they often contain additives, such as anti-microbial compounds (to prevent bacterial degradation) [2,3], corrosion inhibitors, emulsifier, pressure additives and anti-foam agents.

The oil concentration should be optimized in order to prevent potential malfunctions and reliability problems. In particular, if C_{oil} is too low, poor lubrication can lead to corrosion of machines, tools and metal parts under work, as well as to proliferation of microflora; on the contrary, too high values of C_{oil} can produce foaming, tool malfunctions due to excessive lubricity and potential health problems for the exposed workers (since oil compounds tend to be dispersed in the environment as aerosols) [4–6].

Unfortunately, under normal working conditions, C_{oil} tends to change due to water evaporation, bacterial attack, oil adhesion to metal parts, etc. Thus, oil concentration should be monitored at regular intervals to compensate excessive deviations from its optimal value.

The official technique to measure C_{oil} in MWF samples is (manual) titration [7]: 100 ml of the fluid under test is titrated with a 0.5 M HCl solution to an endpoint of pH = 4 and the volume of titrant necessary to reach such an endpoint is used to determine C_{oil}. This technique is accurate and substantially unaffected by the contaminations inevitably occurring when the MWFs are used, but must be performed by trained personnel in a laboratory: hence, it is not suitable for "in-situ" measurements within industrial plants.

For this reason, the standard technique used in industry is refractometry [8]: a few drops of MWF are placed on the refractometer prism and exposed to light; the fluid refractive index is then read on the instrument scale and converted into oil concentration by means of the Brix scale (quantifying the solid content dissolved in the emulsion). Refractometers can be used within production environments and are also relatively cheap. However, their most common manual versions (costing about 200 US$) present a few drawbacks, since: they need to be frequently calibrated; the accuracy depends on the user's skill and is affected by fluid contamination; samples with certain composition do not provide clear readings; automatic compensation for the effect of temperature (T) is not provided.

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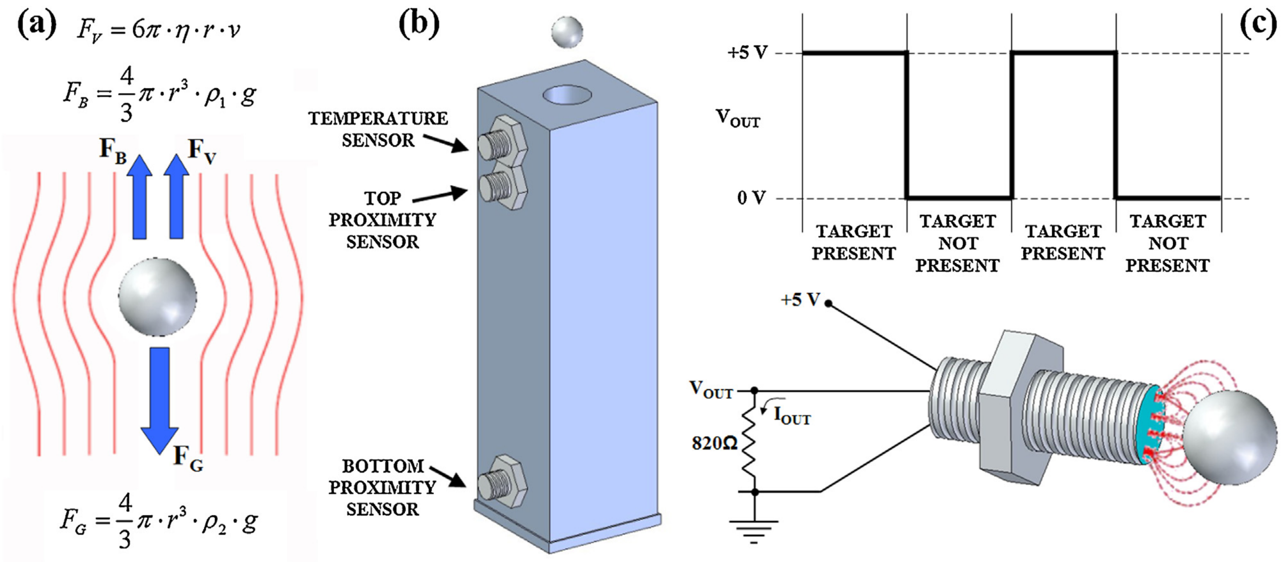

Fig. 1. (a) Forces acting on a sphere falling within a liquid medium, (b) a sketch of the designed instrument, (c) inductive proximity sensor used to detect the sphere transit.

Recently, portable digital refractometers (with a cost of 300–400US$), featuring temperature compensation and digital display, have been introduced into the market. While these instruments address some of the problems of analog refractometers, when dealing with (long) used MWFs accuracy is still a problem because of the influence of solid contaminants on the Brix scale. Furthermore, working with a few drops of fluid, refractometers have problems of statistical significance of the results.

On the other hand, low-cost portable instruments for accurate “in-situ” measurements are desirable for quality control in industrial productions and a number of solutions have been proposed in different fields, such as, for instance: gas chromatography for analysis of combustible gases in coal mining [9]; multi-sensor data-logging for medical surveillance in harsh environments [10]; automatic characterization of ice-cream mixes by impedance spectroscopy [11]; electronic system to control ice-cream freezing by electrical characteristic analysis [12]; biosensors for glucose measurements [13]; electronic sensor systems for acidity [14,15], peroxide value and total phenolic content [16] in olive oil.

In this context, this work presents a novel instrument to measure oil concentration in MWFs that exploits the falling ball principle, mainly used for fluid’s viscosity but never before applied to the case of interest here. To this purpose, the time (t_{fall}) required for a sphere of known density and volume to fall under gravity for a given distance within the sample of interest is automatically measured and converted into an accurate value of C_{oil}.

To reach this goal, first the applicability of the falling ball principle to the case of interest has been studied by means of a bench-top set-up then, based on the positive results of the experiments, a fully automatic, battery-operated portable instrument has been developed that can be used by anybody and in any environment for quick and accurate “in-situ” measurements of C_{oil} in MWFs.

Such an instrument presents substantial innovations with respect to most commercially available falling ball viscometers, in that: 1) the sphere transit time is automatically detected by means of inductive proximity sensors; 2) measurements are carried out at room temperature (T), instead of at a standard temperature. This requires that T be measured (in our case, by means of the integrated PT100 sensor) so as to account for the effects of temperature (by means of a suitable algorithm). Avoiding a (controlled) heating system, this solution reduces the power consumption making it suitable for a battery-operated, portable instrument.

Beside the application addressed in this paper, the instrument presented in this paper has many other possible applications, since liquid viscosity is an important parameter in various industrial fields, such as, for instance: food quality assurance [17]; cosmetics [18]; paints [19]; oil [20].

The rest of the paper is organized as follows. Section 2 illustrates the application of the falling ball method to the measurement of C_{oil} in MWFs. Section 3 describes the experiments done with a bench-top set-up in order to validate the method introduced in the previous Section. Section 4 describes the portable instrument developed for the application of interest here. Finally, conclusions are drawn in Section 5.

2. Materials and methods

2.1. The falling ball approach for oil concentration measurement in MWFs

Viscosity is an important property of fluids that can be measured with a variety of scientific instruments [21] among which the falling ball principle of interest for this work.

A sphere moving in a fluid is subject to three forces, as depicted in Fig. 1(a) [22], namely: gravity (F_G); buoyancy (F_B) and viscosity (F_V).

F_G (acting downward) is the product of the sphere mass and the gravitational acceleration:

$$F_G = m_s \times g = \frac{4}{3}\pi \times r^3 \times \rho_2 \times g; \qquad (1)$$

F_B, exerted by the fluid and opposing the sphere’s motion, can be expressed as:

$$F_B = m_l \times g = \frac{4}{3}\pi \times r^3 \times \rho_1 \times g; \qquad (2)$$

finally, F_V, also opposing the sphere’s motion, can be expressed as:

$$F_V = 6\pi \times \eta \times r \times v. \qquad (3)$$

In the above Equations: m_s is the sphere mass; m_l the mass of the liquid displaced by the ball; ρ_2 the sphere density; ρ_1 the liquid density; r the sphere radius; g the gravity acceleration; η the dynamic viscosity of the liquid; v the sphere velocity.