Nomenclature

Symbols	**Definition**
$a_{E,W,N,S,T,B,P}$	East, west, north etc. coefficients in the discretized equations
a_{ij}	Anisotropic stress, $a_{ij} = \overline{u_i u_j}/k - 2\delta_{ij}/3$
$A_{e,w,n,s,t,b}$	Areas of the east, west, north etc. cell faces
A_2	Second invariant of anisotropic stress, $A_2 = a_{ij}a_{ij}$
$A_x^\xi, A_x^\eta, A_x^\zeta$	Components of the area vector, $A_x^\xi = J\partial\xi/\partial x$; $A_x^\eta = J\partial\eta/\partial x$; $A_x^\zeta = J\partial\zeta/\partial x$
c_h	Constant of integration in the temperature log-law
c_i, d_i, e_i	Subgrid interpolation functions
c_l	Constant in near-wall length-scale definition
c_m	Integral moment (in the spinning disc flow, $c_m = M/0.5\rho\Omega^2 r^5$)
c_p	Constant-pressure specific heat
c_w	"Constant" in the differential Yap correction
$c_{\varepsilon 1}, c_{\varepsilon 2}$	Constants in the modelled ε transport equation (Equation 2.15)
c_μ	Coefficient or function in eddy-viscosity formula (Equation 2.9)
$c_1 - c_7$	Constants in non-linear $k-\varepsilon$ model (Equation 2.27)
C	Constant of integration
C_D	Coefficient of drag
C_F	Coefficient of friction
C_P	Coefficient of pressure, $C_P = (P - P_0)/0.5\rho U_0^2$

C_B^*, C_K^*, C_S^*	Components of pressure drag on Ahmed body, due to the base, nose cone and rear slant, respectively
C_R^*	Friction drag on Ahmed body
C_W	Total drag on Ahmed body
d_{ij}	Diffusion term in the $\overline{u_i u_j}$ transport equation
$dl_e dy$	Equilibrium length-scale gradient in the differential Yap correction
D	Diameter (in the impinging jet flow, the diameter of the inlet pipe)
$D_{e,w,n,s,t,b}$	Diffusion coefficients for the east, west, north etc. cell faces
$\mathbf{e}_i, \mathbf{e}^i$	Cartesian covariant and contravariant unit vectors, respectively (N.B. these are equivalent, $\mathbf{e}_i \equiv \mathbf{e}^i$)
E	Integration "constant" used in wall functions ($E \approx 9.79$ for smooth walls)
f_{RS}	Damping term in the differential Yap correction
f_1, f_2, f_μ	Damping functions used in the low-Reynolds-number $k-\varepsilon$ model
F	Difference between the predicted and equilibrium length-scale gradients in the differential Yap correction
$F_{e,w,n,s,t,b}$	Convective mass flux through the east, west, north etc. cell faces
F_{wall}	Wall force, $F_{wall} = -\tau_{wall} A$
g	Determinant of the g_{ij} matrix
$\mathbf{g}_i, \mathbf{g}^i$	Curvilinear covariant and contravariant base vectors, respectively
g_{ij}, g^{ij}	Covariant and contravariant metric tensors, respectively
G	Production rate of turbulent kinetic energy, sometimes denoted P_k
G_{ij}	Adjoint of the g_{ij} matrix
h	Heat transfer coefficient, $h = q_{wall}/(T_{wall} - T)$
H	Height (in the impinging jet flow, the height from the inlet pipe to the wall)
J	Jacobian of transform matrix for curvilinear coordinate system
J_ϕ^j	Contravariant components of the scalar flux vector, $\mathbf{q}$

k	Turbulent kinetic energy, $k = \frac{1}{2}(\overline{uu}+\overline{vv}+\overline{ww})$
L	Reference length (in the Ahmed body flow, L is the height of the Ahmed body)
l	Length scale
l_m	Mixing length
M	Moment, defined in the spinning disc flow as $M = -2\pi \int_0^r r^2 \tau_\phi \mathrm{d}r$
n	Displacement in the wall-normal direction
$\hat{\mathbf{n}}$	Wall-normal unit vector
$\hat{n}_x, \hat{n}_y, \hat{n}_z$	Cartesian components of the wall-normal unit vector, $\hat{\mathbf{n}}$
Nu	Nusselt number (Equation 5.1)
P	Mean pressure
$P(\sigma/\sigma_t)$	Jayatilleke P-function in the temperature log-law
P'	Pressure correction (in the SIMPLE algorithm) or mean pressure plus the isotropic Reynolds stress component $\left(P' = P + 2\rho k/3\right)$ in the momentum equation
Pe	Cell Peclet number, $Pe = F/D$
P_{ij}	Production term in the $\overline{u_i u_j}$ transport equation
P_k	Production rate of turbulent kinetic energy, sometimes denoted G (Equation 2.13)
$\overline{P_k}$	Total average production rate of turbulent kinetic energy in near-wall cell
P_{kuv}	Production rate of turbulent kinetic energy due to shear stress
$P_{\varepsilon 3}$	Gradient production term in low-Re model $\tilde{\varepsilon}$-equation, sometimes denoted E (Equation 2.24)
P_0	Reference pressure
$\mathbf{q}$	Scalar flux vector
q_{wall}	Wall heat flux
r	Radius
r_b	Outside disc radius

R_v	Viscous sublayer Reynolds number, $R_v = k_v^{1/2} y_v/\nu$
R_ϕ	Residual for discretized ϕ-equation
Re	Reynolds number, $Re = Ul/\nu$
$R_t, \tilde{R}_t$	Turbulent Reynolds number, $R_t = k^2/\nu\varepsilon$; $\tilde{R}_t = k^2/\nu\tilde{\varepsilon}$
Re_τ	Reynolds number based on the wall friction, $R_\tau = U_\tau L/\nu$
Re_ϕ	Rotational Reynolds number, $Re_\phi = \Omega r^2/\nu$
s	Physical distance parallel to the curvilinear ζ-axis
s_P	Contributions to linearized source term which are a function of the dependent variable
s_U	Source term in discretized transport equation
$S, \tilde{S}$	Dimensionless strain invariants (Equation 2.32) or source term
S_I	Dimensionless third invariant of the strain-rate tensor
S_{ij}	Strain-rate tensor, $S_{ij} = \partial U_i/\partial x_j + \partial U_j/\partial x_i$
$\hat{\mathbf{t}}$	Tangential, or wall-parallel, unit vector
$\hat{t}_x, \hat{t}_y, \hat{t}_z$	Cartesian components of the wall-parallel unit vector, $\hat{\mathbf{t}}$
T	Temperature
T_{wall}	Wall temperature
T_τ	Friction temperature, $T_\tau = q_{wall}/\rho c_p U_\tau$
T^+	Dimensionless temperature, $T^+ = (T_{wall} - T)/\mathrm{T}_\tau$
$u_i = u, v, w$	Turbulent velocities (i.e. instantaneous minus mean velocities)
$\left.\begin{matrix}\overline{uu}, \overline{vv}, \overline{ww} \\ \overline{uv}, \overline{uw}, \overline{vw} \\ \overline{u_i u_j}\end{matrix}\right\}$	Reynolds (turbulent) stresses
$\widehat{\overline{u_i u_j}}$	Non-linear components of the Reynolds stress
$\overline{u_n^2}$	Reynolds stress in the wall-normal direction
$\mathbf{U}$	Velocity vector
U, V, W	Mean velocity components

U_{ref}	Reference velocity used to non-dimensionalize variables in STREAM
U_x, U_y, U_z	Cartesian components of the velocity vector, **U**
U_0	Free-stream velocity
U_τ	Friction velocity, $U_\tau = \sqrt{\tau_w/\rho}$
U^+	Dimensionless velocity, $U^+ = U/U_\tau$
W	Tangential velocity in cylindrical-polar coordinates
x, y, z, x_i	Cartesian coordinate directions
y^+	Dimensionless distance to the wall, $y^+ = yU_\tau/\nu$
y^*	Dimensionless distance to the wall, $y^* = y\sqrt{k}/\nu$
Y_c	Yap correction
Y_{dc}	Differential Yap correction

Greek Symbols

α	Under-relaxation factor or scaling factor used in the UMIST-*N* wall function calculation of wall-normal velocity
β	Rear-slant angle of the Ahmed body (to the horizontal)
β^i_j	Elements of the inverse Jacobian matrix which are used to obtain curvilinear components from Cartesian components, $\beta^i_j \equiv \partial\xi^i/\partial x_j$
Γ_ϕ	Diffusion coefficient for parameter ϕ
Γ_{ijk}	Christoffel symbol of the first kind
Γ^k_{ij}	Christoffel symbol of the second kind
$\delta_{ij}, \delta^{ij}, \delta^j_i$	The Kronecker delta (if $i = j$ then $\delta_{ij} = \delta^{ij} = \delta^j_i = 1$, otherwise, if $i \neq j$ then $\delta_{ij} = \delta^{ij} = \delta^j_i = 0$)
Δ	Denotes change in given variable
$\Delta x, \Delta y, \Delta z$	Physical cell dimensions (i.e. distance between cell-faces) in Cartesian coordinates
$\Delta\xi, \Delta\eta, \Delta\zeta$	Computational cell dimensions (i.e. distance between cell-faces) in curvilinear coordinates

ΔVol	Cell volume
ε	Rate of dissipation of turbulent kinetic energy
$\bar{\varepsilon}$	Average rate of dissipation of turbulent kinetic energy in near-wall cell
$\tilde{\varepsilon}$	Isotropic part of turbulence energy dissipation (where, by definition, $\tilde{\varepsilon} = 0$ at the surface of a solid boundary)
ε_{ij}	Dissipation term in the $\overline{u_i u_j}$ transport equation
η	Maximum of the strain and vorticity invariants, $\eta = \max(S, \Omega)$, or wall-parallel curvilinear coordinate in the UMIST-*N* wall function
θ	Momentum thickness $(\theta = \int_0^\infty \lvert W/\Omega r (1 - W/\Omega r) \rvert \, dy)$ or angle between two vectors
κ	von Kármán constant in the velocity log-law, $\kappa \approx 0.42$
κ_h	von Kármán constant in the temperature log-law, $\kappa_h = \kappa/\sigma_t$
λ	Function used in Johnson & Launder wall function, thermal conductivity $(\lambda = \mu c_p/\sigma)$ or Taylor microscale
λ_t	Turbulent thermal conductivity
μ	Molecular or dynamic viscosity
μ_{eff}	Effective viscosity, $\mu_{eff} = \mu + \mu_t$
μ_t	Turbulent (eddy) viscosity
ν	Kinematic viscosity, $\nu = \mu/\rho$
ν_t	Kinematic turbulent (eddy) viscosity
$\xi_i = (\xi, \eta, \zeta)$	Curvilinear coordinate directions. In the UMIST-*N* wall function, the ξ- and η-axes are parallel to the wall and the ζ-axis intersects the wall.
ρ	Density
ρ'	Reference density used to non-dimensionalize variables in STREAM
σ	Molecular Prandtl number, $\sigma = \mu c_p/\lambda$
$\sigma_k, \sigma_\varepsilon$	Empirical constants in k and ε transport equations
σ_t	Turbulent Prandtl number, $\sigma_t = \mu_t c_p/\lambda_t$

τ	Shear stress
τ_{wall}	Wall shear stress
ϕ	General variable or scalar parameter
ϕ_{ij}	Redistribution or pressure-strain correlation
φ	Ahmed body rear slant angle (to the horizontal) as used by Ahmed *et al*. (equivalent to β, see above)
ω	Specific rate of dissipation of turbulent kinetic energy, $\omega = k/\varepsilon$
Ω	Angular velocity
$\Omega, \tilde{\Omega}$	Dimensionless vorticity invariants (Equation 2.35)
Ω_{ij}	Vorticity tensor, $\Omega_{ij} = \partial U_i/\partial x_j - \partial U_j/\partial x_i$

Subscripts

b	Bulk value
$body$	Pertaining to the Ahmed body without the stilts
$E,W,N,S,T,B,$ $EE,WW,NN,SS,$ $TT,BB,$ e,w,n,s,t,b	Node and face values of variables
i	Covariant components, $i = 1,2,3$
in	Inlet value
(i)	Physical covariant components
nb	Neighbouring nodes
NL	Non-linear
P	Value at the near-wall node or current node
tot	Total
v	Value at the edge of the viscous sublayer
$wall$	Wall value
x,y,z	Derivative with respect to the Cartesian coordinate components

ξ, η, ζ	Derivative with respect to the curvilinear coordinate components
τ	"Friction" value (as in the friction velocity, U_τ)

Superscripts

$calc$	Calculated value at present iteration
i	Contravariant components, $i = 1,2,3$
(i)	Physical contravariant components
n	Wall-normal
new	Final or new value at present iteration
old	Value at previous iteration
t	Tangential or wall-parallel
T	Transpose of the matrix
$+$	Non-dimensional near-wall value scaled by U_τ
$*$	Non-dimensional near-wall value scaled by $\sqrt{k}$, guessed values in SIMPLE algorithm or assigned boundary value
$()^*$	In the UMIST-*N* wall function, $()^*$ denotes that the upstream value of the gradient inside parenthesis is transformed from the coordinate system in upstream cell into the coordinate system of the current cell, so that both upstream and current cells use the same base vectors
$'$	Characteristic variables used in STREAM to non-dimensionalize variables, or correction values in SIMPLE algorithm

Acronyms

AIAA	American Institute of Aeronautics and Astronautics
AGARD	Advisory Group for Aerospace Research & Development
ASM	Algebraic Stress Model
ASME	American Society of Mechanical Engineers
CFD	Computational Fluid Dynamics
CHF	Constant Heat Flux

CL	Chieng & Launder wall function
CPU	Central Processing Unit
CWT	Constant Wall Temperature
DGLR	Deutsche Gesellschaft für Luft- und Raumfahrt
DIA	Direct Interaction Approximation
DNS	Direct Numerical Simulation
EPSRC	Engineering and Physical Sciences Research Council
ERCOFTAC	European Research Community on Flow, Turbulence and Combustion
EVM	Eddy-Viscosity Model
IUTAM	International Union of Theoretical and Applied Mathematics
JL	Johnson & Launder wall function
LEVM	Linear Eddy-Viscosity Model
LES	Large Eddy Simulation
LSTM	Lehrstuhl für Strömungsmechanik
MOVA	Models for Vehicle Aerodynamics
NLEVM	Non-Linear Eddy-Viscosity Model
N-S	Navier-Stokes
PLDS	Power Law Differencing Scheme
PSL	Parabolic Sub-Layer
QDNS	Quasi-Direct Numerical Simulation
QUICK	Quadratic Upwind Interpolation for Convection Kinematics
RANS	Reynolds-Averaged Navier-Stokes
RDT	Rapid Distortion Theory
RMS	Root Mean Square, $\left(\sqrt{\overline{\phi^2}}\right)$
RNG	Re-Normalization Group

SAE	Society of Automotive Engineers
SCL	Simplified Chieng & Launder wall function
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations
SSG	Speziale, Sarkar & Gatski differential stress model
SST	Shear Stress Transport turbulence model
STREAM	Simulation of Turbulent Reynolds-averaged Equations for All Mach numbers
TDMA	Tri-Diagonal Matrix Algorithm
TEAM	Turbulent Elliptic Algorithm – Manchester
T-S	Tollmien-Schlichting
TVD	Total Variation Diminishing
UMIST	University of Manchester Institute of Science and Technology or Upstream Monotonic Interpolation for Scalar Transport
UMIST-*A*	Unified Modelling through Integrated Sublayer Treatment - an *Analytical* approach
UMIST-*N*	Unified Modelling through Integrated Sublayer Treatment - a *Numerical* approach
URANS	Unsteady Reynolds-Averaged Navier-Stokes
VLES	Very Large Eddy Simulation