

Program EDDYBL

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Contents

1	Procedure for Running EDDYBL Source Code	2
1.1	eddybl_start	2
1.2	eddybl	2
1.3	Restart	2
1.4	Format of the file	3
2	EDDYBL Results	5
3	Equation and Transformation Details	8
3.1	Coordinates Transformation	8
3.2	Wall-normal velocity	8
4	Program EDDYBL Overview	9
5	Setup for Case M6 LargeSpan	9
5.1	Opening Menu	9
5.2	Freestream Conditions	10
5.3	Geometry Grid	11
5.4	Edge/Wall Conditions	12
5.5	Initial Profiles	13
5.6	Gas Properties	14

1 Procedure for Running EDDYBL Source Code

1.1 eddybl_start

The Program **eddybl_start** will prepare the profiles for the main Program **eddybl**.

- Input Files. Program **eddybl_start** read the input file (**eddybl_start.inp**) from the terminal which has the details for all the parameters. When running Program **eddybl_start**, it reads the following files “**Edge_WallProperty.dat**” and “**InitialFinalSlop.dat**” if the option **ireadWallProp** = 1.
- Output Files. Program **eddybl_start** can generate the following files. 1. **eddybl.dat**: the input file for Program **EDDYBL**. 2. **Profile_inflow.dat**: the initial profile for starting the computation. 3. **table.dat**: the nondimensional Edge/Wall properties for starting the computation. 4. **Check_eddybl_start.prt**: information for checking the input value. 5. **Check_Profile_inflow.dat**: the plotting data for checking the initial profile.

1.2 eddybl

The main Program **EDDYBL** will read the files generated by the Program **eddybl_start**.

- Output Files. Program **EDDYBL** generates the following files. 1. **Stat_eddybl.dat**: the profiles for starting the DNS computation, which has the variables $z, \frac{z}{\delta}, z^+, \bar{u}, \bar{v}, \bar{w}, \bar{p}, \bar{T}$, eddy viscosity μ_T and turbulence kinetic energy k . 2. **profil2c.dat**: used to initial Program **EDDY2C**. 3. **Check_eddybl.prt**: a comprehensive print file for the results of the computation. It has all the integral parameters at each step and dimensionless boundary-layer profiles at the final step. 4. **Int_eddybl.dat**: plotting data at each streamwise locations with Δx defined in the file **eddybl_start.inp**. Including variables are $x, Re_\theta, Cf_e, \delta, \delta^*, \theta, \tau_w, u_\tau, z_\tau, Re_\tau$. 5. **Profile_output.dat**: for restarting a run if desired.

1.3 Restart

- 1. Set **irestart=1** and give the inflow profile file name for the restart problem in the input file **eddybl_start.inp**. 2. Change the parameter **xend** in the input file **eddybl_start.inp** and run Program **eddybl_start**.

1.4 Format of the file

The content of the **Edge_WallProperty.dat** is list below.

Warning: If **xbeg** is less than **xloc_min**, the Edge/Wall properties in the region (**xbeg** ≤ **x** ≤ **xloc_min**) keep the same with the properties at the location **xloc_min**. In the same way, if **xend** is great than **xloc_max**, the Edge/Wall properties in the region (**xloc_max** ≤ **x** ≤ **xend**) keep the same with the properties at the location **xloc_max**.

xloc(m)	pe(pa)	tw(k)	qw	rvwald	rmi(m)	z(m)	zcurv(1/m)
0.	673.6	300	0.	0.	0.3048	0.	0.
6.096	673.6	300	0.	0.	0.3048	6.096	0.

Nothing is read below #####
Edge/wall properties corresponding to num_profile = 2 for the current example

xoc(m)	pe(pa)	tw(k)	qw	rvwald	rmi(m)	z(m)	zcurv(1/m)
0.	673.6	300	0.	0.	0.3048	0.	0.
6.096	673.6	300	0.	0.	0.3048	6.096	0.

xloc: arclength along the body
xloc = 0 m for the minimum streamwise location for the computation
xloc = 6.096 m for the maximum streamwise location for the computation
pe: pressure at the boundary-layer edge
Tw: surface temperature
qw(watts/(m³sec)): surface heat flux
rvwald(kg/(m²sec)): surface mass transfer rate
rmi: boundary radius
z: axial distance along the body
zcurv: curvature of the body. This is the reciprocal of
the radius of curvature.

The content of the **InitialFinalSlop.dat** is list below.

dpds	dTwds	dqwds	dmds	drds	dzds	dKds
0.	0.	0.	0.	0.	1.	0.
0.	0.	0.	0.	0.	1.	0.

Nothing is read below

The first line is the initial slop.
The second line is the final slop.

dpds(N/m³): value of the streamwise pressure gradient.
dTws(k/m): value of the streamwise surface-temperature gradient.
dqws(Watts/m³sec): value of the streamwise surface heat-flux gradient.
dmds(kg/(m³sec)): value of the streamwise mass-flux gradient.
drds(Dimensionless): value of the streamwise body-radius gradient.
dzds(Dimensionless): value of the streamwise axial-distance gradient.
dKds(1/m²): value of the streamwise curvture gradient.

2 EDDYBL Results

Figure 1 shows the comparison results from three turbulence models. The reference length δ_{ref} is chosen at the station where $Re_\tau = 2000$.

All distributions of the variables have almost the same slop in the downstream of the domain. The reason for the jump using the Stress-omega model is not clear now.

Figure 2 shows the restart case. The computation from Box1 to Box2 is continuous.

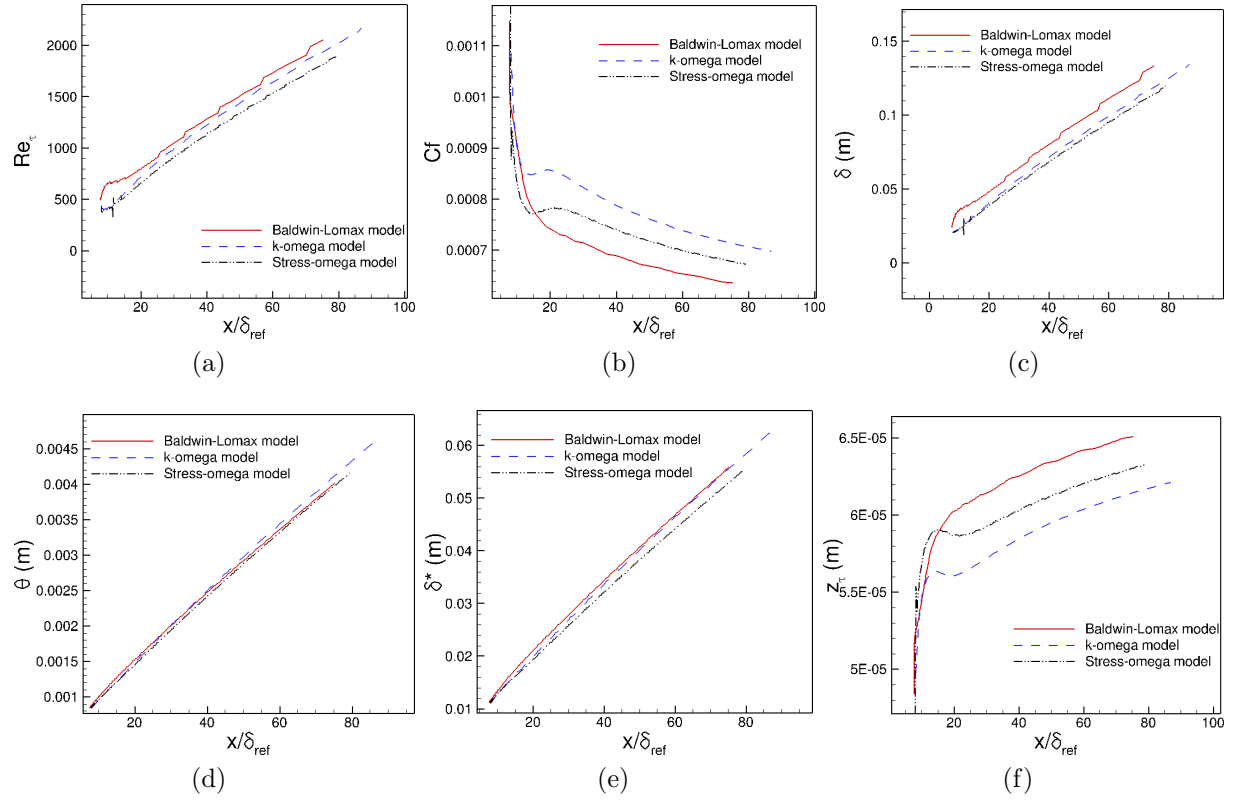


Figure 1: Streamwise distribution of (a) Re_τ , (b) Cf , (c) δ , (d) θ , (e) δ^* and (f) z_τ .

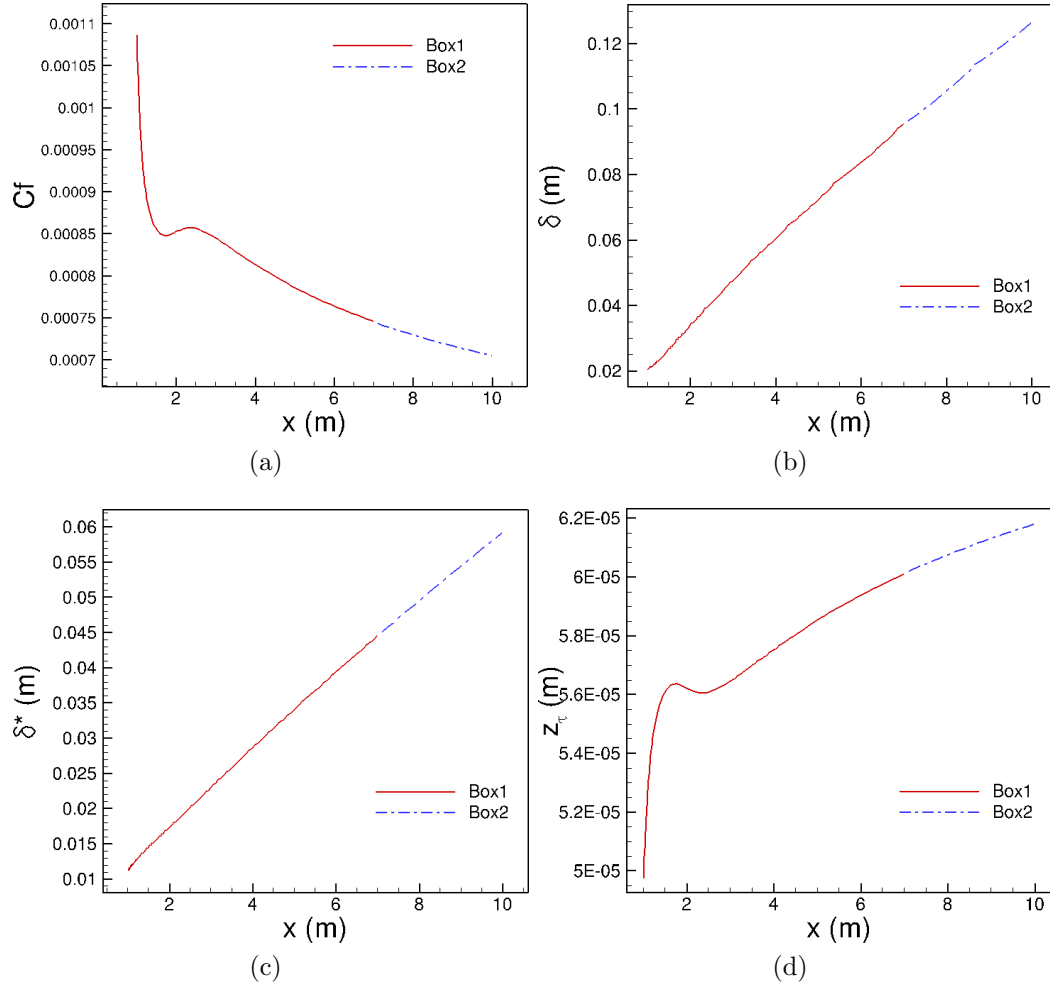


Figure 2: Streamwise distribution of (a) C_f , (b) δ , (c) δ^* and (d) z_τ for restart problem.

δ_{ref} (mm)	Re_τ	z_τ (μm)	u_τ (m/s)	θ (mm)	δ^* (mm)
123	2000	61.7	38.2	4.3	58.3

Table 1: Parameters at the reference location.

$N_x \times N_y \times N_z$	L_x/δ_{ref}	L_y/δ_{ref}	L_z/δ_{ref}	Δx^+	Δy^+	Δz_{min}^+	Δz_{max}^+
$4140 \times 1400 \times 2400$	20.0	3.63	20.0	9.63	5.14	0.51	5.33

Table 2

δ (mm)	Re_τ	z_τ (μm)	u_τ (m/s)	θ (mm)	δ^* (mm)
23.77	453.1	52.6	45.07	0.948	12.9

Table 3: Parameters for Case M6Tw076 at the station $x_a = 54.1\delta_i$.

Case	$N_x \times N_y \times N_z$	L_x/δ	L_y/δ	L_z/δ	Δx^+	Δy^+	Δz_{min}^+	Δz_{max}^+
M6Tw076	$1600 \times 800 \times 500$	34.08	9.09	23.06	9.63	5.14	0.51	5.33
M6AI	$1920 \times 320 \times 500$	40.90	3.63	23.06	9.63	5.14	0.51	5.33

Table 4: Grid resolution and domain size for the direct numerical simulations. L_x , L_y , and L_z are the domain size in the streamwise, spanwise, and wall-normal directions, respectively. Δx^+ and Δy^+ are the uniform grid spacing in the streamwise and spanwise directions, respectively, with the viscous length scale $z_\tau = 52.6\mu m$ being that at $x/\delta_i = 54.1$. Δz_{min}^+ and Δz_{max}^+ are the minimum and maximum wall-normal grid spacing for $0 \leq z/\delta_i \leq 5$. $\delta_i = 13.8mm$

3 Equation and Transformation Details

3.1 Coordinates Transformation

Physical coordinates (s, n) . Transformed coordinates (ξ, η)

$$\begin{aligned}\xi(s) &= \int_0^s \bar{\rho}_e \tilde{u}_e \mu_e ds \\ \eta(s, n) &= \frac{\bar{\rho}_e \tilde{u}_e}{\sqrt{2\xi}} \int_0^n \left(\frac{\bar{\rho}}{\bar{\rho}_e} \right) dn\end{aligned}\tag{1}$$

The dependent variables are transformed according to:

$$\begin{aligned}F(\xi, \eta) &= \frac{\tilde{u}}{\tilde{u}_e}, \Theta(\xi, \eta) = \frac{\tilde{T} - \tilde{T}_e}{\tilde{T}_e} \\ V(\xi, \eta) &= \frac{2\xi}{\bar{\rho}_e \tilde{u}_e \mu_e} \left[F \left(\frac{\partial \eta}{\partial s} \right) + \frac{\bar{\rho} \tilde{v}}{\sqrt{2\xi}} \right] \\ K(\xi, \eta) &= \frac{k}{\tilde{u}_e^2}, \hat{W}(\xi, \eta) = \frac{2\xi \omega}{\tilde{u}_e^2}, \hat{\varepsilon}(\xi, \eta) = \frac{2\xi \tilde{\varepsilon}}{\tilde{u}_e^4}\end{aligned}\tag{2}$$

where $\frac{\partial \eta}{\partial s} = \frac{1}{2\xi} \bar{\rho}_e \tilde{u}_e \mu_e \eta(s, n)$

The transformed continuity equation is:

$$2\bar{\xi} \frac{\partial F}{\partial \xi} + \frac{\partial V}{\partial \eta} + F = 0\tag{3}$$

where $\bar{\xi} = \frac{\xi}{\rho_\infty U_\infty \mu_r}$. μ_r is the value of μ for $T = T_r = U_\infty^2/c_p$.

3.2 Wall-normal velocity

If $(Re \gg 1)$, then $\frac{\partial F}{\partial \xi} \approx 0$. We get the following equation.

$$\frac{\partial V}{\partial \eta} = -F\tag{4}$$

thus $dV = -F \times d\eta$. Program EDDYBL uses this relation to calculate the wall-normal velocity.

From the equation 2 and $\frac{\partial \eta}{\partial s} = \frac{1}{2\xi} \bar{\rho}_e \tilde{u}_e \mu_e \eta(s, n)$, we can get

$$\tilde{v} = \frac{\bar{\rho}_e \tilde{u}_e \mu_e}{\sqrt{2\xi}} (V - F) \frac{1}{\bar{\rho}}\tag{5}$$

4 Program EDDYBL Overview

Program **EDDYBL** is a two-dimensional and axisymmetric, compressible boundary-layer program for laminar, transitional and turbulent boundary layers.

In order to run Program **EDDYBL**, the following files are needed.

File Name	Function
eddybl.exe	Executable Program EDDYBL
eddybl_data.exe	Input-data preparation Program EDDYBL_DATA
eddybl_plot.exe	Plotting Program EDDYBL_PLOT
eddybl_start.exe	Initial-profile Program EDDYBL_START

Table 5: Files for Program **EDDYBL**.

1. The first step is to run Program **EDDYBL_DATA**. After successfully completing the input data, click on the button with the label “Write Input-Data Files”. This runs Program **EDDYBL_START**, which generates initial profiles that will be used by Program **EDDYBL**.
2. Now click on the button with the label “Run Program EDDYBL”. This runs Program **EDDYBL**.
3. Click on “View Program Output” to view, print and edit output file **eddybl.prt**.
4. Click on the “Plot Computed Profiles” button to create a plot.

5 Setup for Case M6 LargeSpan

5.1 Opening Menu

Figure 3 shows the main menu after running Program **EDDYBL_DATA**. For the current case, you must make the following four changes.

1. Select the k-epsilon model (Jones-Launder)
2. Select Sarkar compressibility term
3. Select SI units

4. Select a Long printout

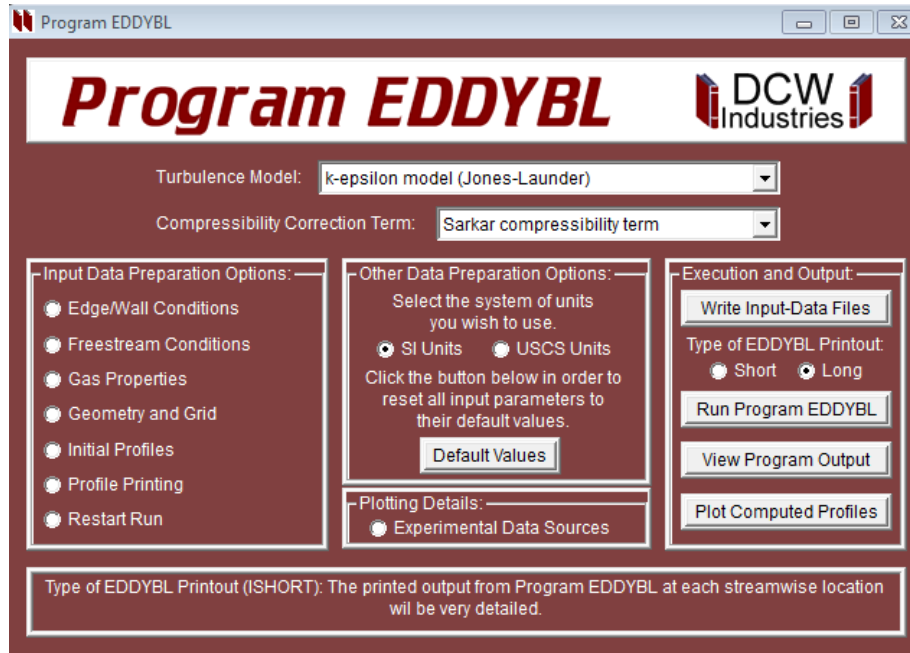


Figure 3: Opening menu of Program **EDDYBL_DATA** after modification.

5.2 Freestream Conditions

Click on the “Freestream Conditions” button will bring you to the menu that accepts input for freestream conditions. Change the total pressure to $P_{t\infty} = 9.17683 \times 10^5$ pa. Then change the total temperature and Mach number to $T_{t\infty} = 432.1$ K and $M_{\infty} = 5.86$, respectively.

Freestream Conditions

Total Pressure: N/m²

Total Temperature: K

Mach Number: Dimensionless

Shock-Wave Angle: degrees

Turbulence Properties in the Freestream:

Turbulence Intensity: Dimensionless

Turbulence Length Scale: Dimensionless

Static Conditions:

Density (kg/m³):

Pressure (N/m²):

Temperature (K):

Velocity (m/sec):

Unit Reynolds Number (1/m):

Shock-Wave Angle (WAVE): The angle any shock wave that is present makes with the centerline.

Figure 4: Freestream-Conditions menu of Program **EDDYBL_DATA** after modification.

5.3 Geometry Grid

Click on the “Geometry and Grid” button. You will set geometric-progression ratio, k_g , initial stepsize, Δs , initial arclength, s_i , and maximum length, s_{stop} .

Keeping the default value $k_g = 1.07$ and number of grid points normal to surface 101 can satisfy the constraint $y^+ < 1$. The initial stepsize can be as large as triple the boundary-layer thickness.

Geometry and Grid

Body Type:
☒ 2 Dimensional
☐ Axisymmetric

Flow Type:
☒ External Flow
☐ Internal Flow

Start at a Stagnation Point?
☐ Yes ☒ No

Channel Width: 3.048000e-001 m

Cone Half Angle: 0 degrees

Number of Grid Points Normal to Surface: 101

Geometric-Progression Ratio: 1.07

Initial Streamwise Stepsize: 6.896000e-003 m

Initial Arclength: 1.000000e+000 m

Maximum Arclength: 8.000000e+000 m

Maximum Streamwise Step Number: 2000

Geometric-Progression Ratio (XK): Rate at which grid-point spacing increases in the direction normal to the surface.

Figure 5: Geometry and Grid menu of Program **EDDYBL_DATA** after modification.

5.4 Edge/Wall Conditions

Click on the “Edge/Wall Conditions” button. For any boundary-layer computation, at a minimum, you must specify freestream pressure and either surface temperature or surface heat-transfer rate.

Click on the “Temperature” button. In the bottom section of the menu labeled “Edge/Wall Property Arrays”, change the values of boundary-layer edge pressure and surface temperature to $p_\infty = 673.6$ pa and $T_w = 300$ K, respectively, on “Line No.” 1 and 2.

The values of s on “Line No.” 1 and 2 are the minimum s_{min} and maximum s_{max} value of the streamwise locations. Make sure $s_{min} < s_i$ and $s_{max} > s_{stop}$.

Edge/Wall Conditions

General Information

Number of Points:

Compute Slopes?
☒ Yes ☐ No

Specify Surface Value of:

☒ Temperature ☐ Heat Flux

The Adiabatic-Wall temperature for this flow is 3.9061e+002 K

Turbulence-Model Parameters...k-omega and stress-omega models only

Roughness-Height Reynolds Number: Dimensionless

Boundary-Condition Parameter: Dimensionless

Initial and Final Slopes of Edge/Wall Properties...These are used in generating spline fits to the data arrays below

	dp/ds N/m²	dTw/ds K/m	dq/ds Watts/(m²sec)	dm/ds kg/(m²sec)	dr/ds Dimensionless	dz/ds Dimensionless	dK/ds 1/m²
Initial:	<input type="text" value="0.000000e+000"/>	<input type="text" value="0.000000e+000"/>	<input type="text" value="0.000000e+000"/>	<input type="text" value="0.000000e+000"/>	<input type="text" value="0.000000e+000"/>	<input type="text" value="1.000000e+000"/>	<input type="text" value="0.000000e+000"/>
Final:	<input type="text" value="0.000000e+000"/>	<input type="text" value="0.000000e+000"/>	<input type="text" value="0.000000e+000"/>	<input type="text" value="0.000000e+000"/>	<input type="text" value="0.000000e+000"/>	<input type="text" value="1.000000e+000"/>	<input type="text" value="0.000000e+000"/>

Edge/Wall Property Arrays...The scroll bar permits viewing and editing as many as 5 lines of array data at a time

Line No.	s m	p N/m²	Tw K	m kg/(m²sec)	r m	z m	K 1/m
1	<input type="text" value="0.000000e+000"/>	<input type="text" value="6.736000e+002"/>	<input type="text" value="3.000000e+002"/>	<input type="text" value="0.000000e+000"/>	<input type="text" value="3.048000e-001"/>	<input type="text" value="0.000000e+000"/>	<input type="text" value="0.000000e+000"/>
2	<input type="text" value="1.209600e+001"/>	<input type="text" value="6.736000e+002"/>	<input type="text" value="3.000000e+002"/>	<input type="text" value="0.000000e+000"/>	<input type="text" value="3.048000e-001"/>	<input type="text" value="1.209600e+001"/>	<input type="text" value="0.000000e+000"/>
3	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>
4	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>
5	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>	<input type="text" value="Not Used"/>

The surface temperature will be specified in the computation. The surface heat-flux will be determined as part of the computation.

Figure 6: Edge/Wall-Conditions menu of Program **EDDYBL_DATA** after modification.

5.5 Initial Profiles

Click on the “Initial Profiles” button. Change the values of skin friction, Reynolds number based on momentum thickness, shape factor and initial boundary-layer thickness to $C_f = 0.00117076$, $Re_\theta = 8737$, $H = 13.2$ and $\delta = 0.020689$ m, respectively.

13

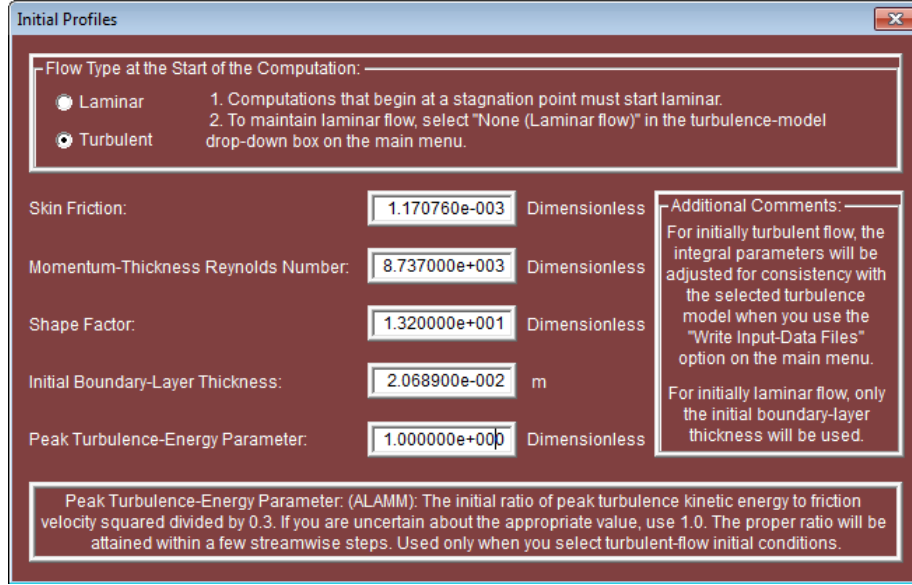


Figure 7: Initial-Profiles menu of Program EDDYBL_DATA after modification.

5.6 Gas Properties

The “Gas Properties” menu includes several thermodynamic properties. Sutherland law can be written as:

$$\mu = \mu_r \frac{T^{1+\omega}}{S + T} \quad (6)$$

The input parameters $SU = 110.4$, $VISCON = 1.458 \times 10^{-6}$ and $VISPOW = 1.5$.

Gas Properties

Specific-Heat

1.400000e+000

Dimensionless

Perfect-Gas Constant

2.870000e+002

m²/sec²/K

Laminar Prandtl Number:

7.100000e-001

Dimensionless

Turbulent Prandtl Number:

8.900000e-001

Dimensionless

Sutherland Viscosity-Law Coefficients...

Coefficient SU:

1.104000e+002

K

Coefficient VISCON:

1.458000e-006

kg · m · K^(vispow-1)/sec²

Coefficient VISPOW:

1.500000e+000

Dimensionless

Set Values for:

☐ Air
☐ Carbon Dioxide
☐ Helium
☐ Hydrogen
☐ Nitrogen
☐ Oxygen

Coefficient SU in the Sutherland Law, (Viscosity) = VISCON · T^{VISPOW} / (SU+T), where T is temperature. To use a power-law viscosity with exponent 'omega', set SU = 0 and set VISPOW =

Figure 8: Gas-Properties menu of Program EDDYBL_DATA after modification.