Thermofluids Virtual Learning Environment for Inquiry-Based Engineering Education

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Abstract: - Thermofluids science plays an important role in industry, technology and environment, and contributes to the sustainable development of modern society. The thermodynamics and fluid mechanics are two essential disciplines of interest to the engineering profession. The study aims to develop the inquiry-based computer virtual laboratory (virtual learning environment) to augment engineering modules using principles of fluid mechanics and thermodynamics, and to increase students' understanding and skills in CAD/CAE/CAM technology and mathematical packages used in mechanical, aerospace and automotive engineering. The iterative nature of the virtual laboratory directly addresses several components of engineering education and follows the cyclic model for knowledge generation and improvement. The CFD tools and other computational components of virtual learning environment are discussed, and their capabilities to be used in teaching process are analyzed. The study demonstrates that CFD becomes a useful tool for undergraduate and postgraduate research and education.

Key-Words: - Inquiry-Based Learning, Thermofluids, Learning Environment, Virtual Laboratory

1 Introduction

Thermofluids science plays an important role in industry, technology and environment, and contributes to the sustainable development of modern society. Principles of thermofluids mechanics and computer-based simulation are crucial to the design of today's complex engineered systems and processes, and come from the need for fast transition from concept to product or final design solution, coupled with the high cost of prototyping. Thermofluids science is moving up the engineering supply chain, and for companies running multistage simulations throughout the design cycle has become standard practice. Principles of thermodynamics and fluid mechanics are used in many commercial and open-source CAD/CAE/CAM (Computer Aided Design, Computer Aided Engineering, Computer Aided Manufacturing) packages.

Large companies understand the impact of numerical simulation on research and design. The reasons why a project manager uses numerical simulation are multiple. Product design and manufacturing organizations are moving from the traditional, multiple and serial design-build-test cycle approach to simulation-led problem solving and performance validation using CAD/CAE/CAM technology. In the *prospective mode*, the aim is to design the system which fulfils the specifications at the lowest development cost by minimising the number of prototypes and tests. In the *explanatory mode*, the desire is to explain observed and unknown phenomena that happened during the development phase of a commercial product.

In the traditional undergraduate mechanical engineering curriculum, thermofluids sits at the peak of the engineering sciences and bridges the gap to the application of those sciences in design.

The qualified engineers should have the ability of applying engineering principles in multiple disciplines and design methods in the computational environment in order to build and test virtual prototypes for commercial product development. It is a challenge to the engineering education in higher education institutions which traditionally tends to lack the integration of knowledge and skills required for solving real world problems.

Many powerful commercial CAD/CAE/CAM packages are used in engineering practice and industry. Learning this software is synonymous with learning the thermofluids. For example, if the student doesn't know the significance of a Fourier number in transient conduction or can't do a simple energy balance on a control volume and isn't willing to learn (from the lecture, the textbook or the help files), then this software will not help student.

Although incorporating thermofluids principles, mathematical packages and CFD (Computational Fluid Dynamics) tools in standard undergraduate and postgraduate curriculum and benefits of using CFD as a research tool are described by many authors [1–10], further work is required. Design and development of a virtual laboratory with emphasis on verification and validation of computational results and engagement of students is a great of interest for engineering curriculum.

The interactive thermofluids collection is considered as virtual laboratory [11], which allows students to take data from a computer screen for post-processing – much as if they are working in a real well equipped experimental laboratory. A thermofluids virtual environment (virtual laboratory) provides an excellent transition between learning the engineering sciences and the design modules.

Inquiry-based learning (IBL) is essentially a student-led style of learning founded in a questioning philosophy. It requires a self-motivated and interactive approach by students to learning by discover, using the university's resources, their tutor and their student colleagues in order to investigate a particular topic or issue. The basis of IBL is that a series of questions can be posed about who, where, why, when, how, giving a deeper understanding of an issue than may be obtained by simply accepting information. There are different forms of IBL and the model adopted in this study involves students selecting their own topic from the case studies provided for future investigation. The tutor's role in an IBL project is to facilitate the students' learning by defining the initial starting point for the task and by providing guidance about resources (data, literature, websites, etc) that might be relevant to completing the inquiry.

IBL in the discipline often takes the shape of problem-based learning (PBL), after students have acquired the basic knowledge necessary [12, 13]. Examples of the implementation and practical use of interactive learning environments are presented in the literature [14–18].

This study aims to develop inquiry-based computer virtual learning environment to augment engineering modules using thermofluids principles, and to increase students' understanding and skills in CAD/CAE/CAM technology and mathematical packages used in mechanical, automotive and aerospace engineering. To meet this aim of the project, four specific objectives are addressed.

- To develop IBL model to engage student transferable skills.
- To create a number of interactive and shareable learning objects regarding to the transferable key skills required to be able to solve problem effectively, and to stimulate problem solving and creative thinking in engineering students.
- To advance students' knowledge and understanding of thermofluids science across engineering fields and scientific application areas.
- To confront student misconceptions in thermofluids and to develop the students' ability to use qualitative and quantitative reasoning.

The thermofluids virtual laboratory is implemented with Matlab and tools of the CAD/CAE/CAM commercial and open source packages, and can be extended by students and staff involved in teaching process. The benefits of virtual laboratory are discussed.

2 Transferrable skills

Higher education has been moving towards an outcomes-based approach where universities are required to explicitly identify the knowledge, skills and attributes that they expect their graduates to have achieved [19, 20].

The creative way of approaching all engineering challenges is being seen increasingly as a 'way of thinking' which is generic across all disciplines. In order to operate effectively, engineering graduates thus need to possess the following characteristics. They will be rational and pragmatic, interested in the practical steps necessary for a concept to become reality. They will want to solve problems and have strategies for being creative, innovative and overcoming difficulties by employing their knowledge in a flexible manner. They will be numerate and highly computer literate, and capable of attention to detail. They will be cost and value-conscious and aware of the social, cultural, environmental and wider professional responsibilities they should display. They will appreciate the international dimension to engineering, commerce and communication. When faced with an ethical issue, they will be able to formulate and operate within appropriate codes of conduct. They will be professional in their outlook, capable of team working, effective communicators, and able to exercise responsibility.

The outcomes of any educational programme can be expressed in terms of two main aspects [19, 20]: knowledge and skills. Skills are divided into those that are specific to the type of programme (e.g., skills in solving material and energy balance), and those that are generic or transferable (e.g., problem-solving skills). In the context of higher education, there is also frequent reference to graduate skills, but these generally mean the same as transferable skills at the level expected of a graduate.

Six key skills for engineering graduates are the following [19, 20]: communications (good at communicating in a variety of forms), team working (ability to work well in teams), problem solving (ability to solve problems pro-actively and with initiative), numeracy, IT skills, self-learning (ability to manage themselves and continue to learn).

Transferable skills are more likely to be developed by students if the skills are embedded within the curriculum, rather than taught in separate activities or classes [19, 20].

The classical approach to teaching and learning involves much practice in applying the principles to a wide range of problems. The problems can range from well-defined and relatively simple ones (only one method of approach, sufficient data is provided, there is only one correct solution) to complex and open-ended problems (several possible approaches, inadequate data, many possible solutions).

It is important however to distinguish between the problem-solving approach and the use of PBL. The problem-solving approach involves the application and integration of previously learned knowledge. PBL is where the problem drives the learning [12, 13]. The problem is posed so that the students discover that they need to acquire some new knowledge before they can solve the problem. This need is then met by the students themselves and/or by the tutor.

There was much agreement that students need to assimilate not just the theory but also advanced applications. More skills are required for the modern engineer. They can ‘feel how things are done right’. While advanced techniques and tools are needed, intuition and knowledge of the basics are essential. Students have to understand the wider engineering problems from inception to implementation.

The teaching of (creative) problem solving offers challenges in the areas of recognising and developing both strategy and method. Teaching and developing process skills in the classroom can be achieved in a number of ways including the use of PBL activities. It should be noted, however, that PBL is distinctly different from problem-solving learning, with the former being used to develop processes in a wider context rather than products in a confined environment.

Inquiry-based teaching is a teaching method that combines the curiosity of students and the scientific method to enhance the development of critical thinking skills while learning science. As learners encounter problems they do not understand, they formulate questions, explore problems, observe, and apply new information in seeking a better understanding of the world. The natural process the learners follow when seeking answers and deeper understanding closely follows the generally accepted scientific method. Often, the answers proposed by learners lead to even more questions – much like the outcomes of research.

Students engage in five activities when they engage in IBL and use the scientific method: question; investigation; use evidence to describe, explain, and predict; connection of evidence to knowledge; sharing of findings.

Inquiry is a fluid process, and one task may lead back to a previous task. This process involves the following steps: ask question about object and events in the environment; plan and conduct a simple investigation; use appropriate tools and techniques to gather and interpret data; use evidence to describe, explain, predict and connect evidence to knowledge; communicate investigation procedures, data and other explanations to others.

The following factors are taken into account: the content and skill needs of the students for future careers; the content and skill needs of the students for various professional school entrance exams; the most appropriate instructional methods taking into account students’ motivations and learning styles; the time constraints; the motivations and interests of these students; the results of engineering education research.

When one examines these factors in detail, it becomes clear that it is not easy to design a course in which students gain a solid understanding of engineering content and learn necessary scientific skills taught by appropriate teaching methods, considering the learning styles and motivations of the students.

Implementation of inquiry-based system will help students to learn engineering concepts and develop skills that will be useful to them in their future careers, and pass professional exams.

3 Inquiry-based learning

The ability to solve problems and creative potential are highlighted as essential characteristics for both undergraduate engineers and qualified engineering professionals in UK and European benchmark and policy statement. Creativity within the sciences, including engineering, is also identified both explicitly and implicitly as an important driver in recent UK reviews relating to economic prosperity and Government science and innovation policies. In

Europe, problem solving and creativity are presented as important competencies in the requirements for European engineer designation.

None of these benchmark statements or policies, however, offers any guidance on how these skills might be fostered let alone assessed.

The traditional model of teaching used in engineering education may not provide sufficient motivation for engineering graduates. Engineering education focuses on problem solving skills, but that teaching in higher education institutions concentrates on teaching content rather than showing the processes involved in problem solving.

In engineering disciplines it is critical to the success of the educational process that students become actively engaged with the material, rather than passive recipients of it. Ideally, this interaction will begin before the class meets on a particular topic in a process of IBL. The relationship between research and undergraduate curriculum in higher education has long been problematic but at undergraduate level terms such as inquiry-based and problem-based are often used interchangeably to describe active learning approaches which encourage students to address a broad range of skills which can ultimately contribute to pure research capability but for many will describe skills which are transferable to a range of contexts.

Educators should constantly evaluate and adjust their teaching approaches to meet the educational needs of their students and society. Development of students' abilities and performance in engineering and science, reading and writing play a key role in teaching. Inquiry-based teaching methods allow teachers to enhance students' science skills and help lifelong learners [21–24].

When students engage in inquiry, they utilize skills from across multiple disciplines by collaborating with others, collecting and interpreting data, organizing and developing representations of their data, and sharing their findings with others. Inquiry-based teaching methods provide flexibility to the teachers and students by facilitating student contribution of their strengths, so students of different developmental levels and learning styles learn together. IBL requires students to actively use their hands and minds, and as a result, students are able to assemble ideas to create their own knowledge and understanding.

There is strong evidence that IBL promotes a deeper understanding, but it is more challenging for the students and it is more challenging and difficult for the tutors and the department to implement.

Students require knowledge of multiple disciplines and complex multi-variable techniques. With so much to know, there’s a temptation to ditch theory and just show students how to use the tools. Nobody agreed with this practice – they felt that teaching only software tools is limiting and of little use to the industry – tools knowledge is essential but needs to be taught alongside, not instead of, the core concepts.

4 Learning environment

Engineers are grounded in a process of progressive problem solving, that is in the process of inquiry into particular practical problems at increasing levels of complexity. However, the typical environment in which engineering students learn about such problems historically has not been conducive to progressive problem solving behaviours, and students are often unable to communicate functionally what they know to others.

Inquiry-based exercises and conventional laboratory exercises differ in the degree of student preparation necessary before conducting the calculations. Often the explicit goal of a conventional laboratory exercise is to confirm a theory presented in a lecture. Thus, for a conventional laboratory exercise, it is very important for students to have seen and worked with the theory before coming to the computing laboratory. In contrast, in an inquiry-based laboratory exercise, students are asked to make screen observations or calculations of phenomena for which they do not have theoretical models. In that case, the virtual laboratory exercise is one of authentic discovery and synthesis. The inquiry-based approach puts more responsibility on the students as they work in the computing laboratory. In this context, the virtual (computing) and physical (experimental) laboratories are different in terms of costs.

Inquiry-based exercises included in virtual environment are designed to expose student misconceptions and to teach students to apply qualitative as well as quantitative reasoning. In order to focus attention on misperceptions, students are asked to predict trends in the calculated data before that data is collected. This is followed with a direct calculation that confirms a correct model or shows the error of an incorrect model. Use of qualitative reasoning is encouraged because the calculations are designed to allow trends in the dependent variables to be readily calculated. It is much harder for students to rationalize a direct calculation that contradicts their preconceptions, than it is for the students to ignore a theory that contradicts their own belief about a physical system or process.

Predictions of the system response are more reliable when students use an engineering model of the system behaviour. Qualitative reasoning involves the use of models (e.g. formulas, equations, mass and energy balances) without necessarily having quantitative data for all terms in the formula. For example, by invoking the Bernoulli equation one concludes that the pressure increases when the velocity decreases.

CAD/CAE/CAM technology becomes a new connecting point where engineering education and the manufacturing industry hold hands and work together to achieve great benefits on both sides of the enterprise. The industry will gain competitiveness and better products through using a smarter way of developing products while the higher equation institutions will produce better qualified and more desirable graduates by equipping the students with the required knowledge, skills and experience.

5 Methodology

Action research strategy developed in [4] is chosen as the main research methodology. Each cycle of action research is involved the processes of planning, acting, observation and reflecting. This process is spiral and iterative, and that more than one iteration of the process is required for the process to be effective (Fig. 1).

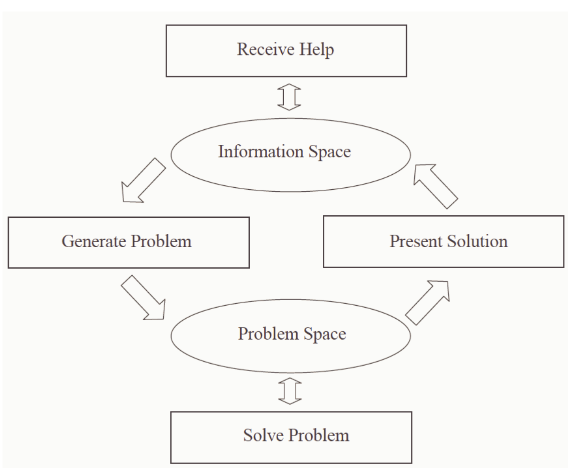

Fig. 1. Problem and information model.

Students operate in two spaces, problem and information, during the creative problem solving process. In the problem space they work directly on the problem and in the information space when they encounter skills or knowledge deficiency. The information space provides tools to mediate the problem solving process. Informational content in each of the spaces is provided using reusable learning objects (RLO).

The problem space is represented by a problem that the students generate, and attempt to solve. Within this space there are also instructional items relating to the basic features and functions, along with practical exercises. Items in the information space are related to assisting with developing the typical stages of the problem solving process (interpreting the problem, planning, processing, and presenting solutions) and mathematical modelling (problem statement, schematic, assumptions and approximations, physical laws, properties, calculations, verification, return to previous step if it is necessary).

RLO content relates to a number of process themes including

- Thinking skills (logical and creative thinking)
- The relationship between learning and problem solving
- Exercises relating to thinking about thinking
- Problem solving, knowledge, intelligence and intuition
- Multiple intelligences
- Procedural methods for problem solving
- Techniques relating to analytical thinking
- Techniques relating to creative thinking
- Critical thinking activities
  - o Self management (time and stress management)
  - o Reflective practice activities (how to think, talk and write reflectively)
  - o Teamwork and group activities
  - o Professionalism
  - o Ethics and sustainability
  - o Communication skills (effective presentation of ideas and solutions)

Each RLO is a self-contained learning unit, and typically consists of several screen-readable pages containing text, plots and diagrams. RLOs are produced in HTML or PDF formats. They may be produced as a self-executable file.

Laboratory uses a combination of teaching styles and materials in order to maximize learning. The teaching style includes the use of PowerPoint presentations and lecture notes in e-book format (they are produced using LaTeX publishing system). Lecture topic is presented in an interactive lecture-discussion format with an emphasis on active student participation in the discussion. The existing teaching materials, used in conventional teaching process, are modified, adapted and integrated with new units in new format.

6 Development of engineering systems

Virtual laboratory consists of problems of increasing levels of complexity which correspond to the development and operation of engineering systems.

During the development and operation of complex engineering systems, several phases can be mentioned, starting from the design phase, to the development phase and later the operation/upgrade phase. In any of these phases, that take place in a competitive market, where delays and cost reduction become a priority, numerical simulation can bring advantages in selecting appropriate designs, validating specific solutions, helping design test benches and measurement plans. Since testing of such complex systems is quite expensive and intricate, there is a need to use computer simulation in a reliable way. The results produced by the code are indeed the actual results observed in a physical experiment. Insuring validation would insure that the results can be used as actual results from the reality of the real world. Since the real world is quite complex, one has to define what is the real world will refer to and what is the measure of reality.

This importance of code validation has been recognized in industry. Several reasons exist for such an implication.

- Codes are a natural place to capitalize research activities for further use.
- Trends are clearly towards multi-scale and multi-physics researches that implies non-linear coupling of existing models, so that codes are the vector giving access to these complex physics.
- Codes also provide a powerful way to bring together researchers from many different areas (physical modelling, numerical and computational methods, data processing, experimental technique).
- Codes are essential to design and understand complex systems that are used in mechanical, automotive and aerospace engineering.
- Codes can be transmitted to industrial partners and are part of research activities.

In order to validate the code results one has to compare them to results that bear some of the reality the code is intended to simulate. Then it is useful to introduce some sort of ordering of the reality. The simplest way is to follow the complexity of the situation that is to be simulated. This hierarchy of validation of models of complex engineering systems is summarized by the schematic presented in the Fig. 2.

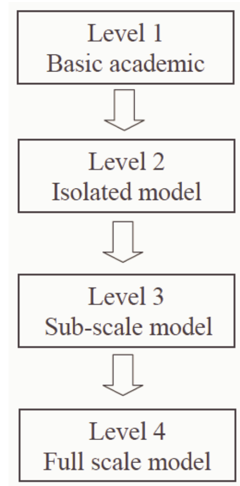

Fig. 2. Hierarchy of models of engineering systems.

The first level includes only one complexity and it seems wise to consider one level of modelling in a geometrically simple configuration. Very often this permits to develop analytical solutions against which the numerical results may be checked. This level is referred to as *basic academic* level. This implies only the flow model or another model for a uniform flow (example is boundary layer flow).

The second level introduces an additional model, other than the flow model, in a still simplified geometry (example is simple burner). This level is referred to as *isolated model* level.

Level three addresses complex situations that occur in simplified systems, such those considered in research laboratory for proof of concept activities. It includes several models in actual situations, representing simplified or *sub-scale model* of actual system.

Finally, a fourth level considers actual industrial applications up to *full scale*.

This hierarchy is followed progressively in order to gain confidence in code performances before considering more complex situations. This is of major importance when analyzing difficulties encountered at one level. For instance, the causes for a given code to produce improper results at level 3, using model 1 and model 2, is much easier to analyze if one knows that model 1 and model 2, when used separately, produced satisfactory results at level 2. If analytical solution is used as often as possible at level 1, they cause to produce valuable results at levels 2-4. The validation effort should imply the definition of appropriate experiments to pave the way of code validation up to level 4, which is the ultimate goal. It must be stressed that those are essential steps in code validation and that these steps are proper to each application. This implies to

- Identify the physical models that are needed and ensure their verification;
- Insure that the necessary steps are taken to provide the needed inputs for the models;
- Define the proper experiments where these models are involved in a gradual way to fulfil level 3 requirements.

The core of the validation procedure, excepting level 1 (where the conditions are clearly known) and level 4 (where the conditions cannot be controlled), is to compare results produced by a numerical code with results obtained experimentally in a controlled environment. The quality of the work is logically dependent on the quality of the possible matching between the simulations and the experiments.

The ideal situation is when both the computations and the experiments are designed together in order to insure that

- The proper measures are taken to define the boundary conditions for the simulations;
- The extent of the simulated experiment is clearly defined and corresponds to some portion of the experiment that can be isolated;
- The data processing is clearly defined and should be as close as possible between the two approaches;
- The simulations are viewed as a numerical experiment and should follow similar procedures.

Another notion that is developed when considering the level 4, stems from the difficulty to exactly describe the complexity of the reality. This introduces the notion of relative validation. The explanation comes from the fact that it may be difficult to produce positive comparisons on quantitative data in a real life situation. Then the search for an absolute comparison (produce identical data) is usefully shifted towards the search of a qualitative validation. In other words, the emphasis is put on the tendencies rather than on the absolute values, that cannot be matched. The usual reason for the impossibility to match absolute values comes from the difficulty to properly define the boundary conditions of an actual system (vibrations, mass flow rate fluctuations, turbulence etc), its geometrical limits or the proper model inputs. Then code validation ensures that the code produces the right tendencies for a change in one of the identified parameters. This relative validation represents a valuable goal for a complex situation and requires that the confidence in the code results has been acquired in the lower levels of the validation procedure.

The complexity of the proper definition of the actual system to be reproduced by the simulation is one limiting factor from the experimental point of view. It is equally matched by a more than real difficulty from the numerical point of view, which entails to mesh issues. Mesh convergence is a classical pre-requisite for any numerical simulation. However, this is a real limit that offers in many practical cases no solutions. Indeed, the simulation of complex systems implies mesh tailoring, which means that the mesh is defined following an a priori knowledge of the physical mechanisms to reproduce (one knows that a shear layer requires from 10 to 20 mesh points across it or that an acoustic wave needs roughly the same amount of mesh points per wave length to be correctly propagated). The geometrical complexity of the system quite often consumes most of mesh point resources so that very little margin is left for mesh independence issues. At the level 4 position, one should realize that a given computation that produces usable results may do so by a delicate balance between resolved scales (assumed to be controlling the observed behaviour) and unresolved scales (that are properly taken care of by the mesh construction choices, that ensure that they are dissipated). Changing the mesh resolution may break this delicate balance by shifting part of the unresolved scales into a badly resolved scale range where their damping is no longer ensured by the numerical scheme. This may pollute the computation and produce erroneous results until the mesh resolution is further increased for that range of scale, but in doing so other unresolved scales will appear and so on. This difficulty limits the full scale a priori use of numerical simulation for complex system and explains the relative validation notion that represents the best of what can be obtained from a purely numerical procedure.

The four levels in development of computational models of complex engineering systems mentioned above are implemented in the virtual laboratory.

7 CFD tools

Computer-based training is gaining greater acceptance in industry to disseminate information. Network-based technology, when utilized properly, can foster and enhance such innovative instructional practices. Technology must be designed with specific problems in mind and should support meaningful collaboration and communication with others who share a real interest in solving real problems.

CFD tools are divided into several groups in terms of level of their complexity. These applications cover the range of simulation ability, from a simple Java applet to cutting edge parallel CFD solver.

Applying the different tools to the same problem will help to compare a contrast the capabilities of the different utilities. In the information space, a brief introduction is given to the thermofluids mechanics (what is fluid dynamics, classification of problems) and the types of physical and engineering systems that are modelled. In the problem space, applications are explored that allow to help convey fundamental concepts in thermofluids mechanics that allow for increased knowledge discovery.

CFD tools considered include slide show, flash and video clips, Java applications and Java applets, Matlab applications, commercial CFD packages and open source CFD toolbox.

Java applets are programs written in the Java programming language. They are often integrated with on-line web-pages. Java is very useful tool for education. Applets allow for easy integration into web based lecture material and on-line exercises. They are interactive and often include graphics. Many good applets with open source code already exist [25]. Applications that automate calculations with data visualization allow students to interact with science, not just observe trends. The code could be made conveniently available in a platform-independent form on the internet. Drawback is a high degree of programming effort. Java is not fast enough for many computational tasks. In this study, simple Java applets are designed for students learning the foundations of thermofluids mechanics. Removing some terms from the Navier–Stokes equations reduces the problem to one that can be solved analytically or numerically. Graphics user interface (GUI) allows students to dynamically change the orientation and design of the system and see real time changes in performance. The goal is to keep the formulation, logic and programming as simple as possible so that the student can easily grasp the flow of the calculations.

Matlab (the manufacture is the Mathworks Inc, www.mathworks.com) is the commercial software package for general mathematical modelling. Matlab is widely used in academic and industrial institutions for engineering and scientific numerical computation, visualization and complex problem solving in a fraction of the time required with a programming language. GUI is designed to lead students through exercises, good quality and easy to implement graphics, software can be used for other academic purposes. However, Matlab is not as fast as native code, and software has a financial cost to students. A set of Matlab functions is developed to simulate the fluid motion using numerical solution of governing equations. GUI is designed into the application to lead the students through the different steps of the solution. This allows for easy step-by-step example problems and allows students to gain experience with the terminology and work flow of CFD, while still learning about the flow problem at hand.

Commercial CFD packages use computers to develop solutions of fluid mechanics problems. A wide range of physical systems and processes can be simulated using numerous techniques and equations. They integrate pre-processor (meshing the object or domain to be analyzed, applying boundary conditions, set solver control parameters), solver (read in the mesh and supporting input files), and post-processor (read in solution and visually display data). The commercial CFD packages are able to solve more complex geometries and investigate regions of the flow where sensors cannot be placed. Once the governing equations for a problem have been derived, the task of solving them numerically is started. A fundamental aspect of CFD is to divide the spatial domain into small cells to form a volume mesh. Advances in mesh generation allow complex CAD geometries to reliably be meshed from solid meshes. Suitable algorithms to solve the equations are then applied. Many commercial CFD packages support distributed memory parallel processing.

This level provides a virtual thermofluids laboratory for teaching and virtually reinforcing concepts in fluid flow and heat transfer. Acquaints students with the terminology of CFD, basics of geometry and mesh generation, setting up a problem, concepts of accuracy and convergence, post-processing are ensured.

Students are asked to review basic CFD tutorials. These exercises give them knowledge of the overall capabilities and software mechanics of solving fluid flow problems and extracting information from a simulation. The students evaluate the importance of boundary conditions as well as vary the mesh quality using near wall boundary layer refinement. Students are able to understand the importance of obtaining mesh independent CFD analysis and how input parameters can impact results. The test cases are released with a validation file that demonstrates the capability and accuracy of the code for selected test cases.

One of open source CFD toolbox is OpenFOAM (Open Field Operation And Manipulation, www.openfoam.com). It represents a collection of solvers and utilities for solution of fluid flows involving different physical phenomena (turbulence, heat transfer etc) as well as several other areas, and is supplied with source code. OpenFOAM is licensed under the GNU general public license.

OpenFOAM includes an extensive set of meshing utilities with limited GUI features, and numerous utilities to import meshes from commercial mesh generators. Pre-processor uses internal command line utilities and viewing mesh with ParaView post-processor. The input files are created or edited with text editor. Web interfaces to OpenFOAM are available (e.g., Ralph Regula CFD portal, sc09.sc-education.org). Web interface makes possible access to OpenFOAM from labs and laptops.

The tutor creates models using standard OpenFOAM features and defines which parameters can be changed by students. Students can view data plots set by the tutor. Students are able to monitor residuals for most models and terminate batch job if solution fails to converge.

To implement and embed inquiry-based exercises to learning and teaching, interactive and matrix-based system Matlab and CFD packages are used as a way to motivate engineering students to develop creative problem solving skills within IBL scenario. Using C/C++ or Fortran compilers (both Windows and Unix operating systems are considered), the Matlab code is transformed to executable module and installed on desktop computer. The Matlab is used to build the interface and communications between different computational tools. To build the distributed inquiry-based system, Java-applet technology is applied.

8 Thermofluids interactive collection

To engage students' curiosity and interest, the computational technology is either simple or easy to understand. Students are more likely to reveal their misconceptions when the numeric technology is familiar or at least not too complex. Where possible, the exercise is designed to force students to make an either-or choice in their prediction of the system response to an input. Those binary choices provide a clear distinction between understanding of the course material and not understanding it.

8.1 Implementation

Computer-based training is gaining greater acceptance in industry to disseminate information. Network-based technology, when utilized properly, can foster and enhance such innovative instructional practices. Technology must be designed with specific problems in mind and should support meaningful collaboration and communication with others who share a real interest in solving real problems. The existing teaching materials are modified, adapted and integrated with new units in new format.

Typical view of the main window of the virtual learning environment is presented in the Fig. 3 (Internet Explorer is used as internet browser).

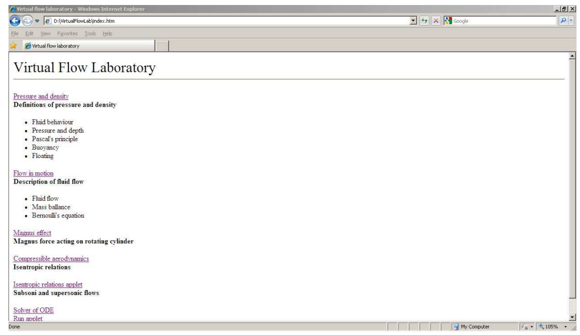

Fig. 3. Main window of learning environment.

The Java language is selected so that such codes could be made conveniently available in a platform-independent form on the internet. The goal has been to keep the formulation, logic and programming as simple as possible so that the student can easily grasp the flow of the calculations.

Several fundamental problems of fluid dynamics are considered and examined how different computational tools can be used to solve the problem and highlight characteristics. The flash-clips explain the definitions of pressure and density, and influence of buoyancy, main features of fluid motion and analysis of fluid flow based on mass balance equation and Bernoulli's equation. Some of flash-clips are related to more advanced problems, e.g. one flash clip introduces to the Magnus effect based on lift force acting on rotating cylinder.

An active collection of executable thermofluids exercises was deployed on computational server of the Kingston University, and is accessible via intranet.

8.2 Features

Research-based numerical algorithms operating behind the scenes are completed to solve the thermofluids problems in real time. Some of topics covered in lectures are much too complicated for the student to create a model, but using well designed, graphically-rich software allows the student to explore the physics by complete immersion.

The iterative nature of the laboratory directly addresses several components of undergraduate education and follows the cyclic model for knowledge generation and improvement.

Many of the useful results were recorded in tables, graphs and correlations. Though convenient and necessary at the time, these pre-computer analysis and design procedures often serve mainly to obfuscate the underlying physics. In contrast to the subject matter, the possibilities for teaching and learning thermofluids concepts have expanded dramatically since the advent of the personal computer.

Virtually everything are studied in thermofluids can be presented visually and dynamically. Even a simple analytical solution can be plotted up readily so that it becomes a physical problem and no longer just a mathematical exercise. Extensive use of graphics for display of the solution means that students can see, and hopefully understand the physics involved and then are ready to move on to design applications. A simple, but graphically-rich demonstration can often make a point much more vividly than the corresponding and often obtuse differential equation or worse, a table of numbers. Students should be able to explain any trends observed on their screens.

Thermofluids models are presented with increasing degrees of complexity from the simplest integral equations (mass balance and energy balance equations for steady state conditions) to full unsteady 3D numerical simulations. In the first case, system under the study does not require a detailed knowledge of the flow. Equations are formulated in terms of finite systems and control volumes. This way is often easier to treat analytically. Once the problem is classified, the equations that describe the fluid system can be derived. Due to complex geometries or lack of realistic analytical equations, numerical methods are used to approximate the fluid equations. In the second case, equations are formulated in terms of infinitesimal control volumes. Solution of ordinary or partial differential equations determines the detailed, point by point, behavior of the flow.

8.3 Case studies

A number of interactive exercises involving transferable key skills have been formulated and implemented as a part of the virtual thermofluids laboratory. Several fundamental problems in fluid mechanics are considered and examined how different computational tools can be used to solve the problem and highlight characteristics. Some of these case studies are described below.

8.3.1 Tank filling

The objective of the tank filling exercise is to develop in students a solid conceptual understanding of the hydrostatic equation. In particular, the experiment confronts the misconception that in a stationary fluid the pressure at a given depth is determined by the weight of the water above that depth. It is possible for students to complete the exercise with only a basic knowledge of physics and without any prior exposure to fluid mechanics.

8.3.2 Compressible aerodynamics

Isentropic flow calculator solves the isentropic flow equations for a variety of inputs. Variables include the Mach number, temperature, density ratios, dynamic to static pressure ratio, critical area ratio, Mach angle, and Prandtl–Meyer angle. Specifying any one variable determines the value of all the other variables. Three sets of relations have been developed: isentropic flow relations; normal shock relations; oblique shock relations. The relations themselves are taken from standard aerodynamics texts.

8.3.3 Flow in nozzle

This Matlab code solves the isentropic flow equations for the flow through a rocket nozzle, a converging-diverging turbine nozzle or a converging turbine nozzle. The solution covers all flow regimes in the nozzle (subsonic and supersonic) depending of the ratio of reservoir pressure and atmospheric pressure. Input variables include the throat area, throat to exit area ratio, total pressure and temperature in the reservoir and free stream pressure. Students can select working gas from a variety of combinations, or specify their own molecular weight, ratio of specific heats, and temperature. Output includes the flow through the nozzle, the thrust, specific impulse, exit velocity and Mach number, and exit static pressure.

Isentropic calculations are implemented in the form of Java applet presented in the Fig. 4. The applet designed can be used for sub-sonic and super-sonic calculations. The calculations are based on mathematical formulas which are presented in standard textbooks on thermodynamics and fluid mechanics.

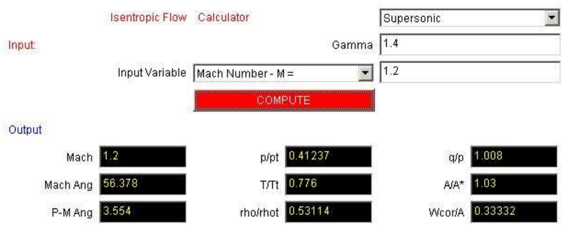

Fig. 4. Screen of Java applet implementing isentropic calculations.

8.3.4 Sudden expansion

The objective of the sudden expansion exercise is to investigate the relationship between pressure drop and area change for the flow air through a sudden expansion in a circular duct. Students calculate the relationship between the pressure across the sudden expansion and the magnitude of the centreline velocity immediately downstream of the sudden expansion. The sudden expansion exercise provides an opportunity to address two student misperceptions. The first is the assumption that fluid pressure must always decrease in the direction of flow. The second is that Bernoulli's equation can always be applied.

The assignment in the exercise is to calculate the pressure difference across the sudden expansion and to relate the pressure difference to the prediction of the Bernoulli equation. Before recording any data, the students are asked to predict the sign of the pressure difference: does the pressure increase or decrease in the flow direction?

The guided-inquiry worksheet guides students through additional analysis with the newly collected data. In particular, students are asked to compare the predicted pressure rise with the pressure rise obtained with the Bernoulli equation. Analysis with the Bernoulli equation points out the misconception to students who first predicted that the pressure must decrease in the flow direction. The calculated pressure rise is several hundred percent smaller than the pressure rise predicted by the Bernoulli equation.

8.3.5 Heat diffusive equation

Heat diffusive equation is a fundamental thermodynamics problem of practical importance. The tools designed involve numerical solution of the heat diffusive equation based on finite difference method and Cartesian meshes. Solution of heat equation is implemented in Matlab based on explicit finite difference scheme for temporal derivative and finite difference scheme of the 2nd order for spatial derivatives. Effects of Fourier number and stability of finite difference schemes are included in analysis. This example helps students to understand that physically corrected solution of heat transfer equation that can be obtained with special combination of mesh step and time step.

9 Benefits

Thermofluids modules are in many undergraduate curriculums. Computational techniques offer many educational benefits in helping convey fundamental thermofluids concepts.

Students not familiar with fluid mechanics seem to like the interactive process and obtaining the solution. Students with fluid mechanics behaviour will benefit from being able to interact with solution results and see system characteristics that have been covered in lecture.

Access to the virtual laboratory gives students the opportunity to not only receive feedback as a result of an assessment, but through the interactive environment students also receive continual feedback during the assessment and are able to immediately self correct. Following this way, students do not have to wait until they receive feedback from their tutor to have their misconceptions clarified, instead gaps in knowledge can be addressed immediately and lead-on tasks are not impinged.

Through the implementation of the virtual laboratory tutors are provided with an extra level of easily accessible diagnostic information pertaining to student performance. Students' problems are having with particular topics can be analysed on a more granular level and through the homework comment box at the end of each problem.

The content coverage includes content through many areas of engineering, and can be useful for students from disciplines outside mechanical, automotive and aerospace engineering.

10 Evaluation

Good assessment techniques are critical in both developing and measuring the success of educational activities. The assessment of both short-term outcomes (individual laboratory experiences) and long-term outcomes (increased student knowledge and enhanced curriculum) are all very important.

Methods of assessment include an informal interview of the entire class, quizzes and surveys.

All students complete pre- and post-lab quizzes in addition to a guided-inquiry worksheet.

1. The pre-lab quiz assesses the students' knowledge before the exercise, and in particular their misconceptions related to the material. The quiz consists of one or two (depending on the exercise) simple qualitative reasoning questions. Students are given points for completing the pre-quiz, but are not graded for correctness of their answers.

2. The laboratory exercise consists of a worksheet of several pages. The purpose of the exercise is to reinforce core concepts by applying direct observation and simple analysis. The laboratory exercise is also designed to further expose and correct misconceptions that the student might have.

3. The post-lab quiz assesses whether students' misconceptions persisted after completing the laboratory exercises. As with the pre-lab quiz, students are given points for completing the pre-quiz, but are not graded for correctness of their answers.

Feedback is obtained by the use of on-line tracking in the virtual learning environment and on-line student questionnaires.

The virtual laboratory has been used in the modules delivered in the Kingston University. These modules are 'Thermodynamics and Fluid Mechanics' and 'Energy Systems' delivered for 2nd and 3rd year MSc students in mechanical and automotive engineering. Groups of students included about 35 students for Thermofluids module, and about 20 students for Energy systems module. Students actively used the virtual learning environment during the term that led to improvement of coursework and exam successive rate. Improvement of mark was about 10% for coursework, and about 6% for exam.

11 Conclusion

The study illustrated the potential of developing students' experience of research to enhance their progression in higher education and their employability.

The thermofluids virtual laboratory based on inquiry-based pedagogical model improves learning of core concepts and increase student appreciation of design work. Virtual laboratory enables students to learn about real-world industrial applications of thermofluids (aero-engines, gas turbines, nozzle-based devices, vehicle aerodynamics). The virtual environment enables students to see how all these topics are related within the course and to understand their global relevance in the rapidly changing world.

The study promotes integration of knowledge acquisition, skill training and industrial application. The virtual laboratory created develops physical insight and is useful for ready application in design and the end-of-chapter homework problems.

The current Matlab toolbox capability is extended to address a number of fluid dynamics and heat transfer problems. Students are able to both learn from and contribute to the growing collection of executable software content as well as applications and interfaces to that software. Then it may be accessible from the universities and organisations interested in this virtual laboratory.

The study provides the opportunity for the students to appreciate some real issues that companies face when migrating from traditional product development process to the simulation-led approach. This prepares students for a job as a virtual engineer or other roles in companies able to facilitate the implementation of simulation-led product design process. The study illustrates a potential of developing students' experience of research to enhance their progression in higher education and their employability.

New facilities to support interdisciplinary projects, industrial group design projects and individual students' projects, and significant expansions to the engineering and education programs are provided.

The virtual laboratory is used in the existing courses run by the School of Mechanical and Automotive Engineering of the Faculty of Science, Engineering and Computing (Kingston University, London, UK). The content coverage includes content through many areas of engineering, and can be useful for students from disciplines outside mechanical and automotive engineering. The virtual learning environment provides wide opportunities for further extension.

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