Teaching Heat Transfer to Engineering Students – a course of computer-based hands-on activities

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Abstract - **Modern data acquisition systems enable basic physical phenomena to be studied by means of clear, simple and instructive hands-on experiments. This paper describes a laboratory course on Heat Transfer phenomena designed, *inter alia*, for training of undergraduate students taking entry level programmes in Civil, Chemical and Process Engineering. The course was designed and developed as part of a Europe wide research collaboration under the EU Leonardo da Vinci Community Vocational Training Action Programme. The experiments to be described involve many innovative features that enable traditionally difficult experiments to be performed quickly and easily and, if desired, in an open-ended manner. The data acquisition hardware and software required are non-specific. Instructions for students and teachers will be available on the project website and will include pre-configured set-ups and sample data files for many commercially available low cost data acquisition systems, as well as for such systems developed within the project.**

Index Terms - Physics education, Heat transfer, Data acquisition, Computerised experiments.

THE COMLAB PROJECT

The Comlab project has been described in detail elsewhere [1]-[3] including at an IEEE conference [4]. Comlab is designed and developed under the EU Leonardo da Vinci Community Vocational Training Action Programme as a multifaceted resource to support teaching and learning in science and technology subjects at a variety of different levels and in various contexts. Materials produced within the project comprise low-cost data acquisition and control systems for hands-on laboratory exercises together with a range of computer based courses and allied software utilities. Comlab courses combine a wide range of appropriate multimedia materials (simulations, animations, video clips, interactive screen experiments, etc) with laboratory activities to provide integrated learning settings. All Comlab courses are available on the world wide web through interactive html environments [5].

In the current phase (2005-07) of the Comlab project at least eight new courses are planned. The subject matter of the present paper relates to just one unit from one of these planned courses, that entitled *Experiments in Food Science and Technology*. The target groups for this course vary widely, from those involved in upper secondary school science classes, through students in vocational programmes involving cooking/catering, to university students taking various engineering programmes such as Chemical, Process or Food Engineering. It is envisaged that each learner would work his/her way (or be guided) through the course in a manner most suited to his/her background and learning objectives but that all learners would initially complete, at a level appropriate to their individual needs, the unit on *Heat Transfer* which is the subject of this paper.

THE UNIT ON HEAT TRANSFER

The unit on Heat Transfer comprises a range of suggested laboratory experiments which can be performed quickly and easily using standard low-cost classroom equipment in conjunction with a data acquisition system (datalogger). The list of exercises includes a number of familiar experiments designed to introduce students to the basic concepts of conduction, convection, radiation, evaporation, etc. In addition, however, many more novel experiments are included which are designed to help students to understand the role of different heat transfer processes in real situations. A number of other experiments are specifically designed as introductions to other units of the course. The sample experiments described in the section which follows below give a flavour of the overall approach involved.

Because of the diverse target groups, each experiment is carefully designed so that learners can be involved at an appropriate level. Initially the learner finds a web environment that is purely qualitative, providing interactive instructions facilitating the taking of data and plotting graphs to show trends. A simple click moves the student to a more quantitative environment involving 'formulas' to enable various calculations to be made (sample calculations are provided and these can be made available to students if the instructor so decides). No mathematical models are involved at this level. A further click brings up the mathematical model underlying the formulas for more advanced users. Most experiments can be extended, if desired, to become more open-ended or project-like.

Experiments are designed to be performed with a computerised data acquisition system. Pre-configured set-ups are provided which may be launched by clicking on an appropriate icon. In all cases a pre-configured set-up for the eProlab data acquisition system, designed as an integral part of the Comlab project, is provided. Pre-configured set-ups for a number of other commercially available low-cost systems are also provided in most experiments (see Table I). The only sensors required are eight K-type thermocouples, connected through the Pico Technologies TC08 interface [8], and two standard thermistor sensors, e.g. from Vernier Software and Technology [7].

TABLE I
DATA ACQUISITION SYSTEMS FEATURED

Manufacturer	Software package	Interface
Comlab [5]	eProlab	CMC-S3, TC08
CMA [6]	Coach6	COACHLABII+
Vernier Software & Technology [7]	LoggerPro	LABPRO
Pico Tecnologies [8]	PicoLab	TC08
National Instruments [9]	Labview	NI6009, TC08

SAMPLE EXPERIMENTS

The following experiments illustrate some of the more innovative features of the laboratory exercises comprising the Heat Transfer unit.

I. Study of convective cooling in liquids

Students engaged in this experiment would previously have studied, as part of the same unit, examples of 'natural' and 'forced' cooling of hot objects in air. Accordingly, they would already be familiar with ideas of Newtonian cooling and would have observed exponential cooling curves. In this experiment they observe that the temperature of a warm object in water also decreases exponentially; the temperature being monitored by a thermocouple in thermal contact with the surface of the object and interfaced to a data acquisition system.

Students are encouraged to observe the convection currents responsible for this cooling. If the process takes place in a glass container (e.g., beaker, small fish tank – see Figure 1), such currents can be made visible in the following way [10]. A beam of light, e.g. from a slide projector, is passed through the container and cast on a white screen (a sheet of good quality paper attached to a wall of the container works well).

FIGURE 1
APPARATUS FOR MAKING CONVECTION CURRENTS VISIBLE.

The particular experimental arrangement in Figure 1 is designed for the study of convection currents generated by a steady electric current flowing in a straight horizontal resistance wire. Students observe the process in both the 'end-on' (Figure 1) and the 'broadside-on' configurations. When the electric current is switched on, a boundary layer of hot liquid is observed to form concentrically around the wire. As the water heats further this breaks out and a narrow sheath of warm liquid is observed to rise vertically.

The three thermocouples shown in Figure 2, placed at known distances vertically above the wire, can be used to detect the passage of the warm front that leads the convection current and hence the speed of the rising current can be measured.

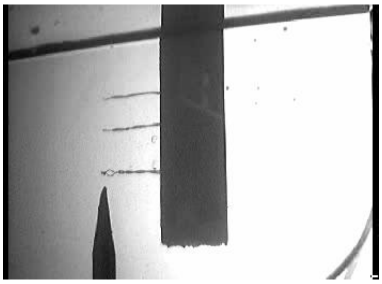

FIGURE 2
RISING CONVECTION CURRENT FROM LINEAR HOT WIRE VIEWED END-ON.

Students are then encouraged to consider the conversion of electrical power to thermal power. This gives rise to a discussion of the mechanism of heat transfer through the boundary layer. Simple 'back-of-envelope' calculations lead quickly to the conclusion that the transfer cannot be explained in terms of conduction across a layer of still water (as distinct from the mechanism of Newtonian cooling in air). This may further lead to a discussion of Rayleigh-Bérnard instabilities [11].

II. Combined convective and radiative cooling

A convenient way to investigate both convective and radiative heat transfer is shown in Figure 3. The body under investigation is a wire wound resistor (typically 10 Ω) in a ceramic casing, through which a steady electric current can be passed. A 12 V power supply capable of delivering up to 1 A and a suitably rated 0 – 20 Ω rheostat connected in series with the resistor prove suitable. The temperature of the resistor is monitored by a thermocouple (0 – 250 °C) in thermal contact with the surface of the resistor. Since the surface area of the resistor needs to be determined, the resistor should have regular shape (approximately 7 mm x 7 mm x 30 mm parallelepiped in the case described below).

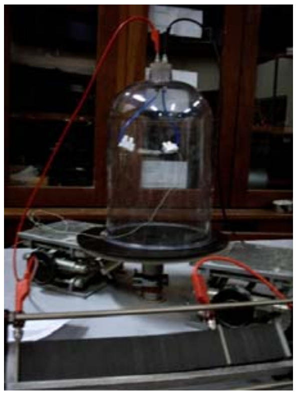

FIGURE 3
APPARATUS FOR STUDYING COOLING BY CONVECTION AND RADIATION.

The resistor and the attached thermocouple are placed in a bell-jar (Figure 3) which may be evacuated when required. Using the rheostat to control the current flowing in the resistor enables the temperature of the resistor to be raised to any selected value up to the maximum range of the thermocouple. When steady state conditions have been reached, the current is switched off, the connecting wires to the resistor are removed and curves are recorded by the data acquisition system for four different cooling environments, viz.

a) cooling in vacuum
b) natural cooling within the bell-jar enclosure (without evacuation)
c) natural cooling in the laboratory (bell-jar removed)
d) forced cooling in the laboratory as a result of a constant flow of air directed at the resistor by a fan

In practice, if strong draughts can be eliminated, little difference is observed between environments b) and c). Figure 4 shows typical cooling curves obtained for situations a), b) and d).

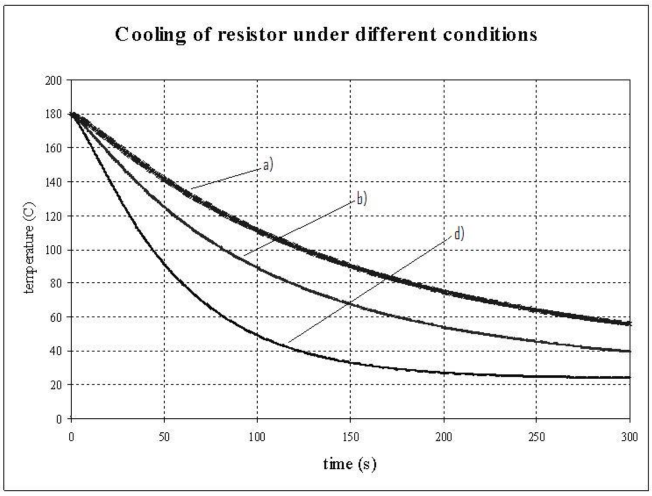

FIGURE 4
PLOT OF TEMPERATURE VERSUS TIME FOR THREE COOLING CONDITIONS.

The combined rate of heat energy loss from a body of surface area S due to both convection and radiation is

$$hS(T - T_a) + \varepsilon\sigma S(T^4 - T_s^4)$$

where the constant h is the heat transfer coefficient for pure convection and depends on the cooling conditions (speed of the air flow over the surface, shape of the body, etc.), ε is the emissivity of the surface and σ is the Stefan-Boltzmann constant. T_a is the temperature of the surrounding air and T_s is the mean temperature of the surrounding radiation sources. Thus the rate of change of temperature of the body is given by

$$\frac{dT}{dt} = \frac{hS}{C}\left(T - T_a\right) + \frac{\varepsilon\sigma S}{C}\left(T^4 - T_s^4\right) \quad (1)$$

where $C = \Delta Q/\Delta T$ is the heat capacity of the body.

Since there is no prospect of integrating (1) to obtain an analytical time-dependence of temperature, cooling curves cannot be used directly to analyse the experimental data. The nature the equation suggests data analysis should be performed on the variation of *dT/dt* with temperature. *dT/dt* versus time behaviour can be obtained directly in most data acquisition systems or determined from the cooling curves by invoking, for example, the SLOPE function in Excel. Figure 5 shows *dT/dt* curves plotted as functions of time for the cooling conditions studied.

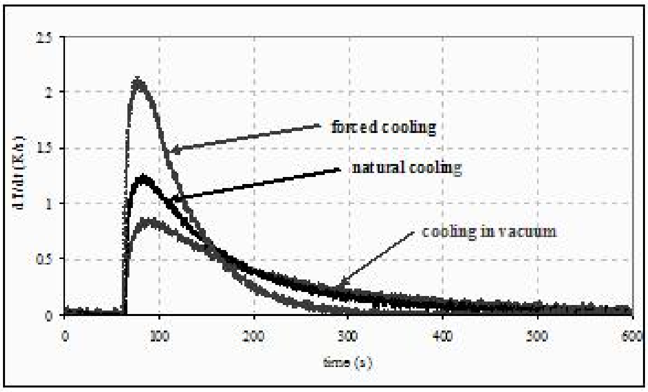

FIGURE 5
PLOT OF *dT/dt* VERSUS TIME FOR THREE COOLING CONDITIONS.

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This data can now be used to generate *dT/dt* versus temperature plots for all three cooling conditions (Figure 6). Since *dT/dt* is directly proportional to the rate of change of heat energy, the data in Figure 6 can also be used to determine the fraction of heat energy lost due to radiative cooling in each case (Figure 7). Students are usually surprised to discover how significant radiation is as a heat transfer mechanism even in situations where the cooling curve is well described by Newtonian cooling.

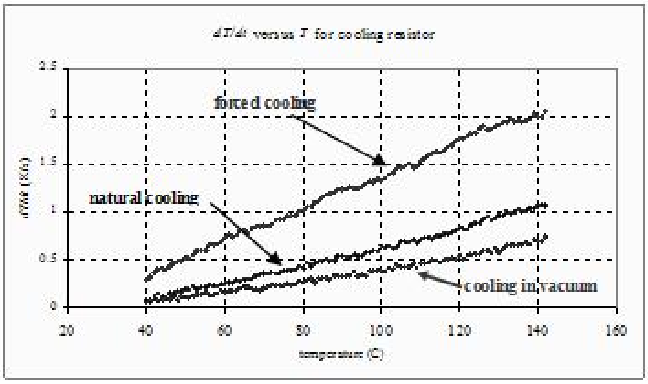

FIGURE 6
PLOT OF *dT/dt* VERSUS TEMPERATURE FOR THREE COOLING CONDITIONS

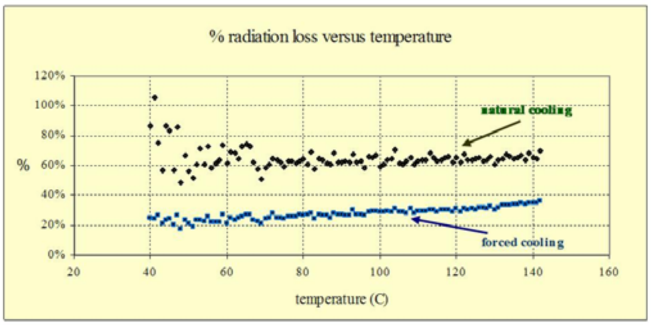

FIGURE 7
PERCENTAGE HEAT LOSS DUE TO RADIATION.

The fraction of cooling due to radiation can now be subtracted from the observed rates of cooling to determine the contribution to the cooling process from true convection. Since the observed rate of heat energy loss is given by

$$\left(\frac{dQ}{dt}\right)_{\text{observed}} = \left(\frac{dQ}{dt}\right)_{\text{convection}} + \left(\frac{dQ}{dt}\right)_{\text{vacuum}} \qquad (2)$$

and so for pure convection

$$\left(\frac{dT}{dt}\right)_{\text{observed}} - \left(\frac{dT}{dt}\right)_{\text{vacuum}} = \frac{hS}{C}\left(T - T_{\text{a}}\right) \qquad (3)$$

The corresponding *dT/dt* dependence on temperature, determined in this way, is shown in Figure 8 for both natural and forced cooling. As expected the results are consistent with linear behavior in both cases. A linear curve-fitting routine can be invoked from which the constant of proportionality (*hS/C*), and hence the true convective heat transfer coefficient *h*, may be extracted (see Figure 8).

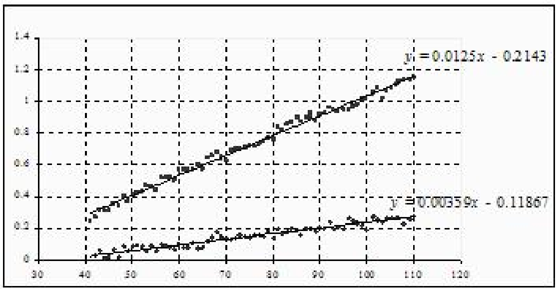

FIGURE 8
PLOT OF *dT/dt* VERSUS TEMPERATURE FOR PURE CONVECTIVE COOLING NATURAL COOLING (LOWER CURVE) ANF FORCED COOLING (UPPER)

III. Combined conductive, convective and radiative cooling

The following experiment, which is a modern version of a classical experiment traditionally associated with Forbes [12], serves as a final example. The apparatus (Figure 9) comprises a metal rod of uniform cross section with temperature probes (K-type thermocouples in this case) attached along its length. One end of the rod is held at a constant high temperature – connected to a steam reservoir in this case. The open cross-section at the other end is usually insulated from the surroundings — this is to simplify the mathematical model but makes very little difference in practice.

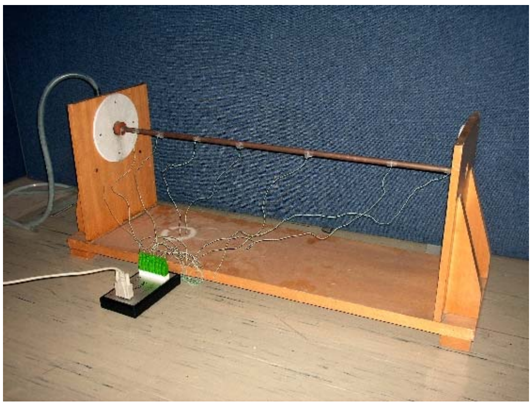

FIGURE 9
THE ‘FORBES’ BAR’ APPARATUS.

Typical data obtained for this experiment using the eProlab data acquisition system is shown in Figure 10.

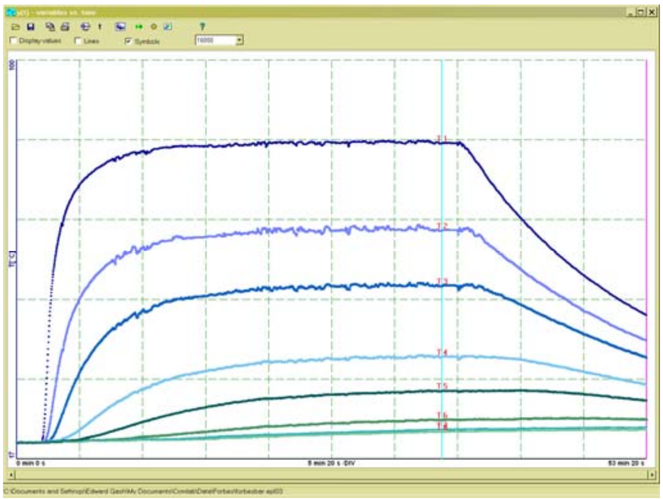

FIGURE 10
PLOT OF TEMPERATURE VERSUS TIME FOR THERMOCOUPLES ON ROD

When thermal equilibrium has been established, the rate at which heat flows through the bar at position *x* is equal to the rate it flows through the bar at $x+\Delta x$ plus the rate of heat loss out through the curved surface between *x* and $x+\Delta x$. That is

$$\left(\frac{dQ}{dt}\right)_{x} - \left(\frac{dQ}{dt}\right)_{x+\Delta x} = hp(\Delta x)\left(T - T_{\text{a}}\right) \qquad (4)$$

from which the temperature distribution along the bar of length *L* may be determined to be

$$T(x) - T_{\text{a}} = \left(T(0) - T_{\text{a}}\right)\frac{\cosh(m(x-L))}{\cosh(mL)} \qquad (5)$$

where *m* is a constant whose value may be determined. Figure 11 shows an example of data obtained by students and the comparison with the model given by (5).

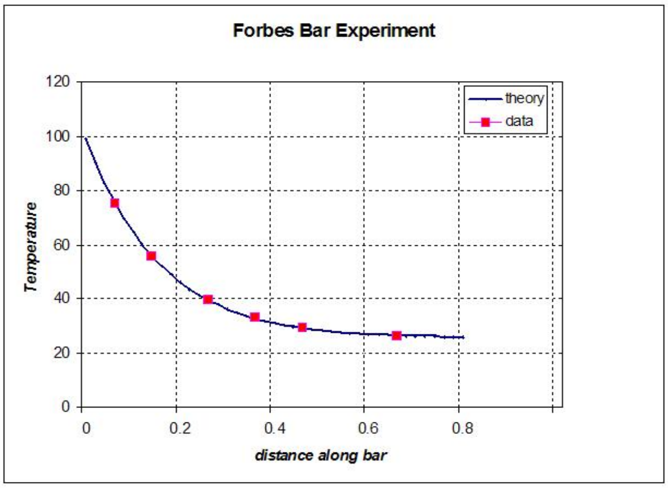

FIGURE 11
COMPARISON OF OBSERVED DATA WITH MODEL FOR ‘FORBES’ BAR’ EXPERIMENT

ACKNOWLEDGEMENT

The primary data acquisition system used (eProLab) was developed at the University of Ljubljana under the EU Leonardo da Vinci Community Vocational Training Action Programme, project N^O SI 143008 *Computerised Laboratory in Science and Technology Teaching* (Comlab). The laboratory course described was assisted by the same programme. Support received is gratefully acknowledged. The author would like to express his thanks for the cooperation provided by Slavko Kocijancic, the Coordinator of the Comlab project, and his colleagues at the Universuty of Ljubljana.

The author also wishes to thank colleagues Pat Twomey, John O'Riordan and Joe Lennon at the Department of Physics, National University of Ireland Cork for their important contributions to the work described in this paper; also to Professor Stephen Fahy for his continual support for the work and for making available the laboratory resources used.

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