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Benchmarking turbulence models for electronics cooling

For this paper the flow around a single wall-mounted obstacle was selected. Both the problem geometry, resembling a building block in electronics and low Reynolds number flow are characteristic of electronics cooling applications. Due to its "classic" configuration, the problem has attracted attention of experimentalists and reliable data are available to benchmark CFD against.

Experiment

The modeled experiment consisted of a 50 mm high and 600 mm wide wind-tunnel with a 15 mm cube placed on the channel floor along the centerline. To ensure turbulence, the flow was tripped 75 cm upstream of the cube. The cube was made of 12 mm copper core coated with a uniform 1.5 mm epoxy layer. The cube's core was kept at constant 75C. The inlet air temperature was kept at 21C and the average velocity was 4.47 m/s yielding Re = 4440 based on the cube's height. For additional details of the experimental setup and measurement techniques refer to [1, 2].

CFD calculations

The experiment was modeled using Coolit's four turbulence models: algebraic [3, 4], differential [5], Secundov eddy viscosity model [6], and Spalart-Allmaras eddy viscosity model [7]. Results for k-e model were borrowed from [8] as implemented in the PHYSICA CFD code [9]. The differential and both eddy viscosity models used default settings. The algebraic model requires the user to specify background turbulence level, which serves as the foundation of the rest of computations. The differential and eddy viscosity models also require turbulence level, but only as an initial guess, which is then recomputed by the model.

We estimated the background turbulence viscosity required by the algebraic model from $\nu_t = \sqrt{\frac{3}{2}} u_{avg} I\, l$, where the average velocity, u_{avg} = 4.47 m/s, the turbulence intensity, I, is estimated from the experimental setup to be approximately 0.05%, and the length scale, l, is computed from the duct's height, l = 0.07 H, where H=0.05 m. Thus, ν_t = 9.6E-6 m^2/s and the background turbulence level, $\frac{\nu_t}{\nu} = 0.64$.

Flow Field

The flow structure around the cube is extremely complicated with oscillating time-dependent vortical structures on all wetted sides of the cube. The schematic below depicts main structures of the flow [10].

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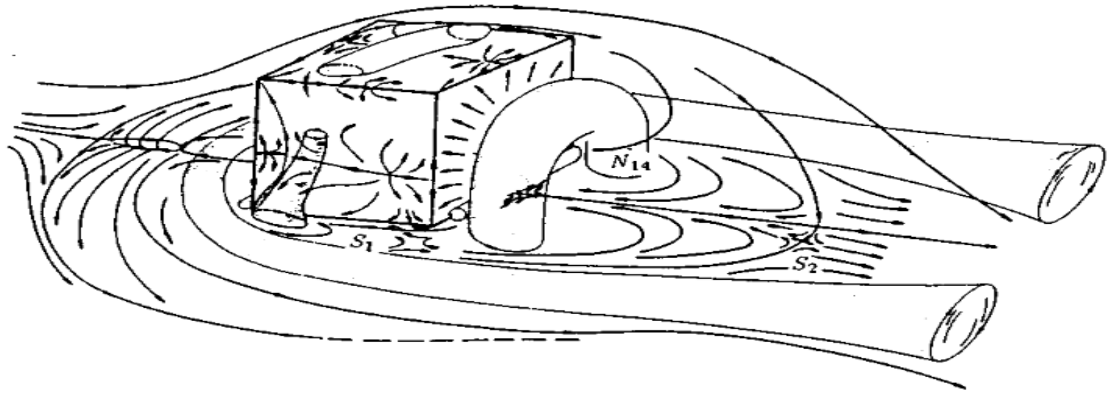
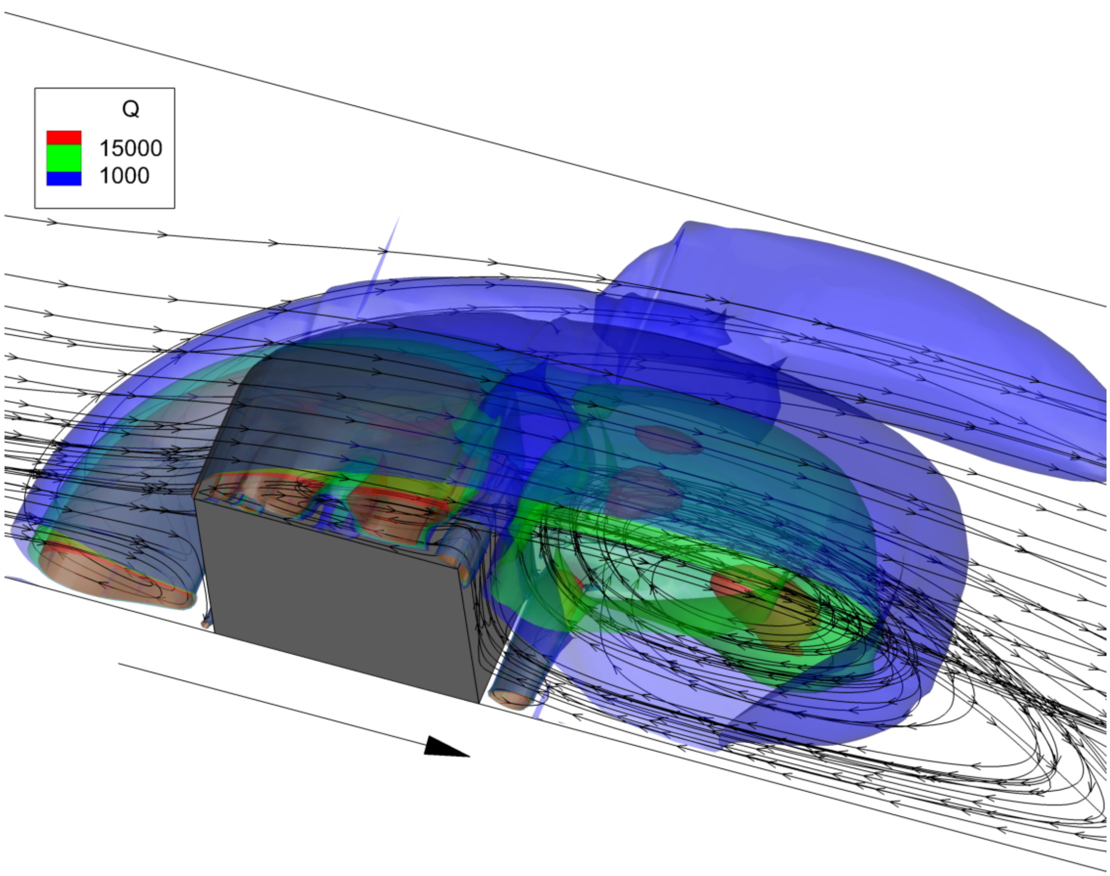


The vortex system starts at the leading edge of the cube with a horseshoe vortex extending along both sides of the obstacle, a large arch vortex at the trailing edge, and a separated flow with associated vortices along the top face of the cube. The following figure shows the flow structure computed by Coolit showing Q-criterion[1] isosurfaces outlining the vortex structure with the section along the channel centerline.

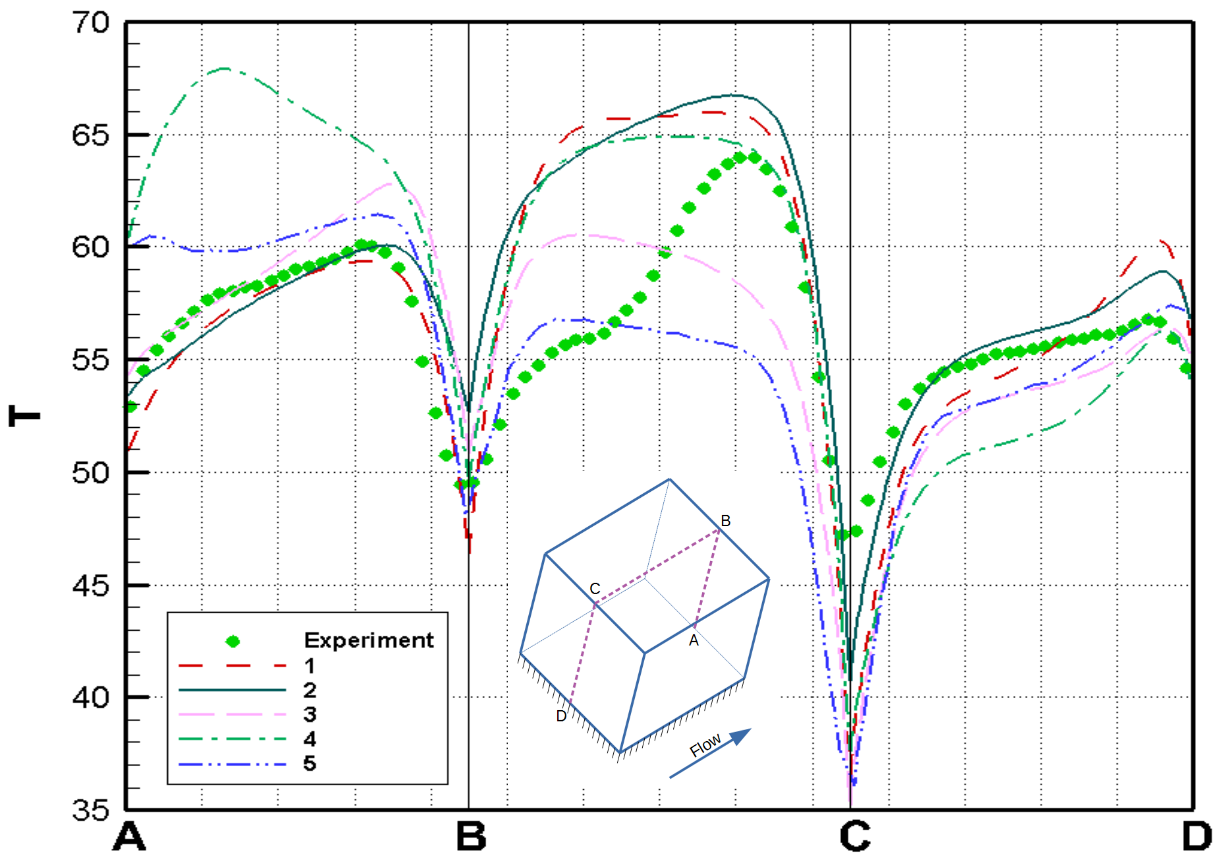


1 Q-criterion isosurfaces represent local balance between shear strain rate and vorticity magnitude.

Results

When turbulence models are used, the fine time-dependent flow structure is averaged to get a smooth steady state solution. This is what is required for engineering simulations the goal of which is to predict average flow and thermal characteristics. All the turbulence models we used were successful in that regard. The question is how accurate their predictions were for average quantities, which is what are normally computed in common electronics cooling application models.

In order to pick some of the flow structures depicted above we used the 183x101x124 non-uniform mesh. The results computed using 5 different turbulence models predicting the surface temperature along the ABCD line are shown below:



the turbulence models are designated as follows:

1 – Differential [5]

2 – Spalart-Allmaras eddy viscosity [7]

3 – Secundov eddy viscosity [6]

4 – Algebraic [3, 4]

5 – k-e [8, 9]

We also computed the average temperature along the ABCD line:

Experiment	Spalart-Allmaras	Secundov	Algebraic	Differential	Standard k-e
56.33	58.38	55.86	58.72	57.5	53.4

All turbulence models predicted fairly well general trends of the temperature. With the exception of Spalart-Allmaras model, the models somewhat miss the trend on the top surface and the algebraic model was too hot in the trailing edge area. The average temperatures shown in the table were also good for all models. All Coolit models predicted the average temperature rise well under 5% of experiment, while the k-e model was slightly above 5%. This was the main takeaway from this study, as detailed computations of turbulence are beyond the reach of any practical scenario and requirements.

Conclusions

In this paper we compared results from the experimental study [1, 2] with CFD simulations. The problem geometry and the turbulence level were to resemble typical flow conditions in electronics cooling applications. Extremely complex flow structure as well as the temperature prediction in a thin 1.5 mm layer of a low thermal conductivity material with steep temperature gradients presented a formidable challenge. We used four turbulence models available in Coolit and have included for reference results from the popular k-e turbulence model [9]. Both detailed and average results were good for both the eddy viscosity and the algebraic models. All Coolit models predicted the average temperature rise well under 5% of experiment, while the k-e model was slightly above 5%.

While the algebraic model produced good results, its accuracy rests on the user-specified background turbulence, which is a formidable task to predict in real-life applications. In contrast, eddy viscosity models don’t require such inputs and compute background turbulence as part of the simulation. The drawback of the eddy viscosity models compared to the algebraic model is the computational time and RAM required for solving a partial differential equation. On modern computers, however, this burden is minimal and amounts to less than 5% both for computational time and RAM requirements. Therefore Coolit’s eddy viscosity models are the optimal choice under most circumstances.

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