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The development of an integrated experimental and computational teaching and learning tool for thermal fluid science

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ABSTRACT: Teaching and learning of thermal fluid science is always challenging due to its complex nature and the mathematics involved. In order to understand the fundamental concepts, a range of relatively expensive hands-on laboratory equipment, as well as skilled staff, are required. Thanks to advanced computational power, many complex phenomena can now be simulated and easily visualised. However, not all can be visualised utilising laboratory experiments. Therefore, the primary objective of this article is to develop a teaching and learning process that can be greatly simplified, cost effectively used, as well as being user-friendly, digestible and attractive, by integrating hands-on practical experiments, video images of *real-world* laboratory experiments and computational simulations. The proposed integrated learning methodology cannot only be useful for on-campus students, but also for distance learning (off-campus) students.

INTRODUCTION

Among all engineering programmes, mechanical engineering requires huge laboratories and workshop facilities, as students need to develop hands-on laboratory and field experiences. Engineering educational establishments in the developed world could maintain such facilities to educate their students with the required technical *real-world* knowledge and expertise. However, such facilities are almost absent in developing countries due to their financial hardships.

Recently, publicly funded universities in Australia, North America and other parts of the developed world have been facing severe financial hardship as a result of governmental subsidy reductions. As such, mechanical engineering programmes have been hard hit and forced to find ways to reduce the costs of capital equipment, the replacement of old facilities and instruments, operating and maintenance costs, and the reduction of supporting staff [1-3].

In order to maintain educational standards and quality, a university is forced to look for alternatives to hands-on practical laboratories and field experiments. One of the alternatives is to utilise a wide variety of computer-aided learning packages and the simulation of laboratory experiments, etc. Although hands-on practical laboratories and field works help students to understand the complex theoretical problems and apply theoretical knowledge in practice, some mechanisms or phenomena are still difficult to visualise. These complex and difficult phenomena can be visualised with the help of powerful computational tools.

A computer-based learning package allows students to understand and learn basic knowledge through a virtual laboratory – even before the start of real laboratory work. However, a virtual laboratory cannot be a total replacement of a real laboratory, as many laboratory experiments cannot be accurately simulated and students will not able to obtain real time and hands-on experience. These real time and hands-on experiences are important as they replicate real engineering problems that need to be solved. Therefore, for effective learning and teaching, both hands-on laboratory experiments, computer based simulations and Web-based visualisations are required [2]. However, a balance between simulation and practical work is also required in order to provide students with an appropriate level of simulated and hands-on laboratory experiences. To the authors' knowledge, no studies on identifying an appropriate balance between simulation and practical work have been reported to the open literature.

At present, in many universities, class sizes are large (up to 200 students) and for laboratory practice, students need to be divided into smaller groups (below 10). Therefore, it is difficult to provide adequate facilities and time to students with limited resources. In order to provide all students some opportunities to conduct the laboratory work within a set time, it is required to reduce the session hours for laboratory experiments. This can be achieved if a video clip of a laboratory experiment is provided to students to familiarise themselves before the actual laboratory starts. Students will be able to complete actual laboratory work in a shortest possible time, as they will not be required to spend more time to become familiar with the laboratory equipment and the basic theory involved. Thus, a two-hour laboratory session can be reduced to one hour without compromising the quality of education. It will also help to reduce operational, labour and other logistical costs.

After completing an actual laboratory experiment, students will be able to conduct the same laboratory work using computer simulation and compare results with the experimental findings. Additionally, students will be able to modify their experiments and obtain a wide range of data, analyse them and compare them with published data. In this process, students can expand their theoretical and experimental knowledge without any extra cost to the university.

It may be noted that, generally, thermal fluid mechanics is one of the most complex and challenging subjects of mechanical engineering programmes, as it deals with the complex nature of flow and heat, and it is usually difficult to understand basic concepts due to the level of mathematics and physics required. Therefore, the primary objective of this work is to develop a cost effective integrated learning method by combining a video clip of a real laboratory work (Web-based), real laboratory work (hands-on work) and a computational fluid dynamics (CFD) (simulation) of a thermal fluid mechanics laboratory experiment for on-campus and off-campus students. A schematic of the proposed teaching and learning tool is shown in Figure 1.

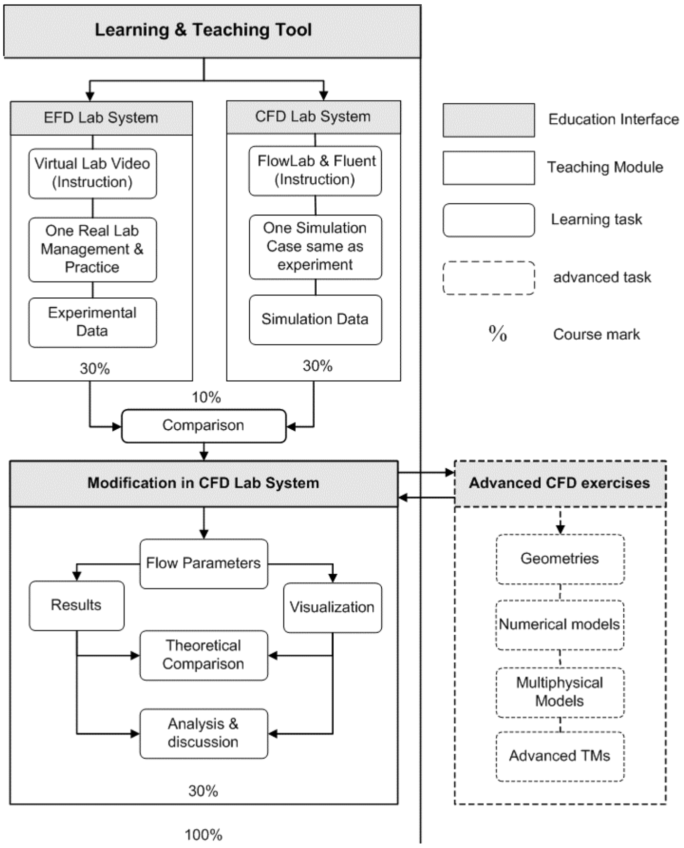

Figure 1: A flow chart for the proposed integrated learning and teaching tool.

TEACHING AND LEARNING TOOLS

Currently, the School of Aerospace, Mechanical and Manufacturing Engineering at RMIT University, Melbourne, Australia, has been restructuring its 1st year and 2nd year courses as a part of the School's formation. For all four programmes, there will be common 1st and 2nd year courses. Currently, thermal fluid science is a common course for all 1st and 2nd year students of all programmes, except for the aerospace 2nd year students. A process is underway to make a common thermal fluid science course for aerospace 2nd year students in 2005 in order to provide a coherent understanding of thermal-fluid science. Additionally, an advanced thermal-fluid course is being run for 3rd year students in mechanical and automotive engineering. Therefore, a common thermal fluid laboratory has been selected for all students of the combined course. The laboratory title is *Drag Measurement of a Circular Cylinder*. Experience and knowledge from this laboratory work can be replicated to other thermal fluid mechanics laboratories later.

An education interface for experimental fluid dynamics (EFD) and computational fluid dynamics (CFD), and related teaching modules are being developed, which provide the convenient routing and linkage of learning and teaching in thermal-fluid dynamics. These include a Web-based course outline, a virtual laboratory tour, EFD hands-on and CFD exercise templates, as well as CFD advanced exercises.

Experimental Fluid Dynamics (EFD)

Experiment Fluid Dynamics (EFD) consists of two parts: a virtual laboratory tour and a real laboratory experiment.

Virtual Laboratory Video

The real experiment on drag measurement of a circular cylinder has been filmed. In the film, an experienced demonstrator explains all the basic theory and gives a step-by-step description of all equipment and laboratory procedures. The film was then converted to a Virtual Laboratory Video and linked with the course's Web interface. Students can visit the course Web site and play the video clip of the laboratory. The video clip can be replayed as many times as students wish. A small test has also been developed with the Virtual Laboratory Video. After watching the video clip, students need to answer several questions and some marks are allocated for the test so that students watch attentively the Virtual Laboratory Video. Upon the completion of the Virtual Laboratory Video, students can proceed to the real laboratory experiment.

Real Laboratory Experiment

The real laboratory experiment on the drag measurement of a circular cylinder is conducted using a portable wind tunnel. The School of Aerospace, Mechanical and Manufacturing Engineering possesses several portable wind tunnels. One of these wind tunnels is shown in Figure 2. It has a square test section of nominal size: 300 mm width x 300 mm height x 500 mm length.

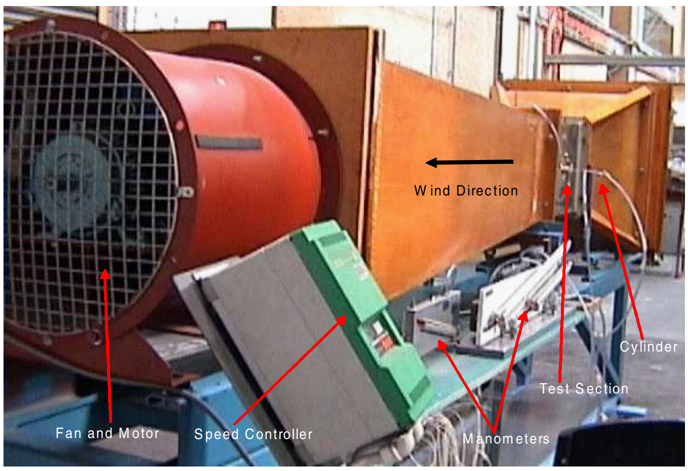

Figure 2: A portable wind tunnel.

Flow is drawn through the tunnel by an axial fan located at the tunnel's exit (see Figure 2). A circular cylinder with a traversing mechanism is mounted in the test section. A Pitot-static tube is mounted on a traversing gear that can move vertically up and down so as to measure the local value of velocity behind the cylinder. For the experiment, in addition to the wind tunnel with a probe traversing mechanism, a circular cylinder with a tiny hole and a protractor, a Pitot static tube with flexible plastic tubing, a manometer, a thermometer and barometer (to measure the ambient temperature and pressure, respectively) are required.

The experimental procedures, parameters to be measured, relevant theory and sample calculations are provided on the Web site for the Virtual Laboratory Video. It should be noted that the aerodynamic drag of the circular cylinder can be determined by integrating the surface pressure around it. The circular cylinder is generally mounted in the tunnel's test section with its axis (hole) normal to the airflow direction. The cylinder carries a static pressure tapping and, because the cylinder can be rotated and its angular position measured with the aid of an attached protractor, the pressure distribution around the entire circumference can be measured by connecting the pressure taping with the manometer.

The measured pressures can be converted to non-dimensional pressure coefficients (C_p). In order to determine the drag forces, it is required to plot a graph C_p versus measured angular position, θ, and integrate the area under the curve (required instructions were given on the Web interface).

Computational Simulation

In order to simulate and visualise flow characteristics around a simple object, such as circular cylinder, various commercial and homemade software can be utilised. *FlowLab* and the powerful engineering application CFD software, *FLUENT*, have been widely used for teaching and learning. The in-house CFD learning and teaching software, *CFDLab* v1.0, provides more CFD templates than *FlowLab*, especially for numerical schemes and algorithms. It is worthwhile to note that the *FlowLab*, *FLUENT* and *CFDLab* v1.0 packages provide different levels concerning the understanding of CFD techniques. *FlowLab* permits the observation of the phenomena of flow field. However, its ability is restricted due to limited changes of numerical methods. *CFDLab* v1.0 focuses on the effects of changes of numerical aspects on flow fields. *FLUENT* provides one way for advanced and special CFD exercises to be tackled by students with real-world applications of fluid flow and heat/mass transfer, and encourages them to improve professional CFD skills for the job market after graduation.

After the real laboratory experiment, students can repeat the same case in 2D simulation within *FlowLab* and learn a fundamental process of CFD simulations by simply selecting different sets of the following: cylinder radius, mesh, physical conditions, iterating parameters of the solver, reporting and post-processing. For example, regarding the pressure coefficients (C_p), students can change the size of the cylinder radius, velocity, etc, and find out the effects of these through plots of pressure distribution and pressure coefficients along the surface of the cylinder in order to understand flow behaviour under different physical conditions. Furthermore, by using *CFDLab* v1.0, students can select different sets of numerical schemes, such as discretisation schemes and under-relax factors, so that they will perceive more clearly how numerical methods impact on the results of CFD simulations and understand how important a role it can play. An example of a CFD set-up and derived results using *FlowLab* are shown in Figures 3 and 4 respectively. CFD learning enhances students' physical understanding of the experimental system, which can be hard to attain from a few point measurements, and can give an impression that modelling involves approximations and tradeoffs, the confirmation of some aspects of the data processing for the experiment (eg that a mixing region is long enough) and confirmation of experiment and correlation.

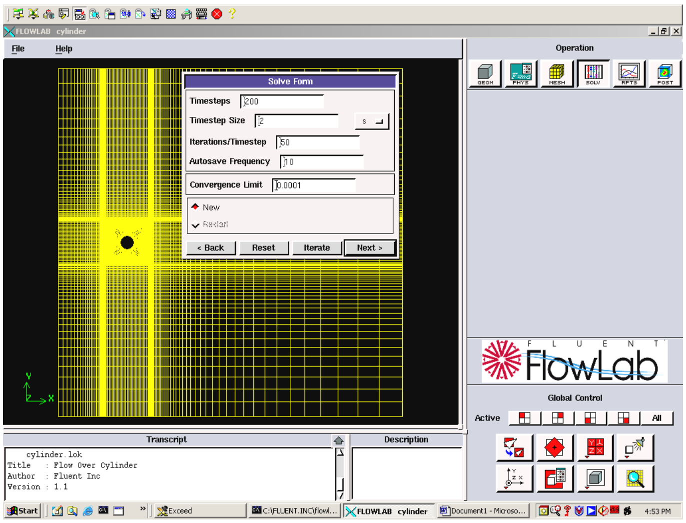

Figure 3: An example of simulation parameter set-up using *FlowLab*.

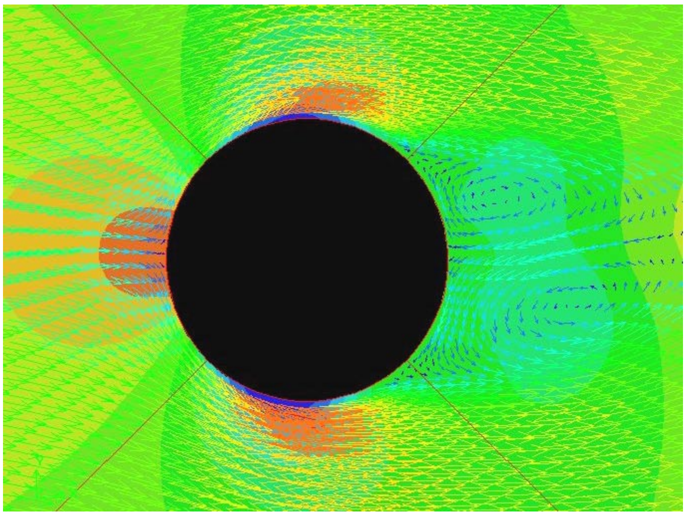

Figure 4: Pressure and velocity contours around a circular cylinder.

Comparison of Data

After completing their laboratory work, students utilise hands-on practical laboratory work and computational simulations to compare results. They will also find out if there are any variations in results and determine the causes of any variations. If the experimental findings compare well with the computational findings, students can proceed to the next steps of their laboratory work.

Modification of Data Using Computational Simulation

Once students are confident that their findings (both experimentally and computationally) have compared well with existing data, they can start to modify experiment parameters, such as the diameter of the circular cylinder, airflow velocity, air density, etc. In the process, students have the opportunity to see the effects of these parameters on the pressure coefficient (C_p) and aerodynamic drag (C_d). They will be able to quantify each parameter's effect, as well as the combined effects of all the parameters on C_p and C_d.

After successful completion of video watching, real hands-on laboratory experiments and computer simulations, students need to conduct a comprehensive analysis and discuss the nature of their findings. A final written report is required from each individual student, along with his/her feedback.

GENERAL DISCUSSION

The combination of hands-on laboratory and computational power should enhance easily students' learning capabilities, understanding and visualisation power of complex problems. An internal survey conducted by the authors and subject evaluation feedback, staff and student consultative meetings and course experience questionnaire surveys indicate that students are keen to learn both experimentally, as well as utilise virtual tools (computer simulations and video clips).

However, a balance between hands-on laboratory work and computational simulation is required in order to achieve the maximum learning outcomes by students as they are become prepared for real world engineering challenges after graduation.

To date, there is no proven borderline between experimental and computational learning methods. Other studies by have tried to partly address this issue [3-9]. Therefore, the proposed learning schemes (watch video of real laboratory experiment → conduct real laboratory experiment → conduct virtual laboratory *computer simulation* → compare results with experimental findings → modify experiment parameters in computer simulations → analyse and then write a final report) is a comprehensive teaching and learning tool. In this scheme of learning and teaching, approximately 30% of the time should be allocated for hands-on practical laboratory work, while the remaining 70% of the time is apportioned to virtual laboratory work, including watching the video clip of the real laboratory experiment. The proposed scheme should reduce the operational costs of real world experiments by up to 50%, as 70% of the total time is spent on the virtual part of the coursework.

Currently, a pilot programme is underway to implement the proposed learning and teaching scheme, and to evaluate the effective learning outcomes. It is anticipated that the combined effort by hands-on and virtual tools will increase the overall students' satisfaction levels by assisting students to acquire a desired real world hands-on practical and theoretical knowledge.

Furthermore, it will help both undergraduate, as well as newly enrolled postgraduate, students to understand various engineering application software, such as *FLUENT*, *FlowLab* and *LabView*, which are widely used for teaching and learning, and research and development. If the proposed scheme is proven to be successful after the pilot trial and evaluation, experience gained from this can be replicated to other programmes within the University, as well as other universities at home and abroad.

CONCLUSIONS

The following benefits can be achieved from the proposed integrated teaching and learning scheme:

- It should help students in larger classes as they can have access to computers individually. Several programmes, like mechanical, automotive, manufacturing and aerospace engineering, can benefit directly as they have a common course structure for the first two years. Students from any programmes within the School, as well as outside, will be able to access the laboratory online at any time if they are connected to the Internet. Proposed virtual thermal fluid laboratories are in line with the University's guidelines to support more than one programme.
- The virtual thermal fluids laboratories will contain online, pertinent interactive subject tutorials and additional illustrations as part of the Web-based learning materials. Numerical simulations can be also used to complement the existing experimental thermal and fluid laboratory resources as a proof-of-concept.
- The proposed virtual fluids laboratories are sustainable and cost effective, as it should not require any ongoing costs – except some minor maintenance costs.

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