Convection in Liquids — Some Illustrative Experiments

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Introduction

The authors of this paper are involved in a research collaboration under the EU Leonardo da Vinci Community Vocational Training Action Programme, namely project SI143008 *Computerised Laboratory in Science and Technology Teaching* (ComLab-SciTech), generally known as the ComLab project [1]. A new phase of this project (ComLab-2) will commence in October 2005, one element of which is the development of a laboratory course on Heat Transfer phenomena for students of Food Science and Technology. It is planned that one of the preliminary experiments which students in the proposed course would undertake will comprise a study of convection in liquids
Effective experimental study of convection requires two facilities, namely (i) a capability for students to be able to 'see' the currents (visualisation) and (ii) the measurement of temperature at a number of points within the body of the liquid. The first of these is relatively easily achieved, at least in the case of transparent liquids, as will be described below. The second requires temperature sensors that have both a low heat capacity and reasonably short response times. Thermocouple sensors would seem to be in only low cost solution in the latter case.

Integration of thermocouple sensors with the data acquisition system

The courses for science and technology teaching developed within the first phase of the ComLab project involved the use of multi-purpose data acquisition (DAQ) systems. To facilitate the delivery of these courses, a number of general purpose DAQ systems, including the software, programming libraries, drivers, etc supporting the hardware, were developed within the project. For most of the experiments in the courses requiring the measurement of temperature, thermo-resistance sensors proved adequate; thus designing novel thermocouple sensors featuring so-called 'cold junction compensation' was considered to be too time consuming and costly in that phase of the project.
For reasons explained above, however, thermocouple probes are required for the study of convection currents in liquids. The UK based company Pico Technologies Ltd offers a system, called TC08, specifically designed to support up to eight thermocouples connected to a PC through either the serial or USB ports [2]. Since the company provides free drivers and programming libraries (DLLs) for a number of development environments, integration of the TC08 with the software of the e-ProLab DAQ system was readily achieved. The pre-calibrated thermocouples appear in the software interface just like other sensors, such as those for light intensity, pressure, force, distance, etc.

Visualisation of convection currents

Figure 1 shows an example of one method [3] that can be used to make convection currents visible. In this case a stream of warm water was being injected into a beaker of cooler water, the difference in temperature being about 10 ºC. A source of light was used to illuminate the beaker from one side and a sheet of paper was attached to the opposite side of the beaker. The explanation of how what seems to be an ‘image’ of the flowing warm water appears on the paper when viewed from outside the beaker is a matter of simple geometrical optics that can be easily understood by physics pupils at upper secondary school or university level [3].

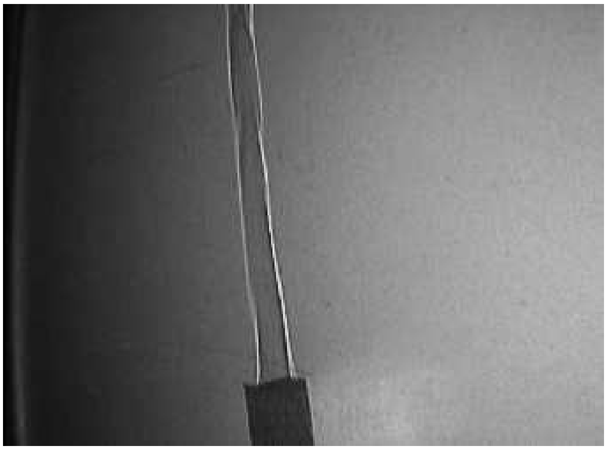

Figure 1: Visualisation of a stream of warm water flowing through cooler water in a beaker.

Figure 2 below shows the angular deviation that would be observed when of a ray of light in water (refractive index = 1.33) is incident on a cylinder of air (refractive index = 1.0). The deflection increases with distance from the centre of the cylinder and reaches maximum, in this case, at approximately three quarters of the distance to the edge, at which point total internal reflection occurs after which the deflection decreases again.

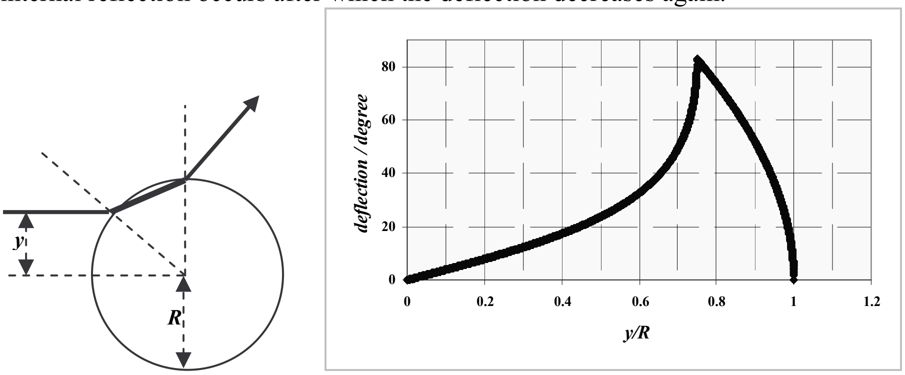

Figure 2: The angular deviation of a ray of light in water incident on a cylinder of air. The angle increases with distance from the centre of the cylinder and reaches maximum at which point total internal reflection occurs after which the deviation decreases again.

When the refractive indices of the two media do not differ by very much, however, the situation is notably different. In the case of water, for example, temperature differences of a few degrees Celsius give rise to variations of refractive index of no more than a few parts in a thousand. Figure 3 shows the same calculation as in figure 2 but, in this case, applied to a cylinder of warm water (refractive index = 1.330) inside slightly cooler water (refractive index = 1.333). It can be seen that, in this situation, the angular deviation of a ray is essentially negligible except when it strikes the cylinder very near the edge, at which point the deviation can be almost 10º before decreasing abruptly to zero.

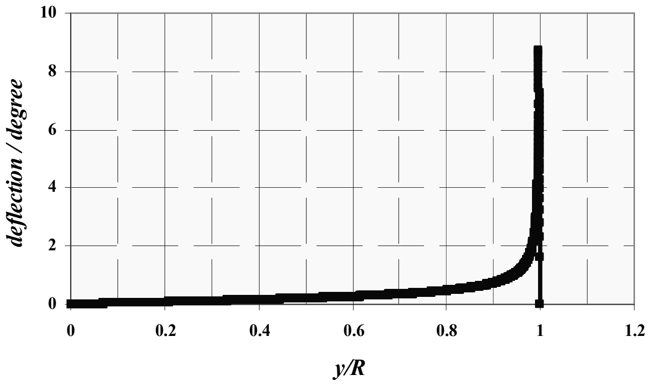

Figure 3: The angular deviation of a ray of light in cold water incident on a cylinder of warmer water.

Thus what seems like an 'image' of the tube of warm water appears on the screen with a bright outline as in figure 1. A similar situation arises if the water inside the tube is colder than the surroundings except that, in this case, the 'image' of the surface will appear dark on the outside. In fact, any curved surfaces within a transparent liquid at which there are sharp thermal gradients will appear as lines on a screen whenever incident light strikes such surfaces at a glancing angle.

Experimental observations of convection currents in water

As a starting point for the study of the heating of liquids by convection, a simple linear electrical heating element was chosen. Figure 4 shows the experimental arrangement where the heating element is set up horizontally and immersed in water in a small commercially available fish tank. In the experiments reported here, the horizontal wire was 20 cm long and had a resistance of the order of one ohm. A 12 V supply that could provide a current of up to 20 A proved a convenient power source.

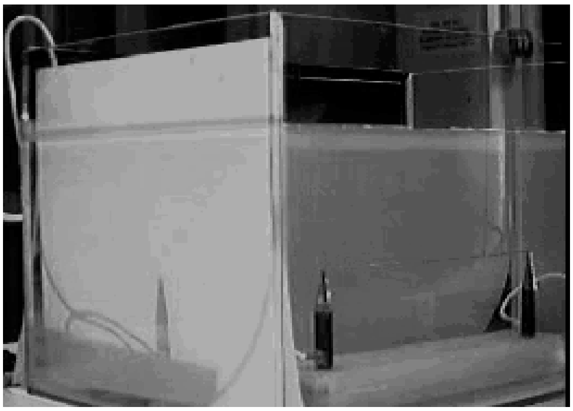

Figure 4: The arrangement for observing convection currents generated in water by a linear heating element.

Figure 5(a) and (b) below show what is observed as a shadow on a paper screen attached to a face of the fish tank when light is projected through the tank from the opposite side. A convection current can be observed rising from the wire as a narrow vertical sheath. In the cases illustrated, the sheath is about 2 mm thick and the water inside the sheath is no more than 4 ºC above the ambient temperature of the surrounding liquid.

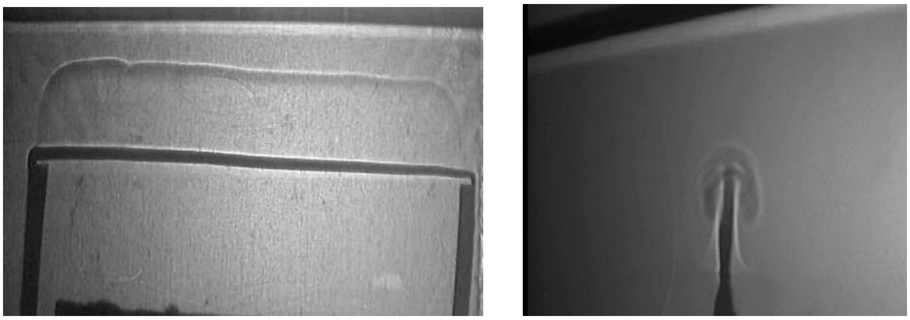

Figure 5(a) (left): Broadside-on view of convection current rising from a horizontal linear heating element. **Figure 5(b)** (right): End-on view of convection current rising from a horizontal linear heating element.

It can be seen in figure 5(a) that a boundary layer forms around the wire (opaque with a bright edge, in this case, because there is a continuous temperature gradient from the surface of the wire to the edge of the boundary layer). Students can be asked to consider a number of ongoing processes and to make the necessary measurements for their study. These might include (i) the transfer of energy from electrical to thermal form, (ii) possible models for heat transfer through the boundary layer, (iii) the effect of viscosity, density and heat capacity of the liquid, etc.

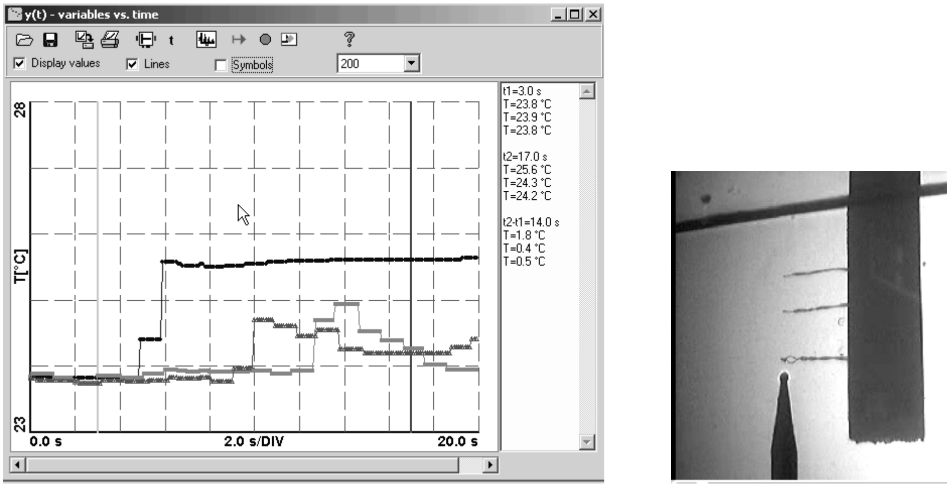

Figure 6: Screen of data acquisition system showing the rise in temperature as the warm front passes each of the thermocouples shown on the right.

In the case of process (i), it is necessary to determine the speed of the rising convection current. This can be achieved by placing a number of thermocouples at know spacing vertically above the wire (on the right in figure 6). Any change in the temperature recorded by each thermocouple in turn can be recorded by the data acquisition system (figure 6, left) and the time taken by the leading warm front to travel between the sensors may be determined. In the case illustrated, the current was observed to rise at approximately 4 mm/s. Thermocouples can also be used to determine the temperature both inside (i.e., at the surface of the wire) and just outside the boundary layer. These measurements are can be used to test any suggested models of the heat transfer mechanism through the boundary layer.

Convection currents in olive oil

As a liquid that differs from water in viscosity and density and as a substance of interest to Food Scientists, olive oil is an obvious material to study. In performing experiments on olive oil, a different (and wholly unexpected!) method of making convection currents visible was discovered. Convection currents in normal olive oil taken from a single container behave in a very similar way to water as described above. When olive oil from two different containers is used, however, an interesting phenomenon is observed when light is projected through the liquid and cast on a screen. While in no way visible to the naked eye when looking directly into the oil, a pattern on the screen of randomly oriented closely spaced curved lines or striations is observed (figure 7(a)). The explanation of the phenomena would seem to arise from slightly different refractive indices of the two oil samples. The substance remains quasi-immiscible for some time; mixing does take place in time, however, and the oil gradually reverts to homogeneous and isotropic form after two hours or so.

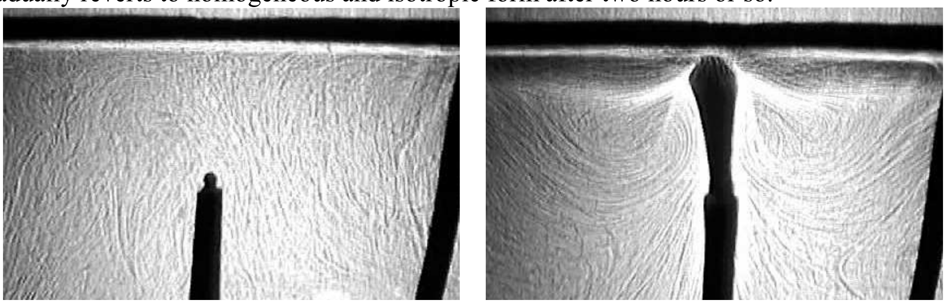

Figure 7 (left): Randomly oriented striations in olive oil before electric current flows in heating element. (right): Observation of convection currents in olive oil.

This gives plenty of time to perform a number of experiments. Once the heating current is switched on, a convection current sheath begins to rise, as in the case of water. The existence of the striations, in this case however, allows the flow of liquid throughout the bulk of the water to be observed (figure 7(b)).

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References

[1] For details of the ComLab project see http://www.e-prolab.com/comlab/

[2] http://www.picotech.com/
[3] Encyclopedia of Physics Demonstration Experiments, The Education Group laserdisc and DVD, demo 14-27
[4] It is a relatively simple exercise, using the laws of refraction ('Snell's law'), to show that the angular deviation in the case of the situation illustrated in figure 2 is given by

$\delta = 2(\phi - \theta)$, where $\phi = \sin^{-1}\left(\frac{n_{\text{out}}}{n_{\text{in}}}\sin\theta\right)$ and $\theta = \sin^{-1}\left(\frac{y}{R}\right)$

where n_{out} and n_{in} are the refractive indices of the media outside and inside the cylindrical surface, respectively.

For angles greater than the critical angle for total internal reflection, $\delta = 2(\pi - 2\theta)$.

Figures 2 and 3 show plots of δ versus y/R for the refractive index values indicated.