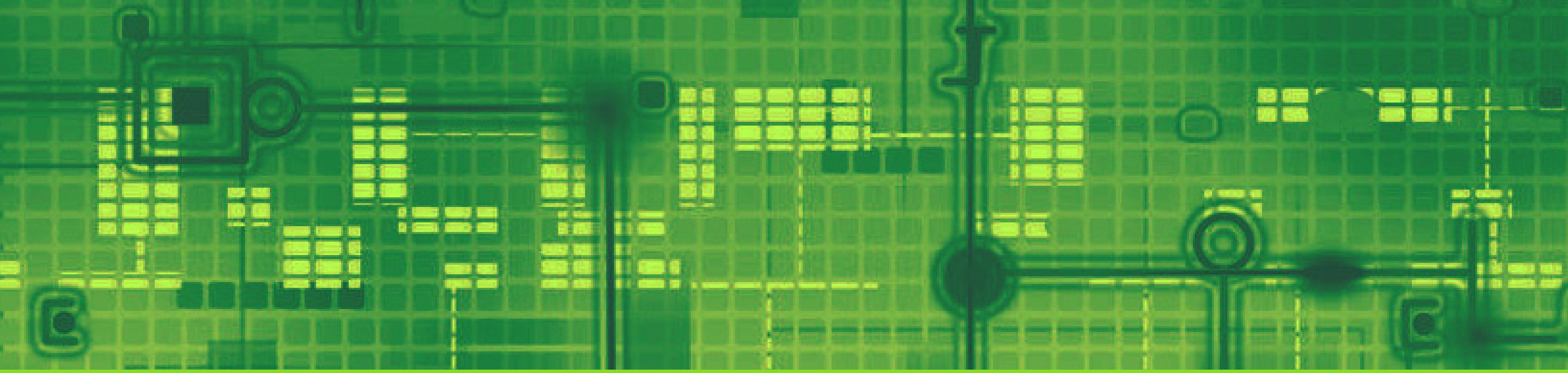

Turbulent Models for CFD Simulation

in Electronics Cooling

The electronics industry is developing and expanding at a rapid rate. Chip makers are putting more functions inside a die and increasing its connectivity and versatility. At the same time, chip sizes are shrinking. The system providers are trying to package more CPU, RAM, DSP, etc. inside their chassis and increase their power density. In an effort to accurately predict airflow around critical components inside densely populated and complicate chassis, thermal and mechanical engineers mainly rely on commercial Computational Fluid Dynamics (CFD) software to optimize chassis design, PCB component lay out, and heat sink selection for better thermal management.

Commercial CFD software solves both fluid flow and heat transfer throughout the system, which enable engineers to predict air flow distribution, chip junction temperature, local heat transfer coefficient and heat sink performance, etc. Due to the complex geometries of components on PCBs and the forced convection cooling of high power chassis, the air flow is turbulent in nature for most cases. To accurately predict the airflow, engineers using the CFD software are required to have certain knowledge of turbulent models to select an appropriate one for their application.

Turbulence is an irregular, disorderly, transient, non-stationary, three-dimensional, highly non-linear, irreversible stochastic phenomenon that occurs at a high Reynolds number. Turbulence is not a fluid property, but is a flow condition. Turbulent flow can be highly nonlinear and is random in nature. Turbulent disturbances can be thought of as a series of three-dimensional eddies of different sizes that are in constant interaction with each other.

This model of turbulence is Lagrangian in nature, with these turbulent flow structures being transported downstream by the mean flow. These structures exist for a limited amount of time before they are dissipated or suppressed away by the field's viscosity. The task of turbulence modeling is trying to find approximate simplified solutions for the Navier-Stokes equations in the manner that either describes turbulence in terms of mean properties or limits the spatial/temporal resolution requirements associated with the full model.

Turbulence models can be classified by what turbulent scales they choose to model. The traditional and classic Reynolds Averaged Navier-Stokes (RANS) uses a time averaging process to remove the necessity of simulating all of the scales of the turbulence spectrum. The RANS approach uses one length scale to characterize the entire turbulent spectrum. To close the equations of the RNGS model, additional equations for both Eddy Viscosity Models and Reynolds Transport Models have to be derived. For the Eddy Viscosity Models, there are zero-equation models, one-equation models and two-equation models.

• In electronics cooling simulations, the most popular are two-equation models, such as k-ε model and k-ω, since they account for transport of both the velocity and length-scale and can be tuned to return several canonical results.

• The Spalart-Allmaras (SA) model is a relatively simple one-equation model that solves a modeled transport equation for the kinematic eddy viscosity. It was originally written as an airfoil-specific RANS model.

• The Reynolds stress model (RSM) is a higher level, elaborate turbulence model. In an RSM model, the eddy viscosity approach has been discarded and the Reynolds stresses are directly computed. The exact Reynolds stress transport equation accounts for the directional effects of the Reynolds stress fields.

• The RNG k-ε model was developed using Re-Normalization Group (RNG) methods to renormalize the Navier-Stokes equations, to account for the effects of smaller scales of motion. In the standard k-ε model, the eddy viscosity is determined from a single turbulence length scale, so the calculated turbulent diffusion is that which occurs only at the specified scale; whereas, in reality, all scales of motion will contribute to the turbulent diffusion. The RNG approach, which is a mathematical technique that can be used to derive a turbulence model similar to the k-ε model, results in a modified form of the ε equation, which attempts to account for the different scales of motion through changes to the production term.

Direct Numerical Simulation (DNS) is, strictly speaking, not a turbulence model at all: It simulates all scales of interest in a well-resolved transient mode with sufficient spatial and temporal resolution. The grid resolution and the maximum allowable time step for a DNS calculation must be small enough to capture the Kolmogorov scales of the turbulent flow, which needs immense resources and makes the simulation unrealistically expensive. Kolmogorov length scales are the smallest scales in the spectrum that form the viscous sub-layer range. In this range, the energy input from nonlinear interactions and the energy drain from viscous dissipation are in exact balance. The small scales are in high frequency, which is why turbulence is locally isotropic and homogeneous.

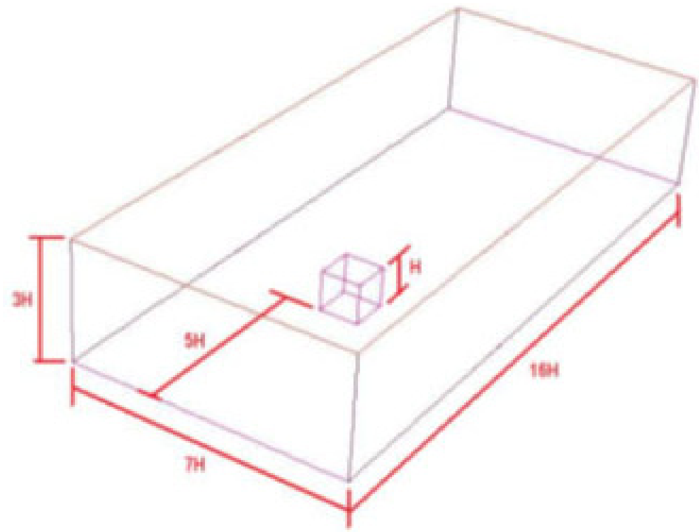

Figure 1. CFD Computational Domain [1]

Ariff et al. [1] compared different turbulent models discussed above on predicting flow across a surface-mounted cube, which represents a classic problem in electronics cooling. In their study, they use a computational domain which is identical to the experimental setup of Meinders et al. [2]. Please refer to Figure 1. Ariff et al. used Fluent to run the CFD simulation and selected the standard k-ε, standard k-ω, Reynolds Stress Model (RSM), Spalart-Allmaras (SA) and renormalization group (RNG) k-ε model to simulate the air flow. They then compared their simulation results with experimental results published by Meinders et al. [2] and the numerical results obtained by Alexander at el. [3] by using Direct Numerical Simulation (DNS) method. In the CFD simulation, a fully developed mean velocity profile is set at the channel inlet. The Reynolds number, based on cube height and bulk velocity, is Re_H=1870.

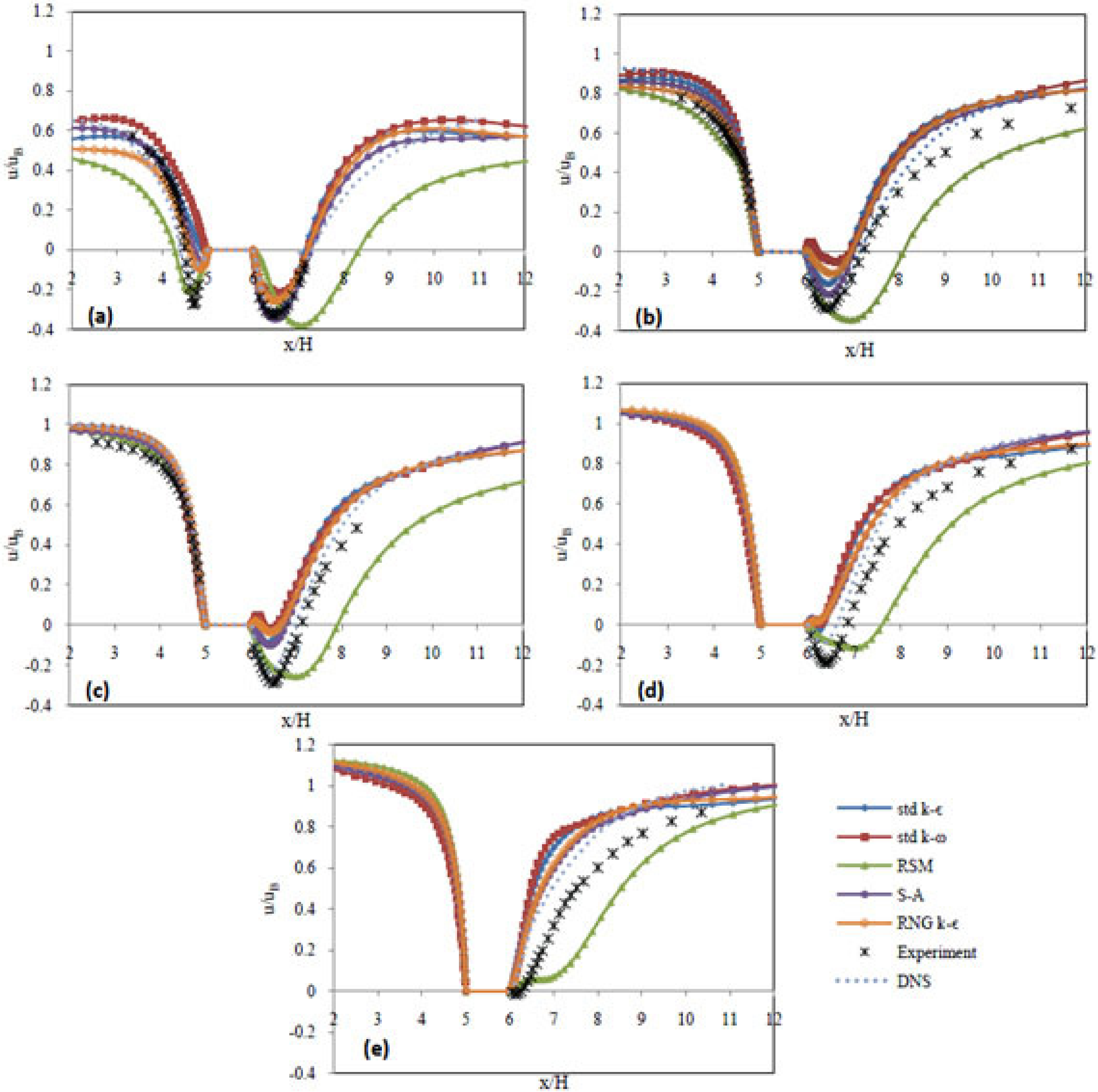

Figure 2. Comparison of the Mean Streamwise Velocity Profiles in the Symmetry Line; (a) y/H=0.1, (b) y/H=0.3, (c) y/H=0.5, (d) y/H=0.7 and (e) y/H=0.9, for Re_H=1870 [1]

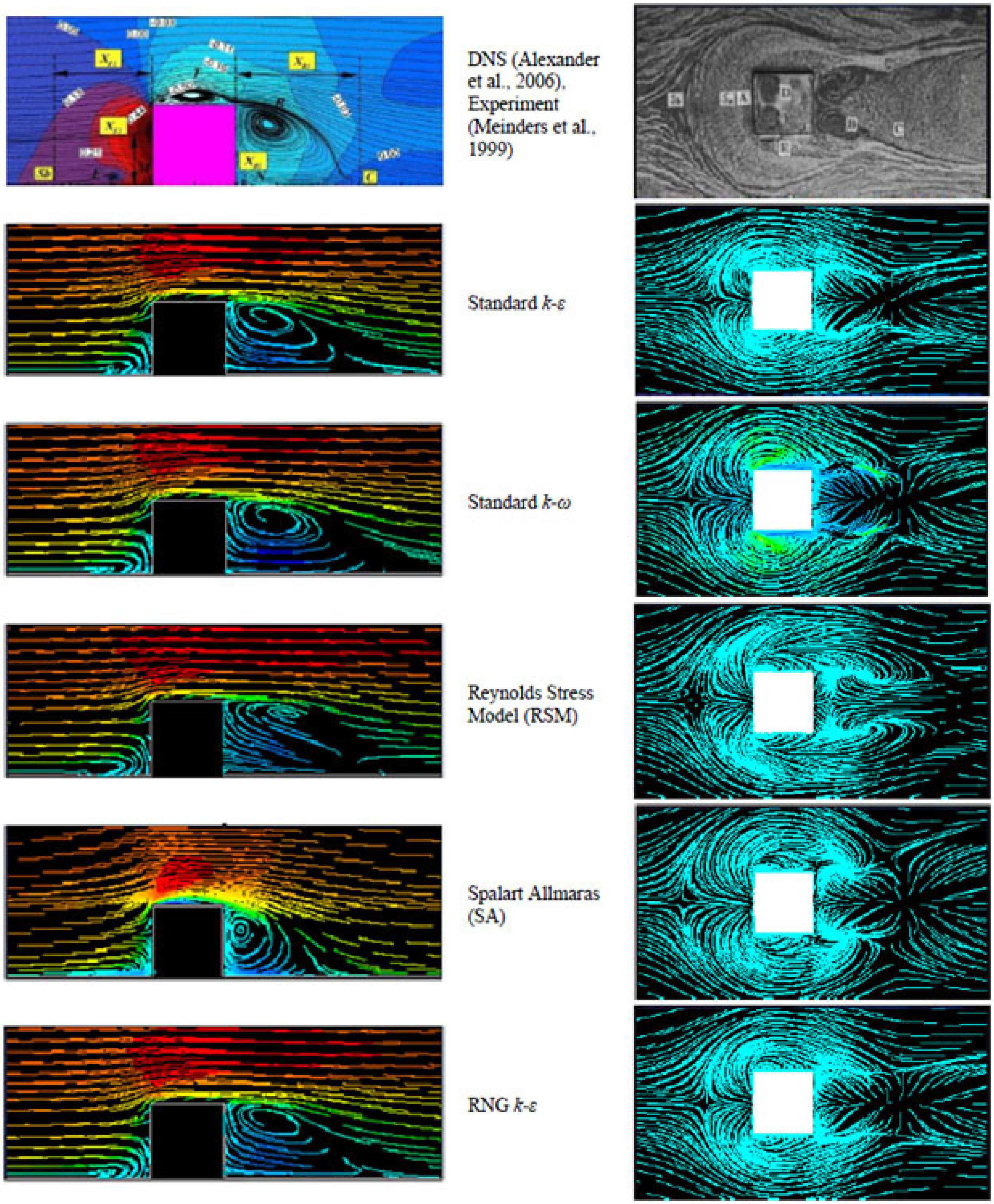

Figure 3. Comparison of Streamlines in Symmetry Plane (Left) z/H=0 and (Right) First Cell From Bottom Wall, for Re_H=1870 [1]

Figure 2 shows the comparison of mean streamwise velocity profiles in the symmetry line at 5 different heights (y/H = 0.1, 0.3, 0.5, 0.7 and 0.9), to illustrate the performance of different turbulence models. The predictions of the more computationally expensive DNS model best agree with experimental results. The standard k-ε, standard k-ω, Spalart-Allmaras (SA) and renormalization group (RNG) models all share the same trend. Overall, the SA and RNG models give better agreement with experimental data. The Reynolds Stress Model (RSM) did well in predicting the reverse flow at the front face at y/H = 0.1, whereas it over-predicts the reattachment region behind the cube.

Figure 3 shows the comparison of streamlines obtained by the different turbulence models. Ariff et al [1] conclude that the vortex structures predicted by all the models vary from one another in terms of location and size, especially in the flow separation, wake and recovery. The patterns look quite similar upwind and near the front face of the cube, but the reverse flow in this area was under-predicted by all the models except for RSM. The same inadequacy is evident on top of the cube, where the DNS predicts a small recirculation zone and other models do not. Table 1 shows the predicted Front Separation (XF) and Reattachment Lengths (XR) of different models and measurement from the experiment. The DNS results agree best with the experimental results. The SA model also agrees well with the experimental results.

Turbulence Model	X_F(H)	X_R(H)
Experiment (Meinders et al., 1999)	1.24	1.44
DNS (Alexander et al., 2005)	1.2	1.5
Std k-ϵ (SWF)	0.64	1.29
Std *k-ω*	1.12	1.63
RSM	0.98	2.48
SA	1.20	1.56
RNG *k-ε*	0.81	1.49

Table 1. Summary of Front Separation (XF) and Reattachment Lengths (XR) for a Wall Mounted Cube by Different Turbulences Models [1]

The study of Ariff et al shows the importance of choosing a suitable turbulence model for even a simple cube mounted on a wall. In most electronics cooling simulations, the standard k-ε models are a default choice due to their versatility. However, Ariff et al show that the k-ε model predicts the trend of the airflow correctly for a low Reynolds number flow across a block, but the model doesn't catch some details of the flow pattern near the cube. For the simulated case, Spalart-Allmaras (SA) turbulence model provides more accurate results than the k-ε model. In a real board and chassis simulation, there are many components or boards that affect the flow distribution. The suitable choice of a turbulence model may be different and is dependent on a user's application. In general, the k-ε turbulence model is not very accurate for practical problems. It tends not to calculate accurately the vortices behind bodies which reduce the heat transfer from components by encapsulating their heat. The k-ε turbulence model is also not specifically effective for high adverse pressure gradient cases. When modeling turbulent flows, experiments have to be used by thermal and mechanical engineers for verification of the CFD model and simulation results.

References:

1. **Ariff, M., Salim, S.M. , and Cheah, S.C., "Wall Y+ approach for dealing with turbulent flow over a surface mounted cube: Part I – low Reynolds number", Proc. Int. Conf. on CFD in the Minerals and Process Industries, CSIRO, Melbourne, Australia, December, 2009.**
2. **Alexander, Y., Lui, H., and Nikitin, N., "Turbulent flow around a wall mounted cube: A direct numerical simulation", Int. J. Heat and Fluid Flow 27, 994-1009, 2006.**
3. **Meinders, E.R, Hanjalic, K., and Martinuzzi, R., "Experimental study of the local convective heat transfer from a wall mounted cube in turbulent channel flow", Trans ASME J. Heat Transfer 121, 564-573, 1999.**