INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 10, Issue 1, 2019 pp.1-14
Journal homepage: www.IJEE.IEEFoundation.org

EDITORIAL

Applications of Computational Fluid Dynamics (CFD) technology in engineering education

Maher A.R. Sadiq Al-Baghdadi

Editor-in-Chief, International Journal of Energy and Environment, Official Journal of the International Energy and Environment Foundation, Najaf, P.O.Box 39, Iraq.

1. Historical background

One of the earliest mathematical writings is the Babylonian tablet YBC 7289 (Figure 1), which gives a sexagesimal numerical approximation of square root, the length of the diagonal in a unit square [1].

Figure 1. Babylonian clay tablet YBC 7289. Mesopotamia (Iraq).

Babylonians in this clay tablet have been used algorithms to compute side lengths of right-angled triangles into areas, and vice versa, similar to our contemporary numerical methods of analysis [2-5]. The Babylonian method is numerically stable, it is converges fast regardless of the initial guess, while

Method X is extremely slowly and hence numerically unstable [2-8]. Numerical analysis continues this long tradition of practical mathematical calculations. Much like the Babylonian approximation of square root, modern numerical analysis does not seek exact answers, because exact answers are often impossible to obtain in practice. Instead, much of numerical analysis is concerned with obtaining approximate solutions while maintaining reasonable bounds on errors. These consist of splitting the volume that is being analyzed (say the material of a beam, or the air in a room) into small elements (typically Platonic solids like prisms or tetrahedral). It is interesting to think that this so-called "meshing" in the engineering world, or splitting a calculation into small portions, was already applied by the old Babylonians. Nowadays, in a very similar manner, computers are used to find the distribution of properties (e.g., stress, deflection, etc.) along a material (e.g., a metal beam), or even the displacement of fluids through volumes (i.e., computational fluid dynamics) [9-12].

The Old Babylonians had knew, understood, and used what is now called the Pythagoras' (or Pythagorean) theorem. They applied it in very practical problems. A remarkable Old Babylonian clay tablet, commonly referred to as Plimpton 322 (Figure 2), was found to store combinations of three positive integers that satisfy Pythagoras' theorem [2, 7, 13]. Today we call them primitive Pythagorean triples where the term primitive implies that the side lengths share no common divisor. The reason behind the tablet was not an interest in the number-theoretical question, but rather the need to find data for a 'solvable' mathematical problem.

Figure 2. Old Babylonian clay tablet (known as Plimpton 322) stores combination of primitive Pythagorean triples. Mesopotamia (Iraq).

2. Computational fluid dynamics and finite element methods

Computational Fluid Dynamics (CFD) and Finite Element Methods (FEM) are the sciences of predicting fluid flow, heat transfer, mass transfer, phase change, chemical reaction, mechanical movement, stress or deformation of related solid structures, and related phenomena by solving the mathematical equations that govern these processes using a numerical algorithm on a computer. We typically use CFD to simulate and analyze fluids and flow and FEM to simulate and analyze various stresses and forces on solids. The results of CFD and FEM analyses are relevant in: conceptual studies of new designs, detailed product development, troubleshooting, and redesign. CFD and FEM analysis complements testing and experimentation, by reduces the total effort required in the experiment design and data acquisition. CFD and FEM complements physical modelling and other experimental techniques by providing a detailed look into our engineering problems, including complex physical processes such as turbulence, chemical reactions, heat and mass transfer, and multiphase flows. Simulations can readily be done of physical phenomena that are difficult to measure, for example, full scale situations, environmental effects and hazards. In many cases, we can build and analyze virtual models at a fraction of the time and cost of physical modelling. This allows us to investigate more design options and "what if" scenarios than ever before. Moreover, flow modelling provides insights into our fluid flow problems that would be too costly or simply prohibitive by experimental techniques alone. The added insight and understanding gained from flow modelling gives us confidence in our design proposals, avoiding the added costs of over-sizing and over-specification, while reducing risk.

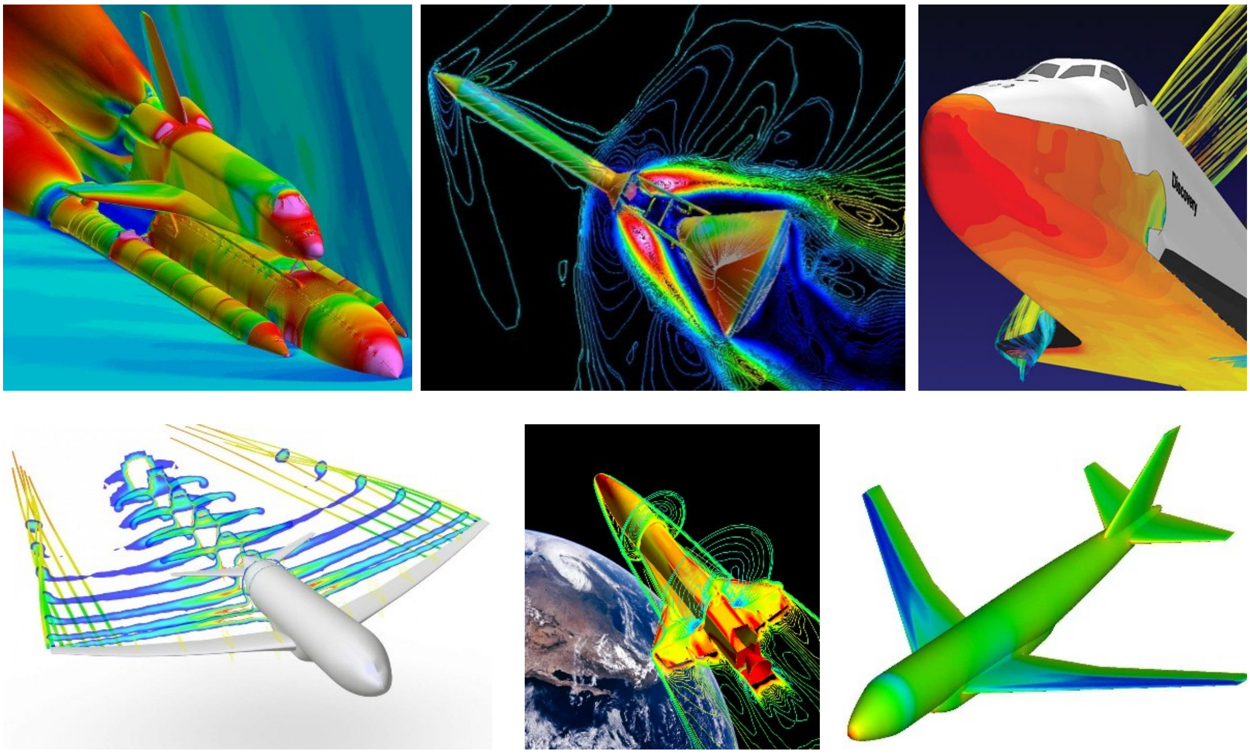
3. CFD and FEM as education tool

While CFD is typically studied at the graduate-level, the ease of use and broad capability of commercial CFD software packages have enabled this tool to be brought down into the undergraduate classroom [14-16]. For an introductory engineering curriculum, such a CFD-based educational software package allows students to readily solve fluid dynamics problems without requiring a long training period. The mission is to expose students to essential CFD concepts and expand the learning experience with real-world applications, which is becoming an increasingly important skill in today's job market. With user-friendly and student-specific graphical user interfaces guiding the students through the stages of geometry - creation and mesh generation, computational simulations and viewing the results by means of vectors, contours, or animated movies - the teaching of CFD has never been so visually exhilarating.

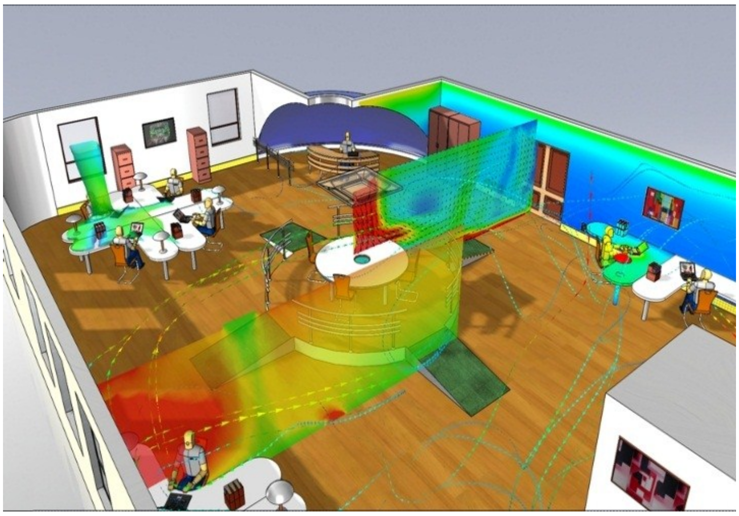
4. Applications of CFD and FEM

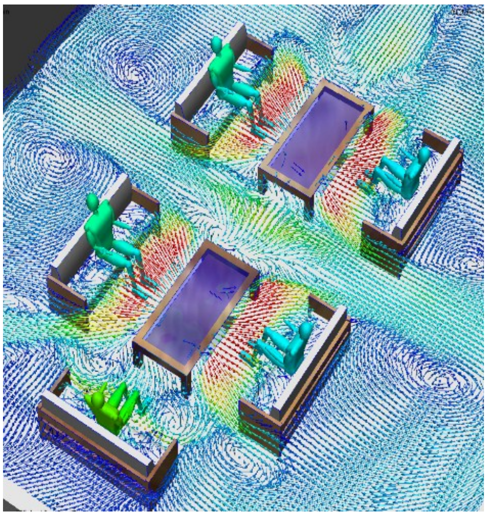
As CFD and FEM have so many advantages, it is already generally used in industry such as aerospace, automotive, industrial equipment, biomedicine, healthcare, chemical processing, heat ventilation air condition, environment, hydraulics, power generation, sports, marine, oil & gas, electronics & semiconductor, architecture & construction, and many, many more!. The list goes on and on. These are but a very few examples of how the methods of CFD and FEM are being used today [18-26].

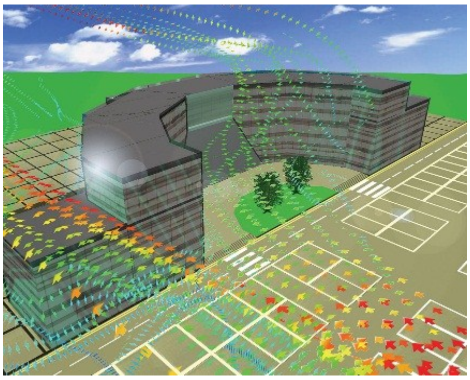
Aerospace

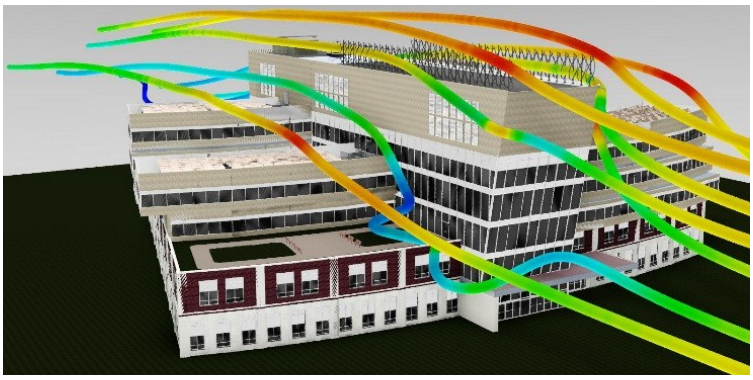


Heat ventilation air condition

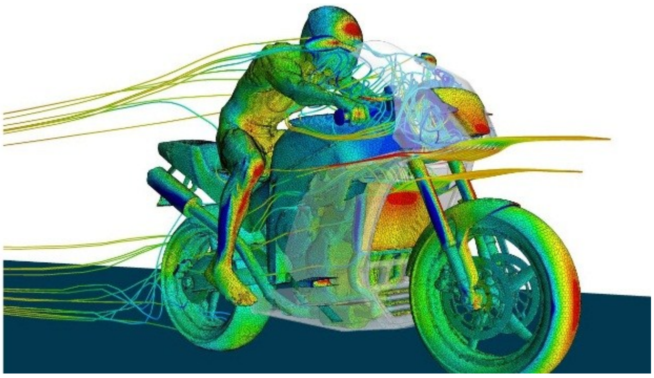


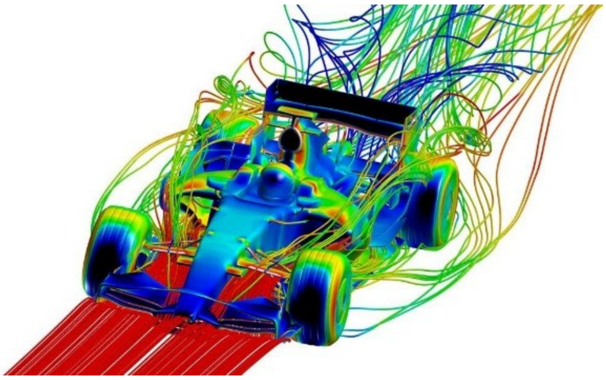


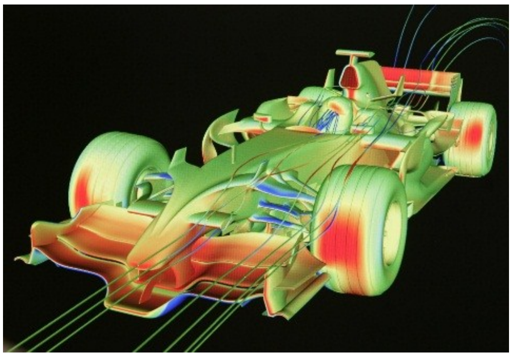


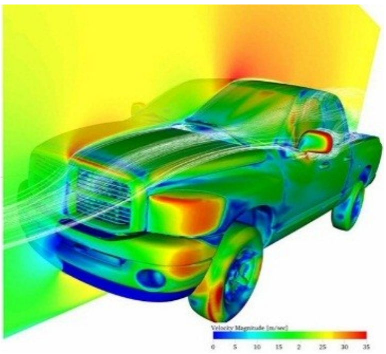


Automotive

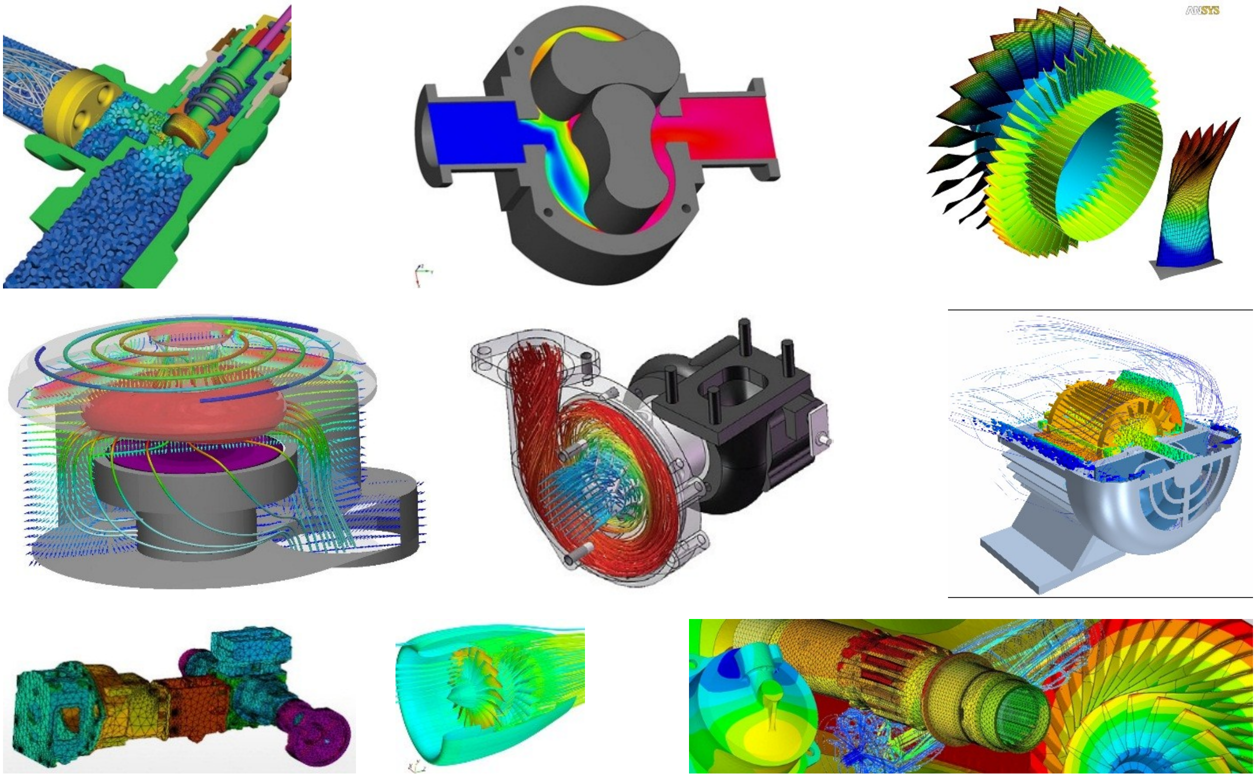




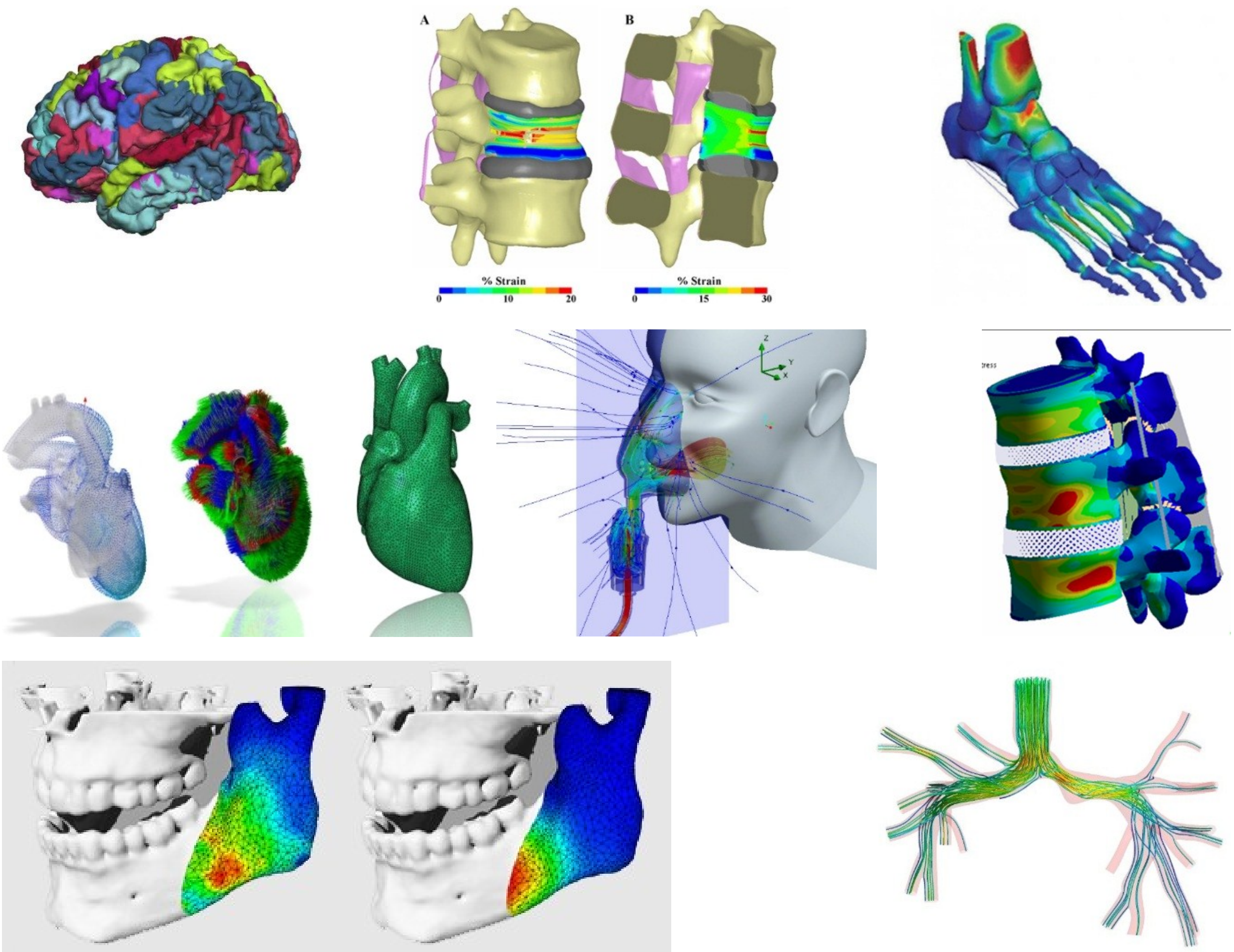




Industrial equipment

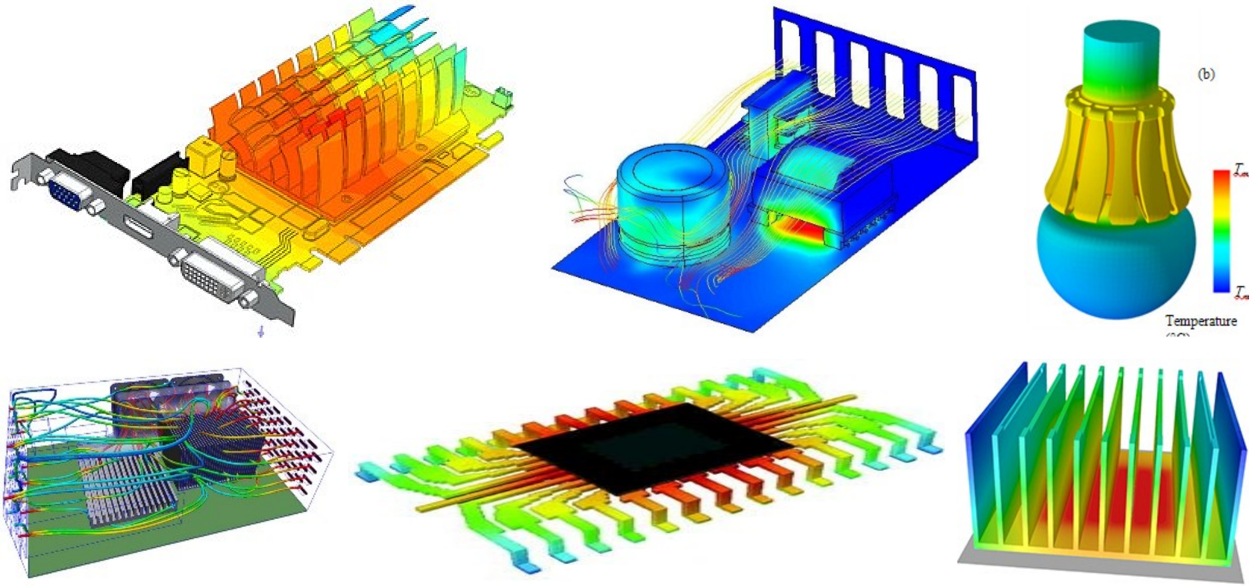


Biomedicine and healthcare

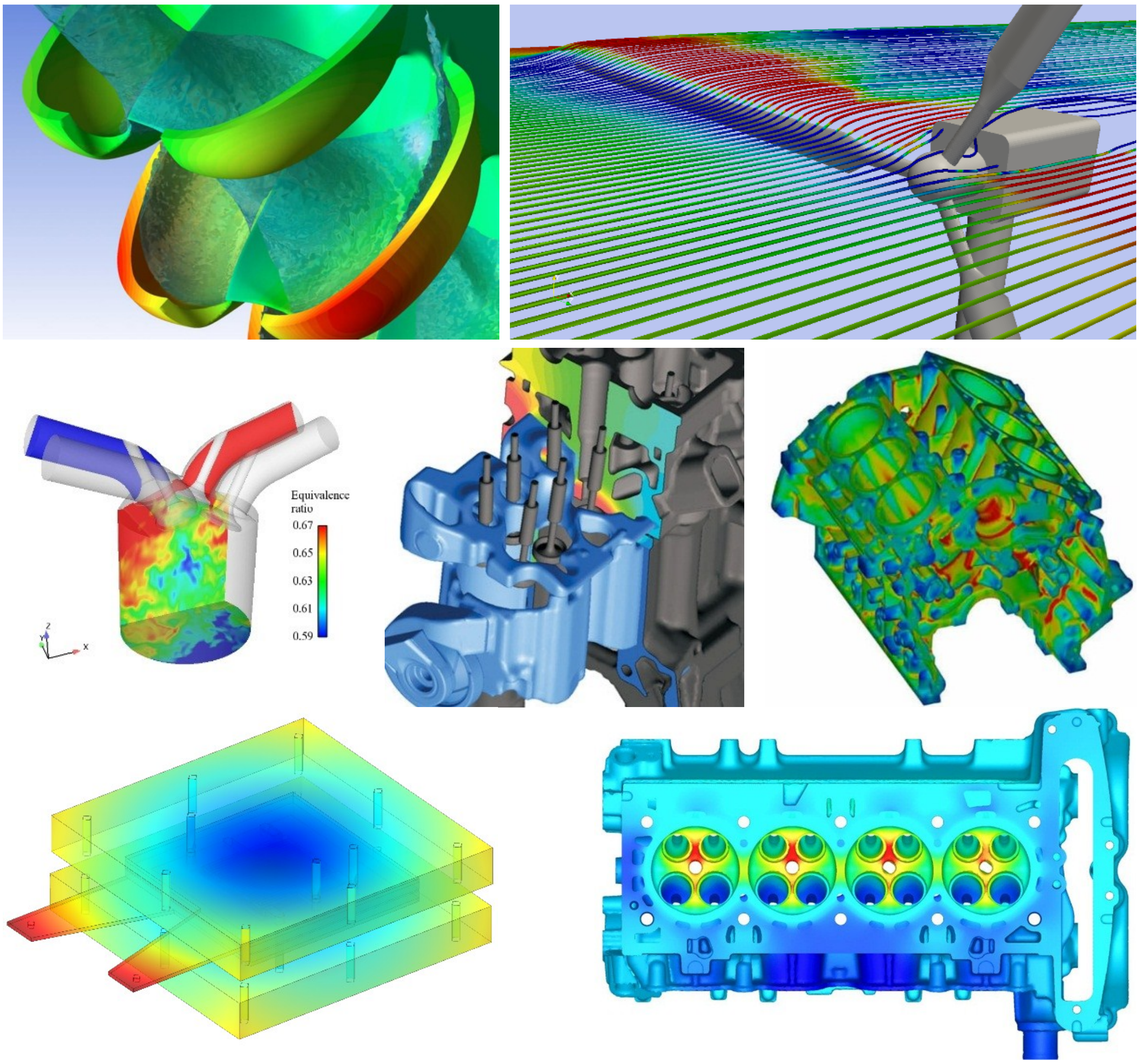


ISSN 2076-2895 (Print), ISSN 2076-2909 (Online)

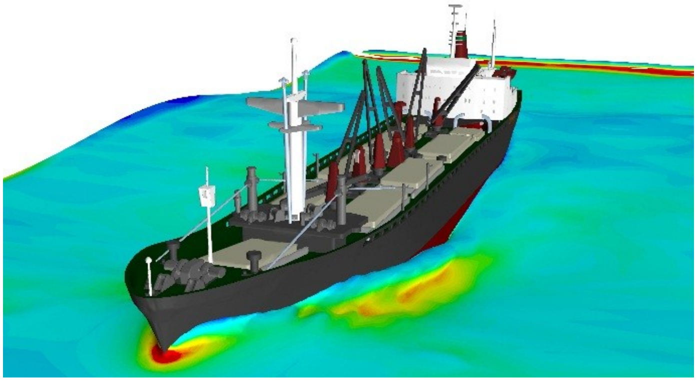
Electronics and semiconductor

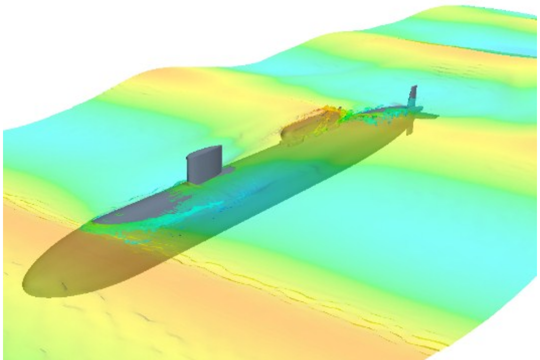


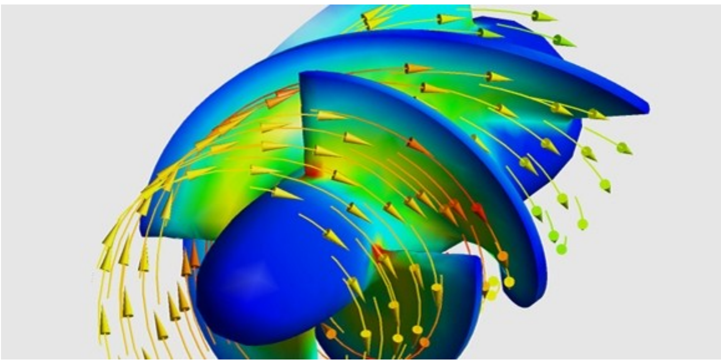
Power generation

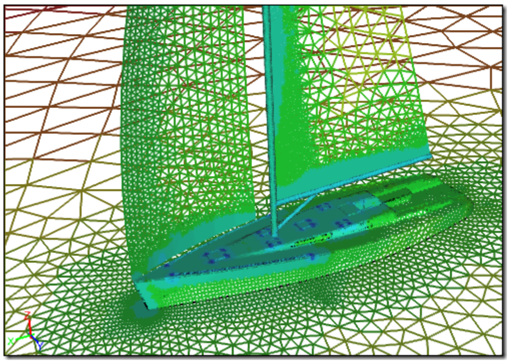


Marine

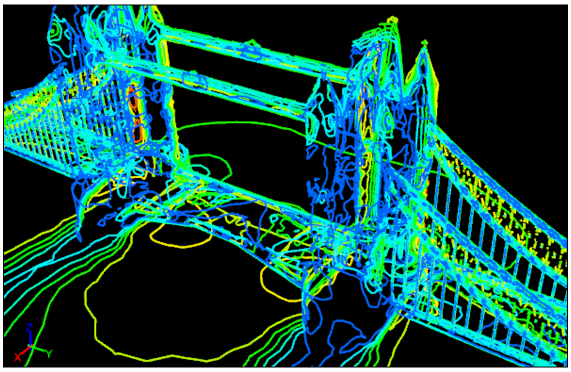


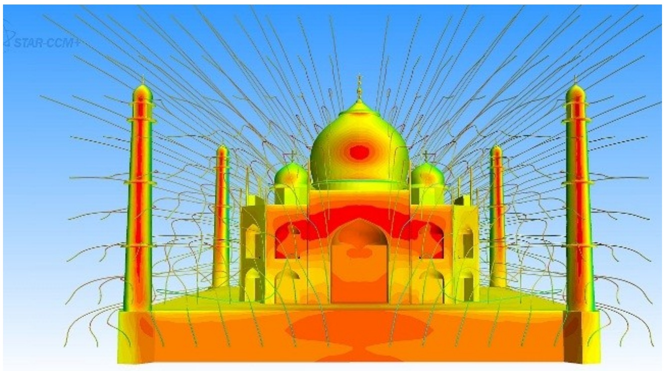


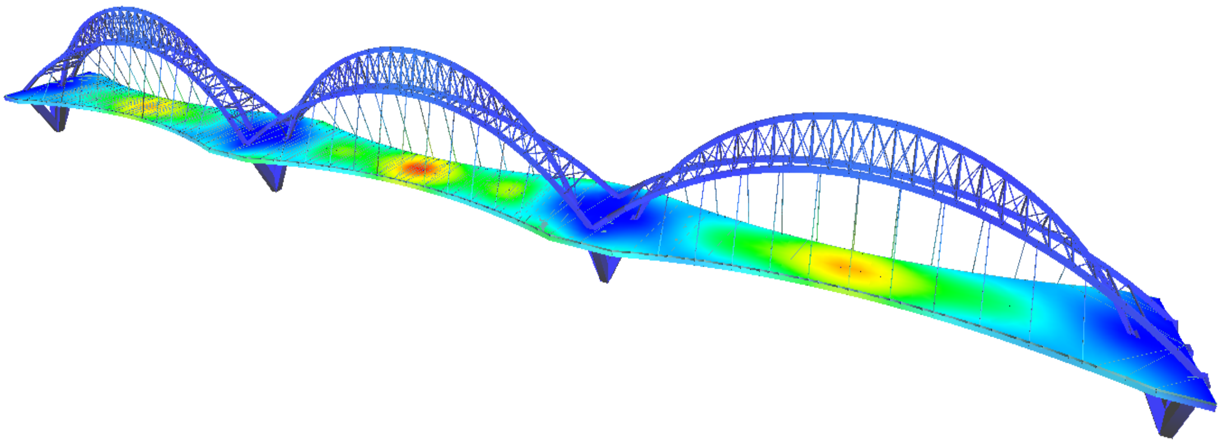




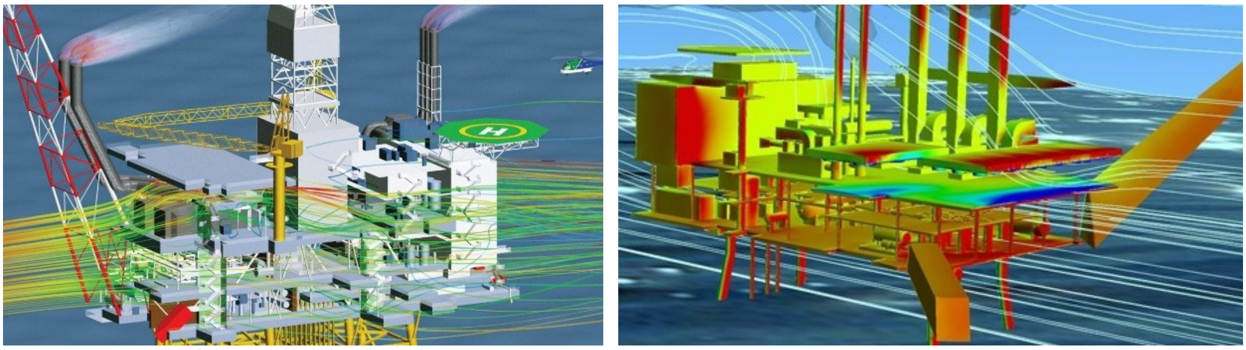
Architecture and construction



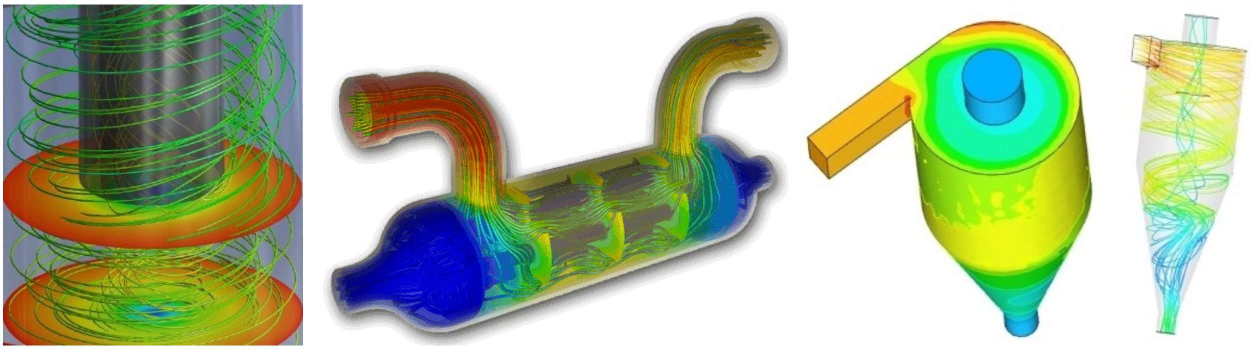




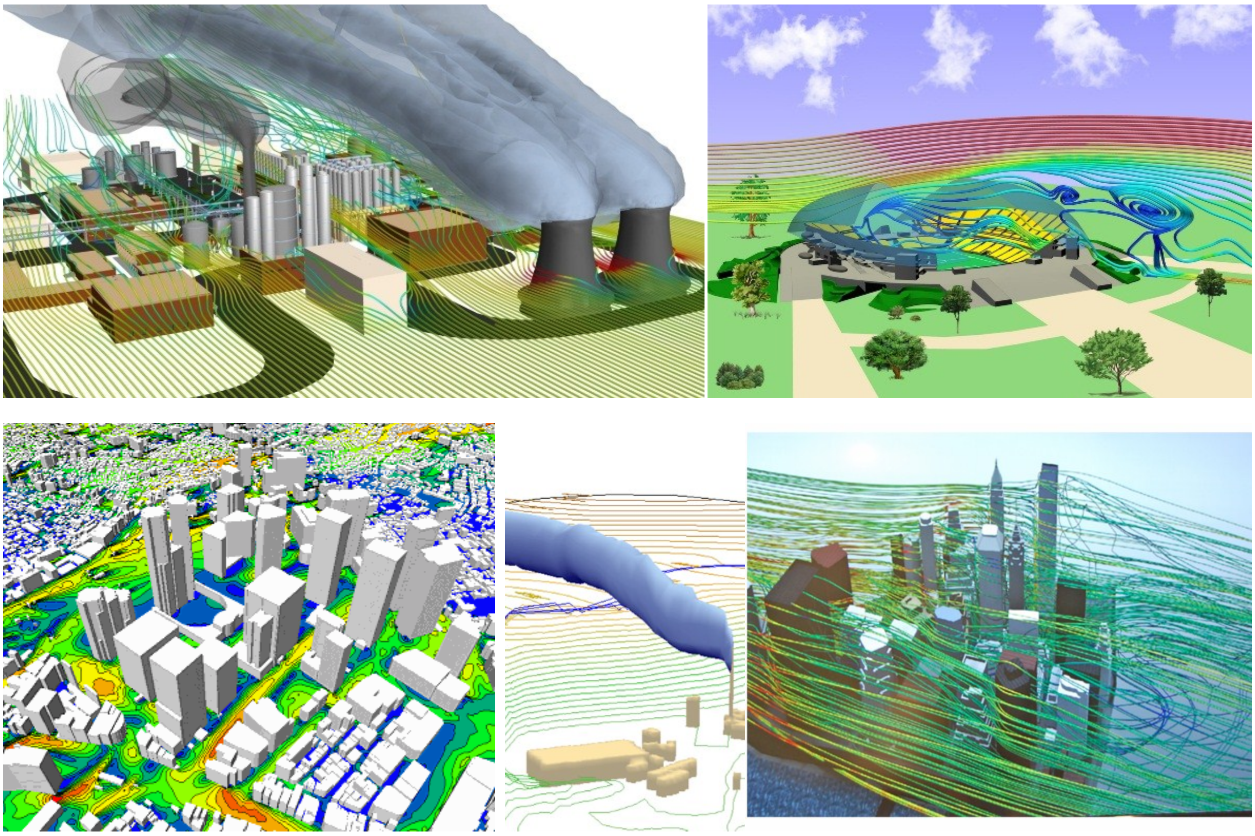
Oil and gas



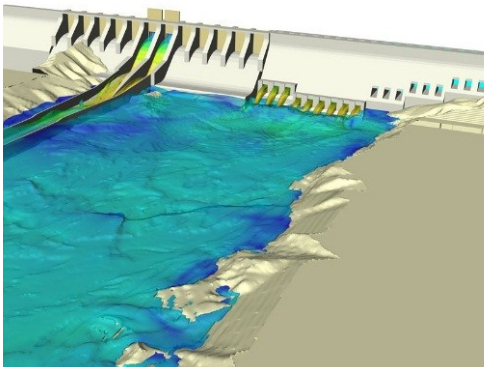
Chemical processing

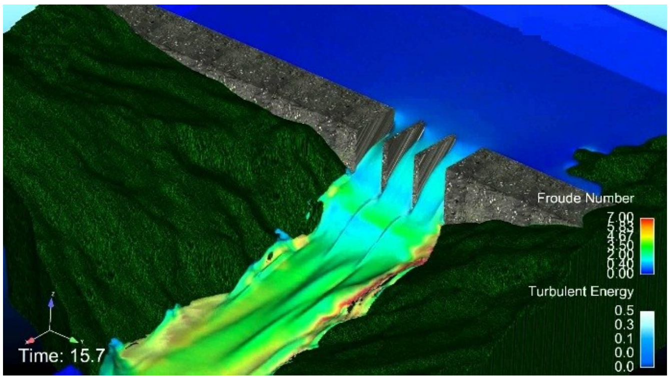


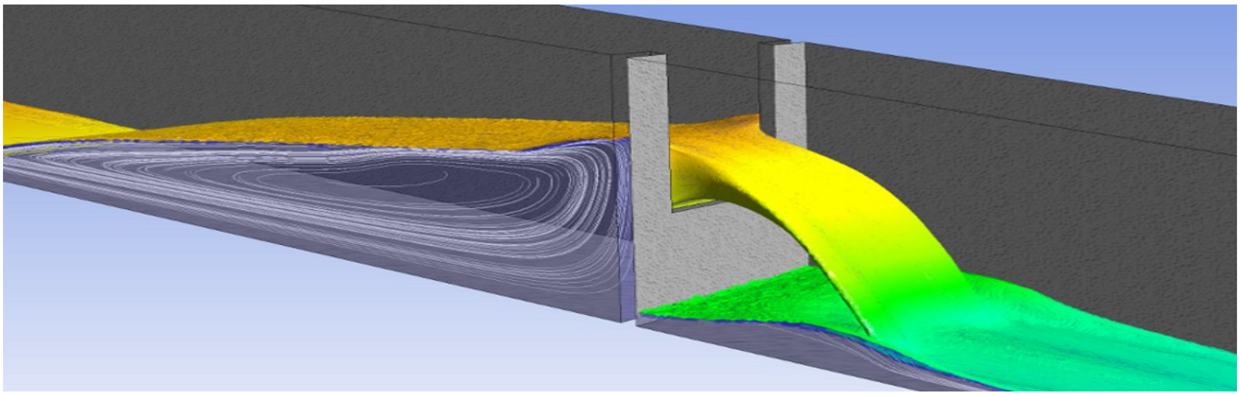
Environment



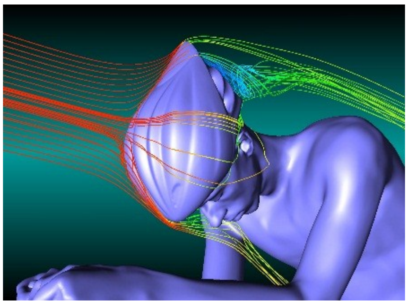
Hydraulics

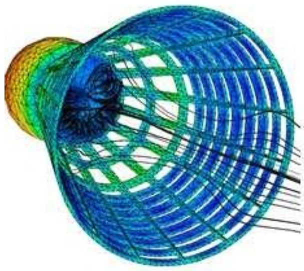


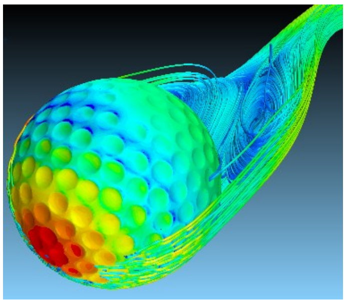


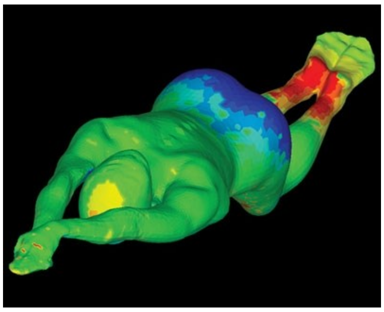


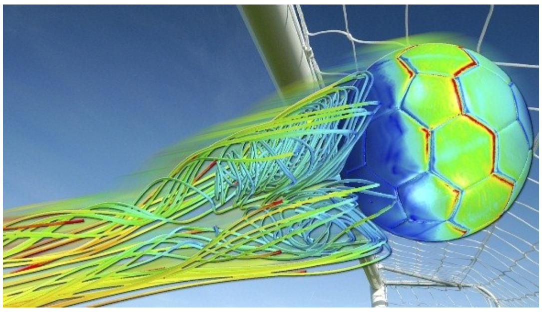
Sports

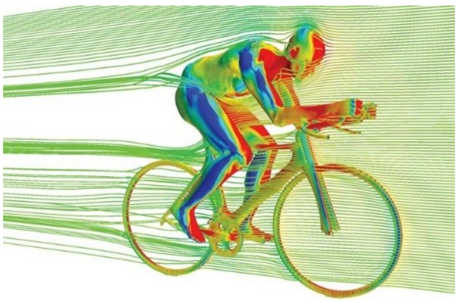


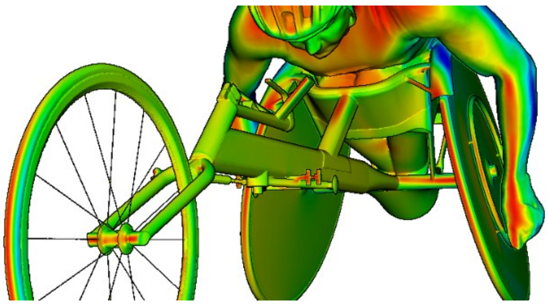












5. Advantages of computational fluid dynamics
There are many advantages in considering computational fluid dynamics. Firstly, the theoretical development of the computational sciences focuses on the construction and solution of the governing equations and the study of various approximations to these equations. CFD presents the perfect opportunity to study specific terms in the governing equations in a more detailed fashion. New paths of theoretical development are realized, which could not have been possible without the introduction of this branch of computational approach. Secondly, CFD complements experimental and analytical approaches by providing an alternative cost-effective means of simulating real-life system. Particularly, CFD substantially reduces lead times and costs in designs and production compared to experimental-based approach and offers the ability to solve a range of complicated problems where the analytical approach is lacking. These advantages are realized through the increasing performance power in computer hardware and its declining costs. Thirdly, CFD has the capacity of simulating flow conditions that are not reproducible in experimental tests found in geophysical and biological fluid dynamics, such as nuclear accident scenarios or scenarios that are too huge or too remote to be simulated experimentally (e.g., Indonesian Tsunami of 2004). Fourthly, CFD can provide rather detailed, visualized, and comprehensive information when compared to analytical and experimental fluid dynamics. Table 1. shows the comparison of experiment and CFD simulation in engineering applications.

Table 1. Comparison of experiment and CFD simulation in engineering applications.

Experiments	CFD simulation
Quantitative description of flow phenomena using measurements.	Quantitative prediction of flow phenomena using CFD software.
• for one quantity at a time	• for all desired quantities
• at a limited number of points and time instants	• with high resolution in space and time
• for a laboratory-scale model	• for the actual flow domain
• for a limited range of problems and operating conditions	• for virtually any problem and realistic operating conditions
• expensive	• cheap(er)
• slow	• fast(er)
• sequential	• parallel
• single-purpose	• multiple-purpose
Equipment and personnel are difficult to transport.	CFD software is portable, easy to use and modify.
Error sources: measurement errors, flow disturbances by the probes, complexity.	Error sources: modeling, discretization, iteration, implementation.

6. CFD modelling procedure
Prior to setting up and running a CFD simulation there is a stage of identification and formulation of the problem in terms of the physical and chemical phenomena that need to be considered. For a given problem, you will need firstly to define your modelling goal, and create the domain for the problem (model's geometry). Specification of the domain geometry is the main task at the input stage and subsequently the user needs to obtain a successful simulation result. Typical decisions that might be needed are whether to model a problem in two or three dimensions. To make the right choices requires

good modelling skills, because in all but the simplest problems we need to make assumptions to reduce the complexity to a manageable level whilst preserving the salient features of the problem at hand. It is the appropriateness of the simplifications introduced at this stage that at least partly governs the quality of the information generated by CFD, so the user must continually be aware of all the assumptions, clear-cut and tacit ones, which have been made.

Analysis begins with a mathematical model of a physical problem, where the conservation of matter, momentum, and energy must be satisfied throughout the region of interest (specify governing equations, "select physics").

Specify physical properties to model, such as viscosity, thermal conductivity, and density to define a problem (add material to model).

Provide appropriate initial and boundary conditions for the problem, user needs specify them for different applications.

Domain is discretized into a finite set of control volumes or cells. The discretized domain is called the "grid" or the "mesh". Specification of the grid design is very important to obtain a successful simulation result. There is no formal way of estimating the errors introduced by inadequate grid design for the domain. Good initial grid design relies largely on an insight into the expected properties of the problem. The only way to eliminate errors due to coarseness of a grid is to perform a grid dependence study, which is a procedure of successive refinement of an initially coarse grid until certain key results do not change. Then the simulation is grid independent. A systematic search for grid-independent results forms an essential part of all high-quality CFD studies.

Specify the study (e.g., stationary, time dependent, etc.). All equations are solved simultaneously to provide solution. The solution is post-processed to extract quantities of interest. Examine the results and consider revisions to the model to ensure property conservation and correct physical behaviour. The flow diagram of the algorithm is shown in Figure 3.

At the end of a simulation the user must make a judgement whether the results are ‘good enough’. It is impossible to assess the validity of the models of physics and chemistry embedded in a program as complex as a CFD code or the accuracy of its final results by any means other than comparison with experimental test work. Anyone wishing to use CFD in a serious way must realise that it is no substitute for experimentation, but a very powerful additional problem solving tool. Validation of a CFD code requires highly detailed information concerning the boundary conditions of a problem, and generates a large volume of results. To validate these in a meaningful way it is necessary to produce experimental data of similar scope. Sometimes the facilities to perform experimental work may not (yet) exist, in which case the CFD user must rely on; previous experience, comparisons with analytical solutions of similar but simpler problems, and comparisons with high-quality data from closely related problems reported in the literature.

Experimental data is the observation of the "real world" in some controlled manner. By comparing the CFD results to experimental data, one hopes that there is a good agreement, which increases confidence that the physical models and the code represents the "real world" for this class of simulations. However, the experimental data likely has uncertainties and contains some level of error. This is usually related to the complexity of the experiment. In comparing the CFD simulation results to experimental data, one should discuss the experimental errors. Plots comparing CFD results and experimental data should include a visual display of the error bars on the experimental data.

CFD computation involves the creation of a set of numbers that (hopefully) constitutes a realistic approximation of a real-life system. One of the advantages of CFD is that the user has an almost unlimited choice of the level of detail of the results, but in the prescient words of C. Hastings [27], “The purpose of computing is insight not numbers.” The underlying message is rightly cautionary. We should make sure that the main outcome of any CFD exercise is improved understanding of the behaviour of a system, but since there are no guarantees with regard to the accuracy of a simulation, we need to validate our results frequently and stringently.

It is clear that there are guidelines for good operating practice which can assist the user of a CFD code, and repeated validation plays a key role as the final quality control mechanism. However, the main ingredients for success in CFD are experience and a thorough understanding of the physics of the problem and the fundamentals of the numerical algorithms. Without these it is very unlikely that the user will get the best out of a code.

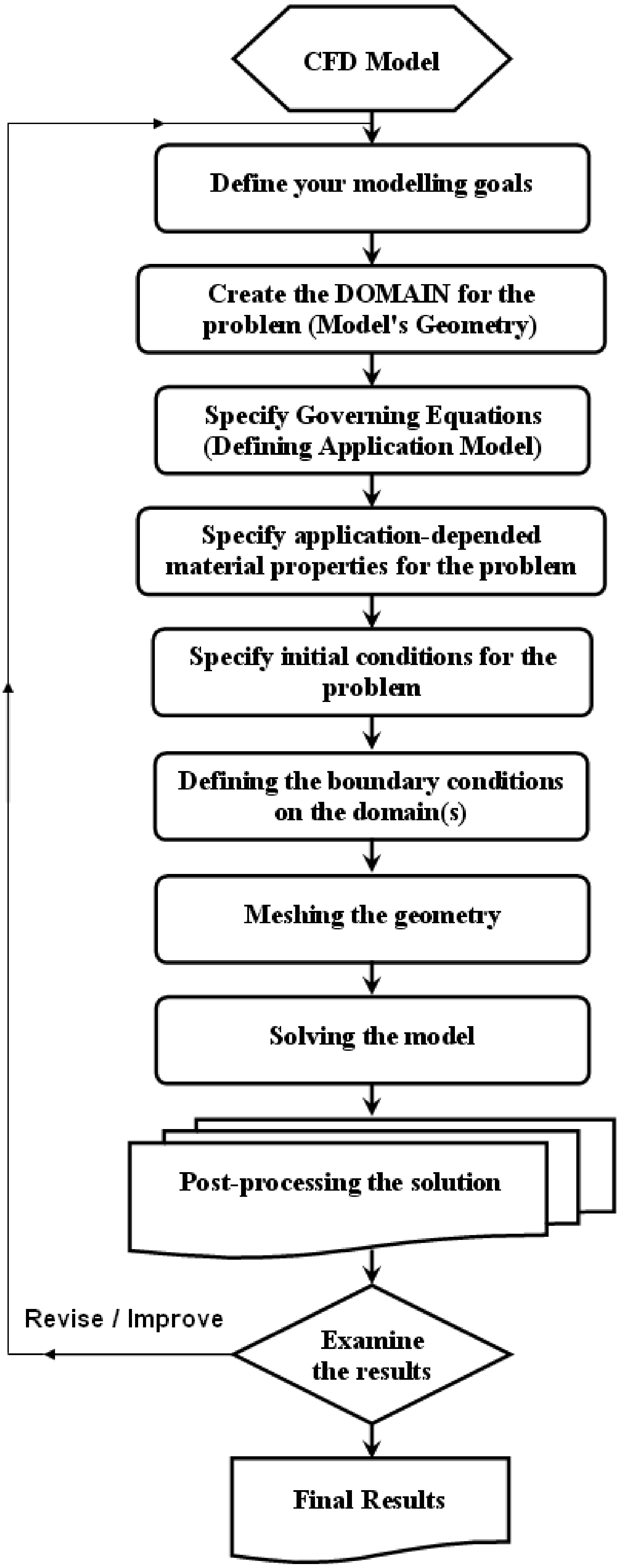


Figure 3. Flow diagram of the CFD modelling procedure.

References

[1] Photograph, illustration, and description of the root(2) tablet from the Yale Babylonian Collection (http://it.stlawu.edu/~dmelvill/mesomath/tablets/YBC7289.html).

[2] Eleanor Robson. Mathematics in Ancient Iraq. A Social History. Princeton University Press, Princeton and Oxford 2008. ISBN: 9780691091822.

[3] S Ilic, M S Petkovic and D Herceg, A note on Babylonian square-root algorithm and related variants, Novi Sad J. Math. 1996, 26 (1), 155-162.

[4] D E Knuth, Ancient Babylonian algorithms, Twenty-fifth anniversary of the Association for Computing Machinery, Comm. ACM 1972, 15 (7), 671-677.

[5] D E Knuth, Errata. Ancient Babylonian algorithms. Comm. ACM 1976, 19 (2), 108.

[6] Friberg, J. Methods and traditions of Babylonian mathematics. Historia Mathematica 1981. Vol. 8, pp. 227-318.

[7] Teia, L. Pythagoras triples explained via central squares. Australian Senior Mathematical Journal 2015, Vol. 29, No. 1, pp. 7-15.

[8] Edward Rothstein. Masters of Math, From Old Babylon. New York Times online article. (http://www.nytimes.com/2010/11/27/arts/design/27tablets.html?_r=2).

[9] J Hoyrup, Babylonian mathematics, in I Grattan-Guinness (ed.), Companion Encyclopedia of the History and Philosophy of the Mathematical Sciences (London, 1994), 21-29.

[10] A E Raik, From the early history of algebra. Quadratic equations among the Babylonians (Russian), Molotov. Gos. Univ. Uc. Zap. 1953, 8 (1), 31-63.

[11] K Muroi, Babylonian mathematics - ancient mathematics written in cuneiform writing (Japanese), in Studies on the history of mathematics (Kyoto, 1998), 160-171.

[12] J S Liu, A general survey of Babylonian mathematics (Chinese), Sichuan Shifan Daxue Xuebao Ziran Kexue Ban 1993, 16 (1), 80-87.

[13] Daniel F. Mansfield, N.J. Wildberger. Plimpton 322 is Babylonian exact sexagesimal trigonometry. Historia Mathematica 2017 44(4), pp.395-419.

[14] Cuneyt Sert, Gunes Nakiboglu. Use of Computational Fluid Dynamics (CFD) in Teaching Fluid Mechanics. American Society for Eng. Edu., AC 2007-1560, 2007.

[15] Junling Hu, Linfeng Zhang. Xingguo Xiong, Teaching Computational Fluid Dynamics (CFD) to Design Engineers. American Society for Engineering Education, AC 2008-1503, 2008.

[16] Henk Versteeg. Application of Computational Fluid Dynamics (CFD) through project-based learning. Higher Education Academy Engineering Subject Centre, Loughborough University, 2010.

[17] Wael Mokhtar. Project-Based Learning (PBL) An Effective Tool to Teach an Undergraduate CFD Course. American Society for Engineering Education, AC 2011-973, 2011.

[18] Maher A.R. Sadiq Al-Baghdadi (Editor). CFD Applications in Energy and Environment Sectors. International Energy and Environment Foundation (IEEF), Iraq. 2011. ISBN: 9781466230651.

[19] Maher A.R. Sadiq Al-Baghdadi (Editor). Engineering Applications of Computational Fluid Dynamics – Volume 1. International Energy and Environment Foundation (IEEF), Iraq. 2011. ISBN: 9781466231061.

[20] Maher A.R. Sadiq Al-Baghdadi (Editor). Computational Fluid Dynamics Modeling in Development of Renewable Energy Applications. International Energy and Environment Foundation (IEEF), Iraq. 2011. ISBN: 9781466231313.

[21] Maher A.R. Sadiq Al-Baghdadi (Editor). Engineering Applications of Computational Fluid Dynamics – Volume 2. International Energy and Environment Foundation (IEEF), Iraq. 2012. ISBN: 9781478329350.

[22] Maher A.R. Sadiq Al-Baghdadi (Editor). Computational Fluid Dynamics Applications in Green Design. International Energy and Environment Foundation (IEEF), Iraq. ISBN: 9781494875756.

[23] Maher A.R. Sadiq Al-Baghdadi (Editor). Engineering Applications of Computational Fluid Dynamics – Volume 3. International Energy and Environment Foundation (IEEF), Iraq. ISBN: 9781511788786.

[24] Maher A.R. Sadiq Al-Baghdadi (Editor). Engineering Applications of Computational Fluid Dynamics – Volume 4. International Energy and Environment Foundation (IEEF), Iraq. ISBN: 9781511974806.

[25] Maher A.R. Sadiq Al-Baghdadi (Editor). Applications of Computational Fluid Dynamics and Finite Element Methods in Engineering Education. International Energy and Environment Foundation (IEEF), Iraq. ISBN: 9781512122428.
[26] Maher A.R. Sadiq Al-Baghdadi (Editor). Engineering Applications of Computational Fluid Dynamics – Volume 5. International Energy and Environment Foundation (IEEF), Iraq. ISBN: 9781540352590.
[27] H K Versteeg and W Malalasekera. An Introduction to Computational Fluid Dynamics - the finite volume method. 2nd Ed., Prentice Hall, 2007. ISBN: 9780131274983.