Appendix D

Program EDDYBL

D.1 Overview

This appendix is the user's guide for Program **EDDYBL**, a two dimensional and axisymmetric, compressible boundary-layer program for turbulent boundary layers that is included on the distribution diskette. An overview of the program's evolution and operation is given, along with details on installing the program on your computer. Two bench-mark runs are described that can be used to make sure the program is operating properly on your computer. The software includes a plotting utility for both video and hardcopy plots on IBM PC and compatible computers.

D.1.1 Acknowledgments

Program **EDDYBL** is a compressible, two-dimensional and axisymmetric boundary-layer program that embodies the Wilcox (1988a) k-ω model, the Wilcox (1988b) multiscale model, and several low-Reynolds-number variants of the k-ϵ model. This program has evolved over the past 20 years and can thus be termed a mature software package. Many U. S. Government Agencies have contributed to development of the program that is based on a program originally developed by Price and Harris (1972). Most notably, various stages of the program's development can be attributed to support by the following agencies.

U. S. Army Research Office
NASA Ames, Langley and Lewis Research Centers
Air Force Office of Scientific Research
Office of Naval Research

Defense Advanced Research Projects Agency
Air Force Weapons Laboratory
Naval Ship Research and Development Center

Additionally, important improvements have been made to this software package as a result of feedback from users, most notably from the outstanding fluid mechanics students at UCLA and USC. The author owes special thanks to Dr. G. Brereton of the University of Michigan whose personal efforts resulted in the addition of the option to use either English or SI units, and to J. Morrison of AS&M for adapting the software to a SUN Workstation.

D.1.2 Required Hardware and Software

Versions of the program are available for the following computers.

Cray X-MP and Y-MP
VAX 11 and 8600
SUN Workstations
Silicon Graphics Iris
Intel 80386, 80486 and Pentium Based Microcomputers
Definicon 68020 and 68030 Coprocessor Boards
Definicon SPARC Coprocessor Boards
IBM PC/XT/AT and Compatibles
Heath/Zenith 100

The program requires at least 320 kilobytes of memory. To achieve sensible computing times, IBM PC/XT/AT and compatibles should have an 8087 or 80287 math coprocessor, and must use Microsoft Fortran Version 5.0 or higher. Intel 80386 based machines must have either an 80387 or Weitek math coprocessor.

D.2 Getting Started Quickly

Because **EDDYBL** and its input-data preparation utility, **SETEBL**, run on many different computers, installation of the software is a little different for each machine. The main difference occurs in the commands needed to compile and link the programs. To install the software on a computer other than an IBM PC or compatible, you must skip ahead to Sections D.3 and D.4. If you have an IBM PC or compatible microcomputer running under the MS-DOS operating system, executable versions of the software package are included on the distribution diskette. Regardless of the computer you are using, once you have executable programs, complete the installation as follows.

1. Read the contents of the file **read.me** in subdirectory **eddybl** on the distribution diskette. This file will tell you of any program revisions as well as the location of all pertinent program files on the diskette. Then, copy the following files to your working directory:

eddybl.exe	**blocrv.dat**	**ploteb.exe**
instl.exe	**heater.dat**	**ploteb.dat**
setebl.exe	**presur.dat**	**exper.dat**

   Omit the files **ploteb.exe**, **ploteb.dat** and **exper.dat** if you are using a computer other than an IBM PC or compatible.

2. Run Program **INSTL** and answer all questions posed by the program. This program generates a file named **grafic.dat** that should be saved in your working directory.

3. If your computer is an IBM PC or compatible, install the **ansi.sys** driver supplied with your MS-DOS operating system by adding the following command to your **config.sys** file:

   device=ansi.sys

   Make sure the file **ansi.sys** is available in your path. If you have not previously had this command in your **config.sys** file, you must now re-boot your computer to install the **ansi.sys** driver.

A simple bench-mark case is built into the software package to allow you to quickly determine that everything is operating properly, and to see how easy it is to use Program **EDDYBL**. Because the input-data preparation utility, **SETEBL**, is menu driven, you will find that very little explanation of the program's operation is needed. After successfully completing the following bench-mark run, the first time user should nevertheless do the example of Section D.5 to be sure the software is properly installed and to learn some of the more subtle features of Program **SETEBL**.

1. The first step is to run **SETEBL**. If you have not installed **SETEBL**, you will be notified with a brief message after which the program will immediately terminate. If this happens, refer to Section D.3 and perform the installation procedure.

2. Assuming the program is properly installed, you will see a message informing you that file **eddybl.dat** does not exist. The message asks if you want to create a new file named **eddybl.dat**. For this sample session, you should answer yes by typing the letter *Y* or *y* followed by pressing the *ENTER* key.

3. Having performed Step 2, you will now be presented with the main menu (Figure D.1) on which ten options are listed. **SETEBL** has built-in default values for all input parameters that correspond to an incompressible (Mach .096) flat-plate boundary layer. When you eventually exit **SETEBL**, these data will be written into an Ascii data file named **eddybl.dat**. For this bench-mark case, if you selected English units as the default when you ran Program **INSTL**, you have no need to change any data. However, this case must be done using English units. If you selected SI units as the default when you ran **INSTL**, you must change to English units. Type either a *U* or a *u* (for Units - note that the U is in reverse video on your display) and press the *ENTER* key to make the change. The menu will change to indicate which units are in effect. Before exiting, you must generate two other data files, viz., **table.dat** and **input.dat** that are needed in order to run Program **EDDYBL**.

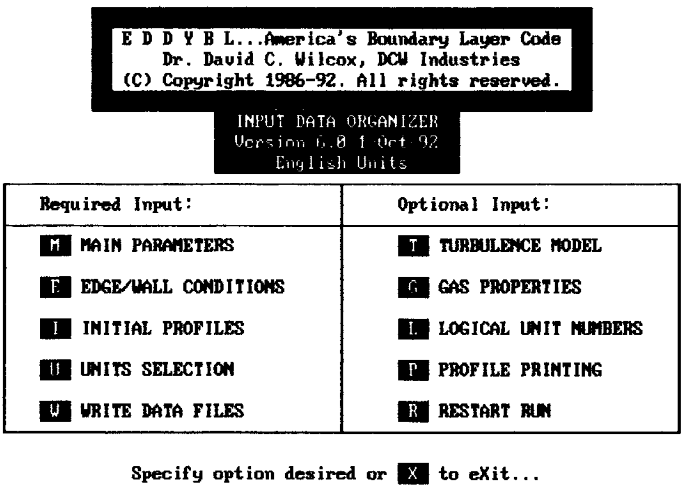

Figure D.1: Opening menu of Program **SETEBL**.

4. To generate these files, select the **Write Data Files** option. To do this, type a *W* or a *w* followed by pressing the *ENTER* key. After a

short wait, you will be notified that the binary data file **table.dat** has been successfully written. You are now presented with the following query in reverse video.

Save the profiles in Ascii form? (X=eXit, Y=Yes, ENTER=No)...

If you desire a copy of the initial profiles to be saved in a disk file named **setebl.prt** for inspection at a later time, respond with a *Y*, *ENTER* sequence; otherwise press the *ENTER* key. After you have responded to this query, a second query will appear, viz.,

Display the profiles on the video? (X=eXit, Y=Yes, ENTER=No)...

If you want to see the profiles on your video display, respond accordingly. Otherwise, press *ENTER*. After you have responded, your screen clears again and a message appears indicating initial profiles are being generated. If you elected to display profiles on your video display, they will now be displayed, a screen at a time. Press *ENTER* to advance to the next screen. Regardless of the options you have chosen, the precise values of the integral parameters for your computed initial profiles are displayed. Finally, a message appears indicating the binary data file **input.dat** has been successfully written and that you must press *ENTER* in order to continue.

5. After you press *ENTER*, control returns to the main menu. At this point you have prepared all input-data files for the bench-mark run. Exit by typing an *X*, *ENTER* sequence.

6. All that remains now is to run Program **EDDYBL**. Program output will be directed to a disk file named **eddybl.prt**. The file **eddybl.prt** supplied on the distribution diskette contains the printout for the bench-mark run on an 80486/Weitek 4167 based microcomputer. Your results should agree to within several decimal places with those in the sample printout. For reference, Table D.1 summarizes approximate computing times (including disk I/O) required for several computers.

7. If you are using an IBM PC or compatible computer, you can generate a video and hardcopy plot of the computational results by running Program **PLOTEB**. Before executing this program, be sure to modify the input-data file, **ploteb.dat**, as required for your system. Section D.8 describes all input parameters in the file.

Table D.1: Computing time for the bench-mark case

Computer	CPU (MHz)	FPU (MHz)	CPU Time(sec)
Cray 2	-	-	1
GA-486L	80486 (25.0)	mW4167 (25.0)	4
Notebook 486DX	80486 (33.0)	80487 (33.0)	5
GA-486L	80486 (25.0)	80487 (25.0)	6
M-317B	80386 (33.0)	mW3167 (33.0)	7
VAX 8600	-	-	10
SPARC	7C601 (20.0)	8847 (20.0)	12
Tandy 4000	80386 (16.0)	mW1167 (16.0)	17
DSI-785+	68020 (25.0)	68882 (25.0)	19
DSI-785+	68020 (20.0)	68882 (20.0)	24
DSI-020	68020 (16.7)	68882 (16.7)	29
VAX 11/785	-	-	36
DSI-020	68020 (16.7)	68881 (16.7)	39
VAX 11/750	-	-	46
DSI-020	68020 (12.5)	68881 (12.5)	52
Tandy 4000	80386 (16.0)	80287 (8.0)	120
Toshiba T1200	8086 (10.0)	8087 (10.0)	143
Turbo 286	80286 (12.0)	80287 (8.0)	154
M-317B	80386 (33.0)	None	232
Tandy 4000	80386 (16.0)	None	624
Turbo 286	80286 (12.0)	None	698
TRS-80 Mod 16	68000 (6.0)	None	890

$\boxed{\text{SPECIAL NOTE}}$

All input to Program SETEBL is case insensitive, i.e., all commands and input can be entered in either upper or lower case.

D.3 Installing SETEBL

To use the supplied executable version of **SETEBL** on an IBM PC or compatible microcomputer, including the default values specified for all input-data parameters, simply copy the executable file to your working directory. Otherwise, if you wish to change some of the default values, or if you are using a computer other than an IBM PC, the first step required to install Program **SETEBL** is to compile and link the program. The main program is the file named **setebl.for**, and the various subroutines are listed in Section D.12. All routines reference three **include** files, **chars**, **comeb1** and **comeb2**. Section D.10 summarizes the commands required to compile and link Program **SETEBL**.

> **The first step required to install SETEBL for your computer is to either copy the executable file to your working directory or to compile and link Program SETEBL.**

In order to use Program **SETEBL**, you must first install it for your particular console. The program makes extensive use of reverse video, direct cursor positioning, and some graphics characters. Since no uniform standard exists for such console characteristics, the appropriate sequences used by your console must be defined for Program **SETEBL**.

D.3.1 Boot-Console Installation

In order to install **SETEBL** on your main (or boot) console, you must generate a binary data file named **grafic.dat** that contains all of the information needed by **SETEBL**. The source code for a program that generates **grafic.dat** customized for your console has been supplied as part of this software package. The program is called **INSTL**, and the source is contained in **instl.for**. If you customize Program **INSTL** or if you are using a computer other than an IBM PC, you must first compile and link Program **INSTL**. Then:

> **The second step required to install SETEBL for your console is to run Program INSTL.**

When you run Program **INSTL**, you will be given the option of specifying whether you want the default units to be English or SI. Make the choice best suited to your needs. You will also have to specify the type of computer you have and, in some cases, the type of console.

When you have successfully run Program **INSTL**, the required binary data file **grafic.dat** will be created and **INSTL** will print a message to that effect. Whenever you wish to run **SETEBL**, simply make sure **grafic.dat** is present in your directory. If it is not present, **SETEBL** displays a message informing you that you are attempting to run an uninstalled version of **SETEBL** and promptly terminates. If you are running Program **SETEBL** on an IBM PC based system, you must also install the **ansi.sys** driver. Thus,

> **The third step required to install SETEBL on an IBM PC based system is to install the ansi.sys driver by adding the following command to your config.sys file.**

device=ansi.sys

If you have not previously had this command in your **config.sys** file, it will not take effect until you re-boot your computer.

D.3.2 Remote-Terminal Installation

For a remote terminal whose characteristics are different from those of your boot console, you can create another **grafic.dat** by making appropriate changes to Program **INSTL**. The program is heavily commented, and customization should be straightforward.

D.4 Installing EDDYBL

To use the supplied executable version of **EDDYBL** on an IBM PC or compatible microcomputer, simply copy the executable file to your working directory. Otherwise, if you wish to make program changes, or if you are using a computer other than an IBM PC, the first step required to install Program **EDDYBL** is to compile and link the program. The main program is the file **eddybl.for** that also makes use of the include files **common** and **cpuid**. Be sure to link with the /e option for the Microsoft Fortran version or the **-pack** option with SVS Fortran-386/Phar Lap to reduce the size of the executable file.

> **The only step required to install EDDYBL for your computer is to either copy the executable file to your working directory or to compile and link Program EDDYBL.**

D.5 Running a General Case

This section explores, in detail, all of the salient features of the input-data preparation utility, **SETEBL**. You will be guided through the various menus and, in the process, you will set up a constant-pressure boundary layer computation for a Mach 1 freestream. For the case you will do, freestream conditions are as follows.

Total pressure, p_{t_∞}	=	482.7 lb/ft^2 (23112 N/m^2)
Total temperature, T_{t_∞}	=	468°R (260 K)
Mach number, M_∞	=	1

The surface will be slightly cooled so that surface temperature is 95% of the adiabatic-wall temperature.

Your goal is to initiate the computation at a plate-length Reynolds number, Re_x, of one million and determine the point where the momentum-thickness Reynolds number, Re_θ, is 6000. You might want to do this, for example, in order to provide upstream profiles for a Navier-Stokes computation. You know from a correlation of experimental data that when $Re_x = 1.0 \cdot 10^6$, the boundary layer has the following integral properties:

Skin friction, c_f	=	.0038
Shape factor, H	=	1.80
B.L. Thickness, δ	=	11.9 θ
Reynolds number, Re_θ	=	1500

Finally, the surface is perfectly smooth, there is no surface mass transfer, and the k-ω model will be used.

D.5.1 Preliminary Operations

To perform this exercise, delete any existing **eddybl.dat** data file that might be in your directory. Although this is not generally necessary, for the purposes of this section it will be easier if you begin with the default values.

As with the bench-mark case of Section D.2, the very first step is to run Program **SETEBL**. If you have not installed the program, you will be notified with a brief message after which the program will immediately terminate. If this happens, go back to Section D.3 and perform the installation procedure.

Assuming the program is properly installed, you will see a message informing you that file **eddybl.dat** does not exist. You will be asked if you want to create a new file named **eddybl.dat**. For this sample session, you should answer yes by typing the letter *Y* followed by pressing the *ENTER* key.

D.5.2 Units Selection

This case can be done in either English or SI units. Examine the main menu to determine which units are in effect. If you wish to change units, type a *U* followed by pressing *ENTER*. The menu will reflect the change in units immediately. If you change your mind and wish to go back to the original units, repeat the *U*, *ENTER* sequence. In the following sections, values are quoted in English units followed by corresponding SI values in parentheses.

D.5.3 Main Parameters

At this point, you will be presented with the main menu on which ten options are listed. Begin by entering the **Main Parameters** sub-menu. To enter this sub-menu, type an *M* followed by pressing the *ENTER* key.

Yet another sub-menu will now appear that gives you the choice of entering input data for either **Freestream Conditions** or **Body Parameters**. There is a third option that allows you to **eXit**. The latter option permits you to return to the previous menu. You will eventually do so, but first you will do some actual data preparation.

Freestream Parameters. Type an *F* followed by pressing the *ENTER* key to descend to the **Freestream Conditions** menu. You will now see a display that includes seven of the primary quantities that specify freestream flow conditions, including freestream total pressure, total temperature, Mach number, shock-wave angle, and some turbulence parameters. The bottom row provides instructions on how to proceed. Press the *ENTER* key several times, for example, and you will see the arrow move from one input variable name to the next. When you reach the last variable, pressing the *ENTER* key again will cause the arrow to move to the uppermost variable. You may make as many passes through the list of variables as you wish.

This particular menu includes a Help option to further explain the meaning of the more obscure input quantities. To display the Help menu, type an *H* followed by pressing the *ENTER* key. After reading this Help menu, pressing the *ENTER* key returns you to the Freestream Conditions data-entry menu.

Having returned from the Help menu, you will now exercise the **Change** option. First, position the arrow in front of Mach number. You accomplish this by pressing *ENTER* twice. Now, type the letter *C* (for Change) followed by pressing *ENTER*. The bottom line of the menu will now change. You are told to specify the new value, and that the FORMAT must be the standard FORTRAN floating-point format E13.6. The default value assigned to the Mach number is .096, corresponding to essentially incompressible flow conditions. Change the Mach number to one by typing 1. (the exponent E+00 is unnecessary but the decimal point is mandatory — this is normal FORTRAN I/O). As with all commands to **SETEBL**, nothing will happen until you press the *ENTER* key. Before you do however, watch the line near the bottom of your display entitled **Static Conditions**. Keeping your eyes on the static conditions line, press the *ENTER* key. If you have done this step correctly, the new static conditions should appear in place of the old. Also, if you look at the value assigned to the Mach number you will find it has been changed to one.

At this point, you can change any of the seven input quantities. In addition to Mach number, you must change total pressure and temperature. Press the *ENTER* key five times in order to position the arrow in front of PT1, the total pressure. Using the change procedure, i.e., type a *C* followed by *ENTER*, insert the desired total pressure of 482.7 lb/ft^2 (23112. N/m^2). You may enter 4.827e+02 (2.3112e+04) or 4.827E2 (2.3112E4), etc. if you wish. Note that your keyboard's normal destructive backspace key can be used to correct typing errors. When your desired new total pressure is correctly entered, press *ENTER* and the change will be made. Verify that the new value for PT1 shown on the display is 4.827000E+02 (2.311200E+04). If you made any mistakes, repeat the change operation until you get it right.

Now press *ENTER* to position the arrow in front of TT1, the total temperature. Using the change procedure, change the value of TT1 to 468. (260.). Don't forget the decimal point or else your total temperature will be .000468 (.000260). Verify that the new value for TT1 shown on the display is 4.680000E+02 (2.600000E+02).

If you have changed Mach number, total pressure and total temperature correctly, the value listed below for static pressure will be very close to 255 lb/ft^2 (12209 N/m^2) and the unit Reynolds number should be approximately $1.24 \cdot 10^6$ ft^{-1} ($4.07 \cdot 10^6$ m^{-1}). Verify that your static conditions match these two values. If they do not, find and correct any errors you have made.

Jot the values of static pressure and freestream unit Reynolds number on a slip of paper for reference later. In general, knowing these values often helps expedite preparation of your input data. Later on, we will see an example of using both parameters.

You have now finished this sub-menu. In order to exit, simply type an *X* followed by pressing the *ENTER* key. Note that, with the exception of Help menus for which only *ENTER* is needed, you return to the previous menu by the *X*, *ENTER* sequence. Also, if you are ever in doubt about what to do, look at the last line of the display for instructions.

Body Parameters, Etc. Now you are back to the **Main Parameters** sub-menu that provides the options of altering freestream conditions, body parameters, etc. Descend to the **Body Parameters** sub-menu by typing the letter *B* followed by pressing *ENTER*. You will be presented with a menu similar to the **Freestream Conditions** sub-menu. As before, press *ENTER* several times to move the arrow. Scan the input variable definitions and default values. Examine the Help menu. In other words, begin discovering that you already know most of what is needed in order to operate **SETEBL**!

There are only two input quantities you need to change, viz., ISHORT and SSTOP. Because you are looking for the point where momentum thickness Reynolds number is 6000, you have no need for the long printout that gives far more detail than you are interested in. Consequently, you should position the arrow next to ISHORT and change its value to 0. This is done by typing *C* and a carriage return; no value need be entered. As an experiment, you might want to try repeating this sequence. If you do, the value of ISHORT will change back to 1. Be sure you have changed ISHORT to 0 after you finish experimenting.

Turning now to SSTOP, use the *ENTER* key to position the arrow next to SSTOP. This is the maximum value of plate length to which you will permit computation to proceed. You are certain that momentum thickness Reynolds number will reach 6000 at a plate-length Reynolds number somewhere between three and five million. Hence, you might want to terminate your run when Reynolds number reaches five million. Referring to the unit Reynolds number of $1.24 \cdot 10^6$ ft^{-1} ($4.07 \cdot 10^6$ m^{-1}) that you jotted down earlier, a quick computation shows that a plate-length Reynolds number of five million occurs when plate length is 4.03 ft (1.23 m). Thus, change SSTOP to 4.03 (1.23).

There are no further changes you need to make at this time on this menu, so you should now exit by typing *X* followed by pressing the *ENTER* key.

At this point, you are done with the **Main Parameters** sub-menu. In order to return to the main menu, type another *X* followed by pressing the *ENTER* key. Remember, nothing happens in **SETEBL** until you press the *ENTER* key.

D.5.4 Taking a Lunch Break

Before continuing setting up a new run, you are going to simulate a lunch break. Imagine that it's time to break for lunch and the systems people upstairs are notorious for causing your VAX 8600 to crash during the lunch hour. Any file you leave open will be lost as a result of a crash. In order to protect your work from such a disaster, simply exercise the exit option by typing yet another *X* followed by pressing the *ENTER* key.

Inspection of your directory will show that a new file named **eddybl.dat** has been created. Verify that the file exists at this time. If it does not, go back to Subsection D.5.1 and omit the mistake you made that caused you to reach this point unsuccessfully.

Now imagine you have returned from lunch, and your microcomputer (which never crashes during lunch because there are no system people to cause it to) is ready to continue serving your data processing needs. At this point, run Program **SETEBL** again. Because the data file **eddybl.dat** exists, the program will go directly to the main menu.

D.5.5 Edge/Wall Conditions

From the main menu, you should now proceed to the **Edge/Wall Conditions** sub-menu by typing an *E* followed by pressing *ENTER*.

This sub-menu contains five options, viz., Pressure Distribution, Heat Transfer, Mass Transfer, Body Geometry and eXit. Type a *P* followed by *ENTER*. The **Pressure Distribution** sub-menu explains that you must prepare a file **presur.dat** that defines the pressure distribution. You must prepare the file with an editor such as MS-DOS 5.0's EDIT, DEC's EDT, UNIX's vi, etc. All you can change in this menu is the number of points you plan on using. You will not change NUMBER because your run will have constant pressure. Thus, you need to specify pressure at two values of plate length. Note that this menu describes in detail the contents and format of **presur.dat**. Exit this menu with the usual *X*, *ENTER* sequence.

Now go to the **Heat Transfer** sub-menu. You are presented with a description of data file **heater.dat** that must be created with your own editor. Note that the adiabatic-wall temperature is given for your information and the value listed should be 459.4°R (255.2 K). The one parameter you can change on this menu is KODWAL which determines whether you plan on specifying surface heat flux or surface temperature. Type a *C* followed by *ENTER* to change KODWAL. Note that the display now indicates temperature is prescribed at the surface. Jot down the adiabatic-wall temperature for later reference. Exit this sub-menu by typing an *X* followed by *ENTER*.

Now go to the **Mass Transfer** sub-menu. This sub-menu describes a file, **blocrv.dat**, that must be prepared externally. You can alter the one parameter NFLAG. The default value is 0, which means **blocrv.dat** is not required to prepare your edge and surface conditions. You have no need to change its value for this application. Note that your display indicates the file **blocrv.dat** will not be required. Exit this sub-menu.

Having exited the **Mass Transfer** sub-menu, you are now back at the **Edge/Wall Conditions** sub-menu. Proceed to the **Body Geometry** sub-menu. No, you didn't make a typing error. This is the same menu you just completed. It has been included for planned future enhancements to **SETEBL**. Exit back to the **Edge/Wall Conditions** sub-menu with an *X*, *ENTER* sequence.

The final option is to eXit. Do so by typing another *X*, *ENTER* sequence.

You are now back at the main menu. You cannot continue until you have prepared input-data files **presur.dat** and **heater.dat** (**blocrv.dat** is not needed because NFLAG is 0). Hence, it is time to exit **SETEBL** and save all the work you have done so far.

D.5.6 Preparing Edge/Wall Condition Data Files

The easiest way to prepare the data files **presur.dat** and **heater.dat** (and **blocrv.dat** as well) is to use an editor such as EDIT, EDT, vi, etc. to modify existing files from a previous run. That is why you left the files from the bench-mark run in your directory. You can delete **blocrv.dat** now if you wish as it won't be needed.

If you have followed all of the instructions correctly, you have the static pressure of 255 lb/ft^2 (12209 N/m^2) and the adiabatic-wall temperature of 459.4°R (255.2 K) jotted down somewhere. Using your favorite editor, change **presur.dat** to the following:

English Units:

```
0.000000E 00  2.550000E 02
1.000000E 01  2.550000E 02
0.000000E 00  0.000000E 00
```

SI Units:

```
0.000000E 00  1.220900E 04
1.000000E 01  1.220900E 04
0.000000E 00  0.000000E 00
```

As explained in the **Pressure Distribution** sub-menu, the first two lines of this file are arc-length/pressure pairs presented in format (2E14.6). The final line is the pressure gradient at the beginning and end of the interval and the data are given in the (2E14.6) format also. You have specified pressure at a plate length of zero and ten feet (meters). This interval must at least cover the planned integration range. The value of the pressure is the static pressure you jotted down earlier.

Turning now to surface temperature, note that 95% of the adiabatic-wall temperature is approximately 436°R (242 K), which is the value you should use. Use your editor to modify **heater.dat** as required, noting that the values of arc length at which you specify wall conditions must match the values used for the pressure distribution. As explained on the Heat Transfer sub-menu, this file must consist of the following four lines:

English Units:

```
0.000000E 00  4.360000E 02  0.000000E 00
1.000000E 01  4.360000E 02  0.000000E 00
0.000000E 00  0.000000E 00
0.000000E 00  0.000000E 00
```

SI Units:

```
0.000000E 00  2.420000E 02  0.000000E 00
1.000000E 01  2.420000E 02  0.000000E 00
0.000000E 00  0.000000E 00
0.000000E 00  0.000000E 00
```

The format of the first two lines is (3E14.6), while the last two lines have format (2E14.6). The first column for the first two lines is arc length, the second is wall temperature, and the third is surface heat flux. Note that since you have chosen to specify surface temperature rather than heat flux, any value can be entered for the heat flux; it won't be used in the computation. Similarly, if you choose to specify surface heat flux, the value assigned to surface temperature is arbitrary. The third line gives surface temperature slope at the beginning and end of the interval, while the last line gives surface heat flux slope. Of course, you are not limited to constant properties in the most general case. You may prescribe as many as 50 different values for edge pressure, surface temperature, etc.

At this point, you have prepared all of the freestream conditions, body parameters, and (from an external editor) the two data files **presur.dat** and **heater.dat**. Before reentering **SETEBL**, examine your directory. In addition to **eddybl.dat**, you should find another file **eddybl.bak**. The former is your most recent version of **eddybl.dat**. The latter is the version you created just before taking your lunch break. **SETEBL** always saves your previous work in a file named **eddybl.bak** to provide you with a little extra protection. You no longer need **eddybl.bak**, so delete it if you wish.

D.5.7 Generating Edge/Wall Conditions

Run **SETEBL** again. When the main menu appears, use a *W*, *ENTER* sequence to execute the Write Data Files option. A message will appear briefly indicating edge conditions are being generated. When all computations are complete, a message appears indicating a data file named **table.dat** has been successfully written. If you receive any other message, there are probably errors in the files you created with your editor in Subsection D.5.6 that you must correct before continuing. What you are doing in this step is executing a subroutine in Program **SETEBL** that accomplishes two ends. First, you generate data file **table.dat** in binary form that is used by Program **EDDYBL**. Second, you compute several parameters appearing in data file **eddybl.dat** that are needed in preparing initial profiles.

D.5.8 Initial Profiles

In addition to the message that **table.dat** has been successfully written, you also receive the message

Save the profiles in Ascii form? (X=eXit, Y=Yes, ENTER=No)...

Since you have not yet prepared the data needed to generate initial profiles, type an *X*, *ENTER* sequence. Upon returning to the main menu, you are now ready to go to the Initial Profiles sub-menu. Type an *I* followed by pressing the *ENTER* key. The sub-menu that appears has three options, viz., **Integral Parameters**, **Grid Parameters** and **eXit**.

Integral Parameters. Go to the **Integral Parameters** sub-menu first by entering another *I*, *ENTER* sequence. Press *ENTER* once to position the arrow next to skin friction. Change the value to 0.0038 in the usual manner. Press *ENTER* again to move the arrow in front of boundary-layer thickness, δ. For the conditions specified above, a quick calculation shows that δ for your unit Reynolds number is .0144 ft (.004389 m). Change the value of DELTA to 0.0144 (.004389). Now move the arrow to shape factor and change its value to 1.8. Finally, move the arrow one more time to momentum-thickness Reynolds number and change its value to 1500., being careful to remember the decimal point. Inspect your work for possible errors. When you have made all entries correctly, exit this sub-menu.

Grid Parameters. Now exercise the *G* option to enter the **Grid Parameters** sub-menu. The first quantity you should change is the initial streamwise stepsize, DS. For this constant pressure case, you can use a stepsize as big as triple the boundary-layer thickness. Hence, change the value of DS to 0.04 ft (0.0122 m). In order to start the computation at a plate-length Reynolds number of one million, the initial plate length (arc length) must be 0.806 ft (0.246 m), a fact you can deduce by using the freestream unit number of $1.24 \cdot 10^6$ ft^{-1} ($4.07 \cdot 10^6$ m^{-1}) you jotted down earlier. Hence, change SI to 0.806 (0.246). The next parameter is XK, the grading ratio. A somewhat coarser grid can be used for this case than the default grid. Change the value to 1.14 which corresponds to grid increments increasing in a geometric progression at a 14% rate. Finally, change the number of grid points normal to the surface, IEDGE, to 51. Again, inspect your work for possible errors. When your entries are error free, exit this sub-menu. Having returned to the **Initial Profiles** sub-menu, you should now exercise the exit option with the usual *X*, *ENTER* sequence in order to return to the main menu.

Generating Initial Profiles. As in Subsection D.5.7, exercise the **Write Data Files** option by entering a *W*, *ENTER* sequence. This will regenerate **table.dat** and you are again presented with the following message.

Save the profiles in Ascii form? (X=eXit, Y=Yes, ENTER=No)...

If you desire a copy of the profiles, in Ascii form, to be sent to a disk file named **setebl.prt** that can be printed and/or examined with an editor after exiting Program **SETEBL**, respond with a *Y*, *ENTER* sequence; otherwise simply press the *ENTER* key. After you have responded to this query, a second query will appear as follows.

Display the profiles on the video? (X=eXit, Y=Yes, ENTER=No)...

If you want to see the profiles on your video display, respond with a *Y*, *ENTER* sequence. Otherwise, press *ENTER*. After you have responded, your screen clears again and a message appears indicating initial profiles are being generated. If you elected to display profiles on your video display, they will now be displayed, a screen at a time. Press *ENTER* to view the next screen. Regardless of the options you have chosen, the precise values of the integral parameters for your computed initial profiles are displayed. Finally, a message appears indicating the binary data file **input.dat** has been successfully written and that you must press *ENTER* in order to continue.

Notice that the value of the conventional sublayer coordinate, y^+, for the point nearest the surface is printed and its value is 0.175. Subroutine START will alert you if this value ever exceeds unity as Program **EDDYBL** requires the value of y^+ nearest the surface to be less than 1 in order to remain numerically stable. If this ever happens, you must either increase XK or IEDGE. When you press *ENTER*, control returns to the main menu.

You will receive a warning if you use the k-ϵ model and the value of y^+ for the point nearest the surface is less than 0.1. Values smaller than 0.1 tend to slow the convergence rate for the k-ϵ model, and may even cause your run to crash.

D.5.9 Selecting a Turbulence Model

In order to select the k-ω model, go to the **Turbulence Model** sub-menu. Type a *T* followed by *ENTER*, and you will find that the fourth quantity listed is a flag called MODEL. Press *ENTER* three times to position the arrow in front of MODEL. Change its value to 0 by typing *C* followed by entering a 0 and pressing *ENTER*. Note that the highlighted bar below the menu now indicates you are using the k-ω model without viscous correction (low-Reynolds-number) terms. Exit back to the main menu.

For general reference, there are ten turbulence models implemented in **EDDYBL**, and the two input parameters MODEL and NVISC are used to make the selection. The choices are as follows.

MODEL	NVISC	Turbulence Model
-1	-	None (Laminar Flow)
0	0	k-ω, viscous corrections excluded
0	1	k-ω, viscous corrections included
1	0	Multiscale, viscous corrections excluded
1	1	Multiscale, viscous corrections included
2	0	k-ϵ, Jones-Launder (1972)
2	1	k-ϵ, Launder-Sharma (1974)
2	2	k-ϵ, Lam-Bremhorst (1981)
2	3	k-ϵ, Chien (1982)
2	4	k-ϵ, Yang-Shih (1993)
2	5	k-ϵ, Fan-Lakshminarayana-Barnett (1993)

D.5.10 Logical Unit Numbers and Plotting Files

Your final input-data changes will cause printed output to go to your line printer rather than to disk file **eddybl.prt**. You will also verify that two disk files named **profil.dat** and **wall.dat** will be created that can be used as starting conditions for another program or as input to a plotting program. Go to the **Logical Unit Numbers** sub-menu by typing an *L*, *ENTER* sequence. The first parameter is IUNIT1 which, by default, is disk file **eddybl.prt**. For Lahey, Microsoft or SVS Fortran versions, change its value to 6. For all other versions, use your normal operating system procedure to direct the contents of **eddybl.prt** to a line printer. Verify that the value for the parameter IUPLOT is some value other than 0. If it is 0, change its value to 10 (or any other convenient value excluding unit 15 and any previously assigned unit number).

Disk file **wall.dat** is written as an unformatted file, each record of which can be read by another FORTRAN program according to the following program fragment.

```
      i=1
10    read(iunit) s(i),res(i),cfe(i),rethet(i),
     *            h(i),che(i),anue(i),pe(i),tw(i)
      if(s(i).ne.-999.) then
        i=i+1
        go to 10
      endif
```

The various quantities saved in disk file **wall.dat** are:

Quantity	Description	Dimensions
s	s, arc length along surface	ft (m)
res	Re_s, Reynolds number based on s	None
cfe	$c_{fe} = 2\tau_w/\bar{\rho}_e\tilde{u}_e^2$, skin friction	None
rethet	Re_θ, Reynolds number based on θ	None
h	H, shape factor	None
che	$\dot{h}/\bar{\rho}_e\tilde{u}_e C_p$, Stanton number	None
anue	$Pr_L s\dot{h}/\mu_e C_p$, Nusselt number	None
pe	P_e, edge pressure	lb/ft^2 (N/m^2)
tw	T_w, wall temperature	$^\circ$R (K)

The first line of the file **profil.dat** generated by Program **EDDYBL** contains the streamwise step number, M, and the number of mesh points normal to the surface, IEDGE. The format for this line is (2I6). The remainder of the file consists of IEDGE lines of data, format (12E11.4), containing the following boundary-layer profile data, with quantities written on each line in the order listed. Note that for the k-ϵ model, the specific dissipation rate, ω, is defined by

$$\omega = \frac{\epsilon}{C_\mu k} \tag{D.1}$$

Also, the tensor T_{ij} is specific to the multiscale model and is given by (see Subsection D.11.2):

$$\bar{\rho}T_{ij} = \tau_{ij} + \frac{2}{3}\bar{\rho}k\delta_{ij} - \frac{2}{3}\bar{\rho}(k-e)\delta_{ij} \tag{D.2}$$

Quantity	Description	Dimensions
y	Distance normal to surface	ft (m)
$\tilde{u}$	Horizontal velocity	ft/sec (m/sec)
$\tilde{T}$	Temperature	$^{\circ}$R (K)
$\bar{\rho}$	Density	slug/ft^3 (kg/m^3)
k	Turbulence kinetic energy	ft^2/sec^2 (m^2/sec^2)
ω	Specific dissipation rate	sec^{-1} (sec^{-1})
$k-e$	Large eddy energy	ft^2/sec^2 (m^2/sec^2)
T_{xx}	Large eddy xx-normal stress	ft^2/sec^2 (m^2/sec^2)
T_{xy}	Large eddy shear stress	ft^2/sec^2 (m^2/sec^2)
T_{yy}	Large eddy yy-normal stress	ft^2/sec^2 (m^2/sec^2)
y^+	Compressible sublayer-scaled distance	None
u^+	Compressible sublayer-scaled velocity	None

You may now exit back to the main menu. All of your input data are prepared and you are ready to run **EDDYBL**. Exit Program **SETEBL** with a final *X*, *ENTER* sequence.

D.5.11 Running the Boundary-Layer Program

Run Program **EDDYBL**. Examination of program output reveals that your run didn't go far enough to determine the point where momentum-thickness Reynolds number reaches 6000. After the 30 steps you specified as the upper limit (the default value for IEND1 - **Main Parameters/Grid Parameters** sub-menu), Re_θ is only 5200. The plate length at the final station is only 2.69 ft (0.82 m), so you allowed a large enough value, i.e., 4.03 ft (1.23 m) for SSTOP.

D.5.12 Restart Run

You could go back to **SETEBL**, increase IEND1 to, say, 35, and simply rerun **EDDYBL**. On an IBM PC/AT without an 80287, that's another 8 or 9 minutes. Since you might not really want to take another coffee break while your job runs, you might prefer a less time-consuming solution. Program **SETEBL** provides such a possibility through its **Restart** option.

Examine your directory and verify that Program **EDDYBL** has created a new file named **output.dat**. This file contains sufficient information to restart your program. Now, run Program **SETEBL** again. From the main menu, go to the Restart Run sub-menu by typing an *R* followed by pressing *ENTER*. This menu will permit you to change IEND1, the maximum streamwise step number, and SSTOP, the maximum value of arc (plate) length. Since your value for SSTOP is clearly large enough, you need only change IEND1. With the usual procedure, change IEND1 from 30 to 35. Now type *X* followed by pressing *ENTER* in order to return to the main menu. Before returning, you will receive a message in reverse video as follows:

"Do you wish to copy OUTPUT.DAT to INPUT.DAT? (Y/N)..."

Respond Yes by typing *Y* followed by pressing *ENTER*. At this point, for all but the VAX version, **SETEBL** will inform you that it first copies **input.dat** to a new file named **input.bak**. For all versions, **SETEBL** then copies **output.dat** to **input.dat**. The point is, the final output of your original run becomes input for the restart run. Additionally, your original **input.dat** has effectively been renamed as **input.bak** (VAX/VMS creates its own backup file so this file is unnecessary). Upon completion of the copy operation, control returns to the main menu (for the VAX version, you are instructed to press *ENTER* to continue). Exit Program **SETEBL**.

At this point, data files **eddybl.dat** and **input.dat** have been modified as needed to continue your run from where you left off. The file **table.dat** requires no modification as SSTOP remains smaller than the top end of the interval for which you have defined edge and surface properties. Had we made SSTOP larger than 10, you would have to make appropriate changes to **presur.dat** and **heater.dat** to make sure edge and surface conditions are defined at least up to the new value of SSTOP. You would then have to regenerate **table.dat** via the Write Data Files option (Subsection D.5.7).

Now, run Program **EDDYBL** again. If you have made no errors, inspection of the printout combined with a little interpolation shows that Re_θ is 6000 at a plate length of approximately 3.15 ft (0.96 m).

D.5.13 Gas Properties and Profile Printing

At this point, you have seen virtually all of Program **SETEBL**'s menus and options. There are two sub-menus we didn't use in this exercise, viz., **Gas Properties** and **Profile Printing**. Both menus are self explanatory and operate in the same manner as the menus you've already explored.

The **Gas Properties** menu allows you to modify thermodynamic properties such as specific heat ratio, universal gas constant, and viscosity-law coefficients. The default values are set up for air with the Sutherland viscosity law. You can implement a **power-law** viscosity relationship by setting SU = 0. Note that if you have a viscosity law of the form $\mu = \mu_{ref}\tilde{T}^n$ then you must set VISCON = μ_{ref} and VISPOW = $n + 1$.

The **Profile Printing** sub-menu permits you to print velocity, temperature, turbulent energy, etc. profiles at specified streamwise stations. Program **EDDYBL** always prints profiles at the final station. Also, whenever **EDDYBL** prints profiles, disk file **output.dat** is automatically written.

D.5.14 Selecting Laminar, Transitional or Turbulent Flow

Program **EDDYBL** can run in three different modes corresponding to (1) pure laminar flow, (2) transition from laminar to turbulent flow, and (3) pure turbulent flow. The two test cases exercise **EDDYBL** in its pure turbulent mode in which integral parameters are specified and IBOUND is set to 1.

To run in the transitional mode, simply select IBOUND = 0 in the **Initial Profiles/Integral Parameters** menu. As a result, exact laminar velocity and temperature profiles will be generated in conjunction with approximate laminar profiles for the various turbulence-model parameters. The actual transition point is determined automatically by the model equations and depends strongly upon the freestream values of k and ω that are specified in the **Main Parameters/Freestream Conditions** menu in terms of ZIOTAE and ZIOTAL. To obtain physically realistic transition Reynolds numbers you must include low-Reynolds-number corrections in the k-ω and multiscale models by setting NVISC = 1 in the **Turbulence Model** sub-menu. Although the k-ϵ models are capable of predicting transition, extremely small streamwise steps are needed with **EDDYBL**, and stable computation is very difficult to achieve.

Even if you are not interested in transition, this mode is nevertheless useful as it provides an alternate method for generating turbulent starting profiles, e.g., by starting laminar and running up to a desired value of Re_θ.

Finally, to run **EDDYBL** as a pure laminar boundary-layer program, the turbulence model can be suppressed by setting MODEL to -1 in the **Turbulence Model** sub-menu. When this is done, turbulence model computations are bypassed and no transition to turbulence occurs.

D.6 Applicability and Limitations

Program **EDDYBL** applies to attached, compressible, two-dimensional and axisymmetric boundary layers. The program computes properties of turbulent boundary layers using the Wilcox (1988a) k-ω model or the Wilcox (1988b) multiscale model, including effects of surface roughness, surface mass transfer, surface curvature, and low-Reynolds-number corrections. The program also includes several low-Reynolds-number versions of the k-ϵ model.

Computations can be initiated either from turbulent starting profiles that are generated from specified integral properties, or from laminar profiles that are automatically generated.

The k-ω and multiscale models are very robust and can be integrated through transition from laminar to turbulent flow with and without low-Reynolds-number corrections. By contrast, the k-ϵ model requires smaller streamwise steps than the k-ω and multiscale models, and, in general, cannot be integrated through transition unless extremely small steps are taken.

If integral properties are unknown and a k-ϵ solution is desired, the optimum procedure is to start laminar with the k-ω model and integrate through transition. Then, select the desired k-ϵ model and use the **Restart** option to continue the run.

Finally, if numerical difficulties are encountered with the k-ϵ model, try changing the value of input parameter *PSIEPS* in the Turbulence Model menu. Table 7.2 lists the default value of this parameter (ψ_ϵ); its purpose is explained in Section 7.3.

D.7 EDDYBL Output Parameters

The following *dimensionless* quantities are printed in the profiles portion of Program **EDDYBL** output.

Name	Symbol/Equation	Definition
i	i	Mesh point number
y/delta	y/δ	Dimensionless normal distance
u/Ue	$\tilde{u}/U_e$	Dimensionless velocity
yplus	$y^+ = u_\tau y/\nu_w$	Compressible sublayer-scaled velocity
uplus	$u^+ = u^*/u_\tau$	Compressible sublayer-scaled velocity
k/Ue**2	k/U_e^2	Dimensionless turbulence energy
omega	$\nu_e\omega/U_e^2$	Dimensionless dissipation rate
eps/mu	μ_T/μ	Dimensionless eddy viscosity
L/delta	$\sqrt{k/\beta^*}/(\omega\delta)$	Dimensionless turbulence length scale
uv/tauw	τ_{xy}/τ_w	Dimensionless Reynolds shear stress
T/Te	$\tilde{T}/T_e$	Temperature ratio

The following quantities are printed in the integral-parameter portion of Program **EDDYBL** output.

Symbol	Meaning	English Units	SI Units
F	Force	pounds (lb)	Newtons (N)
L	Length	feet (ft)	meters (m)
M	Mass	slugs (sl)	kilograms (kg)
Q	Heat flux	Btu/second (Btu/sec)	Watts (W)
T	Time	seconds (sec)	seconds (sec)
Θ	Temperature	°Rankine	Kelvins

Name	Symbol/Equation	Definition	Dimensions
beta	$\beta = (2\xi/U_e)dU_e/d\xi$	Pressure gradient parameter	None
Cfe	$c_{fe} = 2\tau_w/\bar{\rho}_e U_e^2$	Skin friction based on $\bar{\rho}_e$	None
Cfw	$c_{fw} = 2\tau_w/\bar{\rho}_w U_e^2$	Skin friction based on $\bar{\rho}_w$	None
delta	δ	Boundary-layer thickness	L
delta*	δ^*	Displacement thickness	L
dPe/ds	$d(P_e/\bar{\rho}_\infty U_\infty^2)/d\bar{s}$	Dimensionless pressure gradient	None
dTe/ds	$d(T_e/T_{ref})/d\bar{s}$	Dimensionless temperature grad.	None
dUe/ds	$d(U_e/U_\infty)/d\bar{s}$	Dimensionless velocity gradient	None
H	$H = \delta^*/\theta$	Shape factor	None
hdot	$\dot{h} = q_w/(T_w - T_{aw})$	Heat transfer coefficient	$QL^{-2}\Theta^{-1}$
Iedge	N	Total no. of mesh points in B.L.	None
Itro		Number of iterations	None
kmax	$\sqrt{\beta^*}(\bar{\rho}k)_{max}/\tau_w$	Maximum turbulence energy	None
M	m	Streamwise step number	None
Me	M_e	Edge Mach number	None
Mue	μ_e	Edge molecular viscosity	$ML^{-1}T^{-1}$
Ne	N_e	Mesh point number at B.L. edge	None
Negtiv		Number of points where $k, \omega, \epsilon < 0$	None
Nerror		Number of points not converged	None
Nskip		No. of points below u^+ = USTOP	None
Nste	$\dot{h}/\bar{\rho}_e U_e C_p$	Stanton number based on $\bar{\rho}_e$	None
Nstw	$\dot{h}/\bar{\rho}_w U_e C_p$	Stanton number based on $\bar{\rho}_w$	None
Nue	$Pr_L s\dot{h}/\mu_e C_p$	Nusselt number based on μ_e	None
Nuw	$Pr_L s\dot{h}/\mu_w C_p$	Nusselt number based on μ_w	None
Pe	P_e	Edge pressure	FL^{-2}
qw	q_w	Surface heat flux	QL^{-2}
radius	r_o	Body radius	L
Recov	r	Recovery factor	None
Redel*	$Re_{\delta^*} = \bar{\rho}_e U_e \delta^*/\mu_e$	Reynolds number based on δ^*	None
Res	$Re_s = \bar{\rho}_e U_e s/\mu_e$	Reynolds number based on s	None
Rethet	$Re_\theta = \bar{\rho}_e U_e \theta/\mu_e$	Reynolds number based on θ	None
Rhoe	$\bar{\rho}_e$	Edge density	ML^{-3}
rho*vw	$\bar{\rho}_w \tilde{v}_w$	Surface mass flux	$ML^{-2}T^{-1}$
s	s	Arc length	L
tauw	τ_w	Surface shear stress	FL^{-2}
Te	T_e	Edge temperature	Θ
theta	θ	Momentum thickness	L
Ue	U_e	Edge velocity	LT^{-1}
utau	u_τ	Friction velocity	LT^{-1}
xi	$\xi = \int_0^s \bar{\rho}_e U_e \mu_e r_o^{2j} ds$	Transformed streamwise coord.	L
yplus	y_2^+	Value of y^+ nearest the surface	None
z	z	Axial distance	L

D.8 Program PLOTEB: Plotting Utility

Program **PLOTEB** creates video and hardcopy plots of skin friction, c_f, or Stanton number, St, versus arc length, s, and a u^+ versus y^+ velocity profile computed with Program **EDDYBL** on IBM PC's and compatibles.

Input-parameter description:

Program **PLOTEB** reads the following sixteen input parameters from disk file **ploteb.dat** in the order listed below. Integer quantities must be formatted according to (7x,i6) while floating-point quantities must be formatted as (7x,f6.2).

mon Monitor type (see Appendix E)
ifore Foreground color (see Appendix E)
iback Background color (see Appendix E)
nprin Printer type (see Appendix E)
mode Graphics-mode flag for printers; number of pens for plotters (see Appendix E)
metric Input arc length units flag
- -1 Input arc length is in meters
- 0 Input arc length is in feet
- 1 Convert from feet to meters

ideccf Number of decimal places for c_f/St scale
idecx Number of decimal places for arc length scale
idecup Number of decimal places for u^+ scale
isymb Symbol type for experimental data points
- 0 Circle
- 1 Triangle
- 2 Square
- 3 Diamond

jstart Number of c_f/St points to skip over at beginning of computation; this is sometimes useful in order to skip over transient behavior at the beginning of a computation. The sign also determines what is plotted.
- > 0 Plot c_f versus s
- < 0 Plot St versus s

kcyccf Increment between points to be plotted for c_f/St versus s
kcycup Increment between points to be plotted for u^+ versus y^+
kfilt 0 to suppress data filtering; otherwise use filtering. The filtering algorithm generates a smoothed curve.
ksize Plot scaling factor. Using 100 yields a full-size hardcopy plot. Smaller values yield a hardcopy plot reduced by *ksize* per cent.

Thus, *ksize* = 50 yields a half-size plot.

symsiz Size of experimental data symbols, in inches

Next, Program **PLOTEB** reads a single, free-formatted, line to indicate where hardcopy print is directed. This line comes immediately after the specified value for *symsiz* and defines the following five additional parameters.

devid Device name of type character*4; valid devices are LPT1, LPT2, LPT3, COM1, COM2, COM3, COM4

nbaud Baud rate for a serial port; valid baud rates are 110, 150, 300, 600, 1200, 2400, 4800, 9600

parity Parity of type character*3 or character*4 for a serial port; valid parity settings are 'even', 'odd' and 'none'

nstop Number of stop bits for a serial port; either 1 or 2

lword Word length for a serial port; either 7 or 8

In addition to disk file **ploteb.dat**, an optional disk file named **exper.dat** containing measured skin-friction and velocity-profile data can be included. The first line of the disk file must contain the number of input data pairs with format (i6). If no c_f or St data are available, place a zero on this line. If c_f or St data are available, this line is followed by s-c_f (or s-St) data pairs with format (2e11.4). Next, enter the data source; as many as twenty characters can be used. The final c_f/St entry is the location of the box citing the data source. Enter a 1 for upper left, 2 for upper right, 3 for lower right, and 4 for lower left (see Figure D.2). The format is (7x,i6). A similar sequence of input parameters follows for velocity-profile data. The order of the data pairs is y^+ first and u^+ last. For example, the bench-mark case is an incompressible flat-plate boundary layer. Experimental data for this flow are given by Coles and Hirst (1969). The sample **exper.dat** included on the distribution diskette is as follows.

```
     5
 1.5978e 00 3.4500e-03
 2.0899e 00 3.3700e-03
 2.5820e 00 3.1700e-03
 3.0741e 00 3.1700e-03
 3.5663e 00 3.0800e-03
WIEGHARDT
iposcf=     2
    12
 4.2400e 01 1.4570e 01
 8.4800e 01 1.6090e 01
```

```
 1.6950e 02 1.7610e 01
 3.3910e 02 1.9080e 01
 5.0860e 02 2.0470e 01
 6.7822e 02 2.1660e 01
 8.4779e 02 2.2510e 01
 1.0173e 03 2.3540e 01
 1.2716e 03 2.4540e 01
 1.5259e 03 2.5290e 01
 1.6954e 03 2.5630e 01
 2.1193e 03 2.5780e 01
WEIGHARDT
iposup=     1
```

Program Output: A video plot with two graphs (see Figure D.2) is created on the screen. When the plot is complete, the following message appears:

Hardcopy output (y/n)?

Enter a *y* or a *Y* to create a hardcopy plot. Pressing any other key terminates the run without creating a hardcopy plot.

Comments:

- The following is a sample input-data file, **ploteb.dat**, for a machine with a standard VGA monitor and an HP DeskJet connected to serial port COM1:.

```
mon    =    18            (Standard VGA monitor)
ifore  =    15            (Bright-white foreground)
iback  =     1            (Blue background)
nprin  =     2            (HP DeskJet)
mode   =     3            (300 dots per inch resolution)
metric=      1            (Convert feet to meters)
ideccf=      1            (One decimal place on Cf scale)
idecs  =     1            (One decimal place on s scale)
idecup=     -1            (Integers on u+ scale)
isymb  =     0            (Circles for experimental data)
jstart=      1            (Skip no points)
kcyccf=      3            (Plot every third Cf point)
kcycup=      1            (Plot every u+ point)
kfilt  =     1            (Use filtering)
ksize  =   100            (Full size plot)
```

```
symsiz=  .080              (.08" experimental data symbols)
'com1' , 9600 , 'none' , 1 , 8
```

The last line indicates the printer is connected to serial port COM1: and the port is set at 9600 baud, no parity, 1 stop bit and 8 data bits.

If disk file **ploteb.dat** is not available, Program **PLOTEB** uses the following set of default values :

mon = 18, *ifore* = 15, *iback* = 1, *nprin* = 24, *mode* = 39, *ksize* = 100, *symsiz* = .08, *devid* = 'LPT1'

Note that *nbaud*, *parity*, *nstop* and *lword* are not used for parallel ports.

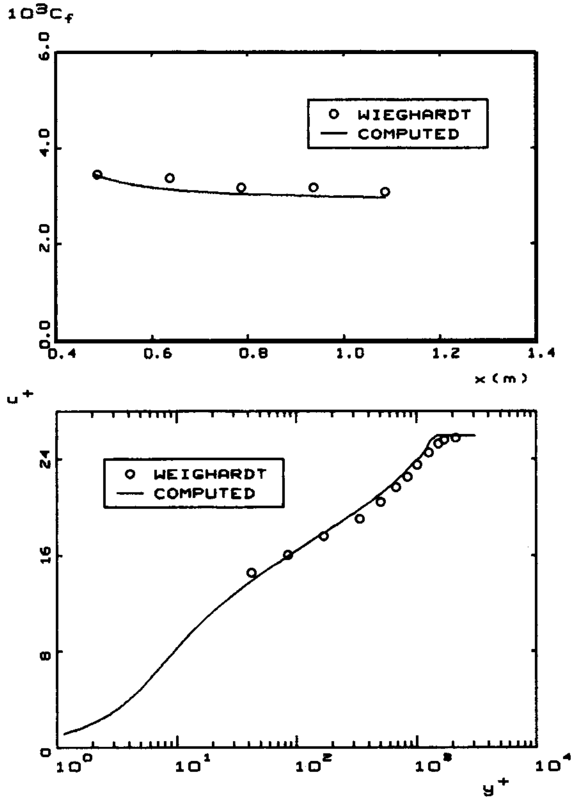

Figure D.2: Sample plot created by Program PLOTEB.

D.9 Adapting to Other Compilers/Systems

If you change computers or compilers, the appropriate modifications may already be included in the source code provided. If your Fortran compiler is an ANSI-77 Standard compiler and supports most of the standard VAX extensions, only three categories of changes are needed.

1. You must determine the correct syntax for the **include** command. Then, note that the source code provided uses the VAX syntax. Make the appropriate change throughout the source code for your compiler. Examples of VAX and other syntax are:

Fortran Compiler	Include Syntax
VAX, SVS, Lahey, Microsoft	`include 'filename'`
Cray (UNICOS), SUN	`include 'filename'`
Microsoft (older versions)	`$include: 'filename'`
SVS (older versions)	`$include filename`
Cray (COS)	`*CALL FILENAME`
	↑
	Column 1

2. Change the value of *icpu* defined in the include file named **cpuid**. The values currently assigned are:

$icpu = 0$	SVS Fortran (680x0, 80386, 80486)
$icpu = 1$	Lahey/Microsoft Fortran (8088, 80x86)
$icpu = 2$	VAX/VMS
$icpu = 3$	SUN Fortran (68020, SPARC)
$icpu = 4$	Cray (UNICOS)
$icpu = 5$	Silicon Graphics Iris

3. The only other compiler-specific syntax differences are located in a subroutine called **NAMSYS** that appears in **eddybl.for**. This subroutine opens disk files depending upon the value of *icpu*. Make any changes required for your system.

4. Search the **EDDYBL** and **SETEBL** source code for occurrences of *icpu* to see if the correct action is taken for your compiler and/or operating system. Make any changes required for your system.

5. Modify Program **INSTL** as required for your video display and/or compiler-specific requirements.

D.10 Compile and Link Commands

This section describes the commands required to compile and link Programs **SETEBL**, **INSTL** and **EDDYBL** for the various Fortran compilers supported. Be sure that you have selected the appropriate value for *icpu* in the include file **cpuid**.

ICPU = 0: SVS Fortran-386 ... Phar Lap and C^3

Special Comments: For the Phar Lap version, add the **+w1167** option to compile for a Weitek math coprocessor. Linker options for either **fastlink** or **386link** can be specified in an environment variable by including the following in your **autoexec.bat** file ...

```
80387 version
set 386link=-l libf28 libp28 -pack -maxr ffffh -s 40000
Weitek version
set 386link=-l libf28w libp28w -pack -maxr ffffh -s 40000
```

Compile and Link:

```
svs instl.for
svs eddybl.for
svs setebl.for edge.for grafic.for initil.for ioebl.for main0.for misc.for
```

ICPU = 0: SVS Fortran-020

Special Comments: Use **pload** in place of **load** for Definicon PM-020 and PM-030 boards.

Compile and Link:

```
load fc instl -lk
load fc eddybl -lk
load fc setebl edge grafic initil ioebl main0 misc -lk
```

ICPU = 1: Lahey Fortran ... LF90

Special Comments: None.

Compile and Link:

```
lf90 instl
lf90 eddybl
lf90 setebl edge grafic initil ioebl main0 misc
```

ICPU = 1: Lahey Fortran ... F77L-EM/32
Special Comments: None.

Compile and Link:

```
f77l3 instl
386link instl
f77l3 eddybl
386link eddybl
f77l3 setebl
f77l3 edge
f77l3 grafic
f77l3 initil
f77l3 ioebl
f77l3 main0
f77l3 misc
386link setebl edge grafic initil ioebl main0 misc
```

ICPU = 1: Lahey Fortran ... F77L
Special Comments: None.

Compile and Link:

```
f77l instl
optlink instl;
f77l eddybl
optlink eddybl;
f77l setebl
f77l edge
f77l grafic
f77l initil
f77l ioebl
f77l main0
f77l misc
optlink setebl+edge+grafic+initil+ioebl+main0+misc;
```

ICPU = 1: Microsoft Fortran
Special Comments: Using the /e option reduces executable file size.

Compile and Link:

```
fl instl.for
fl eddybl.for
fl /c setebl.for edge.for grafic.for initil.for ioebl.for main0.for misc.for
link setebl edge grafic initil ioebl main0 misc,,nul, /e;
```

ICPU = 2: VAX Fortran

Special Comments: None.

Compile and Link:

```
for instl
link instl
for eddybl
link eddybl
for setebl
for edge
for grafic
for initil
for ioebl
for main0
for misc
link setebl,edge,grafic,initil,ioebl,main0,misc
```

ICPU = 3: SUN Fortran ...SUN/OS or MS-DOS/SP-1

Special Comments: Using the **-O3** option yields the maximum degree of optimization.

Compile and Link:

```
f77 instl.f -O3 -o instl
f77 eddybl.f -O3 -o eddybl
f77 setebl.f edge.f grafic.f initil.f ioebl.f main0.f misc.f -O3 -o setebl
```

ICPU = 4: Cray Fortran ...UNICOS

Special Comments: None.

Compile and Link:

```
cf77 -o instl instl.f
cf77 -o eddybl eddybl.f
cf77 -o setebl setebl.f edge.f grafic.f initil.f ioebl.f main0.f misc.f
```

ICPU = 5: Silicon Graphics Iris

Special Comments: None.

Compile and Link:

```
f77 -o instl instl.f
f77 -o eddybl eddybl.f
f77 -o setebl setebl.f edge.f grafic.f initil.f ioebl.f main0.f misc.f
```

D.11 Additional Technical Information

The program uses the conventional Levy-Lees variables [see Hayes and Probstein (1959)] and much of the program notation follows that of Harris and Blanchard (1982). The numerical procedure is the Blottner (1974) variable grid method augmented with an algorithm devised by Wilcox (1981b) to permit large streamwise steps. Section 7.3 of the main text provides an in-depth discussion of the algorithm. This section first presents the governing equations for mean-flow properties and all turbulence-model equations implemented in the program. Then, the transformed, nondimensional form of the equations is presented for the k-ω and k-ϵ models.

D.11.1 Mean-Flow Equations

The equations governing conservation of mass, momentum and mean energy for all models are the same. For compressible two-dimensional ($j = 0$) and axisymmetric ($j = 1$) boundary layers, the program uses body-oriented coordinates (s, n), where s is arc length and n is distance normal to the surface. The equations are as follows.

$$\frac{\partial}{\partial s}(\bar{\rho}\tilde{u}) + \frac{1}{r^j}\frac{\partial}{\partial n}(r^j\bar{\rho}\tilde{v}) = 0 \tag{D.3}$$

$$\bar{\rho}\tilde{u}\frac{\partial \tilde{u}}{\partial s} + \bar{\rho}\tilde{v}\frac{\partial \tilde{u}}{\partial n} = -\frac{dP}{ds} + \frac{1}{r^j}\frac{\partial}{\partial n}\left[r^j\left(\mu\frac{\partial \tilde{u}}{\partial n} + \bar{\rho}\tau\right)\right] \tag{D.4}$$

$$\bar{\rho}\tilde{u}\frac{\partial \tilde{h}}{\partial s} + \bar{\rho}\tilde{v}\frac{\partial \tilde{h}}{\partial n} = \tilde{u}\frac{dP}{ds} + \mu\left(\frac{\partial \tilde{u}}{\partial n}\right)^2 + \bar{\rho}\epsilon + \frac{1}{r^j}\frac{\partial}{\partial n}\left[r^j\left(\frac{\mu}{Pr_L} + \frac{\mu_T}{Pr_T}\right)\frac{\partial \tilde{h}}{\partial n}\right] \tag{D.5}$$

The perfect gas law is used as the equation of state and the fluid is assumed calorically perfect so that

$$P = \bar{\rho}R\tilde{T} \quad \text{and} \quad \tilde{h} = C_p\tilde{T} \tag{D.6}$$

In Equations (D.3) through (D.6): $\tilde{u}$ and $\tilde{v}$ are streamwise and normal mass-averaged velocity components; $\bar{\rho}$, P and $\tilde{h}$ are fluid density, pressure and enthalpy; μ and μ_T are molecular and eddy viscosity; τ is specific Reynolds shear stress; ϵ is turbulence dissipation rate; Pr_L and Pr_T are laminar and turbulent Prandtl numbers; $\tilde{T}$ is mass-averaged temperature; R is the perfect gas constant; and C_p is specific heat at constant pressure.

D.11.2 k-ω and Multiscale Model Equations

For both the k-ω and multiscale models the dissipation, ϵ, is given by

$$\epsilon = \beta^* \omega k \tag{D.7}$$

where k is turbulence kinetic energy and ω is specific dissipation rate. The equations for k and ω applicable to compressible boundary layers are as follows.

$$\bar{\rho}\tilde{u}\frac{\partial k}{\partial s} + \bar{\rho}\tilde{v}\frac{\partial k}{\partial n} = \bar{\rho}\tau\frac{\partial \tilde{u}}{\partial n} - \beta^* \bar{\rho}\omega k + \frac{1}{r^j}\frac{\partial}{\partial n}\left[r^j\left(\mu + \sigma^* \mu_T\right)\frac{\partial k}{\partial n}\right] \tag{D.8}$$

$$\bar{\rho}\tilde{u}\frac{\partial \omega}{\partial s} + \bar{\rho}\tilde{v}\frac{\partial \omega}{\partial n} = \alpha\frac{\omega}{k}\bar{\rho}\tau\frac{\partial \tilde{u}}{\partial n} - \beta\bar{\rho}\omega\left[\omega + \hat{\xi}\frac{\partial \tilde{u}}{\partial n}\right] + \frac{1}{r^j}\frac{\partial}{\partial n}\left[r^j\left(\mu + \sigma \mu_T\right)\frac{\partial \omega}{\partial n}\right] \tag{D.9}$$

For the k-ω model, the Reynolds shear stress is given by

$$\bar{\rho}\tau = \alpha^* \mu_T \frac{\partial \tilde{u}}{\partial n} \tag{D.10}$$

For the multiscale model, the Reynolds stresses are computed from the following equations:

$$\bar{\rho}\tilde{u}\frac{\partial \tau}{\partial s} + \bar{\rho}\tilde{v}\frac{\partial \tau}{\partial n} = \left[(1-\hat{\alpha})\sigma_y - \hat{\beta}\sigma_x + \frac{2}{3}(1 - \hat{\alpha} - \hat{\beta} + \frac{3}{4}\hat{\gamma})k\right]\bar{\rho}\frac{\partial \tilde{u}}{\partial n} - C_1\beta^*\bar{\rho}\omega\tau \tag{D.11}$$

$$\bar{\rho}\tilde{u}\frac{\partial \sigma_x}{\partial s} + \bar{\rho}\tilde{v}\frac{\partial \sigma_x}{\partial n} = \frac{2}{3}\left[2(1-\hat{\alpha}) + \hat{\beta}\right]\bar{\rho}\tau\frac{\partial \tilde{u}}{\partial n} - C_1\beta^*\bar{\rho}\omega\sigma_x \tag{D.12}$$

$$\bar{\rho}\tilde{u}\frac{\partial \sigma_y}{\partial s} + \bar{\rho}\tilde{v}\frac{\partial \sigma_y}{\partial n} = -\frac{2}{3}\left[(1-\hat{\alpha}) + 2\hat{\beta}\right]\bar{\rho}\tau\frac{\partial \tilde{u}}{\partial n} - C_1\beta^*\bar{\rho}\omega\sigma_y \tag{D.13}$$

where C_1 is defined in terms of the ratio of large eddy energy $(k - e)$ to turbulence kinetic energy according to

$$C_1 = 1 + 4\left(\frac{k-e}{k}\right)^{3/2} \tag{D.14}$$

and $(k - e)$ satisfies the following equation.

$$\bar{\rho}\tilde{u}\frac{\partial}{\partial s}(k-e) + \bar{\rho}\tilde{v}\frac{\partial}{\partial n}(k-e) = \left(1 - \hat{\alpha} - \hat{\beta}\right)\bar{\rho}\tau\frac{\partial \tilde{u}}{\partial n} - \beta^*\bar{\rho}\omega k\left(\frac{k-e}{k}\right)^{3/2} \tag{D.15}$$

The quantities σ_x and σ_y are the stress deviator components given in terms of the normal Reynolds stress by

$$\sigma_x = \frac{\overline{\rho u'^2}}{\bar{\rho}} - \frac{2}{3}k \quad \text{and} \quad \sigma_y = \frac{\overline{\rho v'^2}}{\bar{\rho}} - \frac{2}{3}k \tag{D.16}$$

The various closure coefficients, viz., α, β, β^*, σ, σ^*, $\hat{\alpha}$, $\hat{\beta}$, $\hat{\gamma}$ and $\hat{\xi}$ are given by the following. First, we define the fully turbulent (subscript ∞), incompressible (subscript i) values by

$$\beta_i = 3/40, \quad \beta^*_\infty = 9/100, \quad \sigma = 1/2, \quad \sigma^* = 1/2 \tag{D.17}$$

$$\hat{\alpha} = 42/55, \quad \hat{\beta} = 6/55, \quad \hat{\gamma}_\infty = 1/4, \quad \hat{\xi} = 0 \text{ or } 1 \tag{D.18}$$

$$\alpha_\infty = \frac{\beta_i\left(1 + \hat{\xi}\sqrt{\beta^*_\infty}\right) - \sigma\sqrt{\beta^*_\infty}\kappa^2}{\beta^*_\infty}, \qquad \alpha^*_\infty = 1 \tag{D.19}$$

If low-Reynolds-number corrections are excluded, we simply use:

$$\alpha^* = \alpha^*_\infty, \qquad \alpha = \alpha_\infty, \qquad \beta^*_i = \beta^*_\infty, \qquad \hat{\gamma} = \hat{\gamma}_\infty \tag{D.20}$$

If low-Reynolds-number corrections are included, we use the following:

$$\left.\begin{aligned} \alpha^* &= \alpha^*_\infty \frac{\alpha^*_o + Re_T/R_k}{1 + Re_T/R_k} \\ \alpha &= \alpha_\infty \cdot \frac{\alpha_o + Re_T/R_\omega}{1 + Re_T/R_\omega} \cdot (\alpha^*)^{-m} \\ \beta^*_i &= \beta^*_\infty \cdot \frac{5/18 + (Re_T/R_\beta)^4}{1 + (Re_T/R_\beta)^4} \\ \hat{\gamma} &= \hat{\gamma}_\infty \cdot \frac{\hat{\gamma}_o + Re_T/R_k}{1 + Re_T/R_k} \end{aligned}\right\} \tag{D.21}$$

where $m = 1$ for the k-ω model, $m = 0$ for the multiscale model, and

$$\alpha^*_o = \beta/3, \quad \alpha_o = 1/10, \quad \hat{\gamma}_o = 2\beta^*_\infty\alpha^*_o/\hat{\gamma}_\infty, \quad R_\beta = 8, \quad R_k = 6 \tag{D.22}$$

$$R_\omega = \begin{cases} 27/10, & k\text{-}\omega \text{ model} \\ 3/4, & \text{Multiscale model} \end{cases} \tag{D.23}$$

The quantity Re_T is turbulence Reynolds number defined by

$$Re_T = \frac{k}{\omega\nu} \tag{D.24}$$

Finally, the compressible values of β and β^* are

$$\beta = \beta_i\left[1 - \frac{\beta^*_i}{\beta_i}\xi^* F(M_t)\right], \quad \beta^* = \beta^*_i\left[1 + \xi^* F(M_t)\right], \quad \xi^* = 3/2 \tag{D.25}$$

The compressibility function $F(M_t)$ is given by

$$F(M_t) = \begin{cases} 0, & M_t \leq M_{t_o} \\ M_t^2 - M_{t_o}^2, & M_t > M_{t_o} \end{cases} \tag{D.26}$$

where $M_t^2 \equiv 2k/a^2$, a is the speed of sound, and M_{t_o} is given by

$$M_{t_o} = 1/4 \tag{D.27}$$

D.11.3 k-ϵ Model Equations

For the k-ϵ model the equations for k and ϵ are:

$$\bar{\rho}\tilde{u}\frac{\partial k}{\partial s} + \bar{\rho}\tilde{v}\frac{\partial k}{\partial n} = \bar{\rho}\tau\frac{\partial \tilde{u}}{\partial n} - \bar{\rho}\epsilon + \frac{1}{r^j}\frac{\partial}{\partial n}\left[r^j\left(\mu + \mu_T/\sigma_k\right)\frac{\partial k}{\partial n}\right] \tag{D.28}$$

$$\bar{\rho}\tilde{u}\frac{\partial \tilde{\epsilon}}{\partial s} + \bar{\rho}\tilde{v}\frac{\partial \tilde{\epsilon}}{\partial n} = f_1 C_{\epsilon 1}\frac{\tilde{\epsilon}}{k}\bar{\rho}\tau\frac{\partial \tilde{u}}{\partial n} - f_2 C_{\epsilon 2}\bar{\rho}\frac{\tilde{\epsilon}^2}{k} + \bar{\rho}E + \frac{1}{r^j}\frac{\partial}{\partial n}\left[r^j\left(\mu + \mu_T/\sigma_\epsilon\right)\frac{\partial \tilde{\epsilon}}{\partial n}\right] \tag{D.29}$$

where

$$\epsilon = \tilde{\epsilon} + \epsilon_o \tag{D.30}$$

and the eddy viscosity is

$$\mu_T = C_\mu f_\mu \rho k^2/\tilde{\epsilon} \tag{D.31}$$

Program **EDDYBL** includes six low-Reynolds-number versions of the k-ϵ model. The models differ in the form of the damping functions f_μ, f_1, f_2, ϵ_o, E, in the values of the closure coefficients, and in the surface boundary condition imposed on $\tilde{\epsilon}$. The damping functions depend upon one or more of the following three dimensionless parameters.

$$Re_T = \frac{k^2}{\tilde{\epsilon}\nu}, \qquad R_y = \frac{k^{1/2}n}{\nu}, \qquad y^+ = \frac{u_\tau n}{\nu} \tag{D.32}$$

The damping functions, closure coefficients and surface boundary condition on $\tilde{\epsilon}$ for the six models are as follows.

Jones-Launder Model

$$\left.\begin{array}{l}
f_\mu = e^{-2.5/(1+Re_T/50)} \\
f_1 = 1 \\
f_2 = 1 - 0.3e^{-Re_T^2} \\
\epsilon_o = 2\nu \left(\dfrac{\partial\sqrt{k}}{\partial n}\right)^2 \\
E = 2\nu\nu_T \left(\dfrac{\partial^2 \tilde{u}}{\partial n^2}\right)^2 \\
C_{\epsilon 1} = 1.45, \quad C_{\epsilon 2} = 2.00, \quad C_\mu = 0.09, \quad \sigma_k = 1.0, \quad \sigma_\epsilon = 1.3 \\
\tilde{\epsilon} = 0 \quad \text{at} \quad n = 0
\end{array}\right\} \qquad (D.33)$$

Launder-Sharma Model

$$\left.\begin{array}{l}
f_\mu = e^{-3.4/(1+Re_T/50)^2} \\
f_1 = 1 \\
f_2 = 1 - 0.3e^{-Re_T^2} \\
\epsilon_o = 2\nu \left(\dfrac{\partial\sqrt{k}}{\partial n}\right)^2 \\
E = 2\nu\nu_T \left(\dfrac{\partial^2 \tilde{u}}{\partial n^2}\right)^2 \\
C_{\epsilon 1} = 1.44, \quad C_{\epsilon 2} = 1.92, \quad C_\mu = 0.09, \quad \sigma_k = 1.0, \quad \sigma_\epsilon = 1.3 \\
\tilde{\epsilon} = 0 \quad \text{at} \quad n = 0
\end{array}\right\} \qquad (D.34)$$

Lam-Bremhorst Model

$$\left.\begin{array}{l}
f_\mu = \left(1 - e^{-0.0165R_y}\right)^2 \, (1 + 20.5/Re_T) \\
f_1 = 1 + (0.05/f_\mu)^3 \\
f_2 = 1 - e^{-Re_T^2} \\
\epsilon_o = 0 \\
E = 0 \\
C_{\epsilon 1} = 1.44, \quad C_{\epsilon 2} = 1.92, \quad C_\mu = 0.09, \quad \sigma_k = 1.0, \quad \sigma_\epsilon = 1.3 \\
\tilde{\epsilon} = \nu \dfrac{\partial^2 k}{\partial n^2} \quad \text{at} \quad n = 0
\end{array}\right\} \qquad (D.35)$$

Chien Model

$$\left.\begin{array}{l}
f_\mu = 1 - e^{-0.0115y^+} \\
f_1 = 1 \\
f_2 = 1 - 0.22e^{-(Re_T/6)^2} \\
\epsilon_o = 2\nu \dfrac{k}{n^2} \\
E = -2\nu \dfrac{\tilde{\epsilon}}{n^2} e^{-y^+/2} \\
C_{\epsilon 1} = 1.35, \quad C_{\epsilon 2} = 1.80, \quad C_\mu = 0.09, \quad \sigma_k = 1.0, \quad \sigma_\epsilon = 1.3 \\
\tilde{\epsilon} = 0 \quad \text{at} \quad n = 0
\end{array}\right\} \quad \text{(D.36)}$$

Yang-Shih Model

$$\left.\begin{array}{l}
f_\mu = \dfrac{\left[1 - exp\left(-1.5\cdot 10^{-4}R_y - 5\cdot 10^{-7}R_y^3 - 10^{-10}R_y^5\right)\right]^{1/2}}{\left(1 + 1/\sqrt{Re_T}\right)} \\
f_1 = \sqrt{Re_T}/\left(1 + \sqrt{Re_T}\right) \\
f_2 = \sqrt{Re_T}/\left(1 + \sqrt{Re_T}\right) \\
\epsilon_o = 0 \\
E = \nu\nu_T \left(\dfrac{\partial^2 \tilde{u}}{\partial n^2}\right)^2 \\
C_{\epsilon 1} = 1.44, \quad C_{\epsilon 2} = 1.92, \quad C_\mu = 0.09, \quad \sigma_k = 1.0, \quad \sigma_\epsilon = 1.3 \\
\tilde{\epsilon} = 2\nu \left(\dfrac{\partial\sqrt{k}}{\partial n}\right)^2 \quad \text{at} \quad n = 0
\end{array}\right\} \quad \text{(D.37)}$$

Fan-Lakshminarayana-Barnett Model

$$\left.\begin{array}{l}
f_\mu = 0.4\dfrac{f_w}{\sqrt{Re_T}} + \left(1 - 0.4\dfrac{f_w}{\sqrt{Re_T}}\right)\left(1 - e^{-R_y/42.63}\right)^3 \\
f_1 = 1 \\
f_2 = \left[1 - 0.22e^{-(Re_T/6)^2}\right] f_w^2 \\
f_w = 1 - exp\left[-\dfrac{\sqrt{R_y}}{2.30} + \left(\dfrac{\sqrt{R_y}}{2.30} - \dfrac{R_y}{8.89}\right)\left(1 - e^{-R_y/20}\right)^3\right] \\
\epsilon_o = 0 \\
E = 0 \\
C_{\epsilon 1} = 1.39, \quad C_{\epsilon 2} = 1.80, \quad C_\mu = 0.09, \quad \sigma_k = 1.0, \quad \sigma_\epsilon = 1.3 \\
\dfrac{\partial\tilde{\epsilon}}{\partial n} = 0 \quad \text{at} \quad n = 0
\end{array}\right\} \quad \text{(D.38)}$$

D.11.4 Transformed Equations

The boundary-layer equations are singular at the leading edge of a body. As noted above, the program uses conventional Levy-Lees variables (ξ, η) to remove this singularity. Body oriented physical coordinates (s, n) are related to transformed coordinates (ξ, η) according to

$$d\xi = \bar{\rho}_e \tilde{u}_e \mu_e r_o^{2j}\, ds \quad \text{and} \quad d\eta = \frac{\bar{\rho}\tilde{u}_e (r_o + n)^j\, dn}{\sqrt{2\xi}} \tag{D.39}$$

where r_o is body radius and subscript e denotes boundary-layer edge. Equivalently, we can write

$$\xi(s) = \int_0^s \bar{\rho}_e \tilde{u}_e \mu_e r_o^{2j}\, ds \quad \text{and} \quad \eta(s,n) = \frac{\bar{\rho}_e \tilde{u}_e r_o^j}{\sqrt{2\xi}} \int_0^n \left(\frac{\bar{\rho}}{\bar{\rho}_e}\right) t^j\, dn \tag{D.40}$$

where t is the transverse curvature defined by

$$t = \frac{r}{r_o} \tag{D.41}$$

The relations between derivatives in the physical (s, n) and transformed (ξ, η) coordinate system are as follows:

$$\left(\frac{\partial}{\partial s}\right)_n = \bar{\rho}_e \tilde{u}_e \mu_e r_o^{2j} \left(\frac{\partial}{\partial \xi}\right)_\eta + \left(\frac{\partial \eta}{\partial s}\right)_n \left(\frac{\partial}{\partial \eta}\right)_\xi \tag{D.42}$$

$$\left(\frac{\partial}{\partial n}\right)_s = \frac{\bar{\rho}_e \tilde{u}_e r_o^j t^j}{\sqrt{2\xi}} \left(\frac{\bar{\rho}}{\bar{\rho}_e}\right) \left(\frac{\partial}{\partial \eta}\right)_\xi \tag{D.43}$$

The dependent variables are also transformed according to:

$$\left.\begin{aligned}
&F(\xi,\eta) = \frac{\tilde{u}}{\tilde{u}_e}, \qquad \Theta(\xi,\eta) = \frac{\tilde{T} - \tilde{T}_e}{\tilde{T}_e} \\
&V(\xi,\eta) = \frac{2\xi}{\bar{\rho}_e \tilde{u}_e \mu_e r_o^{2j}} \left[F\left(\frac{\partial \eta}{\partial s}\right) + \frac{\bar{\rho}\tilde{v} r_o^j t^j}{\sqrt{2\xi}} \right] \\
&K(\xi,\eta) = \frac{k}{\tilde{u}_e^2} \qquad \hat{W}(\xi,\eta) = \frac{2\xi\omega}{\tilde{u}_e^2}, \qquad \hat{\mathcal{E}}(\xi,\eta) = \frac{2\xi\tilde{\epsilon}}{\tilde{u}_e^4}
\end{aligned}\right\} \tag{D.44}$$

The transformed equations for the k-ω and k-ϵ models can then be expressed as follows.

$$2\xi\frac{\partial F}{\partial \xi} + \frac{\partial V}{\partial \eta} + F = 0 \tag{D.45}$$

$$2\bar{\xi}F\frac{\partial F}{\partial \bar{\xi}} + V\frac{\partial F}{\partial \eta} - \frac{\partial}{\partial \eta}\left[t^{2j}L\left(1+\bar{\mu}_T\right)\frac{\partial F}{\partial \eta}\right] + \bar{\beta}\left(F^2 - \Theta - 1\right) = 0 \quad \text{(D.46)}$$

$$\begin{aligned} 2\bar{\xi}F\frac{\partial \Theta}{\partial \bar{\xi}} + V\frac{\partial \Theta}{\partial \eta} - \frac{\partial}{\partial \eta}\left[t^{2j}L\left(\frac{1}{Pr_L} + \frac{\bar{\mu}_T}{Pr_T}\right)\frac{\partial \Theta}{\partial \eta}\right] & \\ -\bar{\alpha}t^{2j}L\left(\frac{\partial F}{\partial \eta}\right)^2 - \frac{\bar{\alpha}}{\hat{\rho}_e\hat{\mu}_e\hat{r}_o^{2j}}\left(\mathcal{E} + \mathcal{E}_o\right) = 0 & \quad \text{(D.47)} \end{aligned}$$

k-ω Model:

$$\begin{aligned} 2\bar{\xi}F\frac{\partial K}{\partial \bar{\xi}} + V\frac{\partial K}{\partial \eta} - \frac{\partial}{\partial \eta}\left[t^{2j}L\left(1+\sigma^*\bar{\mu}_T\right)\frac{\partial K}{\partial \eta}\right] & \\ +2\bar{\beta}FK - t^{2j}L\bar{\mu}_T\left(\frac{\partial F}{\partial \eta}\right)^2 + \frac{\beta^*}{\hat{\rho}_e\hat{\mu}_e\hat{r}_o^{2j}}WK = 0 & \quad \text{(D.48)} \end{aligned}$$

$$\begin{aligned} 2\bar{\xi}F\frac{\partial W}{\partial \bar{\xi}} + V\frac{\partial W}{\partial \eta} - \frac{\partial}{\partial \eta}\left[t^{2j}L\left(1+\sigma\bar{\mu}_T\right)\frac{\partial W}{\partial \eta}\right] & \\ +2(\bar{\beta}-1)FW - \alpha\frac{W}{K}t^{2j}L\bar{\mu}_T\left(\frac{\partial F}{\partial \eta}\right)^2 & \\ +\frac{\beta}{\hat{\rho}_e\hat{\mu}_e\hat{r}_o^{2j}}\left[W + \hat{\xi}\,\frac{\hat{\rho}_e\hat{r}_o^j\sqrt{2\bar{\xi}}}{\hat{\epsilon}}\frac{t^j}{(1+\Theta)}\frac{\partial F}{\partial \eta}\right]W = 0 & \quad \text{(D.49)} \end{aligned}$$

$$\bar{\mu}_T = \frac{2\bar{\xi}\hat{\rho}_e}{\hat{\mu}_e\hat{\epsilon}^2}\frac{K}{L(1+\Theta)^2W}, \qquad \mathcal{E} = \beta^*KW, \qquad \mathcal{E}_o = 0, \quad \text{(D.50)}$$

k-ϵ Model:

$$\begin{aligned} 2\bar{\xi}F\frac{\partial K}{\partial \bar{\xi}} + V\frac{\partial K}{\partial \eta} - \frac{\partial}{\partial \eta}\left[t^{2j}L\left(1+\frac{\bar{\mu}_T}{\sigma_k}\right)\frac{\partial K}{\partial \eta}\right] & \\ +2\bar{\beta}FK - t^{2j}L\bar{\mu}_T\left(\frac{\partial F}{\partial \eta}\right)^2 + \frac{1}{\hat{\rho}_e\hat{\mu}_e\hat{r}_o^{2j}}\left(\mathcal{E} + \mathcal{E}_o\right) = 0 & \quad \text{(D.51)} \end{aligned}$$

$$
\begin{aligned}
2\bar{\xi}F\frac{\partial\mathcal{E}}{\partial\bar{\xi}} + V\frac{\partial\mathcal{E}}{\partial\eta} - \frac{\partial}{\partial\eta}\left[t^{2j}L\left(1+\frac{\bar{\mu}_T}{\sigma_\epsilon}\right)\frac{\partial\mathcal{E}}{\partial\eta}\right] \\
+2(2\bar{\beta}-1)F\mathcal{E} - C_{\epsilon 1}f_1\frac{\mathcal{E}}{K}t^{2j}L\bar{\mu}_T\left(\frac{\partial F}{\partial\eta}\right)^2 \\
+\frac{C_{\epsilon 2}f_2}{\hat{\rho}_e\hat{\mu}_e\hat{r}_o^{2j}}\frac{\mathcal{E}^2}{K} - \Sigma = 0
\end{aligned}
\tag{D.52}
$$

$$
\bar{\mu}_T = C_\mu f_\mu \frac{2\bar{\xi}\hat{\rho}_e}{\hat{\mu}_e\hat{\epsilon}^2}\frac{K^2}{L(1+\Theta)^2\mathcal{E}}, \qquad \mathcal{E}_o = \frac{A}{U_\infty^3}\frac{2\bar{\xi}}{\hat{u}_e^4}\epsilon_o, \qquad \Sigma = \frac{A^2}{U_\infty^4}\frac{(2\bar{\xi})^2}{\hat{\rho}_e\hat{u}_e^6\hat{\mu}_e\hat{r}_o^{2j}}E \tag{D.53}
$$

The quantities $\bar{\alpha}$, $\bar{\beta}$ and L are defined by

$$
\bar{\alpha} \equiv \frac{\tilde{u}_e^2}{C_p\tilde{T}_e}, \qquad \bar{\beta} \equiv \frac{2\xi}{\tilde{u}_e}\frac{d\tilde{u}_e}{d\xi}, \qquad L \equiv \frac{\bar{\rho}}{\bar{\rho}_e}\frac{\mu}{\mu_e} \tag{D.54}
$$

and the following dimensionless quantities have been introduced:

$$
\left.
\begin{array}{lll}
\bar{\xi} = \dfrac{\xi}{\rho_\infty U_\infty \mu_r A^{2j+1}}, & \hat{r}_o = \dfrac{r_o}{A}, & \hat{u}_e = \dfrac{\tilde{u}_e}{U_\infty} \\[2ex]
\hat{\rho}_e = \dfrac{\bar{\rho}_e}{\rho_\infty}, & \hat{T}_e = \dfrac{\tilde{T}_e}{T_r}, & \hat{\mu}_e = \dfrac{\mu_e}{\mu_r} \\[2ex]
\hat{\epsilon} = \sqrt{\dfrac{\mu_r}{\rho_\infty U_\infty A}}, & W = \dfrac{\hat{W}}{\rho_\infty \mu_r A^{2j}}, & \mathcal{E} = \dfrac{\hat{\mathcal{E}}}{\rho_\infty \mu_r A^{2j}}
\end{array}
\right\}
\tag{D.55}
$$

Finally, note that subscript ∞ denotes freestream flow condition, A is a reference length, T_r is the reference temperature defined as

$$
T_r = U_\infty^2 / C_p \tag{D.56}
$$

and μ_r is the value of μ for $T = T_r$.

D.12 Software Package Modules

Boundary-Layer Program Source:

eddybl.for	Source code for Program **EDDYBL**
common	Include file for Program **EDDYBL**
cpuid	Include file specifying CPU type

Data-Preparation Utility Source:

setebl.for	Source code for the main program
edge.for	Source code for edge condition menus
grafic.for	Source code for reading graphics data
initil.for	Source code for initial profile menus
ioebl.for	Source code for I/O subroutines
main0.for	Source code for main input parameter menus
misc.for	Source code for miscellaneous menus
chars	Include file for Program **SETEBL**
comeb1	Include file for Program **SETEBL**
comeb2	Include file for Program **SETEBL**

Installation Program Source:

instl.for	Source code for Program **INSTL**

Bench-Mark Case Input Data:

blocrv.dat	Mass-transfer, body-curvature data file
heater.dat	Heat-transfer, surface-temperature data file
presur.dat	Pressure-distribution data file

Plotting Files:

exper.dat	Experimental data file for plotting program
ploteb.dat	Primary plotting-program data file

Bench-Mark Case Output:

eddybl.prt	Output from bench-mark test case

Executable Files for IBM PC and Compatible Microcomputers:

eddybl.exe	Program **EDDYBL**
instl.exe	Program **INSTL**
ploteb.exe	Program **PLOTEB**
setebl.exe	Program **SETEBL**