M4D, a Research CFD Code for the Calculation of Classical and Turbulent Flows

by Joan G. Moore

M4D is a 3-d, optionally time dependent, CFD program. It is written like a language. I.e., commands are read from an input file, initially standard input. The list of commands and the associated input set up both the CFD example considered and the solution procedure used: steady or unsteady, inviscid, laminar or turbulent including transitional flows. M4D is easily expanded, and nothing is hidden - all the C source code is openly available.

Why

The reasons for writing M4D and making it available are:
(1) to demonstrate the advantages of variable, adaptive, convection biased, control volumes (with a fixed grid) so that the need for adding artificial dissipation is eliminated. Tri-linear profiles in space for convected properties gives 3-d compact second order accuracy.
(2) to demonstrate the implementation of the MARV (or MARVS) Reynolds stress model.
Neither of these is easy to code, so that without an available CFD program to demonstrate their usefulness, the ideas are less unlikely to be tried. These ideas also go together, since artificial dissipation can easily obscure the results of turbulence models, and Reynolds stress models do not provide the same computational stability as Boussinesq (2-Eq.) turbulence models.

The third reason for writing M4D is:
(3) to provide a framework to test both steady and time accurate calculation procedures.

Geometry

M4D uses a single block *ijk* grid but with the option of coincident points and lines, so that it may look like and have some of the advantages of a block structured grid, but also retain simplicity. The location of each grid point is specified in Cartesian coordinates. Each grid point is also assigned a type, f-flow, w-wall, s-solid, or some other character chosen by the user. The types are used to affect the control volume choice, and whether or not equations for particular points should be solved.

The discretization using tri-linear property profiles frees M4D from the artificial numerical constraint of nearly orthogonal, nearly uniform spaced grid points. Think of it as a curve fitting exercise – the grid needs to be adequate so that linear profiles can adequately represent the physics.

A grid for a 2-d turbine cascade is shown in Fig. 1. Grid lines in the *i*-grid direction are shown in red and go from the inlet at left to the flow exit at the bottom right. Grid lines in the *j*-grid direction are in blue and span the pitch from repeating-boundary to repeating-boundary. A *c*-grid around the leading edge is formed by collapsing volumes along 'corner' diagonals, which are both *i* and *j* grid lines. The portions of the grid lines which pass through the solid blade are not shown.

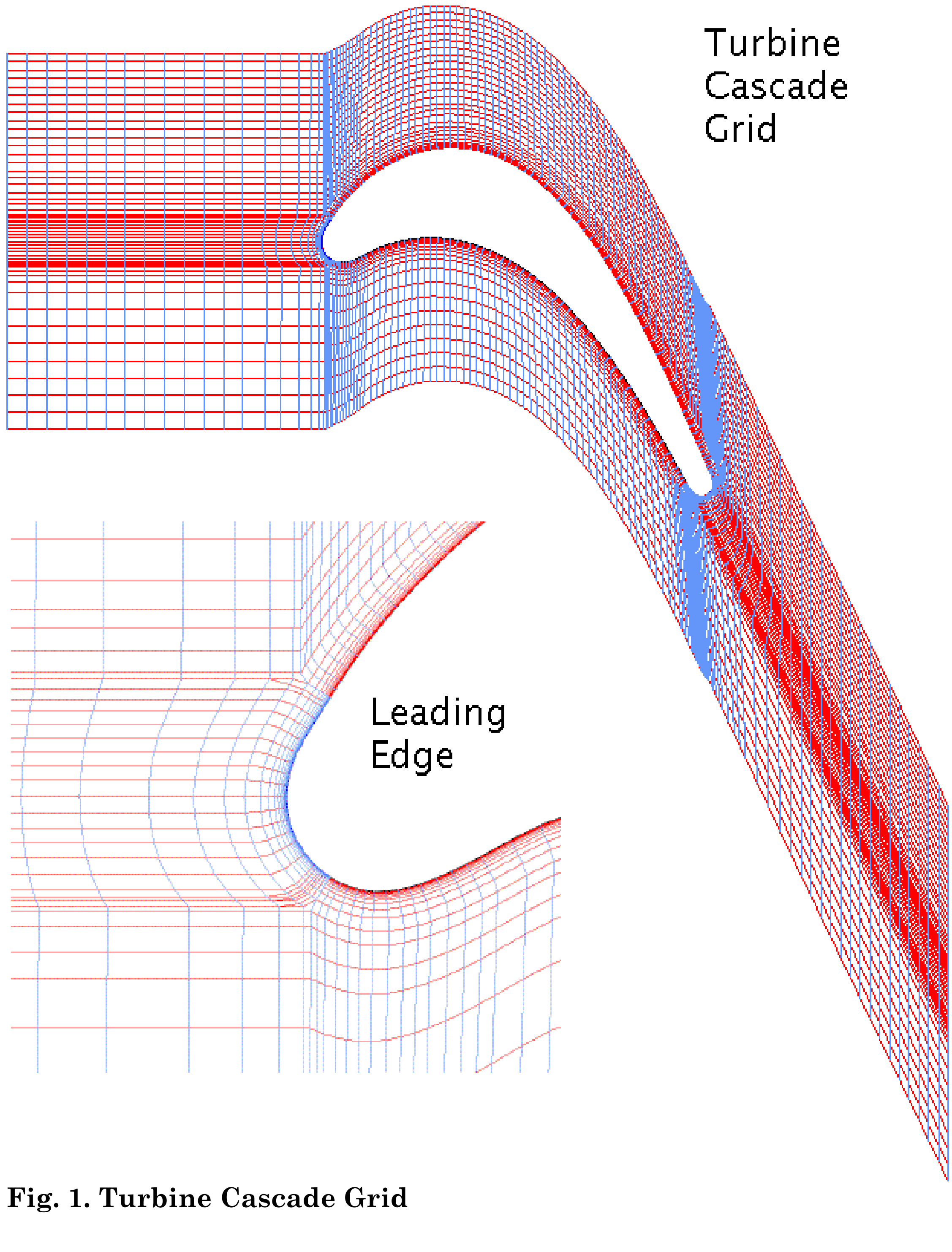


Fig. 1. Turbine Cascade Grid

Differential Equations

The current scope of M4D includes:

(1) Incompressible or steady flow continuity,

$$\partial \rho U_i / \partial x_i = 0.$$

The equations are integrated over the between-the-points volumes and satisfied using a pressure-correction method. A simple but flexible multi-block approach is available to iteratively solve the pressure-correction equations, as well as center-point update and TDMA line solvers.

(2) Conservation equations for:

(a) momentum, U_i, with the option of frame rotation about the z-axis;

(b) the 7-Eq. MARV (Moore and Moore, 2006) and MARVS (Moore and Moore, 2015) Reynolds stress models, q, ω, and b_{ij};

(c) a Coakley 2-Eq. turbulence model, q and ω (Moore and Moore, 2009, slide 2.6);

(d) and any conserved species including an EVM model (Moore and Moore, 2010) for turbulent mixing of thermal energy.

The conservation equations take the generic form

$$\rho \frac{\partial \phi}{\partial t} + \rho U_i \frac{\partial \phi}{\partial x_i} - \frac{\partial}{\partial x_i} \mu \frac{\partial \phi}{\partial x_i} - \frac{\partial}{\partial x_i} \mu_t \frac{\partial \phi}{\partial x_i} - \frac{\partial}{\partial x_i} \mu_{t_{ik}} \frac{\partial \phi}{\partial x_k} = S_\phi .$$

The equations are integrated over the adapted control volumes, Moore and Moore, 2014, (but not in time) to form equations for the property ϕ at the individual grid points. Individual commands give spatial coefficient sets of ϕ for each of the terms on the left hand side.

In general, iterative procedures are used to satisfy the conservation equations for both steady and unsteady flows. The equations are rewritten for the change in ϕ over an iteration ($\int dVol$ not shown for simplicity),

$$C\delta\phi_{\text{centerpoint}} + \rho \frac{\partial \delta\phi}{\partial t} + \rho U_i \frac{\partial \delta\phi}{\partial x_i} - \frac{\partial}{\partial x_i} \mu \frac{\partial \delta\phi}{\partial x_i} - \frac{\partial}{\partial x_i} \mu_t \frac{\partial \delta\phi}{\partial x_i} - \frac{\partial}{\partial x_i} \mu_{t_{ik}} \frac{\partial \delta\phi}{\partial x_k} = R_\phi ,$$

with the addition of a center-point term which is used to provide relaxation for non-linear instabilities. Individual commands calculate appropriate coefficients C for each property. The equations are solved with center-point update and/or TDMA line solvers.

Note that density, ρ, and laminar viscosity, μ, are stored as arrays, and the equations are written consistent with compressible flow. However, M4D, does not currently include an equation of state or a compressible energy equation. So far heat transfer calculations have relied on the conserved species equation with appropriate boundary conditions.

Boundary Conditions

Repeating boundaries may be set in the *i, j,* and/or *k* grid directions. Symmetry planes may also be set at each of the (6) ends of the *i, j,* and/or *k* grid directions. The restriction is that these must be flat planes of constant *x, y,* or *z*, so that the velocity components and components of b_{ij} are appropriately restricted.

Fixed values of primary properties, ϕ, may be set anywhere. This is used for inlet and fixed-value wall boundary conditions. The default wall boundary condition, if the equations are solved for these points, is no viscous flux across the wall. An exception is the command which will impose a uniform wall heat flux for a temperature/energy equation. The turbulence model equations for ω and b_{ij} are solved with fixed wall values, then separate commands reset the wall values appropriate to the model.

Exit pressure boundary condition choices are (a) no change in pressure at the specified exit, (b) a uniform change in pressure at the specific exit to obtain a specified flow rate across the exit, (c) a uniform difference in pressure between the exit and neighboring interior plane with either a specified flow rate across the exit, or one pressure point on the exit plane fixed.

Output and Imbedded Plot Package

All variables (other than temporary ones) are stored in named arrays. These are available at the command level and may be modified, printed, or dumped to a file to be reread or saved for another program.

The imbedded plot package creates:

(1) line plots using either linear or log scales. These can be used to monitor convergence or plot line results of one variable against another.

(2) vector, color-fill contour and/or grid plots of properties on grid planes, flat cut planes, or an unwrapped blade view. This can be used to plot final results, monitor convergence, or save images during a time accurate calculation which can be turned into a video.

Plot images are exported as individual .gif files. External software from the web can be used to combine the images to form animated .gif files, or to create standard .mp4 videos.

Working Examples

Input files and sample output for several working examples are available. The CPU times listed are for a 2010 Mac Mini with a 2.4 GHz Intel Core 2 Duo running Mac OS X Version 10.6.4.

Box Cavity Unsteady inviscid transient of a conserved species convected around a 180 degree bend, Fig. 2. Demonstrates the adaptive control volume method. CPU 2.4 secs. Example from Moore and Moore, 2014; video on M&M homepage.

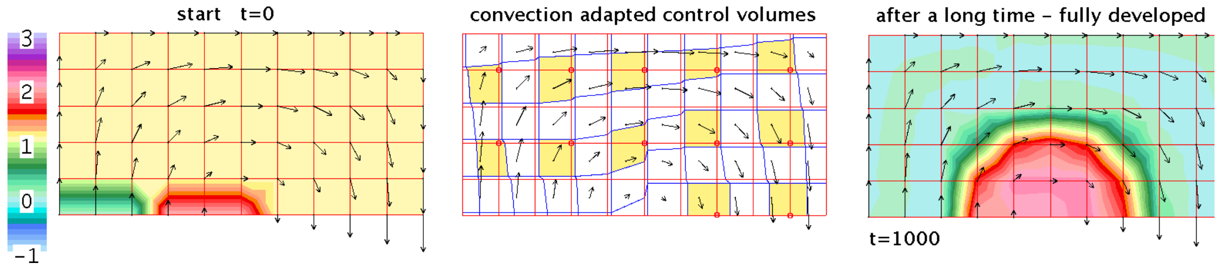


Fig. 2. Box Cavity example.

Kelvin-Hemholtz Instability The development of an inviscid shear layer, as it wobbles then rolls up into a vortex, Fig. 3. Equations: Incompressible continuity, 2-d inviscid time-accurate momentum, and for comparison vorticity as a conserved species. The adaptive control volumes change as the flow develops. CPU 31 min. Example from Moore and Moore, 2014; videos on M&M homepage.

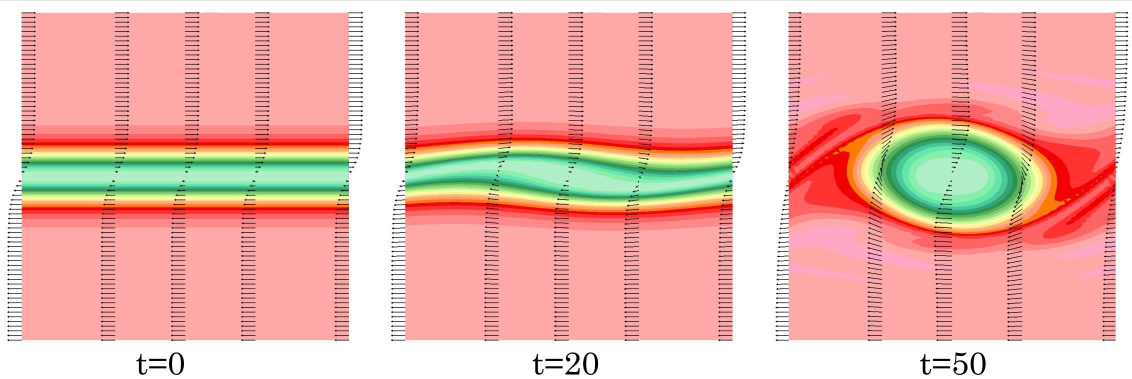
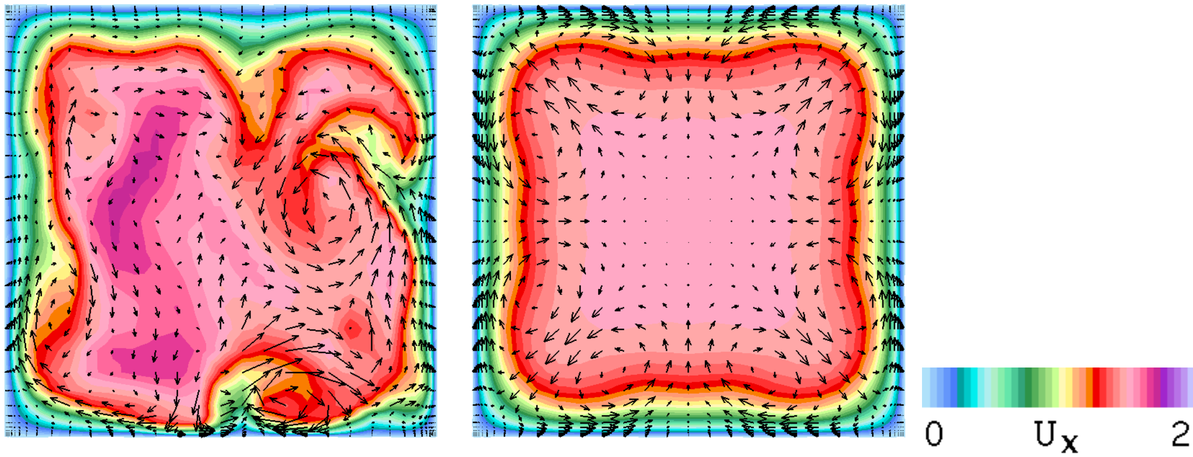


Fig. 3. Kelvin-Helmholtz Instability. Vorticity and selected lines of velocity vectors.

Near-DNS of Flow in a Square Channel 3-d laminar time-accurate calculation for $R_\tau = 300$, Fig. 4. Like the example from Moore and Moore, 2014, except redone from uniform flow and a very coarse grid, 14x27x27. Then 2 finer grids, 14x35x35 and 26x35x35 for a domain $\Delta x, \Delta y, \Delta z$=6,2,2. (The duct width is 2.) CPU 6.3 hours.

This calculation has implications for LES. The adaptive control volumes give stable discretization of convection so that there is no need to add a Boussinesq sub-grid scale model to stabilize the numerical procedure (in fact it would be an embarrassment). This means that a more physics based sub-grid scale model could be considered.

Video of results from Moore and Moore, 2014, on M&M homepage.

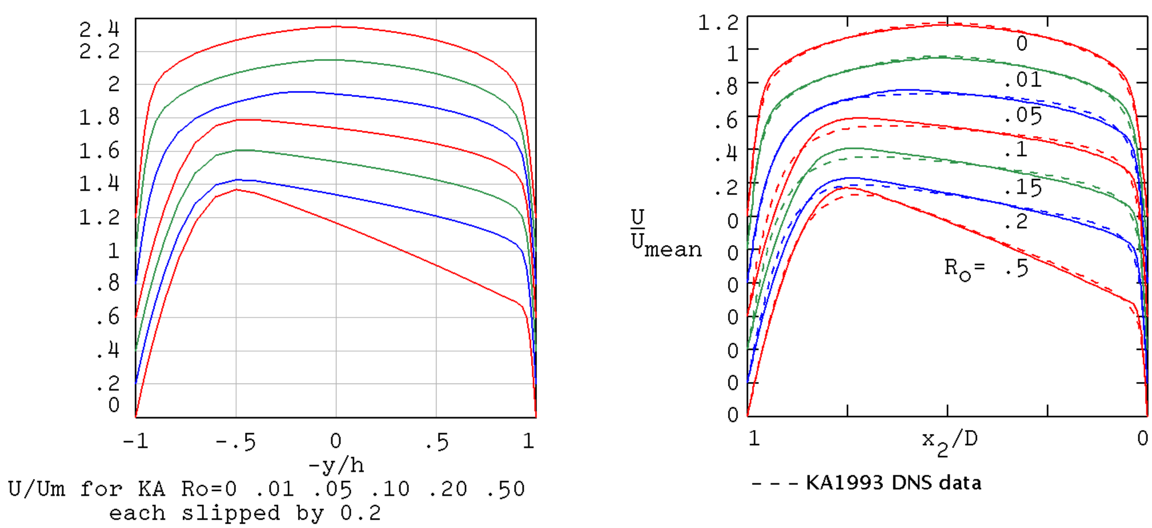


Sample instantaneous,
dt for vectors = 0.8.

Time-, x-, and octant-average,
dt for vectors = 5.

Fig. 4. Near-DNS in square channel. U_x velocity contours with U_y U_z velocity vectors.

2-D Fully Developed Rotating Channel This is a basic test case to check that the Reynolds stress model is correctly implemented. $R_\tau = 194$, $R_o = 0$ to 0.5, Fig. 5, as for the DNS of Kristoffersen and Andersson, 1993. Like in Moore and Moore, 2006, except for the MARVS Reynolds stress model. Equations: steady x-momentum (with a specified *dp/dx)*, and the Reynolds stress model properties. CPU 11 secs.



MARVS model using M4D

MARV model, MM2006, Fig. 13.4.1

Fig. 5. Mean velocity profiles for rotating channel.

Kasagi Backstep 2:1 backstep, $R_D = 9550$, Fig. 6. As in Moore and Moore, 2009, slide 2.8, but using the MARVS Reynolds stress model and a coarser grid. Steady 2-d flow calculation. Fully developed channel flow inlet (fixed properties) at 4 step heights upstream of the step, and exit boundary condition (c) with fixed mass flow rate at 15 step heights downstream of the step. CPU 4 minutes.

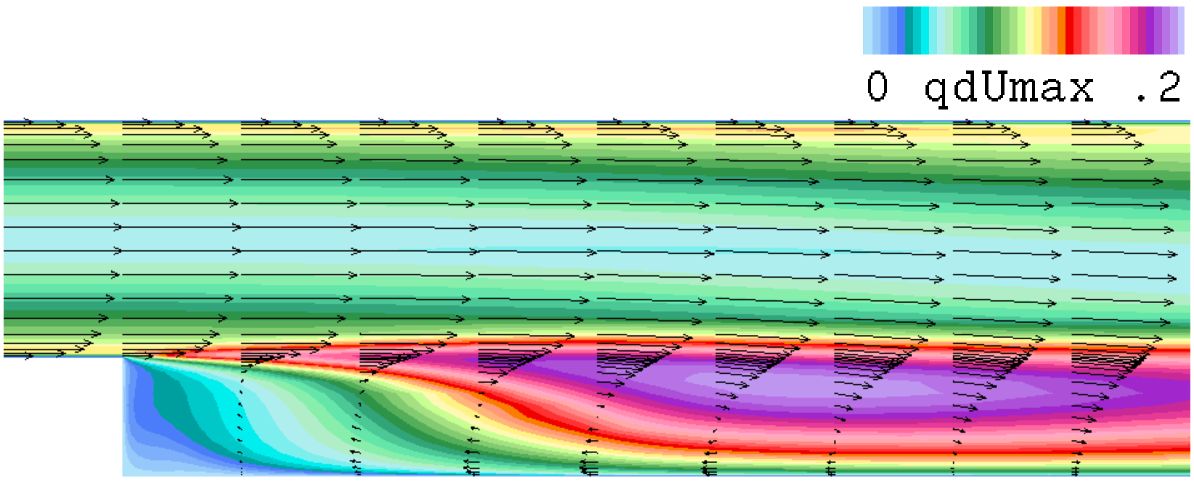


Fig. 6. Kasagi Backstep. Contours of *q/U*

2-D Turbine Cascade with Heat Transfer Steady 2-d flow with Reynolds stress model as in Moore and Moore 2010, except using the MARVS model and the grid in Fig. 1. After the flow and turbulence model properties are converged (CPU 13 minutes) a conserved species equation with a uniform heat flux boundary condition is satisfied to obtain the wall Nusselt numbers, Fig. 7, left (CPU 8 secs).

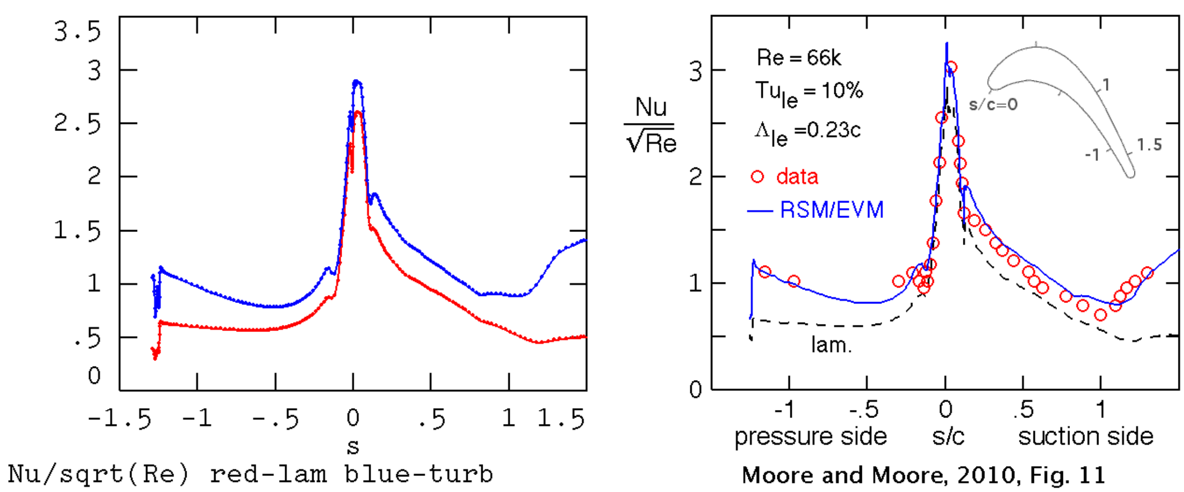


Fig. 7. Transitional Turbine Cascade Nusselt numbers.

Who, When

M4D has been written by Joan G. Moore. Writing began in earnest in 2010 with a 'clean sheet of paper', but with 40 years experience both writing and using steady 3-d CFD codes. It is written entirely in C to distinguish it from her earlier codes which were in Fortran. It has been written with a lot of support and ideas from her husband, John Moore, and no external sponsorship either commercial or government.

It is NOT an entry level “let's use the simplest discretization, we can always use a better/finer grid” code. It comes with no guarantees or warrantees, just the hope that it will be useful to students and others interested in fluid mechanics, fluid dynamics, turbulence, CFD and CFD methods.

References

Moore, J.G., and Moore, J., 2006, *Functional Reynolds Stress Modeling,* Pocahontas Press, Blacksburg, Virginia, 2006. (Available on Amazon.com)

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M&M homepage: moore64.home.comcast.net
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