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On the application of the light-attenuation technique as a tool for non-intrusive buoyancy measurements

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ABSTRACT

This article describes the application of the light-attenuation technique as a tool for measuring dilution occurring in buoyancy-driven flows. Whilst this technique offers the experimental fluid dynamicist the ability to make rapid synoptic buoyancy measurements non-intrusively, its successful application requires careful selection of chemical dye, dye concentration, illumination and optics. After establishing the advantages offered by methylene blue as a dyeing agent, we assess the accuracy of buoyancy measurements made using this technique compared with direct measurements made with density meters. Density measurements obtained using light-attenuation differ from those obtained using the density meter by typically less than 3%. It is hoped that this article will provide useful advice with regards to its implementation in the field of buoyancy-driven flows.

1. Introduction

The light-attenuation measurement technique uses a passive coloured tracer to infer changes in the density field by remotely monitoring the dilution of the tracer in the flow. Whilst in use in fluid mechanics since the 1990s (see, for example, [1] or [2]), the light-attenuation technique is in fact an adaptation of a technique known as spectrophotometry in organic chemistry. To the best of our knowledge, the application of this technique in the context of buoyancy-driven fluid flows was pioneered by Dalziel (see [3]).

However, whilst conducting our own research on buoyancy-driven flows we found actually very little information with regards to the successful implementation of this technique and had to devote significant effort to determine how to apply it effectively.

This paper describes the practical application of the light-attenuation measurement method to buoyancy-driven flows and relates the lessons learnt whilst attempting to implement the technique in the context of our own research.

2. Principles of spectrophotometry

We begin by giving an overview of the principles of spectrophotometry on which the light-attenuation measurement technique is based. The principles are common knowledge in the field of physical chemistry and a detailed explanation can be found in many chemistry textbooks, for example [4] or [5].

Electromagnetic radiation stretches from sub-sonic waves (wavelength $\lambda \sim O(10^6)$ m) to gamma rays ($\lambda \sim O(10^{-9})$ m). The sensitivity of the human eye is limited to a narrow range, $360 \lesssim \lambda \lesssim 780$ nm, within which it sees individual wavelengths as colours.

Colour in chemical solutions is due to the chemical absorbing a portion of the incident radiation within the visible spectrum. The portion of the electromagnetic spectrum absorbed is referred to as the absorption band of the solution and determines its colour, whilst the proportion in which the radiation is absorbed determines its opacity.

The proportion in which the chemical solution absorbs the incident radiation is characterised by its transmittance Tr, defined as $Tr = I/I_i$, where I_i and I are the intensity of the radiation before and after passing through the solution, respectively.

The transmittance is related to the properties of the solution by

$$ln(Tr) = -\epsilon bc, \tag{1}$$

where b (m) is the distance travelled through the solution or path length, c (ppm) is the concentration and ϵ (ppm m) is the coefficient of molar absorption which is specific to λ and the chemical in the solution.

Expression (1) is often written as

$$A = -ln(Tr), \tag{2}$$

where A is the absorbance of the solution. This is known as the *Lambert–Beer law* and forms the basis for spectrophotometry measurements.

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The most common application of the Lambert–Beer law is for the purpose of carrying out measurements of the concentration of a chemical species in solution. If ϵ and b are known, then all that is required to measure c is a light source and a photometer.

3. Limitations of the Lambert–Beer law

The Lambert–Beer law has two limitations which need to be kept in mind. The first is that it is only valid for small values of c. As c increases, interactions between adjacent molecules cause the absorbance to become non-linear.

The second limitation is that the Lambert–Beer law is only valid for a particular value of ϵ. Hence, as ϵ varies depending on the wavelength of the incident electromagnetic radiation, it is necessary to use monochromatic light.

In practice, truly monochromatic lighting conditions are difficult to achieve, however, selecting a narrow range of wavelengths at a peak of the absorption spectrum of the solution yields similar results.

In the context of fluid flow measurements this can be achieved by using a polychromatic light source and removing undesired wavelengths using a coloured filter placed between the experimental apparatus and the photometer.

When carrying out spectrophotometric measurements it has to be borne in mind that the logarithmic relationship between A and Tr imposes limits on the accuracy of measurements. The relationship between A and Tr is shown in Fig. 1. Photometers normally record Tr, however, calculations of c are based on A. Hence values of Tr at either end of the range can make accurate calculations of c difficult.

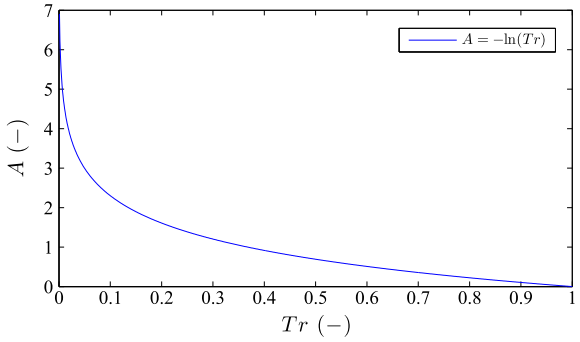

Fig. 1. Absorbance, A, as a function of transmittance, Tr. The steep and shallow gradients at the extremes of the range of Tr can make accurate estimates of A difficult.

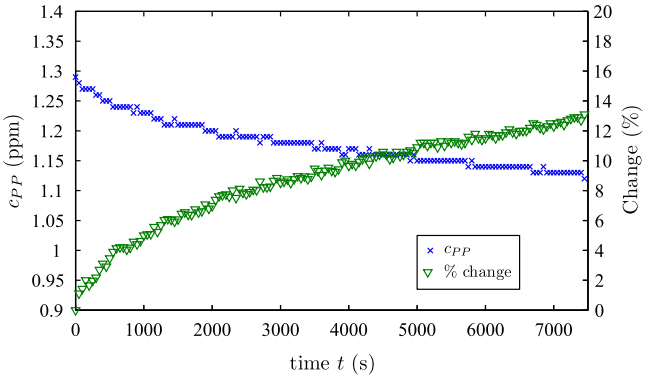

Fig. 2. Evolution of the concentration of potassium permanganate, c_{PP}, over time. The concentration of potassium permanganate can be seen to progressively decrease.

4. Application to fluid flow measurements

In the context of fluid flow measurements, the light-attenuation technique is usually implemented by staining the fluid of interest using a passive tracer chemical and monitoring its dilution using a camera. The dilution of the tracer is inferred from the attenuation caused by the dye to a light source placed in the background.

As the Lambert–Beer law enables the concentration of the tracer to be determined by comparing the attenuation of the background light with its unattenuated intensity, the dilution of the tracer in the flow can easily be measured and the density field of the flow deduced.

The light-attenuation technique has proven particularly useful for measurements of buoyancy fields in buoyancy-driven flows. The advection of the tracer is correlated to the advection of buoyancy and it is therefore essential to choose the tracer in such a way that it dilutes by similar processes to the buoyancy of the fluid, usually advection and turbulent diffusion.

Since the tracer is the means by which light-attenuation measurements are made possible, the selection of an appropriate chemical is critical. A suitable tracer should fulfil the following two conditions:

- be strongly absorbent at low concentrations;
- not react with the fluid it is dissolved in.

The current article is based on observations carried out using two different dyeing agents.

Initially potassium permanganate ($KMnO_4$) was tried. This was selected on the basis that it had been used successfully in previous studies of buoyancy-driven flows (see, for example, [2,6] or [7]).

In our experiments potassium permanganate was used to infer the dilution of fresh- and salt-water solutions. Fresh water was normal tap water, and after several series of experiments it was found that potassium permanganate molecules oxidised with the dissolved organic carbon (DOC) in the tap water. These reactions caused the tracer to become colourless and resulted in the measurements indicating an improbable loss of mass/buoyancy.

Tap water fit for human consumption usually has DOC $\approx$2 ppm, similar to the concentration at which potassium permanganate is useful for light-attenuation measurements. Thus, oxidation reactions occurring during the experiments had a noticeable impact on the measurements.

In order to gauge the rate at which errors were introduced in the measurements by oxidation reactions, experiments were carried out in which potassium permanganate was simply injected into tap water contained within a clear glass tank and light-attenuation measurements were carried out over approximately 2 h.

The initial concentration of potassium permanganate was $c_{PP} \approx 1.4$ ppm which is slightly less than the limiting concentration for which reliable light-attenuation measurements can be made using this tracer (see Fig. 3).

The results of these experiments are shown in Fig. 2. It can be seen that c_{PP} progressively decreases over time.

From Fig. 2, the total mass loss implied over the observation period is of the order of 15%. This might or might not be deemed significant depending on, for example, the duration of the experiments and the accuracy of the results required. However, this source of error, as well as the fact that potassium permanganate is considered a hazardous chemical, should be borne in mind whenever potassium permanganate is considered as a candidate dye for light-attenuation measurements.

As a result of this implied mass loss, methylene blue ($C_{16}H_{18}N_3SCl$) was subsequently used to carry out further light-attenuation measurements due to it being relatively inoffensive