How to –

Understand Computational Fluid Dynamics Jargon

Editing Author:

Althea de Souza

"If language be not accorded priority over subject, then the subject can have no reliable priority at all" L.J.K. Setright

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Preface

NAFEMS is a non-profit making association of organisations using, developing or teaching engineering analysis tools including the finite element method for solid mechanics and various computational fluid dynamics technologies.

This booklet is one of a series produced by NAFEMS on the technology known as Computational Fluid Dynamics (CFD). The titles of some of the booklets in this series are:

- Why Do Computational Fluid Dynamics?
- How To Get Started with Computational Fluid Dynamics
- Introduction to Grid and Mesh Generation for CFD
- How to Plan a CFD Analysis
- First Work Book of Examples

Computational Fluid Dynamics is a very powerful engineering tool, enabling a wide variety of flow situations to be simulated, reducing the amount of testing required, increasing understanding and accelerating development. It can be applied to a very wide range of applications and this breadth of application means that personnel from a wide range of different backgrounds come into contact with CFD; be they managers, engineers (mechanical, chemical, biomedical, civil or even electronic) or people involved in sales or marketing. The use of CFD jargon can therefore be particularly frustrating.

The aim of this booklet is to provide short and hopefully clear definitions for the more commonly used CFD terms and acronyms. In many cases this will provide sufficient understanding. Where more detail or depth is required, the reader is referred to the textbooks listed in the bibliography and the increasing range of CFD and application specific textbooks now available.

This booklet is not a fully comprehensive list of all terms that are used in the context of CFD. Later editions of this booklet are planned to cover additional terms as required. Comments and suggestions from users will be welcomed as will suggestions for future publications (via the members discussion area on the NAFEMS website or by e-mailing either NAFEMS or the CFD Working Group Chairman directly).

Disclaimer

Whilst this publication has been carefully written and subject to peer group review, it is the reader's responsibility to take all necessary steps to ensure that the assumptions and results from any computational fluid dynamics analysis which is made as a result of reading this document are correct. Neither NAFEMS nor the authors can accept any liability for incorrect analyses.

Contents

1. Introduction

Unfortunately, jargon is a necessary, but often confusing part of any technical discipline. Where terms have specific technical meaning within a particular field, they are often not obvious to newcomers to that field. The purpose of this booklet is to provide engineers and their managers who come into contact with Computational Fluid Dynamics (CFD) and users of CFD software with a resource to assist in understanding this complex field.

The list includes the most commonly used terms and is not intended to be fully comprehensive. Definitions and descriptions are designed to give a level of understanding which can then be progressed further with the aid of other resources, such as those listed in the bibliography at the back of this booklet or using other CFD, fluid flow, numerical analysis or application specific texts.

It should be noted that some terms have different meanings in different fields. The purpose of this booklet is to provide a guide to meanings within the context of CFD.

In several cases it is common for terms to be abbreviated to their initial letters. In those cases both the full term and the abbreviation are listed and cross-referenced.

A similar booklet has previously been published by NAFEMS on finite element jargon. In that case several mathematical, computer and solid mechanics terms were also described. The present publication differs from its forerunner in that it is generally limited to CFD terms only.

Additional publications on aspects of CFD analysis are planned by NAFEMS. Items currently available are:

Why Do Computational Fluid Dynamics

How to Get Started with Computational Fluid Dynamics

NAFEMS Workbooks of CFD Examples

NAFEMS Introduction to Grid and Mesh Generation for CFD

CFD Analysis: Guidance for Good Practice

leaflet

A short overview follows of the CFD analysis process to provide some general information on CFD analysis for newcomers to the field.

2. CFD – An Overview

Computational Fluid Dynamics (CFD) is a computer based mathematical modelling tool that can be considered the amalgamation of theory and experimentation in the field of fluid flow and heat transfer. It is now widely used and is acceptable as a valid engineering tool in industry.

CFD calculations are based upon the fundamental governing equations of fluid dynamics: the conservation of mass, momentum and energy. These equations combine to form the Navier-Stokes equations, which are a set of partial differential equations that cannot be solved analytically except in a limited number of cases. However, an approximate solution can be obtained using a discretisation method that approximates the partial differential equations by a set of algebraic equations. There are a variety of techniques that may be used to perform this discretisation; the most often used are the finite volume method, the finite element method and the finite difference method. The resulting algebraic equations relate to small sub-volumes within the flow, at a finite number of discrete locations.

A typical CFD simulation consists of several stages, described below.

A. Approximation of the geometry.

The geometry of the physical system needs to be approximated by a geometric CAD type model. The more closely the model geometry represents the actual geometry, the more accurate the results are likely to be.

B. Creation of the numerical grid within the geometrical model.

To identify the discrete, finite locations at which the variables are to be calculated, the geometry is divided into a finite number of cells that make up the numerical grid. Before doing this, it is necessary to identify the physical flow phenomena expected (turbulence, compressible flow, shocks, combustion, multiphase flow, mixing, etc.) so the grid generated is suitable to capture these phenomena.

C. Selection of models and modelling parameters.

Once the geometry and grid have been established, the mathematical models and parameters for those phenomena are then selected and boundary conditions defined throughout the domain.

D. Calculation of the variable values.

Discretisation yields a large number of algebraic equations (one set for each cell). These equations are then generally solved using an iterative method, starting with a first guess value for all variables and completing a computational cycle. Error or residual values are computed from the discretised equations and the calculations repeated many times, reducing the residual values, until a sufficiently converged solution is judged to have been reached.

E. Determination of a sufficiently converged solution.

The final stage in the solution process is to determine when the solution has reached a sufficient level of convergence. When the sum of the residual values around the system becomes sufficiently small, the calculations are stopped and the solution is considered converged. A further check is that additional iterations produce negligible changes in the variable values.

F. Post Processing.

Once a converged solution has been calculated, the results can be presented as numerical values or pictures, such as velocity vectors and contours of constant values (e.g. pressure or velocity).

G. Solution Verification and Validation

Once the solution process is complete, each solution should be verified and validated. If this cannot be completed successfully, re-simulation may be required, with different assumptions and / or improvements to the grid, models and boundary conditions used.

3. Definitions

A

Accuracy

a measure of the similarity of a simulation to the physical flow it is intended to represent. See also model accuracy, numerical accuracy, validation and verification.

Adams Methods

a common type of multi-point temporal scheme that requires several time levels as opposed to the usual two. It can be generated by fitting a polynomial to variables through time.

Adams-Bashforth Method

explicit Adams method.

Adams-Moulton

implicit Adams method.

Adaptive grid refinement

refinement of a computational grid based, for example, on regions with steep flow gradients. This can be an automatic, manual or semi-manual procedure.

Additive decomposition

decomposition of an array [A] into components of which the original matrix is the sum, i.e. [A] = [B] + [C]

ADI technique

the Alternating-Direction-Implicit technique, which is generally a temporal solution approach, where the use of explicit and implicit solution techniques is alternated with time in different co-ordinate directions.

Adiabatic wall condition

a perfectly thermally insulated or lagged wall, represented by a boundary condition of zero normal heat flux.

Aeroelasticity

fluid / structure interaction between elastic components (e.g. wings and aerofoils) and the surrounding fluid flow field. Also occurs in turbomachinery and heat exchangers.

Algebraic grid generation

a grid generation method in which the mesh is interpolated from the bounding, geometry-constrained edges. See also differential grid generation.

Algebraic multigrid

a technique for speeding up the solution of an iterative technique by reducing the number of iterations necessary for convergence. It involves the systematic coarsening of the original computational grid into a series of coarser grids. In addition to solving the equations for the original grid, equivalent equations are also solved on each coarser grid, transferring corrections onto the finer levels. This allows the solution procedure to take into account the overall solution error and global continuity, thus reducing long wavelength errors.

Algebraic Stress Model (ASM)

a type of turbulence model that solves for the Reynolds stresses but ignores transport terms. The model is a simplification of a full differential "RSM" (Reynolds Stress Model).

Alternating-direction-implicit technique

see ADI.

Amdahl's law

when parallel processing at the loop level (using, for example, an auto-parallelising compiler) the least efficient part of the code (that which would not parallelise) will strongly limit the potential increase in computational performance.

Amplification factor

a concept arising from Von Neumann stability analysis. If e_{n+1} is an error at a time level $n+1$ and e_n a value at a time level n the amplification factor is defined as $A = e_{n+1}/e_n$. For a stable scheme $|A| \leq 1$, i.e. the error decreases with time.

Amplification matrix

amplification factors are derived considering a single equation. Typical Computational fluid dynamics (CFD) problems involve sets of equations in matrix form. An amplification matrix extends the amplification factor concept to groups of equations.

Analytical domain

see domain.

Analytical solution

a solution that is obtained directly using analytical methods as opposed to using computational or iterative methods.

Approximate factorisation technique

a manipulation (factorisation) of equations to produce a more convenient or efficient solution form, without sacrificing the formal order of the numerical scheme. Also known as splitting.

Arrhenius kinetic rate

an expression to determine the reaction rate in a kinetically limited reaction.

Artificial compressibility

some CFD methods for compressible flow combine the continuity equation with the equation of state to yield an equation for pressure. These methods are extended to incompressible flow by adopting an 'equation of state' for the fluid containing a small amount of compressibility.

Artificial dissipation

see numerical dissipation.

Artificial viscosity

an inaccuracy arising from the discretisation process that manifests itself as an apparent increase in the specified fluid viscosity. Artificial viscosity improves the stability of a solution at the expense of solution accuracy.

ASM

see Algebraic Stress Model.

Aspect ratio

a measure of quality for a computational grid. In two-dimensions, the ratio of cell height to cell width.

A-stability

an unconditionally stable temporal scheme (in practice it corresponds to an implicit temporal scheme).

Axis boundary condition

a boundary condition at the centreline of an axi-symmetric geometry.

Axi-symmetric grid

a cylindrical polar co-ordinate system grid in which all derivatives with respect to the tangential co-ordinate direction are assumed to be zero.

B

Back substitution

the final phase when solving simultaneous equations using Gaussian elimination.

Backscatter

usually, turbulence energy is dissipated from larger to smaller eddies. The reverse can also occur and this is called backscatter.

Backward differencing

the method by which the derivative of a variable at a point is approximated by the ratio of a) the difference in values of the variable at a backward point and the original point and b) the distance between the points.

Backward staggered grid

see staggered grid.

Backwards facing step

this is a standard CFD benchmark test. It is a channel flow where the lower channel wall is constructed to produce a sudden expansion (a step change) in the channel height. The step change forces separation and produces a simple test case for evaluating the performance of algorithms when modelling separated flows.

Banded matrix

a matrix that has a structured appearance, the elements appearing as neat adjacent diagonal lines.

Basis functions

also known as shape or interpolation functions, are used to calculate the value of a variable over an element in terms of the discrete values at the nodes.

Beam and Warming scheme

a modification to the Crank-Nicolson scheme that improves its speed of convergence. The modification treats terms in which the transported variable and variable transporting it are the same i.e. terms of the form $\partial \rho uu / \partial x$.

BEM (Boundary Element Method)

a numerical solution method where only the boundary of a domain is discretised with elements. There are no elements covering the interior domain. A limitation of the method is that only problems with constant interior properties can be solved.

Benchmarking

the process of performance testing relative to some performance indicator (a benchmark).

Bernoulli equation

this refers to an equation that expresses conservation of fluid kinetic energy, gravitational potential energy and energy associated with pressure in the absence of all other energy transfer mechanisms, including viscous dissipation. Typical form is:

$$\frac{\rho u^2}{2} + \rho g h + p = a \text{ (constant).}$$

Biconjugate gradient method

an iterative method for solving large systems of algebraic equations. The solution is obtained by aiming for the minimum residual by choosing next search direction vectors and bi-directional vectors which are, as nearly as possible, in the directions of steepest descent. These directions are subject to the overriding condition that they are orthogonal with respect to the coefficient matrix.

Block structured grid

a grid that comprises of several connected structured sub-grids (blocks).

Body fitted co-ordinates

the use of a co-ordinate system fitted to the geometry such that the grid points lie on the domain surfaces. Such grids frequently have the accuracy advantage that the grid lines are approximately parallel or orthogonal to flow streamlines.

Body force

a force acting on the fluid in the frame of reference of the calculation due to effects other than pressure and viscosity, e.g. gravitational or centripetal forces, magnetic or electrostatic fields or general motion of the frame of reference.

Boundary condition

spatial or temporal specification of variable values or behaviour necessary to produce a unique solution.

Boundary Element Method

see BEM.

Boundary fitted co-ordinates

similar to body fitted co-ordinates.

Boundary layer

the layer of fluid adjacent to solid surfaces that has been affected, through viscous action, by the presence of the solid surface. There are many mathematical descriptions for the boundary layer's extent and these are required in many turbulence models. The simplest description is the region, adjacent to a solid surface, where the fluid velocity is less than the free stream velocity (velocity outside the boundary layer) by more than 1 %.

Boundary points

points on the boundary of a domain.

Boundary value problem

a problem where the final solution is dependent on just the boundary conditions and not the initial conditions.

Boundedness

a property of a numerical scheme in which the predicted values are limited within certain physically realistic bounds.

Boussinesq approximation

in CFD there are two types of Boussinesq approximation:

- In purely buoyancy driven flows, where density variations are small, it can be possible to ignore density variations in all equations except the source term for the velocity component equation that is parallel to the gravity vector.
- In turbulent flows, it is widely used to approximate the relationship between Reynolds stresses and eddy viscosity (multiplied by the fluid mean strain rate).

Bow shock wave

shock wave occurring at the bow or leading edge of an object.

Briley and McDonald method

a lesser used alternative to the Beam Warming Scheme.

Bubnov-Galerkin method

a way of referring to the standard Galerkin Finite Element method where, in the discretisation process, weighting functions are equal to shape functions.

Buffer layer

a region in the turbulent boundary layer linking the viscous sub-layer to the fully turbulent zone.

Buoyancy term

a body force term associated with density changes. These can be due to temperature differences or changes in species concentrations.

Burger's equation

a non-linear, one-dimensional idealised form of the Euler equation (the Navier-Stokes equation with zero viscosity). It is often used for the detailed mathematical analysis of solution procedures.

C

Calorifically perfect gas

a gas for which a linear relationship exists between temperature and internal energy. See thermally perfect gas and perfect gas.

Capillary convection

when a free surface has a significant temperature gradient, the variations in surface tension force (which is a function of temperature) can cause a fluid shear stress to arise. The fluid tends to move from the region of high to low temperature and this process is called capillary or Marangoni convection.

Cartesian grid

a grid in which lines of constant x, constant y and constant z are orthogonal.

CCCT (Curvature compensated convective transport)

a convective term treatment (i.e. a means of interpolating to control volume faces from adjacent grid points).

Cebeci-Smith method

a density weighted technique for defining mean turbulent variables that reduces the number of products of density fluctuations with other fluctuating quantities (these authors also devised a popular mixing length turbulence model).

Cell

discrete area or volume over which governing equations are integrated. The complete group of cells should define the domain under consideration

Cell Reynolds number

see Peclet number.

Cell-centred scheme

a discretisation scheme in which values of the dependent variables are stored at the centre of each cell.

Cell-vertex scheme

a discretisation scheme in which values of the dependent variables are stored at the vertices of each cell.

Central coefficient

coefficient associated with the node at the centre of a cell.

Central differencing scheme

a discretisation approach in which the convective terms are calculated using a polynomial representation for the quantity of interest, with the polynomial centred on the point of interest. It may be a first order method where a simple linear average is used but is more often referred to as a second order method where the solution is represented as a quadratic. It may also be a higher order method. See discretisation schemes.

CFD

see Computational Fluid Dynamics.

CFL condition

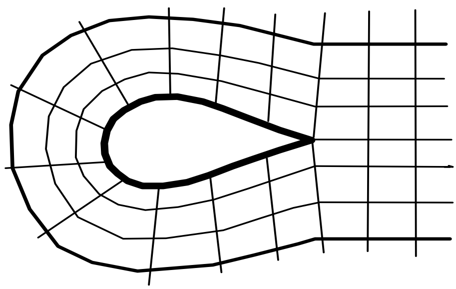
the Courant-Friedrich-Lewy condition states that the Courant number should be less than or equal to unity.

CGM (conjugate gradient method)

a method for solving non-linear simultaneous equation sets that involves searching for the minimum of a function.

C-grid

a curvilinear grid that is wrapped round an object in a 'C' shaped form.



Characteristic lines

lines along which the derivatives of the velocity components are indeterminate and across which they may be discontinuous.

Chebyshev acceleration

a technique for accelerating convergence of the crude Jacobi method (a method for solving simultaneous equation sets).

Chebyshev polynomial

an orthogonal function that can be used in spectral type methods. Cosine based expression can also be used to generate meshes suitable for resolving laminar boundary layers (see NAFEMS document on CFD meshes)

Checker-board pressure field

a pressure field of alternating values, in the manner of a chessboard. It is obtained by using a solution technique that wrongly ignores the influence of every other pressure node in the solution procedure. This problem is overcome by using staggered grids or special ‘momentum interpolation’ techniques such as that proposed by Rhie and Chow.

Chimera grid

a Chimera grid comprises sub-grids of different natures that overlay at edges and enable the mapping of complex geometries. The method is well suited to the modelling of moving bodies. A mesh of a particular type can be wrapped round the body and this mesh can move through a background mesh that conforms to the main fluid region.

Choleski factorisation

a technique used for the decomposition of a matrix into upper and lower triangles. It is used in the application of the basic Gaussian elimination procedure and is suitable only for the solution of positive definite systems in which all the eigenvalues of the matrix are positive.

Clebsch representation

an economical representation (in terms of the number of solution variables) for inviscid rotational flows. For practical cases, it is generally restricted to steady flows.

Closure

generally used in relation to turbulence modelling. For turbulent flows, the governing equations (when the RANS approach is used) have turbulence correlations that need to be accounted for using empirically based models. Such models enable *closure* of the problem i.e. give sufficient equations for the number of unknowns, thus enabling a solution to be produced. Examples of closure models include k-ε, RSM etc..

Coincident nodes

nodes that occupy the same location in space and that may result in collapsed cells or grid discontinuities.

Cole-Hopf transformation

a mathematical transformation that allows the analytical solution of Burger's equation for many combinations of initial and boundary conditions.

Collapsed element

an element in which two or more nodes are coincident, sometimes known as a degenerate element.

Collocation

in most modern CFD codes, the variables are all located in the same place (either a cell centre, cell vertex or cell face centre). However, in the past, problems coupling the velocity and pressure fields resulted in variables being stored in different locations. This approach has some computational advantages but does not lend itself to complex general geometry solution procedures and efficient coding.

Collocated grid

a computational grid in which collocation of solution variables is applied.

Compact differencing

a differencing scheme which uses close neighbours to obtain differencing methods that have an accuracy greater than second order.

Completeness

a property of an iterative method in which the approximate solution converges to the exact solution.

Composite grids

complex geometries are sometimes modelled using several relatively simple connected or 'Composite Grids'. This is sometimes called the multiblock approach.

Compressible flow

flow (of gases) where speeds are sufficiently high, causing significant fluid density changes. In some cases (where the Mach number exceeds unity) pressure discontinuities, known as shocks, may occur. A commonly used 'rule of thumb' for judging whether a flow is compressible is if the Mach number exceeds 0.3 in one or more regions.

Computational domain

see domain.

Computational efficiency

a general phrase that refers to how economical a computer program is with respect to storage or processing power.

Computational fluid dynamics (CFD)

the field of solving complex non-linear differential equations governing fluid flow using computer.

Computational molecule

in CFD, variables are considered to be stored in different discrete points in both space and time. The computational molecule uses lines to show the connectivity and topology of nodes and / or cells associated with the discretisation process for a single solution point.

Computational plane

an approach for modelling flows in complex geometries that involves the transformation of the governing equations for a simple co-ordinate system (say x-y) into a co-ordinate system that matches the shape of the geometry (see Conformal Co-ordinates). The governing equations for the co-ordinate system that matches the complex geometry are generally more complex than the original equations and are solved in what is called the computational plane. The grid in the computational plane has a uniform orthogonal form and hence requires less sophisticated solver technology.

Condition number

the ratio of the maximum to the minimum eigenvalues of a matrix. Condition number values much larger than one can lead to very slow convergence of a CFD problem. To overcome, this preconditioning can be used.

Conditional stability

stability that is conditional on some criteria being fulfilled (see stability criterion and the CFL condition).

Conduction

the diffusion of thermal energy (heat).

Conformal co-ordinates

co-ordinates that conform to the shape of a generally fairly complex region. For example, when modelling an aerofoil a co-ordinate system with lines that wrap round the wing could be used.

Conformal mapping

the use of mathematical transformations to solve equations for relatively complex geometries. Mapping enables equations to be solved on a relatively simple domain.

Conforming element

an element in which inter-element continuity conditions are satisfied along the complete extent of inter-element boundaries.

Conjugate gradient method (CGM)

see CGM.

Connectivity

when using unstructured grids, it is necessary to express which Node are connected to each other. These data are called connectivity information and are usually stored in look-up tables.

Conservation

the preservation of an extensive property in a closed system, see conservative variables

Conservation form of equations

equations written in a form that directly represents the quantity conserved; mass, momentum, energy, rather than velocity and temperature. The equations can then be expressed as:

Rate of Change of Conserved Quantity = Diffusion + Convection + Sources - Sinks

Conservative discretisation scheme

a numerical scheme in which the discretisation of the algebraic equation describing the transport processes for a dependant variable is such that conservation of the associated extensive property is mathematically assured.

Conservative form of flow equations

an equation form that, regardless of grid size, obeys conservation laws.

Conservativeness

the property of a numerical scheme in which the laws of conservation are adhered to.

Consistency

the property of a numerical scheme in which the algebraic equations produced by the discretisation process are equivalent to the original governing equations as the grid spacing tends to zero.

Contact discontinuity

a discontinuity across which density and tangential velocity may be discontinuous but pressure and normal velocity are constant and there is no mass transfer. The best known discontinuity found in CFD is due to shock waves.

Continuity

a system that exhibits continuity and expresses conservation (generally of mass).

Contour plots

a representation of a surface showing lines of constant value for a particular variable such as temperature (isotherms) or pressure (isobars). The regions between the lines are often filled to produce continuously coloured plots representing variable values.

Contravariant components

vector components projected normal to co-ordinate surfaces. See covariant components.

Control points

points at which discretised equations are solved and variable values are obtained.

Control surface

the bounding surface of a control volume.

Control volume

the volume over which the partial differential equations describing fluid flow are integrated to obtain discretised (algebraic) equations.

Control volume method

a numerical solution method in which the domain is divided into a finite number of control volumes. The governing equations are then discretised and solved for the individual volumes as part of the whole.

Convection

transport of a property by fluid movement.

Convergence

property of a numerical method to tend towards a single answer.

Convergence criterion

criterion by which a solution is judged to determine if it is sufficiently converged. Convergence is normally dependent on satisfaction of a number of such criteria.

Convergence error

the difference between the iterative and exact solutions of the discretised equations.

Co-ordinate stretching

a grid generation method involving stretching of the grid in one co-ordinate direction or more.

Corrected viscosity scheme

a scheme used to improve the accuracy of the Lax-Friedrichs scheme.

Correction formulae

approximation of flow variables by the sum of a guessed value and a correction value.

Corrector step

additional step used to improve on a guessed set of values (used in pressure-velocity coupling methods such as SIMPLE, PISO, etc.).

Couette flow

a flow driven solely by boundary movement in which there is no pressure gradient. Hence an analytical solution is possible (see NAFEMS CFD Workbook of Examples).

Coupled particle flow

flow of discrete particles, bubbles or drops in a continuum in which the movement of the particles influences the flow of the continuum and vice versa.

Coupled solver

a solver that typically solves for continuity, momentum and energy (and potentially species) simultaneously. It is an alternative to a segregated solver and is often used for compressible flows.

Courant number

the speed of sound, multiplied by the ratio of the time step length to the cell length. This ratio is the time required for a quantity or fluid particle to be convected through a small distance. Therefore, the Courant number can be viewed as a time step to convection time scale ratio.

Courant-Friedrichs-Lewy (CFL) condition

see CFL condition

Covariant components

for simulating fluid flow and heat transfer in complex geometries, the governing equations are expressed in generalised curvilinear co-ordinates in which the dependent variable can be cartesian, covariant or contravariant velocity components. The covariant velocity components align with the curvilinear co-ordinates but are not orthogonal to the cell faces. It has the advantage that the cross pressure gradient terms in the momentum equation disappear.

Crank-Nicolson scheme

a semi-implicit solution scheme for unsteady flows.

Critical condition

condition at which the nature of a flow changes, e.g. from laminar to turbulent or where a shock wave is produced.

Curvature compensated convective transport

see CCCT.

Curvilinear grid

a grid based on curvilinear co-ordinates.

Cyclic boundary condition

a boundary condition in which conditions at one surface of the calculation domain are assumed continuous with those at another, employed for cyclically repeating flows. Also sometimes known as a periodic boundary condition.

Cyclic grid

a cyclic grid repeats in a cyclic manner.

Cylindrical co-ordinates

co-ordinates based on a length, radius and angle.

D

Damkohler number

in combustion, the ratio of reagent diffusion to characteristic chemical reaction time across the flame.

Deferred correction

in convective schemes, the use of higher order discretisation schemes such as QUICK may give rise to instability and unbounded solutions under some flow conditions. This is due to the appearance of negative main coefficients. To alleviate the stability problem, these schemes are formulated in a different way such that the troublesome negative coefficients are placed in the source term so as to retain positive main coefficients for the terms treated implicitly. This is known as deferred correction as the coefficients placed in the source term are treated explicitly.

Degenerate element

see collapsed element.

Delta form

a form of writing discrete or differential equations that enables a temporal linearisation. Effectively, an efficient time integration approach.

Derivatives

variables differentiated with respect to either time or space.

Diagonal dominance

see diagonally dominant matrix.

Diagonalisation

manipulation of a matrix to produce a diagonal matrix (a matrix in which all values are zero except those on the leading diagonal).

Diagonally dominant matrix

a matrix with diagonal dominance has values on the leading diagonal that are significantly larger than those elsewhere.

Differencing scheme

a discretisation scheme that uses the difference between known variable values to predict additional values. The higher the order of a scheme, the more accurate it is generally considered. See discretisation scheme.

Differential grid generation

a grid generation method in which the mesh is generated by iteratively solving an equation set, typically the Laplace equation, which links the computational grid to the physical grid. See also algebraic grid generation.

Diffusion

the natural movement of species or properties from regions of high concentration to those of lower concentration. Diffusion is modelled mathematically using Fick's Law.

Diffusion Coefficient

a coefficient relating the rate of transport of a species or property to its concentration gradient in the carrier fluid. The value of the coefficient will depend on both the fluid and the diffusing species.

Diffusion Equation

see Fick's Law.

Diffusive conductance

ratio of diffusion coefficient to cell size, sometimes used in definition of cell Peclet number.

Direct methods

solution methods that solve a set of equations directly without the need for an iterative scheme. Also known as direct solution methods. See iterative method.

Direct Numerical Simulation (DNS)

a method in which the turbulent flow is directly numerically simulated without any form of time or length averaging, i.e. both the mean flow and all turbulent fluctuations (eddies) are simulated. Since turbulent eddies are both three-dimensional and unsteady (time-variant), simulations using this method must also be both three-dimensional and unsteady and, since the length and time scales of turbulent eddies cover a large range, both the grid size and the time-step size must be very small to account for the smallest fluctuations. This makes this method very computationally expensive and even with current state-of-the-art computer hardware, only practical for simple flows at low Reynolds numbers.

Direct solution methods (for linear algebraic systems)

see direct methods.

Dirichlet boundary conditions

a type of boundary condition where values of the flow variables are imposed on the boundaries of the flow domain.

Discontinuities

sudden changes in the value of a variable. For example, shock waves.

Discrete phase

second phase in a multiphase flow dispersed in a continuum and consisting of discrete entities such as particles, drops or bubbles.

Discretisation

process by which the governing partial differential equations are converted into algebraic equations associated with discrete elements.

Discretisation error

difference between the exact solution of the governing equations and the exact solution of the algebraic equations obtained by discretising them.

Discretisation schemes

the method by which the continuous variables and equations are turned into discrete variables and discrete equations.

Dispersive error

an error resulting from numerical dispersion.

Dissipation error

an error resulting from numerical dissipation.

Dissipative scheme

a scheme that artificially adds numerical dissipation.

Distributed resistance

a method for simulating a region of porous medium by the presence of a momentum sink.

Divergence

the progression of a numerical scheme away from any single answer. The opposite of convergence.

DNS

see Direct Numerical Simulation.

Domain

the geometrical region over which a simulation is performed. Sometimes referred to as the analytical domain or computational domain.

Domain of dependence

the region in the x-t plane enclosed by the two characteristics and the x-axis. See region of dependence.

Domain of influence

the region in the x-t plane bounded by the two characteristics and occurring later than the intersection point of the characteristics. See region of influence.

Donor cell differencing

see Upwind differencing.

Donor cell upwind

the upwind variable value used in upwind differencing.

Douglas and Rachford method

an Alternative Direction Implicit (ADI) method for solving the heat conduction equation in which the first step is approximated over the entire time interval and the second step is only introduced for stability reasons. It is sometimes called “Stabilisation Correction Scheme”.

Douglas Gunn splitting algorithm

an ADI approach that is stable in three-dimensions.

Duplicate nodes

more than one node which occurs at a single geometrical location.

Dynamic boundary condition

a boundary condition which changes with time.

Dynamic pressure

pressure due to local kinetic energy ($^1/_2\rho v^2$).

Dynamic similarity

a similarity of forces.

E

Eddy Break Up model

a reaction model in which the rate of reactant consumption is specified as a function of local flow turbulence properties and not the kinetic rate.

Eddy viscosity

a coefficient of proportionality between the Reynolds stresses and the mean velocity gradients. Unlike the molecular viscosity, the turbulent viscosity is a property of the local state of the turbulence and not a property of the fluid. Its value varies from point to point in the fluid.

Einstein convention

in tensor notation, whenever a certain index is repeated in the term, the term must be summed with respect to that index for all admissible values of the index. The summation convention allows us to omit writing the summation symbol.

Elements (and element types)

the basic building blocks of the finite element model, which together form the (finite element) grid. In CFD, elements are normally triangular or quadrilateral in 2D and tetrahedra, prisms (wedges), pyramids or hexahedra in 3D.

Elliptic equations

partial differential equations of the form $Au_{xx} + 2Bu_{xy} + Cu_{yy} = F(x,y,u,u_x,u_y)$ for which $AC - B^2 > 0$. A number of classical steady-state mathematical descriptions of fluid flow and heat transfer are expressed as elliptic equations; examples include the irrotational flow of an incompressible fluid (the Laplace equation) and steady state conductive heat transfer. In a physical sense, elliptic equations describe behaviour in which the influence of a perturbation extends in all directions. For example, if the temperature is raised locally in a solid, heat is conducted away in all directions; or if a compressible fluid accelerates around an obstacle in steady irrotational flow, the effects of the acceleration are transmitted in all directions to the surrounding fluid. This behaviour contrasts with that described by parabolic and hyperbolic equations.

Energy equation

an equation derived from the first law of thermodynamics which states that the rate of change of energy of a fluid particle is equal to the rate of heat addition to the fluid particle plus the rate of work done on the particle.

Errors

see accuracy, aliasing, convergence error, diffusion error, discretisation error, dispersive error, dissipation error, floating point errors, grid independence, ill-posed problem, modelling errors, order of accuracy, residual, round-off error, truncation error.

Euler equations

the governing equations for inviscid compressible flow.

Euler-Euler multiphase method

a multiphase method in which the different phases are treated as interpenetrating continua using the concept of a phasic volume fraction.

Eulerian frame of reference

a frame of reference based on a co-ordinate system as opposed to being based on a moving fluid element as used in the Lagrangian method.

Euler-Lagrange multiphase method

a multiphase method in which the continuous phase is modelled using the Eulerian method and the dispersed phase (generally less than 15% volume fraction) is modelled using the Lagrangian method. See also Particle Source in Cell Method.

Expansion factor

ratio of a dimension of adjacent grid cells.

Explicit approach

a numerical scheme in which a single algebraic equation is used to evaluate each new nodal variable at a single time step.

External flows

flows over the external surface of an object (e.g. an aerofoil).

F

False diffusion

see numerical diffusion.

Fan modelling

enables a geometric region to operate as a momentum and turbulence source to simulate the effect of a fan.

Favre-averaging

density weighted averaging used in deriving turbulent flow equations for cases where there are significant fluid density variations.

FCT

see flux-corrected transport method.

FDM

see finite difference method.

FEM

see finite element method.

Fick's Law

states that species diffuse in the direction of decreasing species concentration just as heat flows by conduction in the direction of decreasing temperature.

Finite approximations

approximations to a continuous function by representing it by finite quantities.

Finite difference method (FDM)

a method for approximating gradients as part of the procedure for numerical solution of differential equations, by estimating a derivative by the ratio of two finite differences.

Finite difference operators

identify the type of differencing scheme applied e.g. forward, backward, central.

Finite element method (FEM)

a computational method that originated from structural analysis but which is also applied to CFD, in which the computational domain is subdivided into a finite number of elements over which discretised equations are solved.

Finite volume method (FVM)

a computational method in which the computational domain is subdivided into a finite number of control volumes over which discretised governing equations are solved. Primarily used for CFD.

First order

an approximation to an equation, or system of equations, where only the first terms in the Taylor expansions for functions are evaluated.

Five-point formula for Laplace equation

approximation for solving the Laplace equation by calculating derivatives using five discrete points in each co-ordinate direction.

Flat plate flow

flow over a flat plate, has a well known boundary layer profile named after Blasius for incompressible flow and typically used as a validation test case.

Floating point errors

errors which occur due to the representation of real numbers in digital computers by a finite number of digits or significant figures.

Fluid properties

the collection of parameters that fully describe the physical properties of the fluid, e.g. density, viscosity, thermal conductivity.

Flux

amount of transfer of fluid property (for example, enthalpy) through a specified surface or surface element.

Flux difference splitting schemes

a type of upwind discretisation scheme.

Flux limiting

a technique for stabilising solution convergence, in the early stages of a solution, by limiting fluxes.

Flux-corrected transport method (FCT)

a type of TVD (total variation diminishing) scheme which aims to correct the excessive dissipation of first order schemes without creating unwanted overshoots and oscillations, typical of second order schemes.

Flux-vector splitting schemes

a type of upwind discretisation scheme.

Forward differencing

the method by which the derivative of a variable at a point is approximated by the ratio of a) the difference in values of the variable at a forward point and the original point and b) the distance between the points.

Forward marching

see marching.

Forward staggered grid

see staggered grid.

Fractional-step method

a second order in time ADI (alternating direction implicit) method based on a factorisation of the Crank-Nicolson scheme method for deriving the pressure field, mostly used for LES and DNS.

Froude number

a dimensionless quantity representing the ratio of inertia forces to gravitational forces, typically used in free-surface flows.

Full approximation scheme

multi-grid technique for accelerating convergence rate in explicit solution methods.

Full multigrid method

a method of increasing the speed of convergence of a solution by computing corrections on a coarser grid to remove low frequency components of errors, and transferring these corrections to the finer grid.

Fully implicit

a method of solution whereby values are computed at all nodes simultaneously.

FVM

see finite volume method.

G

Galerkin and Bubnov method

the Bubnov-Galerkin method is also known as the Galerkin method where the weighting functions are made equal to the interpolation functions.

Galerkin method

a form of the method of weighted residuals. See weighted residual formulation.

Gauss elimination

a systematic process of elimination for obtaining solutions to a set of linear equations.

Gauss points

see Gaussian quadrature.

Gauss theorem

a theory which relates an integral throughout a volume to an integral over its bounding surface.

Gaussian quadrature

sometimes known as Gaussian integration it is a commonly used form of evaluating numerically the integrals that appear in finite element formulations. Generally, more sampling points (Gauss Points) in an element (see grid/mesh), where both the position and weighting is optimised, will reduce the integration error and give a more accurate solution.

Gauss-Seidel iteration method

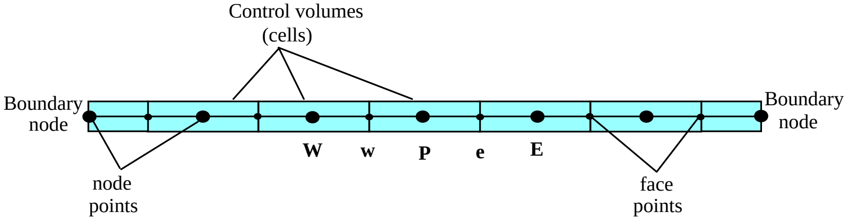
an iterative method of solving an equation of the form **Ax**=**b**, where **A** is a matrix and **x** & **b** are vectors, by iterating from an initial guess to the solution.

Generalised co-ordinates

a system of non-orthogonal co-ordinates used for geometrical representation.

Geographical notation

a notation used in discretisation techniques for the values at and near to a node value (P) according to their relative position (N, n, S, s, E, e, W, w for north, south, east and west). f and b are sometimes used as analysis directions in the third dimension. In one-dimensional flow the notation is illustrated as shown.



Geometrical model

the representation of the physical geometry defining the shape and extent of the computational flow domain to be modelled.

Geometric multigrid method

see multigrid.

Global constraint

a physical or numerical constraint that acts throughout the numerical model.

Godunov scheme

a method for discretising hyperbolic equations, which is often used in high speed, flow CFD codes.

Governing equations

the mathematical equations that describe the physics of the flow under consideration. These will typically be the conservation equations of mass, momentum and energy but may additionally include equations for the transport of turbulence and species mass, for example.

Graetz number

a dimensionless number representing the relative importance of conduction normal to the flow to thermal convection in the direction of the flow. It is the ratio of time required for heat conduction from the centre of a channel to the wall and the average residence time in the channel.

Grashof number

the fundamental dimensionless quantity for natural convection dominated flows. The Rayleigh number is often used in place of the Grashof number, being equal to the Grashof number multiplied by the Prandtl number.

Grid / mesh

the outcome of splitting up the computational domain (discretisation) into a number of elements or cells defining the discrete points at which the numerical solution is computed. The points are normally the cell centres or cell vertices.

Grid adaption

see adaptive grid refinement.

Grid density

the number of cells in a given volume. A region of high grid density contains more cells than a region of low grid density. A higher grid density should be used in regions where the solution variables change rapidly so that their gradients can be computed and represented accurately. Lower grid density can be used where the solution is changing less in order to reduce the computational effort.

Grid generation

the act of generating a set of grid points for which the solution will be calculated.

Grid growth rate

the rate at which grid cell size changes from one cell to the next adjacent cell.

Grid independence

having run a simulation on a sequence of grids (usually refining each time) and found the same results for each grid, the solution is considered grid-independent. The converged solution is therefore independent of the size of grid (beyond a certain limit) used to obtain the solution.

Grid non-uniformity

a grid with varying grid density.

Grid points

the discrete points that define the structure of the grid/mesh.

Grid refinement

the act of refining a grid such that the distance between adjacent grid points is reduced enabling a more accurate calculation and representation of the solution.

Grid Reynolds (Peclet) number

also known as the cell Reynolds number or Peclet number.

Grid velocity

represents the velocity of the grid for problems involving grid movement.

Griffith number

a dimensionless quantity representing the relative importance of viscous dissipation to conduction. It is an indicator of the coupling of energy and momentum equations and is sometimes known as the Nahme number.

H

Hanging nodes

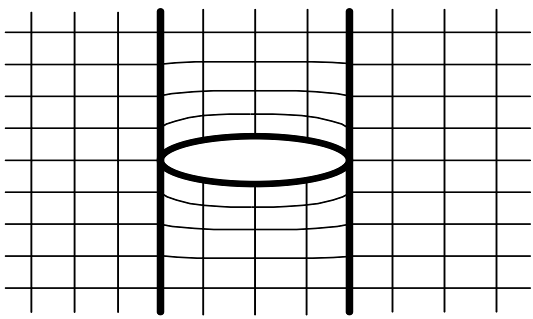
nodes not fully attached to all the surrounding elements. They can lead to an error in the finite element method where all nodes are assumed to be linked to elements.

Hexahedral elements

finite elements with six faces, i.e. cuboid or brick elements.

H-grid

a grid split open to form the shape of an H around a smooth body shape.



Higher order

when a derivative of a partial differential equation is approximated, if the truncation error due to difference approximation is of the order two or more, then the difference scheme is known as a higher order scheme.

Hybrid discretisation scheme

the use of two or more different discretisation schemes depending upon some property of the flow, such as the Peclet number.

Hybrid grid

a computational grid containing more than one cell or element type.

Hydrostatic pressure

the pressure due to depth, calculated by the product of density, gravity and depth.

Hyperbolic equations

partial differential equations of the form $Au_{xx} + 2Bu_{xy} + Cu_{yy} = F(x,y,u,u_x,u_y)$ for which $AC - B^2 < 0$. Examples of problems that are described by hyperbolic equations are steady inviscid two-dimensional supersonic flow, and time dependant problems with negligible dissipation such as the wave equation. Hyperbolic equations also dominate the analysis of vibration problems. An important feature of phenomena governed by hyperbolic equations, is that there exists from any point in the mathematical space in which the equations operate, a set of "characteristics" - lines (or surfaces in 3-D) along which the partial differential equations can be reduced to ordinary differential equations. This feature allows the use of special and very efficient computational algorithms to solve the equations, based on the "Method of Characteristics".

I

IGES (International Graphics Exchange Standard)

a neutral file format used to translate geometrical information between different CAD, CAE and analysis software packages.

Ill-posed problem

a problem in which the description of the problem is not self consistent, is not complete or is overconstrained.

Implicit approach

a numerical scheme in which the solution of the entire grid is required for each time level. For a single time level, it is very computationally expensive compared to the explicit approach but can often be used with much larger intervals between time levels (i.e. much larger time steps).

Incompressible flow

flow where the density is not a function of pressure, i.e. the flow remains at a constant density (less than approximately Mach 0.3) in all locations.

Indirect method

see iterative method.

Initial boundary value problem

a problem for which the solution can be obtained by specifying two initial conditions and a boundary condition. Hyperbolic problems are initial boundary value problems.

Initial conditions

conditions at the initial (start) time in a time dependant simulation.

Inner iterations

an iterative step embedded within an iterative scheme. For example, a single iterative step or iteration may require the solution to a set of equations. These equations may themselves be solved by an iterative method. The iterations required to determine the solution to this set of equations can be considered to be “inner iterations” within the overall iterative scheme.

Interface capturing method

a method for identifying interfaces caused by severe density or other property changes.

Interface tracking method

a numerical approach for tracking interfaces (see Interface Capturing).

Internal flows

a fluid flow domain that is contained by and passes through a solid structure. All boundaries of the domain can be defined as walls, periodic boundaries, inlets or outlets. Compare with external flows.

Inviscid flow

flows for which viscosity or shear effects can be neglected. By making this assumption the Euler equations (a subset of the Navier-Stokes equations) can be used, simplifying the solution techniques.

Irregular grid

sometimes known as an unstructured grid (although a regular grid can also be unstructured). An irregular grid has no regular array of cells that can be grouped into rows, columns and layers.

Irrotational flow

flows in which the curl of the velocity is equal to zero. In physical terms, individual elements of fluid have motion described by translation without rotation. By making this assumption along with the inviscid assumption a potential flow problem can be solved.

Isoparametric elements

curved sided elements that are generated by mapping between a rectilinear co-ordinate system and a curvilinear co-ordinate system. Where the co-ordinate transformation formulae are identical to the interpolation formulae the elements are called isoparametic elements.

Iteration

a step in an iterative process. See iterative method.

Iterative method

a process in which the equations are not solved directly but indirectly by a series of iterative steps or iterations. An initial estimate of the solution is made, and an algorithm defined whereby the estimate is improved until it satisfies the equations to within some specified tolerance (see convergence criterion). Linear systems can be solved directly in one step by direct methods. Non-linear systems, typical of CFD problems, will necessarily be iterative.

J

Jacobi iteration method

an iterative method for the solution of a system of simultaneous linear algebraic equations in which the dependent variable at each grid point is solved using initial guess values for the neighbouring points of previously computed values.

Jameson's multistage method

Runge-Kutta type method that is used for the solution of Euler's equation.

Jury problems

problems involving elliptic equations where the solution within the domain depends on the total boundary around the domain.

K

k-ε turbulence model

a two-equation turbulence model, formulated by the use of the eddy-viscosity hypothesis, where the effect of turbulence is captured by the fluid turbulent kinetic energy (k) and energy dissipation rate (ε).

Kolmogoroff scale

in a turbulent flow, the scale associated with the smallest eddies.

Kutta condition

this requires that equal static pressures exist on both sides of the sharp trailing edge of an airfoil. It is required in potential flow calculations to obtain a solution to lifting airfoils. It is also imposed in some specialist numerical solvers of the Euler equation.

L

Lagrangian frame of reference

a frame of reference that moves with a particle or element of fluid. The equations of fluid flow can be derived in this frame of reference. Methods for solving the dynamics of particles or fluids by 'tracking' their position in space relative to a fixed reference frame are referred to as Lagrangian methods.

Laminar Flamelet model

a reaction model that considers a turbulent flame front to be represented as an array of laminar 'flamelets'.

Laminar flow

flow in which fluid moves in layers, without turbulence. Diffusive and dissipative effects take place only by molecular diffusion. Laminar flow usually exists at low Reynolds numbers. In practice, for normally encountered flows of low viscosity (air, water), laminar flow only occurs at low velocity or very small physical length scales. However boundary layers can exhibit laminar behaviour even at high speeds and on relatively large engineering components, because the dominant length scale is the small thickness of the boundary layer.

Laminar sub-layer

in a turbulent boundary layer, the region of fluid closest to the wall where the fluid motion is dominated by viscous effects and turbulent motion is suppressed by viscous action.

Laplace equation

a steady-state transport equation for a variable ϕ of the form:

$$\nabla^2\phi = 0 = \frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} + \frac{\partial^2\phi}{\partial z^2}.$$

Large eddy simulation (LES) turbulence modelling

this may be considered a compromise between direct numerical simulation (DNS) and the use of turbulence models (RANS). The unsteady flow equations are solved for the mean flow and larger eddies and a ‘sub-grid scale’ model is used to simulate the effects of the smaller eddies. Since it is the largest eddies which contain the most energy and interact most strongly with the mean flow, the LES approach results in a good model of the main effects of the turbulence. Since the grid size no longer has to be small enough to allow for the smallest turbulent eddies, this method is much less computationally expensive than DNS and may be applied to a wider range of flows. However, time dependant simulations using relatively fine meshes are still necessary, so the computational requirement is still high.

Law of the wall

an assumed log law profile adjacent to the wall, which models the effect of the wall across the boundary layer.

Lax-Wendroff method

an explicit finite difference method particularly suited to marching numerical solutions, either in space or time. Similar to MacCormack’s method.

Leapfrog method

a three level discretisation scheme for unsteady flows based on the mid-point integration rule.

Leith’s scheme

a central difference based version of the QUICKEST discretisation scheme (which was developed prior to QUICKEST).

LES turbulence modelling

see large eddy simulation turbulence modelling.

Line relaxation

an iterative method in which variables are solved on a series of lines perpendicular to the flow and sweeping through it.

Linearisation

approximation of local variations of a parameter by a linear form.

Local time stepping

a convergence acceleration technique used for steady state problems which are solved using a time dependant method, in which local time steps vary between cells.

Log-law

a logarithmic profile assumed to represent the positional variation of a variable close to the wall in a boundary layer. See law of the wall.

Low Reynolds number turbulence model

a turbulence model that is valid for low Reynolds Number flow regimes, usually close to boundaries.

LU factorisation

decomposition of a matrix into ‘upper triangular’ and ‘lower triangular’ forms. This can lead to an easy solution of the resulting triangular set of equations.

M

MacCormack’s method

an explicit finite difference method particularly suited to marching numerical solutions, either in space or time. Similar to the Lax-Wendroff method.

Mach number

a dimensionless number that is the ratio of the speed of fluid flow to the speed of sound in the fluid.

Magnusson model

a commonly used reaction model in which the rate of a reaction is calculated based on the finite chemistry and also based on the turbulence (generally using the eddy break-up model). The slower of the two rates is assumed to govern the reaction process and is used to obtain the solution.

Marangoni convection

see capillary convection.

Marangoni number

a number characterising the thermal forces at the surface of a free surface flow.

Marching

an explicit method that computes a solution at a given step as a function of known values at the previous step.

Marker-and-cell method

a type of free surface method in which weightless markers in each cell are used to track the free surface profile. It is similar to the volume of fluid method.

Mesh

see grid.

Method of characteristics

a method for solving a set of hyperbolic equations by setting out the equations in the form of 'characteristics' that relate the variables uniquely.

Method of lines

method by which the discretised transport equations can be expressed as temporal ordinary differential equations. In this way, any standard ordinary differential equation approach can be used in the solution process.

Mixing length

in turbulent flow, a characteristic (or typical) distance travelled by fluid particles in a direction normal to the flow (also known as Prandtl's mixing length) or a characteristic size for turbulent eddies.

Mixture fraction

a non-dimensional variable used to describe the relative quantities of two species or phases.

Model Accuracy

a measure of the similarity of a conceptual model to the physical flow it is intended to represent and one of the measures by which a solution is validated.

Modelling errors

errors due to the difference between the physical flow and the exact solution of the mathematical models being solved.

Momentum equation

an expression of Newton's Second Law, where the rate of change of momentum equals the sum of forces on a fluid particle.

Moving mesh

a mesh which is updated with time, in order for moving boundary problems to be analysed.

Multi-block approach

a meshing technique in which several 'blocks' of structured grid are combined to enable the meshing of complex geometries.

Multigrid method

a technique used to accelerate the convergence of iterative solution techniques based on the solution of a set of simultaneous correction equations. Adding neighbouring discretised equation coefficients generates these correction equations. The coefficient addition enables the correction equations to be solved for a smaller (and hence faster to solve) array than that used for the main discretisation equations. Also known as geometric multigrid, it is an alternative to algebraic multigrid.

Multiphase flow

flow consisting of two or more phases (gas, liquid, solid), e.g. gas bubbles rising through a liquid.

Multistage method

see Runge-Kutta time stepping.

MUSCL approach

Monotone Upstream-centred Schemes for Conservation Laws. A method for the generation of second order upwind schemes via variable extrapolation.

N

Nahme number

see Griffith number.

Navier-Stokes equations

the momentum equations for viscous flow.

Neighbour coefficients

coefficients used to simplify discretised governing equations.

Neighbouring nodes

the nodes adjacent to the node of a control volume in the Finite Volume method.

Neumann boundary condition

where values of flow variable derivatives are imposed on the boundaries of the flow domain.

Newton's method

a method for solving non-linear equations using inner and linearised outer iterations.

Newtonian fluid

fluid in which viscous shear stresses are assumed proportional to the velocity gradient perpendicular to the flow direction and the constant of proportionality is independent of the flow field.

No slip condition

where velocity components at a solid wall are set equal to the velocity of the walls, i.e. the fluid does not slip over the wall but exhibits a velocity gradient from stationary flow at the wall to the free stream velocity.

Nodal point

see grid point.

Node

see grid point.

Non-conforming elements

those in which the shape functions do not satisfy the continuity condition of the boundaries of an element, i.e. it is possible for the element edges to overlap or form gaps.

Non-conservation form of equations

partial differential equations obtained for an infinitesimal fluid element that travels through the flow (as opposed to being fixed in space and which therefore results in the conservation form of the equations).

Non-dimensional form of equations

an equation form in which each term is non-dimensionalised using reference values for length, time, velocity, pressure etc.. This process potentially lends itself to a better appreciation of the dominant flow physics.

Non-orthogonal grid system

A system in which the grid lines are not always at right angles, enabling meshing around irregular geometries.

Non-reflecting boundary condition

a boundary condition that does not permit the reflection of pressure waves.

Non-uniform grids

A grid in which the computational cells vary in size and / or shape.

Normalisation

the adjustment of a series of values, using division by a constant, to provide a consistent reference value.

Numerical Accuracy

a measure of the accuracy of the numerical treatment (i.e. discretisation and convergence) and one of the measures by which a solution is verified.

Numerical diffusion

a type of numerical error that smears simulated flow gradients giving the same effect as flow diffusion. It is due to truncation errors that arise as a result of representing the fluid flow equations in discrete form. It is inversely related to the grid resolution. Numerical diffusion may also be reduced by the use of higher order discretisation schemes and alignment of the grid lines with the streamlines. It is also known as false diffusion and it results in a diffusive error.

Numerical dispersion

a numerical effect on the solution in Fourier space in which waves are spread in space, but not changed in amplitude.

Numerical dissipation

a numerical effect on the solution in Fourier space in which the variation of the coefficients (or amplitude) is reduced.

Numerical grid

see grid.

Numerical instability

an increasing oscillation of an iterative solution or the growth of errors due to round-off or truncation in a numerical scheme.

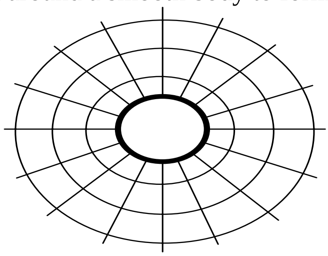
Numerical viscosity

an error resulting from finite difference approximations causing excess energy dissipation.

O

O-grid

a curvilinear grid wrapped around a smooth body to form the shape of an O.



One-sided differencing

first order numerical differentiation (forward or backward) as opposed to second order central differencing.

One-step reaction

simplest chemical reaction. One group of reactants forms one group of products directly.

Operator splitting

decomposing a differential equation solution scheme into several stages.

Order of accuracy

the number of terms retained in the series expansion used to approximate the equations in their discretised form.

Orthogonal grid

a grid in which intersections of grid lines are all perpendicular or near perpendicular.

Orthonormal functions

a pair of functions that are orthogonal to each other and normalised.

Oscillatory pressure solutions

see checker-board pressure field.

Outer iterations

progress of differential equation solutions from one (false) time step to the next after resolving non-linearity of the difference equations.

Outflow boundary condition

boundary with specified flow rate out of the flow domain.

Outlet boundary condition

boundary at which fluid leaves the flow domain. Often specified as a constant pressure boundary.

Over-relaxation

extrapolation of results from one iteration to the next, often leading to instability.

P

Panel methods

A rapid computational method for determining the value of a potential function (and hence surface velocities and pressures) on discrete panels representing a surface geometry. The method is suited to flows that can be considered inviscid, incompressible and irrotational, features typical of many high speed vehicle aerodynamic applications. Boundary layer calculations, compressibility corrections and wake surfaces extend the use and accuracy of panel method calculations.

Parabolic equation

partial differential equations of the form $Au_{xx} + 2Bu_{xy} + Cu_{yy} = F(x,y,u,u_x,u_y)$ for which $AC - B^2 = 0$. Examples of problems that are described by parabolic equations include many time dependant problems such as unsteady viscous flow and unsteady heat conduction. Steady problems can also be parabolic; for example, equations describing one-dimensional supersonic flow fall into this category. In a physical sense, parabolic equations describe behaviour in which the influence of a perturbation extends in only one direction in either time or space. Examples are developing viscous flow in a duct or pipe, or attached (unseparated) boundary layer flow. Here the equations are such that the dominant terms governing transport in the streamwise direction are those describing convection. As long as the flow remains attached with no local flow reversal, these convective terms always operate in the bulk flow downstream direction.

Particle source in cell (PSIC) method

a multiphase Eulerian-Lagrangian method in which a low volume dispersed phase is modelled as discrete sources of mass, momentum and energy in the continuum flow field.

Particle trajectories

paths of discrete material elements suspended in a continuum fluid.

Patching

the pre-iterative definition of flow variables at specific locations.

Pathline

an imaginary line which represents the path travelled by an individual particle of fluid. In steady flow, pathlines coincide with streamlines.

PDF (Probability Density Function)

description of the probability of an event at a given value of an independent variable, especially used in reactions.

Peclet number

dimensionless number that is the ratio of convection to diffusion (mass transfer) or conduction (heat transfer). It is the equivalent of the local or cell Reynolds number.

Penalty formulation

a means of reducing the computational effort in incompressible flow problems by eliminating the continuity equation as well as the pressure term from the momentum equations. Pressure can subsequently be recovered from the computed velocity field.

Pentadiagonal matrix

a matrix containing zeroes in all elements except the diagonal, the subdiagonal, the superdiagonal and slots adjacent (vertically or horizontally) to the subdiagonal and superdiagonal.

Periodic boundary condition

a boundary condition for flows which are periodic in space (see cyclic boundary condition) or periodic in time.

Periodic grid

a grid used to represent geometries that repeat periodically in space. It is often used in conjunction with periodic boundary conditions.

Petrov-Galerkin

a finite element method of discretisation that uses modified weighting functions. The Petrov-Galerkin method differs from the Galerkin or Bubnow-Galerkin method in that the weighting functions are different from the interpolation functions.

Phase velocity

the velocity of one component in a multi-phase flow.

Physical boundary condition

a physical property at a boundary.

Physical properties

a description of the material characteristics (density, viscosity, thermal conductivity, heat capacity etc.).

Picard iteration

the solution of integral equations by successive iterations.

PISO algorithm

the Pressure Implicit with Splitting Operators algorithm is a pressure velocity coupling algorithm involving one predictor and two corrector steps.

Point source

an isolated point from which something (i.e. mass, momentum, energy) issues into a flow field.

Point sink

an isolated point through which something (i.e. mass, momentum, energy) leaves a flow field.

Point-collocation method

weighting function for method of weighted residuals.

Poisson solvers

methods of solving Poisson's (elliptic) equations.

Polar grid

grid based on spherical co-ordinates (two angles and radius).

Porous jump boundary condition

a one-dimensional version of porous media modelling used to model thin walled membranes, such as mesh screens, filter papers or perforated plates, which exhibit a known pressure drop. The pressure loss is simulated as occurring between adjacent cells.

Porous media modelling

the use of a geometric region operating as a momentum sink via terms for inertial and viscous resistance. This can be used to represent the pressure drop occurring through a variety of media including packed beds, tube banks, etc..

Positive definite matrix

a matrix is positive definite if the dot product with itself is equal to zero, if and only if, the matrix is itself zero.

Post-processing

extracting the required data from a completed simulation and presenting it in a readily understood form, often graphically.

Potential flow

steady, inviscid, incompressible and irrotational flow.

Prandtl number

a dimensionless number that is the ratio of momentum diffusivity to thermal diffusivity.

Prandtl's mixing length

see mixing length.

Pre-conditioning (and pre-conditioning matrix)

a convergence acceleration technique used in iterative methods.

Predictor step

see predictor-corrector method.

Predictor-corrector method

a method for integrating ordinary differential equations by extrapolating a polynomial fit of derivatives from previous points to new points (predictor step) This is then used to interpolate the derivative (corrector step).

Pre-processing

definition of the flow to be simulated (fluid properties, geometry, mesh generation, boundary conditions etc.).

Pressure boundary condition

a boundary where the local pressure is defined.

Pressure coefficient

a dimensionless description of local pressure that has several different definitions according to the application.

Pressure correction

a modified form of the continuity equation that is used with momentum equations to solve for pressure and velocities (e.g. SIMPLE algorithm).

Pressure–velocity coupling

the linkage of pressure and velocity in the simultaneous solution of momentum and continuity equations.

PRESTO scheme

the PREssure STaggering Option is a method of calculating the cell face pressure using a continuity balance for a ‘staggered’ cell, centred on the cell face.

Primitive variables

density, pressure and velocity components.

Probability Density Function

see PDF.

Projection method

a method in which a velocity field is constructed then corrected to satisfy continuity.

Prolongation

a method to interpolate a value/correction from coarse to fine grids (multi-grid).

Pseudo-compressibility

a method of adding an artificial compressibility term to the continuity equation to solve the incompressible Navier-Stokes equations using time dependent compressible methods.

Pseudo-path line

a vector contained within a characteristic surface.

Pseudo-transient method

see pseudo-unsteady formulation.

Pseudo-unsteady formulation

a time-marching technique following the numerical solution in time until steady-state is reached.

Pseudo-velocity

a type of guessed velocity used in the SIMPLER algorithm.

PSIC method

see particle source in cell method.

Q

Quadratic interpolation

see QUICK and QUICKEST.

Quadratic upwind differencing scheme

see QUICK and QUICKEST.

Quadridiagonal matrix

matrix with four diagonally arranged terms.

Quadrilateral elements

four sided, two dimensional elements.

Quasi-linear differential equations

non-linear equations that are assumed to contain locally-constant coefficients.

Quasi-one-dimensional nozzle flows

flows for which the flow properties are assumed to vary in the axial direction only.

QUICK upwind scheme

a third-order accurate upstream-weighted quadratic interpolation scheme. The QUICK scheme, as its name implies, uses a quadratic function that passes through three node values, to determine the required node value. It computes the cell boundary value of the variable based on the values in the two adjacent cell centres and at a third cell centre at an additional upstream point. See discretisation scheme.

QUICKEST upwind scheme

the QUICK scheme estimated, developed for the unsteady advection-diffusion equation and only used with explicit solvers.

R

Radiation

electromagnetic transport of thermal energy.

Random vortex method

an algorithm capable of tracing the action of elementary turbulent eddies and their cumulative effects, without imposing any restriction upon their motion.

Rankine-Hugoniot relations

conservation equations across a steady, normal shock in terms of ratios.

RANS (Reynolds averaged Navier Stokes)

a form of the Navier Stokes equations in which additional terms (known as Reynolds stresses) are included to account for the time averaged effects of turbulence. See Turbulence Models.

Rayleigh number

dimensionless expression of the strength of a buoyant flow, with laminar/turbulent transition occurring typically between 10^8 and 10^{10}.

Realisable

satisfying mathematical constraints due to physics.

Reduced Navier-Stokes equations

the Navier-Stokes equations can be reduced for a variety of flow situations including incompressible flows (density variation terms removed) and isothermal flows (temperature variation terms removed).

Reference pressure

fixed location absolute pressure value to which other pressures are related.

Region of dependence

region within the Mach cone ahead of and able to affect a supersonic body.

Region of influence

region within the Mach cone affected by passage of a supersonic body.

Relaxation technique

a finite difference technique particularly suited for the solution of elliptic partial differential equations.

ReNormalisation Group (RNG) k-ε turbulence model

see RNG k-ε turbulence model.

Residual

error calculated from summing terms in partially converged equations.

Residual norm

normalised residual to help judge overall convergence.

Restriction

multi-grid term: smooth residual from fine to coarse grid.

Reynolds analogy

analogy between heat and momentum transfer where Prandtl Number is equal to one.

Reynolds averaged Navier Stokes

see RANS.

Reynolds number

a dimensionless number that is the ratio of inertial to viscous forces.

Reynolds stress model for turbulence

see RSM.

Reynolds stresses

additional terms produced by time averaging the turbulent Navier Stokes equations; physically, the nine stress components associated with turbulent transport of momentum.

Reynolds transport theorem

Reynolds transport theorem describes the relationship between Eulerian and Lagrangian frames of reference.

Reynolds-averaging

ensemble averaging to remove small scale unsteadiness to enable the simulation of turbulent flows.

Richardson extrapolation

a method of approximating a variable value using several different grids and an error estimate.

Richardson number

a stability criterion for stratified flows.

Richardson's method

an extrapolation method for improving approximate finite-difference results without the explicit use of a difference correction.

Richtmyer algorithm

a two-step scheme that avoids estimation of a Jacobian matrix.

Riemann problem

a system containing discontinuous neighbouring states e.g. a shock problem.

RNG k-ε turbulence model

a variant of the standard k-ε turbulence model where the model constants are derived from Renormalisation Group theory and are based on statistical techniques as opposed to empirical techniques as used in the standard k-ε model.

Robin boundary condition

a linear combination of a variable's specified value and its normal derivative.

Roe linearisation

a method of extending the linear wave decomposition to non-linear equations.

Roe's approximate Riemann solver

Roe linearisation of the conserved flux Jacobians applied to hyperbolic equations.

Rotating frame of reference

a physical coordinate system that rotates at constant angular velocity in order to observe fluid motion relative to an object rotating at (usually) the same angular velocity. Flow equations and calculations employ extra terms to accommodate the effects of rotation. Usually applied to turbomachinery flows.

Rothalpy

rotational stagnation enthalpy. The total energy content in a steadily rotating frame of reference.

Round-off error

an error caused by the storage of a real number using a restricted number of digits, rounding off to the nearest value.

RSM (Reynolds stress model)

a closure turbulence model with six equations for Reynolds stress transport and the scalar dissipation rate.

Runge-Kutta scheme

an explicit non-linear time integration technique.

Runge-Kutta time stepping

a method of stabilising a higher order Runge-Kutta scheme, also known as a multistage method.

S

Scalar control volume

the control volume containing the scalar variables in a staggered grid arrangement.

Scalar flux

rate of flow of a scalar quantity per unit area.

Scale similarity model

a sub-grid scale model for the behaviour of turbulent eddies.

Schmidt number

a dimensionless number that is the ratio of kinematic viscosity to diffusivity and is the analogue for the diffusion of chemical species to the Prandtl number for the diffusion of heat.

Schwartz-Christoffel transformation

formula to produce conformal mapping of a closed region in the physical plane to the upper half of the transform plane.

Second order scheme

a scheme which is second-order accurate in terms of a Taylor series.

Secondary flows

flows in a transverse plane to the main streamwise flow.

Segregated solver

A solver in which the governing equations are segregated from one another and solved sequentially. This approach is often used for incompressible flows. It is an alternative to a coupled solver.

Self preservation

a flow where functions of flow variables become invariant with distance in the flow direction.

Semi-Implicit

a method of solution which is a mixture of an explicit and a fully implicit method.

Shallow water equations

equations that describe the time-dependent and spatial distribution of the height of a free surface in a stream with velocity.

Shape functions

known functions used in the Finite Element method to approximate field variables by linear combinations.

SIMPLE algorithm

(Semi-Implicit Method for Pressure-Linked Equations) an algorithm which is used to compensate for the lack of an explicit pressure equation in the Navier Stokes equations using an iterative procedure consisting of a predictor and a corrector step.

SIMPLEC algorithm

the basic SIMPLE algorithm can suffer from slow convergence properties and can, in certain circumstances, also suffer from a lack of robustness and over-sensitivity to under-relaxation parameters. To overcome these limitation several variants of the SIMPLE algorithm have been derived. SIMPLEC is one of these variants.

SIMPLER algorithm

(SIMPLE Revised) the basic SIMPLE algorithm can suffer from slow convergence properties and can, in certain circumstances, also suffer from a lack of robustness and over-sensitivity to under-relaxation parameters. To overcome these limitations several variants of the SIMPLE algorithm have been derived. SIMPLER is one of these variants.

Singularity method

a technique to solve a linear Laplace equation. A linear superposition of known elementary flow fields, such as vortex and source singularities, is defined. The unknown coefficients of this linear superposition are obtained by stipulating that the resultant velocity field satisfies the condition of vanishing normal velocity along solid body surfaces.

Sink

negative source term.

SIP (strongly implicit procedure)

a technique for solving simultaneous equation sets, also known as Stone's Method. Alternative techniques include TDMA, Gauss-Siedel, conjugate gradient.

Skew upwind scheme

a higher order discretisation scheme where the interface value of the dependent variable is established by the upstream conditions in the flow direction. Often accurate but can produce non physical under- or overshoots in the regions of steep gradients.

Skewness

a non-dimensional parameter which characterises the extent to which a cell is deformed from an equilateral cell of equivalent volume and the same basic shape (triangle, square, cube, etc.).

Skin friction coefficient

a non-dimensional parameter that characterises the viscous friction forces of the flow over a solid surface.

Solution adaptive mesh

a CFD grid that automatically adjusts to the emerging CFD solution. It has the substantial advantage that steep gradients of dependent variables can be resolved with a locally refined grid, which does not have to be fixed in advance of starting the simulation. Solution adaptive grids are often used in the capture of sharp flow features such as shocks or moving deflagration fronts.

Solution of algebraic equations

CFD simulations are based on the solution of some form of the governing Navier-Stokes equations. These are highly non-linear partial differential equations that cannot, except in a few trivial cases, be solved analytically. Typically, the partial differential equations are discretised and rearranged to form a set of algebraic equations, essentially consisting of a large set of simultaneous equations. Solution of the algebraic equations provides an approximate discrete solution of the governing flow equations.

Solutions vector

a vector of dependent flow variables. Usually an expression confined to the external aerodynamics CFD community. As an example, the solution vector for the Euler equations consists of the three components of velocity, pressure and internal energy.

Source terms

terms which appear in the general conservation equation of a variable and which cannot be accommodated in the unsteady, convective or diffusive terms. They are meant primarily for internal generation processes such as heat generation in a fluid, production of a chemical species in a reaction, and the generation of turbulent kinetic energy. However when the corresponding physical quantity is destroyed rather than produced, the source term becomes negative and may be known as a sink term.

Space marching

early CFD methods were often limited, by restricted RAM, to the solution of a parabolic form of the governing equations using a space-marching method. In this technique the solution is marched downstream, with no upstream influence of downstream conditions allowed. This permits one to effectively solve 3-D problems by storing only 2-D arrays, and 2-D problems by storing only 1-D arrays. Attached boundary layer and supersonic flows are typical candidates for space-marching approaches.

Spectral method

a method that uses the Fast Fourier Transform or similar polynomial method to solve Navier-Stokes equations or other partial differential equations. Commonly used for Direct Numerical Simulations. Spectral methods are higher order methods, of the N-th order if there are N grid points.

Spline methods

an implicit finite difference relationship for the first and second derivative derived from the Taylor series expansions of the transport equations. Spline methods have been used extensively in Finite Element codes, but have not been found to be advantageous for finite volume / finite difference codes.

Splitting methods

see approximate factorisation technique

Spurious oscillations

unphysical oscillations of a solution generated by the discretisation scheme.

Stability

the property of a numerical method that progresses towards a solution without wild oscillations or divergence.

Stability analysis

a mathematical procedure examining the behaviour of a discretisation scheme and providing criteria for its stability.

Stability criterion

for a given discretisation scheme, a stability criterion provides the conditions, for instance, on time-step or space discretisation, to achieve convergence.

Staggered grid

in a staggered grid, the velocity components are calculated at the points that lie on the faces of the control volumes while all the other variables are calculated at the centre of the control volumes. A grid is forward or backward staggered depending on whether the staggered grid is offset forwards or backwards.

Steady state flow

a flow field that is independent of time.

Steepest descent methods

a method for finding the minimum value of a function.

Steger-Warming flux splitting

an upwind discretisation scheme that splits the fluxes according to the signs of the eigenvalues. This scheme aims to capture discontinuities.

Stencil

a representation of a difference formula, based upon the values at neighbouring points.

STEP

an international standard for the exchange of CAD / CAM data (ISO 10303, The STandard for the Exchange of Product model information).

Step size

spatially, the step size is the cell size. Temporally, the step size is the size of the time increments.

Stiff problems

stiff problems occur when there are two or more very different scales of the independent variables on which the dependent variables are changing.

Stokes equations

Fluid flow equations where convection terms are neglected with respect to viscous terms.

Stokes' hypothesis

an approximation that can be applied when the Reynolds number is small compared to one, i.e. for strongly viscous-dominated flows. It neglects convection terms with respect to viscous terms and results in the Stokes equations.

Stream function

the mathematical description of two-dimensional flows that allows the velocity field to be represented in terms of a single function ψ such that v = -grad ψ.

Streamline

an imaginary instantaneous line, which characterises a flow such that, at every point along the line, the velocity vector is tangent to the line. For steady flow, streamlines and path lines are identical.

Streamline co-ordinates

a co-ordinate system fitted to the flow such that a co-ordinate direction is aligned with the flow streamlines.

Streamline upwind scheme

a scheme used to stabilise the higher order symmetric operators from the Galerkin method by adding numerical diffusion in the streamwise direction only, thus preserving the accuracy of the Galerkin method in the cross-stream direction. This scheme is often used in Finite Element Analysis and for convection dominated flows.

Stretching function

a stretching function is used to define how the separation of grid lines varies. If there is no stretching, the grid is uniform. However, a non-uniform grid is often needed to optimise the number of cells used. In this case, a stretching function may be used to fix the disposition of the grid lines.

Strongly implicit procedure

see SIP

Strouhal number

a dimensionless number used to characterise the periodicity of unsteadiness occurring in flows exhibiting a dominant frequency of unsteady behaviour. The number is calculated from the product of frequency and representative dimension of an object immersed in the flow, divided by the free stream velocity. In physical terms, it represents the ratio of the time of transit of the free stream fluid past the object, to the period of the dominant unsteadiness.

Structured grid

a grid in which the cells (hexahedra in three dimensions or quadrilaterals in two dimensions) form a regular pattern. The grid lines are continuous across the domain and are usually aligned with the co-ordinate directions or mirror the boundary topography. Each grid cell in a structured grid can thus be defined by a matrix of two or three numbers representing positions along a grid line in each co-ordinate direction.

Subgrid scale

an effect or geometrical entity that is smaller than the size of a single grid cell.

Subsonic flow

flow that is slower than the speed of sound, i.e. the Mach number is less than unity.

Substantial derivative

physically the average time rate of the change of a variable.

Successive over-relaxation (SOR)

a method of solving matrices.

Superficial velocity

a velocity in a porous medium where the fluid volume is not reduced to take account of the degree of blockage; i.e. the velocity that would occur if the mass flux of fluid was distributed over the entire area occupied by fluid and solid.

Supersonic flow

flow that is faster than the speed of sound, i.e. the Mach number is greater than unity.

Sutherland's formula

a formula for the dynamic viscosity as a function of temperature using a constant known as the Sutherland constant.

Sweep direction

the direction in which the matrix is solved.

Symmetry boundary condition

boundary condition where the normal velocity is zero and the normal gradients of all other variables are also zero.

T

TDMA

see tri-diagonal matrix algorithm.

Tetrahedral elements

3D computational cells that are tetrahedral in shape - i.e. have four sides.

Thermally perfect gas

a gas for which (pV)/(mT) is constant.

Thomas algorithm

see tri-diagonal matrix algorithm.

Time marching

a solution technique to obtain a steady state solution by solving transiently until the rate of change from one time step to the next is negligible.

Time step

the incremental change in time for which a flow is being solved.

Total pressure

the static pressure plus the dynamic pressure or the pressure obtained by bringing a fluid to rest isentropically.

Total Variation Diminishing (TVD) schemes

a higher order differencing scheme.

Transfinite interpolation

an algebraic method of interpolating a mesh.

Transient

see unsteady.

Transitional flow

flow which changes from exhibiting laminar behaviour to turbulent behaviour

Transonic flow

flow that changes from subsonic to supersonic or vice versa.

Transport equation

a differential equation describing the redistribution of a property or quantity through a medium or through space.

Transportiveness

a property of the numerical scheme that accounts for the direction in which the relative strengths of convection and diffusion influence the flow.

Triangular element

a two dimensional computational cell that is triangular in shape.

Tri-diagonal matrix algorithm (TDMA)

a particularly efficient method used to solve the matrix equation set **Ax** = **b**, where **A** is such that all non-zero coefficients align themselves along three diagonals.

Truncation error

the result of the truncation of the expansion series used in the discretisation scheme.

Turbulence

a chaotic state of fluid motion where the velocity and pressure change continuously with time.

Turbulence characteristic length

a typical dimension of a turbulent eddy.

Turbulence models

sets of equations that determine the turbulent transport terms (Reynolds stresses) in the mean flow equations. They are based on hypotheses about turbulent processes and generally require significant empirical input in the form of constants or functions. These time averaged models do not simulate the details of the turbulent motion (the turbulent eddies), only the effect of turbulence on the mean flow behaviour. Thus, with a particular set of empirical constants, they are valid only for a certain flow or at most a range of flows. This is also known as a RANS approach (Reynolds Averaged Navier-Stokes).

Turbulence production

the generation of turbulence.

Turbulence spectrum

the distribution of eddy scales from smallest to largest which are present in a flow.

Turbulent dissipation

the reduction in turbulent kinetic energy caused by the work done by the smallest eddies converting turbulent kinetic energy to thermal internal energy.

Turbulent energy

see turbulent kinetic energy.

Turbulent flux

transport of a quantity associated with turbulent motion.

Turbulent kinetic energy

the kinetic energy associated with the turbulent fluctuations in velocity.

Turbulent length scale

the length scale characteristic of the largest eddies which contain most of the turbulent kinetic energy.

Turbulent Prandtl number

in the "eddy viscosity model" of turbulence, transport of momentum due to turbulence is modelled by adding an effective viscosity representative of local turbulence conditions (the eddy viscosity) to the true fluid viscosity in the diffusion terms of the momentum equations. By analogy, transport of heat due to turbulence is modelled by adding an effective thermal diffusivity to the true fluid thermal diffusivity in the diffusion terms of the energy equation. The turbulent Prandtl number is the ratio of the eddy viscosity to this effective thermal diffusivity.

Turbulent scalar transport

see turbulent flux.

TVD schemes

see Total Variation Diminishing schemes

Two-equation model

a turbulence model that uses two transport equations to model the effects of turbulence in the RANS equations.

Two-level scheme

a temporal scheme that stores variables at two time levels.

U

Unconditional instability

the property of a scheme which is always unstable, regardless of values of parameters such as cell size or size of time steps.

Unconditional stability

the property of a scheme that is always stable, i.e. no constraints exist on parameters such as cell size or time step size.

Uncoupled particle flow

flow of discrete particles (bubbles or drops) in a continuum in which the movement of the particles does not influence the flow of the continuum.

Underrelaxation

an algorithm restraining the amount by which a variable may change from one iteration to the next.

Uniform grid

a computational grid in which each cell is the same size and shape.

Unstable scheme

a scheme which does not exhibit stability, i.e. it does not converge.

Unsteady flow

flow which changes with time.

Unstructured grid

a grid in which the cells form no regular pattern. Unstructured grids allow highly complex geometries to be modelled with relative ease compared to structured grids and allow for greater cell concentrations in regions of flow complexity.

Upwind differencing scheme

a discretisation scheme that uses the upstream variable values. Also known as donor cell differencing.

Upwind formulation

see upwind differencing scheme.

URANS

unsteady Reynolds Averaged Navier Stokes. See RANS.

V

Validation

the process of determining how accurately a simulation represents the real world. cf Verification.

Van Leer's flux splitting

basically a technique for discretising convective terms, sometimes called the MUSCL scheme. Alternative approaches include QUICK (a form of upwinding) and central differences. MUSCL includes a free parameter and for certain values, MUSCL reduces to QUICK or second order central differencing.

Variational formulation

a minimalisation formulation used in the finite element method, especially for structural analysis.

Vector plots

a method of displaying a vector quantity at discrete grid locations, using arrows to illustrate both magnitude and direction.

Velocity correction

used in pressure correction methods, such as SIMPLE, to correct for guessed velocity values.

Velocity defect law

a law that treats the wall shear stress as the cause of a defect, which decreases with distance from the wall.

Velocity profiles

sectional variation in velocity, e.g. parabolic variation in fully developed laminar pipe flow.

Verification

the process of determining if a simulation accurately represents the conceptual model. A verified simulation does not make any claim relating to the representation of the real world by the simulation. cf. Validation

Vertex centred

a formulation in which cell vertices are located mid-way between cell centres.

Vertex-based formulation

a formulation in which the variable values are stored at the cell vertices.

Very large eddy simulation

see URANS.

Viscosity

the resistance of a fluid to shear; relating shear stress to the rate of angular deformation of fluid elements.

Viscous dissipation

the dissipation of turbulent kinetic energy caused by work done by the smallest eddies against viscous stresses.

Viscous interaction

see viscous-inviscid interaction.

Viscous stresses

stresses due to the resistance of relative movement of fluid layers either past one another or other fluids or solids. They are generally the dominant forces in near wall regions.

Viscous sub-layer

the region close to a wall in which the viscous forces dominate the flow.

Viscous wall units

values of y+.

Viscous-inviscid interaction

a flow field in which significant interaction takes place between a growing boundary layer and the adjacent inviscid flow.

Volume-of-fluid method

a multiphase (multi-fluid) technique in which a single set of momentum equations is shared by the fluids and the volume fraction in each cell is tracked through the domain. This method is generally used where the interface between the fluids is of interest.

Von Karman constant

the constant used in a semi-empirical relationship developed by Theodore von Karman to relate turbulent mixing length to velocity gradient. Most commonly encountered in CFD in the formulation of wall functions for turbulent boundary layers.

von Neumann stability method

a method of assessing the stability of a numerical scheme.

Vortex methods

methods that simulate incompressible viscous flows using point vortices that satisfy Laplace’s equation.

Vorticity

a vector quantity that characterises the strength of rotation in a flow. The curl of velocity.

VRANS

see URANS.

W

Wall damping functions

functions used to modify the k-ε turbulence model for low Reynolds number flows.

Wall functions

functions used to describe the effects of turbulent boundary layers in the region adjacent to a wall, without resolving details of the near wall flow and eliminating the need for high grid resolution in the viscous sub-layer.

Weighted residual formulation

a form of the method of weighted residuals. The most general technique in finite element methods for defining an integral formulation of the physical problem, and which seeks to reduce errors through an appropriate choice of element weighting and interpolation functions.

Weighting functions

an averaging technique in which the discrete computed values are weighted according to the level of some property (such as mass, area, density etc.) in the cell relating to each value for which the average is required.

Well-posed problem

a problem for which the solution depends, in a continuous way, on the initial and boundary conditions.

Wiggles

physically unrealistic numerical oscillations in variable values resolved on the computational grid.

Y

y+

a non-dimensional description of distance from a wall in relation to local flow and wall shear stress parameters. The expression of distances from the wall in y+ ‘units’ is important in defining velocity and turbulence distributions in a universal form suited to wall functions. A very important requirement in the application of wall functions in CFD is that the computational cells adjacent to the wall have a height, usually expressed in y+ units, compatible with the wall functions being employed.

Z

Zero gradient boundary condition

a boundary condition where a variable is defined as constant across the boundary.

Zero-equation models

the simplest type of turbulence models, also known as mixing length turbulence models, in which the turbulent kinetic energy is determined from the mean velocity field.

Zonal method

– a method in which different mathematical models are applied to different regions in the geometrical domain.

Zone of dependence

see region of dependence.

Zone of influence

see region of influence.

Nomenclature

It should be noted that several of the characters have more than one definition. This is a result of the wide range of disciplines to which CFD is applied. In different circumstances, characters may be used to represent different terms. This nomenclature is not definitive, neither is it absolutely rigid, however the intention is to provide a standardised set of characters for NAFEMS CFD publications.

a	Convection velocity of wave speed (m/s)
A	Cross-sectional area (m^2)
A	Global representation of spatial disctretisation
$[A]$	Coefficients matrix for discretised equations
c	Speed of sound (m/s)
C_p	Specific heat at constant pressure (J/kg K)
C_v	Specific heat at constant volume (J/kg K)
C	Courant number (dimensionless)
C	Convection coefficient (kg/m s)
C_D	Coefficient of drag (dimensionless)
C_p	Pressure coefficient (dimensionless)
C_μ, $C_{\mu 1}$, $C_{\varepsilon 1}$, $C_{\varepsilon 2}$	Turbulence model constants
e	Internal energy per unit mass (J/kg)
f	Flux function
f	Friction factor (dimensionless)
Fr	Froude number (dimensionless)
g	Acceleration due to gravity (m/s^2)
Gr	Grashof number (dimensionless)
h	Specific enthalpy (J/kg)
h	Height (m)
H	Total enthalpy (J)
i,j,k	Array or grid point location identifiers
I	Rothalpy (J)
J	Jacobian or total flux (convection + diffusion) (W/m^2)

k	Coefficient of thermal conductivity (J/m K)
k	Turbulent kinetic energy (m^2/s^2)
l	Turbulence length scale (m)
L	Differential operator
L	Characteristic length (m)
m	Mass (kg)
m	Mass fraction (dimensionless)
$\dot{m}$	Mass flowrate (kg/s)
M	Mach number (dimensionless)
n	General co-ordinate direction
$\boldsymbol{n}$	Normal vector
N	Finite element interpolation function
Nu	Nusselt number (dimensionless)
p	Pressure (Pa)
P_A	Atmospheric pressure (Pa)
Pe	Peclet number (dimensionless)
Pr	Prandtl number (dimensionless)
q	Heat flux (W/m^2)
Q	Source term; matrix of non-homogeneous terms (W/m^3)
r, θ, z	Cylindrical polar spatial co-ordinates
R	Expansion factor or computational cell growth rate factor
R	Specific gas constant (J/kg K)
R	Local curvature parameter
Ra	Rayleigh number (dimensionless)
Re	Reynolds number (dimensionless)
s	Specific entropy (entropy per unit mass) (J/kg K)
S	Characteristic surface
S	Space discretisation operator
$\boldsymbol{S}$	Surface vector

S	Source or sink term (variable) (W/m^2)
Sc	Schmidt number (dimensionless)
S_{ij}	Mean strain rate tensor
$[S]$	Discretised source term matrix
t	Time (s)
T	Temperature (K)
T_{ref}	Reference temperature (K)
T_i	Turbulence intensity
u,v,w	Instantaneous velocity components (m/s)
u', v', w'	Random fluctuating velocity components (m/s)
U, V, W	Average velocity components (m/s)
U_o	Characteristic velocity scale (m/s)
$\boldsymbol{v}$	Velocity vector with cartesian components u, v, w (m/s)
$\boldsymbol{V}$	Eigen vectors of space-discretisation matrix
V	Total volume (m^3)
x,y,z	Spatial coordinates (m)
X, Y, Z	Dimensionless coordinates
$y+, y*$	Dimensionless wall distance parameters
z	Amplification factor of time-integration scheme

Greek letters

α	Diffusivity (dimensionless)
β	Diffusion coefficient (dimensionless)
γ	Ratio of specific heats (dimensionless)
Γ	Diffusion coefficient (dimensionless)
Γ	Circulation; boundary of domain Ω
δ	Boundary layer thickness (m)
δ	Central difference operator
$\delta+$	Forward difference operator

δ^{-}	Backward difference operator
δ_{ij}	Kronecker delta
Δ	Laplace operator
Δt	Time step (s)
$\Delta x, \Delta y, \Delta z$	Spatial mesh size in x, y and z directions (m)
ΔT	Temperature difference (K)
ε	Error of numerical solution
ε	Rate of dissipation of the turbulent kinetic energy (m^2/s^3)
ε_D	Dissipation or diffusion error
ε_ϕ	Dispersion error
ζ	Vorticity vector
η	Non-dimensional difference variable in local co-ordinates
λ	Eigenvalue of amplification matrix
λ	Length scale (m)
λ	Temporal discretisation control parameter
μ	Dynamic viscosity (Pa s)
μ_t	Turbulent viscosity (Pa s)
ν	Kinematic viscosity (m^2/s)
ξ, η, ζ	General transformed co-ordinates (non-dimensional)
ρ	Density (kg/m^3)
ρ	Spectral radius (m)
σ	Courant number (dimensionless)
σ	Diffusion Prandtl number or turbulence fluctuation scale
$\overline{\overline{\sigma}}$	Shear stress tensor
τ	Integral time (s)
τ_t	Reynolds stress (Pa)
τ	Relaxation parameter (dimensionless)

$\bar{\bar{\tau}}$	Stress tensor
ϕ	Velocity potential
ϕ	Phase angle in von Neumann analysis
ϕ	Variable experiencing convection and diffusion (variable)
Φ	Phase angle of amplification factor
Φ	Flow discriminant
χ	Wave number vector
ψ	Stream function
ψ	Rotational function
ω	Time frequency of plane wave (/s)
ω	Over-relaxation parameters
ω	Angular velocity (rad/s)
Ω	Eigenvalue of space discretisation matrix
Ω	Vorticity (m/s)

Subscripts

ave	Average value
e	External variable
i, j, k	Mesh point locations in x, y and z directions or axial, radial and tangential directions
max	Maximum value
min	Minimum value
n	Normal component
n,e,s,w,f,b	Control volume faces neighbouring a central main grid point P
N,E,S,W,F,B	Main grid points neighbouring a central main grid point P
NB	General neighbour grid point
o	Stagnation values
P	Central grid point under consideration
ref	Reference value
S	Pertaining to the surface

u, v, w	Pertaining to listed velocity components
v	Viscous term
w	Pertaining to wall
x, y, z	Components in x, y, z directions
z, r, θ	Pertaining to the axial, radial and tangential directions respectively
∞	Free stream value

Superscripts

+	Dimensionless variable
n	Iteration or time level
new	Pertaining to new value
old	Pertaining to old value

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