CHAM

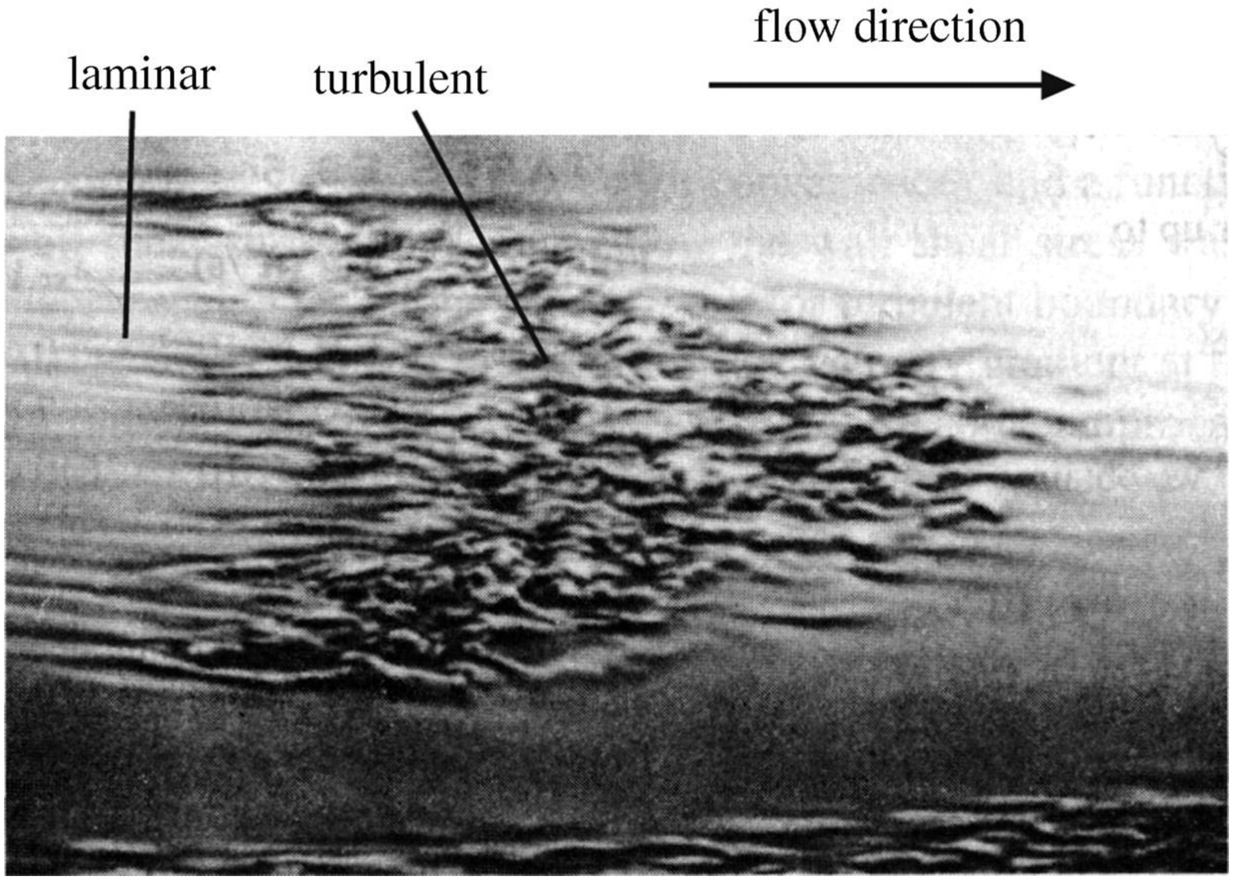
Turbulence Modelling

Turbulence Modelling

CHAM

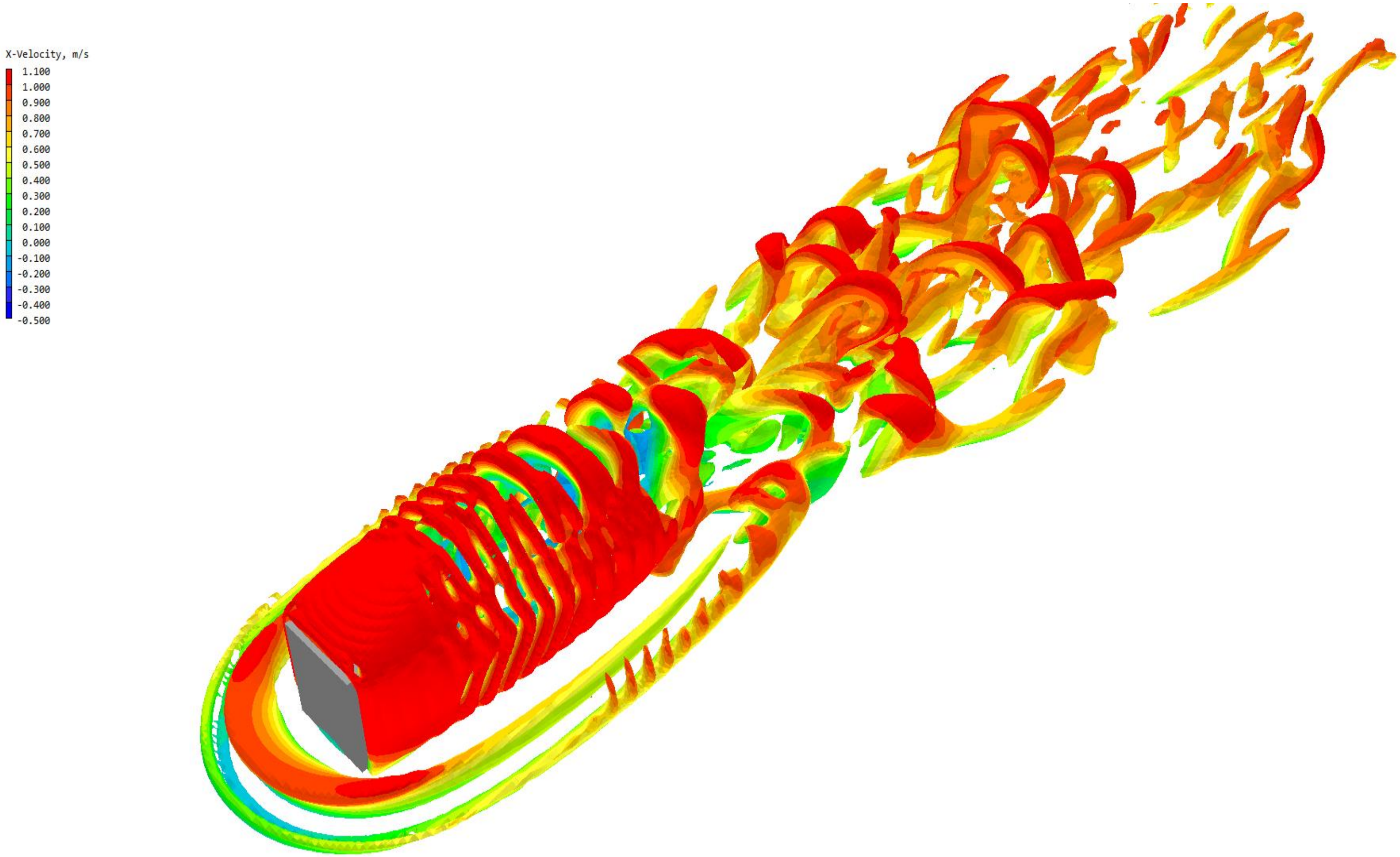
- What is turbulent flow ?

What is turbulent flow?



- From Munson B.,Young D., Okiishi T. (2005) *Fundamentals of fluid mechanics* (Wiley, New York, NY), 5th edn.

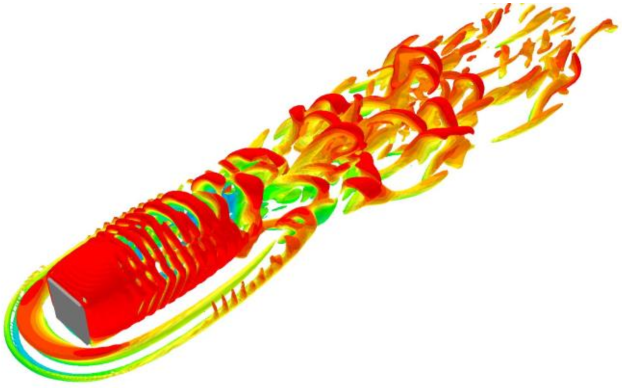
What is turbulent flow?



Turbulent flow in the wake of a wall-mounted cube

What is turbulent flow

Turbulence has a number of characteristic features:



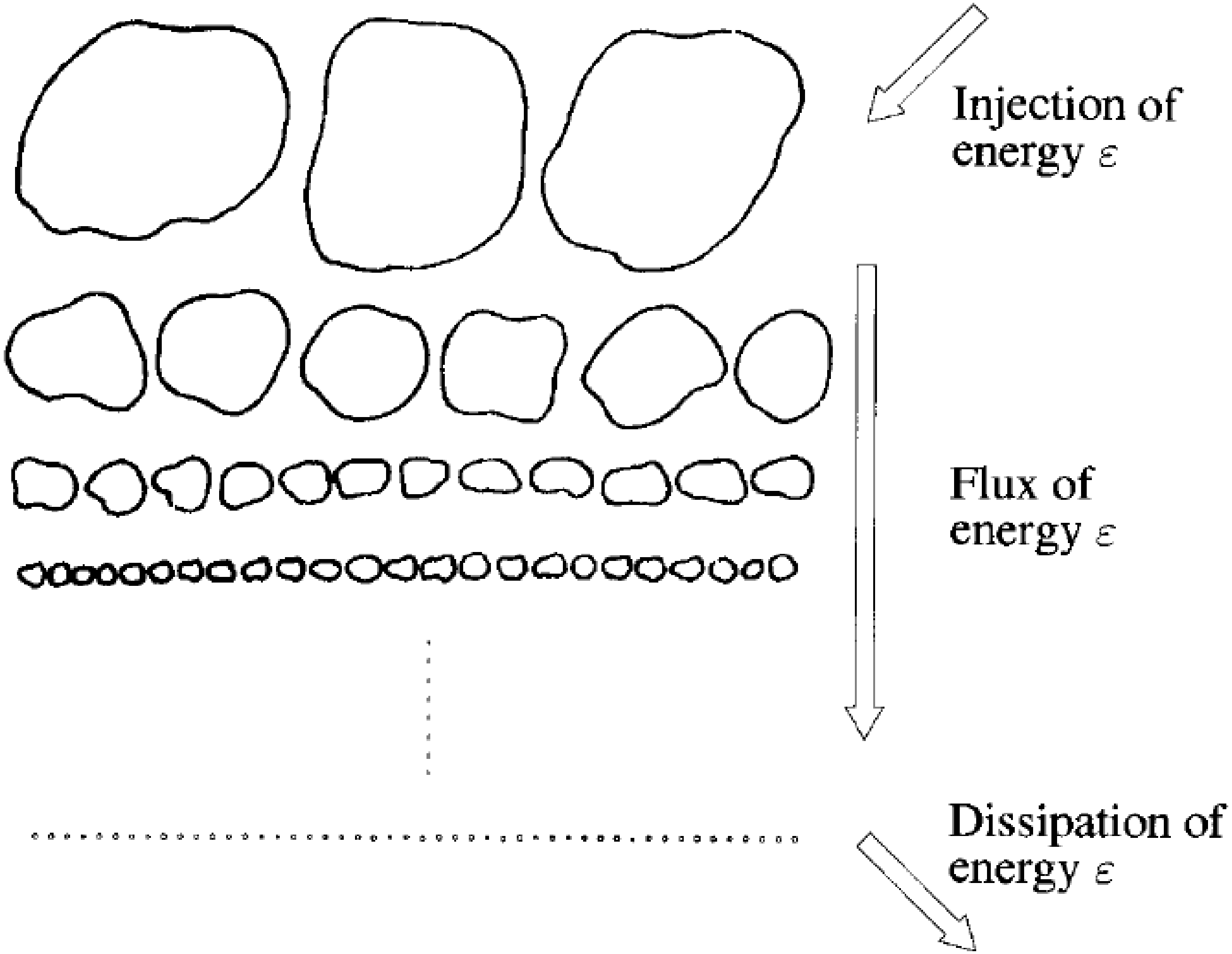
1. Irregular, random, chaotic;
   spectrum of different eddy sizes.
2. Always 3D.
3. Large Reynolds Number.
4. Rotational. Vortices transfer energy from large to small scale.
5. Diffusive. Turbulence causes rapid mixing, increases heat transfer and flow resistance. This is the single most important aspect of turbulence from an engineering point of view, and it is unrelated to fluid viscosity.
6. Dissipative; kinetic energy in the small eddies is transformed into internal energy.

What is turbulent flow?

- The turbulent motion has a wide spectrum of eddy sizes, and large and small eddies can coexist in the same volume of fluid.

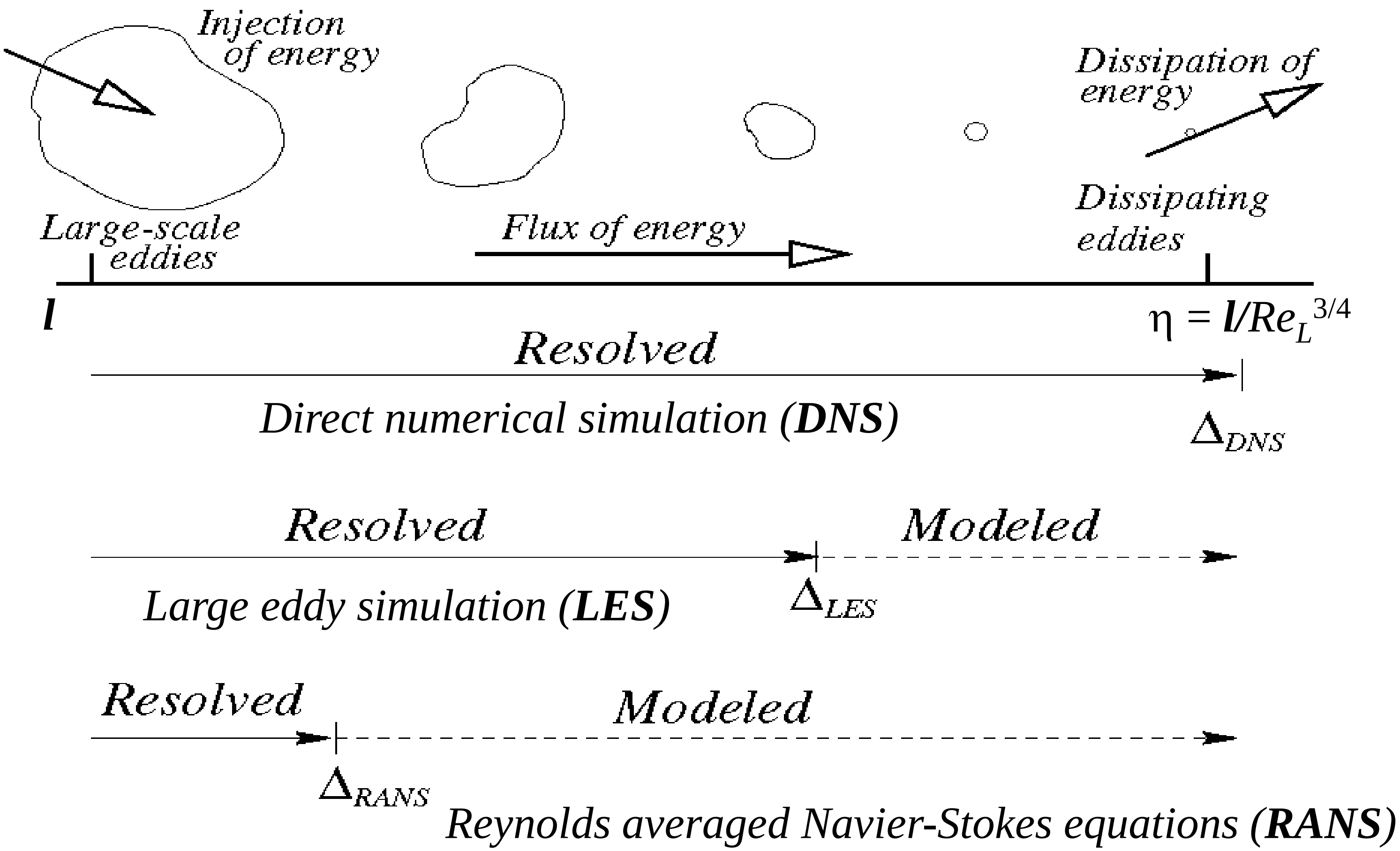
- Turbulent fluctuations can generate rates of momentum transfer far greater than those due to molecular diffusion.

Turbulent length scale and energy distribution



Prediction Methods
DNS, LES & RANS

CHAM



*Direct numerical simulation (**DNS**)*

*Large eddy simulation (**LES**)*

*Reynolds averaged Navier-Stokes equations (**RANS**)*

Large Eddy Simulation

- LES involves:
  - direct 3D transient simulation of the large-scale motion,
  - use of a sub-grid-scale (SGS) model for turbulence scales smaller than the grid spacing.

- LES has advantages because the large eddies, which are hard to model in a universal way, are simulated directly.

Large Eddy Simulation

- Disadvantages and problems of LES:
  - expensive, and may need very fine mesh near walls,
  - need for stochastic processing of the results,
  - how to specify randomness at inlet boundaries.

- PHOENICS provides a LES capability using the Smagorinsky subgrid-scale model.

- This is beyond the scope of this introductory lecture.

RANS turbulence models

- A turbulence model is a computational procedure to close the system of mean flow equations.
- For most engineering applications it is unnecessary to resolve the details of the turbulent fluctuations, but only need to know how turbulence affects the mean flow.
- RANS turbulence models allow the calculation of the mean flow, without calculating the full time-dependent flow field.
- For a turbulence model to be useful it:
  - should have wide applicability,
  - be accurate, and simple,
  - and economical to run.

RANS turbulence models

- Engineers are not concerned with all the details of the turbulent motion, but rather with its main effects.
- We therefore time-average the equations. The variables are decomposed into mean and fluctuating quantities, where the mean values are obtained by averaging over a long time scale.
- The equations for the mean quantities are very similar to before, but have additional terms.
- These additional terms can be modelled in terms of a supposed “turbulent” viscosity ν_T .

RANS turbulence models

- This turbulent viscosity ν_T depends on the state of the turbulence, and must be determined by the turbulence model.

- The task of the turbulence model is to determine the value of ν_T in every cell.

Two-equation models

- A commonly used approach for obtaining ν_T is to solve two additional transport equations (i.e. turbulence is generated and then convected).
- These equations can either be for:
    - k and ε (epsilon) or for
    - k and ω (omega).
- k is generated by velocity gradients.

- k - kinetic energy of the turbulence.
- ε - dissipation rate of turbulent energy.
- ω - turbulence frequency.
- Note that ε and ω relate to the scale of the turbulence.

Two-equation models

- The turbulent viscosity ν_t is obtained as follows.
- For a k-ε model, $$\nu_t = C_\mu C_d \frac{k^2}{\varepsilon}$$
- (Note - C_μ and C_d are constants.)
- For a k- ω model, $$\nu_T = \frac{k}{\omega}$$
- So:
  - transport equations solved to get k and ε/ω in every cell,
  - ν_T then obtained in every cell from above relations.

Two-equation models

- And remember that:
- ν_T controls the rate of turbulent mixing.
- As we have seen, this is the most important aspect of turbulence from an engineering point of view.
- In PHOENICS, ν_T can be plotted by storing ENUT.
  (“Models” / ”Turbulence models - settings”)
- In PHOENICS, k is KE, ε is EP, ω is OMEG.

The standard k-ε model

- Advantages of the standard k-ε model:
  - economical to run,
  - leads to stable calculations that converge relatively easily,
  - Really quite good predictions for many flows.

- But - “really quite good” does not mean perfect!

- There are some problems with the standard k-ε model…

The standard k-ε model

- The k-ε model is known to be too dissipative - the turbulent viscosity in recirculation zones tends to be too high, thus damping out vortices, e.g.:
  - jet penetration is under-predicted,
  - reattachment length for backward-facing step is under-predicted.

- The RNG k-ε model attempts to correct this deficiency by using slightly different constants, and by adding a source term to the EP equation.
- Chen and Kim devised an alternative improved k-ε model by similar means.

Improvements to the k-ε model

- **RNG** - although very good for separation and reattachment, its predictions for jets and plumes are inferior to the standard k-ε model.
- **Chen-Kim** - predicts reattachment points and vortices almost as well as RNG does, but preserves the good behaviour for jets and plumes of the standard model.

- On this basis, the Chen-Kim k-ε model has been selected as the default PHOENICS turbulence model.
- It has good general applicability, efficiency and stability.

Buoyancy

- Buoyancy can affect turbulence.
- In stably-stratified flows (dense below light), turbulence is damped.
- In unstably-stratified flows (light below dense), turbulence is augmented.
- These effects are represented by additional terms, which must be switched on when required,
- In VR, “Models” / “Buoyancy effect on turbulence”.
- These terms are off by default - must be switched on when required.
- Important in modelling fire scenarios.

Other two-equation models

- Other more sophisticated two-equation models are available, e.g.

- Kato-Launder k-ε model
- MMK k-ε model
- Realisable k-ε model
- Wilcox revised k-ω model (2008)
- k-ω SST model

Other two-equation models

- Some of these may give improved results under certain circumstances,
- e.g. improved turbulence prediction in stagnation regions.
- On the other hand some are less good than Chen-Kim at predicting flow separation.
- The SST model is good for turbomachinery - but requires significantly fine meshing.
- No turbulence model is perfect!
- If you are unsure which model to use - stick with the default Chen-Kim model.

LVEL Model

- Situations in which air flows through multiple narrow spaces (e.g. electronics cooling) present a problem.
- There may be too few grid cells in flow passages for the k-ε model to be meaningful.
- The LVEL model has been specially designed for this situation.
- The model is very cheap to run as no additional equations are solved (no KE or EP).

LVEL Model

- LVEL calculates the turbulent eddy viscosity from a formula restricted to wall-bounded flows.

- Requires knowledge of the local velocity and the normal distance to the nearest wall, which is available in PHOENICS.

- Advantages:
  - can be used in “cluttered” spaces,
  - valid at low and high turbulent Reynolds nos.

- Disadvantage - turbulence cannot be convected.

Wall Boundaries

- The two-equation turbulence models are valid at high Reynolds Numbers - but near the wall velocity falls and viscous effects become important.
- Two ways of dealing with the problem:
  - Wall functions
  - Low-Reynolds Number extension to the turbulence model
- Wall functions ‘bridge’ the viscous sub-layer with empirical formulae.
- These formulae connect the wall conditions (e.g. the wall shear stress) to the dependent variables at the near-wall grid node which is presumed to lie in fully-turbulent fluid.

Wall Functions

- There are three wall functions provided in PHOENICS:
  - Equilibrium wall function (the default),
  - Generalised non-equilibrium wall function,
  - Fully-rough wall function.
- Set in “Sources” / “Coeff for auto wall functions”.
- All calculate the near-wall velocity profile from a logarithmic expression. All can account for surface roughness.
- The generalised wall functions provide better heat transfer coefficients for separated flow.
- For atmospheric boundary layers (i.e. wind cases) the fully-rough form must be used.

Wall Functions

A final word on wall functions…

- For the wall function to work properly, the near-wall cell centre must lie outside the laminar sub-layer.
- Mathematically, require $y^+ \geq 11.126$.
- (y^+ is a non-dimensionalised distance from the wall.)
- Sometimes for the given mesh y^+ may be too small.
- This is solved by activating “Scalable Wall Functions” (tick-box in Sources Menu)…
- … which evaluates the shear stress as if $y^+=11.126$.