Computational Fluid Dynamics-1(CFD-I)

Course Number: 33-31-076-32

Course Content:

1- An Introduction to CFD and the Finite Volume Method (FVM)
2- Numerical Solution of the 1D Generic Transport Equation and Its Simplified Forms
   - Discretization of the Diffusion Term
   - Discretization of the Advection Term
   - Discretization of the Steady Advection-Diffusion Equation
   - Discretization of the Transient Term
   - Discretization and Linearization of the Source Term
3- Numerical Solution of INSE via Pressure-Based Methods
   - Discretization of 1D Incompressible Flow Equations
   - Pressure-Velocity Decoupling Issue and Its Remedies
   - Discretization of 2D Incompressible Flow Equations
4- Solver Technologies
   - Solution Algorithms for the Coupled Set of Discrete Flow Equations
      - SIMPLE Family of Methods
   - Solution Methods for a Set of Linear Algebraic Equations
      - Direct Solvers
      - Base Iterative Solvers
      - Multigrid Solvers
5- Selected Advanced Topics

Course Description:

This course provides some background information to those graduate students who are interested in the numerical solution of fluid flow problems. Finite volume method is advocated as a convenient discretization recipe and is used throughout the course. To avoid the unnecessary logistic complications in multi-dimensional problems, the focus is on 1D problems. Also, the course is built around the numerical solution of incompressible flow governing equations via pressure-based methods. Multi-dimensional implementation issues and compressible flow problems are discussed in another graduate course (CFD-II).

Chapter 1 provides an introduction to the MATLAB programming environment. MATLAB is suggested for the implementation of the numerical schemes in this course. However, students are allowed to use other computer tools and languages if they prefer to do so. Also, the structure of a MATLAB code, written by Professor G. D. Stubley at the University of Waterloo in Waterloo, Ontario, Canada, is introduced to students. Template files are provided to those students who would like to follow that style of coding. One-dimensional grid generation and stretching functions are briefly reviewed in this Chapter.

Chapter 2 includes topics on the discretization of generic terms which comprise a typical transport equation. Discretizations of diffusion and advection terms as well as the time integration options are discussed here. The concept and importance of the source term in a transport equation is also discussed in this Chapter. By allowing the source term to be non-linear, an opportunity is obtained to discuss various linearization methods.

Chapter 3 takes on the numerical solution of 1D and 2D Incompressible Navier-Stokes Equations (INSE). While the discretization of generic terms is surely part of the deal here, new surprising issues arise due to the peculiar role of the pressure in incompressible flows. These issues are, therefore, discussed in some details afterwards.

Chapter 4 is totally devoted to a classical topic in linear algebra, i.e. solution of a set of linear algebraic equations. Well-known direct and iterative solvers are discussed first, followed by a rather thorough discussion on the revolutionary multigrid technique.

Chapter 5 is a regulatory Chapter, which allows the instructor to tune the course content with the interests of the students. Typically, additional numerical schemes, e.g. PISO, fractional-step and characteristic-based operator splitting methods, are discussed in this Chapter. Furthermore, the difficulties associated with the satisfaction of the incompressibility condition can be elaborated here.

Course Resources:

The following text books are recommended for this course:

[1] H. K. Versteeg and W. Malalasekera, An Introduction to Computational Fluid Dynamics: The Finite Volume Method, Prentice Hall, 1995, 2007.

[2] S. V. Patankar, Numerical Heat Transfer and Fluid Flow, Hemisphere Publishing Corporation, 1980.

[3] J. H. Ferziger and M. Peric, Computational Methods for Fluid Dynamics, Springer (3rd ed) 2002.

Also, the following articles/papers are used and/or referred to during class discussions:

1967- J. Chorin, A numerical method for solving incompressible viscous flow problems, J. Comput. Phys. 2 (1967) 12-26.

1982- U. Ghia, K. N. Ghia, C. T. Shin, High–Re for incompressible flow using the Navier–Stokes equations and a multigrid method, J. Comput. Phys. 48 (1982) 387–411.

1983- C. M. Rhie, W. L. Chow, Numerical study of the turbulent flow past an airfoil with trailing edge separation, AIAA J. 21 (1983) 1525--1532.

1985- J. Kim, P. Moin, Application of a fractional--step method to incompressible Navier--Stokes equations, J. Comput. Phys. 59 (1985) 308-323.

2002- B. Yu, W. Tao, J. Wei, Discussion on momentum interpolation method for collocated grids of incompressible flow, Numer. Heat Transfer, Part B. 42 (2002) 141-166.

2006- J. L. Guermond, P. Minev, J. Shen, An overview of projection methods for incompressible flows, Comput. Methods Appl. Mech. Eng. 195 (2006) 6011- 6045.

2007- M. Darwish, I. Sraj, F. Moukalled , A coupled incompressible flow solver on structured grids, Numer. Heat Transfer, Part B, 52 (2007) 353-371.

2008- E. Erturk, Numerical solution of 2–D steady incompressible flow over a backward facing step, part I: high Reynolds number solutions, Comput. Fluids 37 (2008) 633–655.

2009- A. Ashrafizadeh, M. Rezvani and B. Bakhtiari, "Pressure-Velocity Coupling on Co-Located Grids Using the Method of Proper Closure Equations", Numerical Heat Transfer, Part B, 56 (3), 259-273, 2009.

2012- M. Nickaeen, A. Ashrafizadeh and S. Turek, "An Alternative Strategy for the Solution of Heat and Incompressible Fluid Flow Problems via Finite Volume Method", Numerical Heat Transfer, Part A, Special Issue: Papers Presented at the "Minisymposium on Computational Radiative and Convective Heat Transfer" in Honor of Professor George D. Raithby, Vol. 62, 393-411, 2012.

Course Evaluation:

CFD-I is a project-based course and there is no mid or final term examination. Students are expected to write codes to solve a number of heat and/or fluid flow problems and to submit professionally-written reports (usually between 3 to 5 term projects). In addition, students might be individually invited by the instructor to answer questions and to explain and run their codes. Students are also expected to prepare and submit a short research article. Some of these articles, chosen by the instructor, should also be presented at the class.

Sample Term Projects:

- Numerical solution of a 1D, linear fin problem
- Numerical solution of a 1D, nonlinear fin problem
- Numerical solution of a 1D duct flow (diffusion excluded)
- Numerical solution of a 1D duct flow (diffusion included)
- Numerical solution of incompressible flow in a convergent-divergent duct
- Convergence acceleration studies in a 1D context via multigrid
- Numerical solution of incompressible flow in a 2D lid-driven cavity
- Numerical solution of incompressible flow in a duct with a backward step.
- Numerical solution of incompressible flow in a duct with a forward step.

Sample Seminar Topics:

- Variants of the momentum interpolation method used in co-located grid arrangements.
- Variants of incompressible solvers based on velocity projection.
- Variants of multigrid accelerators.
- Numerical solution of unsteady incompressible flows.