

MECH 510

Programming Assignment 3

Prepared for:

Prof. Carl Ollivier-Gooch

CEME 2050, UBC

Prepared by:

Nicholas Earle

UBC # 21943600

Date:

November 23rd, 2018

# Introduction

The objective of this assignment was to write a program to solve the incompressible, laminar energy equation in two dimensions given a velocity field. This was to be done using a second order centred space discretization for both the convective and diffusive terms. It was then solved using each of an explicit and implicit time advance scheme. The explicit scheme was chosen to be the two stage Runge Kutta (RK2) scheme simply because it is also a second order scheme, so it would produce the same order of accuracy without any extra programming. As for the implicit scheme, the implicit Euler method was used. This was done using approximate factorization of the matrices to obtain a series of tri-diagonal matrices which were then solved using the Thomas algorithm as given. All of these schemes were combined to solve the overall problem of determining the thermal development of a flow in a channel.

The assignment was broken down into seven parts to make the task more manageable and provide numerous checks along the way. Below the results for each of these parts are described in the following order. Parts 1 and 2, which are concerned with the validation and confirmation of the flux and source terms. Parts 3 and 4 are programming the explicit and implicit time advances, which are combined with parts 5 and 6, which test the stability, accuracy, and efficiency of both schemes. And, finally, part 7 is the real problem of determining the thermal development of the flow in a channel given certain initial conditions and boundary conditions.

# Formulation

First, we much define the incompressible, laminar energy equation in two dimensions:

Where, is the temperature, and are the velocity fields in the and directions, respectively, is the Reynolds number, is the Prandtl number, and is the source term as defined by:

Where, is the Eckert number. Now in order to discretize this function we can integrate of a control volume and apply the Gauss divergence theorem and approximate the derivatives using a second order centred scheme as follows:

Applying these to equation 1, above, we arrive at the semi-discrete form of the energy equation using second order centred differences.

Where the discretized source term is:

From now on the combination of each of the equations above will simply be referred by as the flux integral at cell *i, j.* We can now look at each of the time advances. Starting with RK2, it is defined as:

Where is the value of the cell at the next time step, is the current value, is the timestep, and can be thought of as the evaluation of the flux integral using the values from step . The implicit Euler time advance, while even simpler in its formulation:

Is much more involved to solve, because we are evaluating the flux integral at a time step at which we do not yet know the data. If we instead use the - form of T, defined as we can write the full discretization as:

Where the right hand side is the flux integral evaluated at the current time step as seen above in equation 4. This however, can be represented in a much more compact form:

Where and are the space discretization of x and y, respectively, in matrix form andis the identity matrix. These matrices must be adjusted accordingly to accommodate any proposed boundary conditions. Now applying approximate factorization to the left hand side we get:

Which can be shown to be second order accurate, which does not hurt the implicit Euler scheme since it is only first order accurate in time. Subbing this back into equation 9, we get:

Where is we define we can split the problem into a system of equations:

Where each of these equations must be solved for every row and every column to obtain the full time step. And finally, once we have solved for we can simply add that to the current time step for the next one:

Following this as with the explicit scheme, the boundary conditions must be reset. Without going into detail each of the tri-diagonal matrices can be solved using Gauss elimination as performed by the Thomas matrix algorithm.

# Results and Discussion

For the problem of defining the thermal development of flow in a channel, a rectangular channel was used with a height to width ratio of 5/1. The velocity fields we given as:

Where . The inflow is to be set to a fixed temperature, while the upper wall was set to , and the bottom wall with the outflow condition set to have no flux across the boundary. The flow conditions we such that and

## Parts 1 and 2

Parts 1 and 2 concerned themselves with ensuring that the flux integral and source term were indeed programmed correctly as to produce expected results. This was tested by setting the temperature and velocity field to values such that the solution to each were known. That is the domain was set using:

Where is programmed correctly would produce results resembling the exact flux:

And the exact source term:

The results below show the flux integral and source term using these conditions set on a square domain of [0,1] x [0,1]. Figure 1, below, shows images of the error for both the flux and source terms for an 80 x 80 mesh on the domain.

|  |  |
| --- | --- |
|  |  |

Figure 1: Flux and Source term error

As you can see in each of these images the error is quite small for each term as can be seen more clearly with the L2 norm of each summarized in Table 1, below.

Table 1: L2 Norm of Flux and Source terms

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Mesh Size | Flux Integral | | Source Term | |
|  | Ratio |  | Ratio |
| 10 x 10 | 8.7732e-02 | -- | 5.7723e-04 | -- |
| 20 x 20 | 2.2301e-02 | 3.9340 | 1.4614e-04 | 3.9499 |
| 40 x 40 | 5.5984e-03 | 3.9834 | 3.6649e-05 | 3.9874 |
| 80 x 80 | 1.4011e-03 | 3.9958 | 9.1696e-06 | 3.9969 |

Looking at the error norms in the table above it is very clear that the space discretization scheme used is, for all intents and purposes, second order accurate. That is that as we double the mesh size, the error decreases by a factor of four, or in our case very nearly four.

## Parts 3 – 5

Parts 3 to 5 of the assignment focus on programming an explicit and implicit time advance scheme and subsequently testing them for stability and accuracy. As mentioned above the explicit scheme used was RK2, simply because it is one of the simplest second order schemes, which pairs nicely with the second order space discretization. The implicit scheme as mentioned above is the implicit Euler scheme.

Using the aforementioned velocity fields, on a domain of [0, 5] x [0, 1] using a 25 x 10 mesh, each scheme was given the initial temperature distribution of , to check whether it indeed converged on the correct solution as given by the inflow boundary condition:

### Explicit Time Advance

Looking at the explicit scheme first, finding the maximum stable time step is the first step in running the program. To do this a stability analysis was performed using the second order centred scheme applied to the energy equation for both the x and y discretizations, using the given parameters, to find the eigenvalues. Now the eigenvalues do depend on the velocity, and with not being constant, the average value of was used, that being said it is difficult to find an exact solution, this will provide us with a good guess to find the actual maximum timestep simply by trial and error. The eigenvalues being:

And likewise for . Plotting these eigenvalues against the stability boundary for RK2, we get the following plots for and .

|  |  |
| --- | --- |
|  |  |

Figure 2: Stability Boundaries for RK2 and 2nd Centred Schemes

Looking at the plots, while it may be difficult to see, the maximum stable time step in is about , while in is So discarding the timestep for y stability we get a good starting point for total stability of about . By trial and error, the actual maximum stable timestep, to three decimal points, was found to be . However, for running the program, it was found that a timestep of about (was the most efficient. The following table shows the results of the explicit scheme for finer and finer meshes. Now, instead of running each iteration for a set number of timesteps where it is unknown whether the solution has converged completely, each will run until the maximum change of any one cell is less than , at which point the loop is broken.

Table 2:Max Time step and Error for Explicit Scheme

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Mesh Size |  |  |  | Ratio |
| 25 x 10 | ~0.053 | 0.04 | 1.1215e-02 | -- |
| 50 x 20 | ~0.030 | 0.02 | 2.8815e-03 | 3.8921 |
| 100 x 40 | ~0.009 | 0.008 | 7.2508e-04 | 3.9740 |
| 200 x 80 | ~0.0022 | 0.0021 | 1.1815e-04 | 6.1369 |

Onto the accuracy of the scheme, as shown by the results above, as the mesh becomes twice as fine, the error decreases by a factor of about four, except for the final case where it decreases by a factor of six, unexpectedly. But from the results of the previous iterations we can say that the scheme is about second order accurate.

### Implicit Time Advance

For the implicit Euler scheme, unlike explicit schemes, theoretically doesn’t have a maximum stable timestep. Instead however, there is a point at which the solution converges much faster but with a greater error, as shown in the next section. As for the accuracy of the implicit scheme, it looks eerily similar to that of the explicit scheme:

Table 3: Timestep and error for Implicit Scheme

| Mesh Size |  |  | Ratio |
| --- | --- | --- | --- |
| 25 x 10 | 0.2 | 1.1214e-02 | -- |
| 50 x 20 | 0.15 | 2.8815e-03 | 3.8921 |
| 100 x 40 | 0.1 | 7.2508e-04 | 3.9740 |
| 200 x 80 | 0.05 | 1.1815e-04 | 6.1369 |

So, if we conclude that the explicit scheme is second order accurate, it would be very hard to argue anything for the contrary for the implicit scheme. The implicit scheme does have efficiency on its side compared to the explicit scheme as explained in the next section.

## Part 6

Part 6 looks at the efficiency of each scheme, and the effect of differing time step has on each. It should be noted that these results were obtained on Ubuntu 18.04 with the GCC GNU compiler, on a machine running an 8 core Intel Core i7-4790 CPU @ 3.6 GHz, with 15.5 GB of memory. Table 4, below, shows the time taken and number of iterations completed before reaching a tolerance of The timestep used for the explicit scheme was about %80 of the maximum stable time step as described above, which tended to give the best results, while for the implicit scheme, the timestep used was the timestep that was found to give the best results. This is opposed to what was specified in the assignment as it says to use the maximum timestep the code will allow, however I found that with an ever increasing timestep, it just took much longer to reach the same conclusion as displayed later on.

Table 4: Efficiency of Explicit and Implicit schemes

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Mesh size | Explicit Scheme | | | Implicit Scheme | | |
|  |  | Iterations |  |  | Iterations |
| 25 x 10 | 0.04 | 0.03056 | 245 | 0.2 | 0.01417 | 43 |
| 50 x 20 | 0.02 | 0.06019 | 173 | 0.16 | 0.01879 | 39 |
| 100 x 40 | 0.008 | 0.42764 | 394 | 0.09 | 0.02430 | 51 |
| 200 x 80 | 0.0021 | 6.11973 | 1415 | 0.05 | 0.4411 | 92 |
| 400 x 160 | 00005 | 94.7845 | 5546 | 0.03 | 3.0052 | 162 |

Looking at these results it is clear that, for optimal timesteps, the implicit scheme is much faster than the explicit scheme requiring only a fraction of the iterations to obtain the same accuracy. However, as with the explicit scheme, the implicit scheme doesn’t perform as well for timesteps that are much too small or much too large. Table 5, below, shows snippet of an experiment showing the error, time, and iterations for the 25 x 10 mesh running with timesteps varying from to , the full results can be seen in the Appendix. Looking at these results there is no clear “maximum time step” (unless it is greater than , which I didn’t test) but there is a point at which the program converges on a different solution, with much greater error. That is at a timestep of about , where the L2 norm goes from 0.01121 to 0.07287, which relatively is a huge jump. Furthermore, when doing the same experiment for the 50 x 20 mesh, we see the same behaviour, as shown in the Appendix. For this case however, the “maximum” timestep is much smaller and the L2 norm changes from 0.00288, which is of course second order accurate with the 25 x 10 mesh, to 0.03142, which is only about half of that of the previous case, leading to the hypothesis that the scheme becomes first order accurate.

Table 5: Implicit SCheme for differing Timestep

|  |  |  |  |
| --- | --- | --- | --- |
| Mesh Size: 25 x 10 | | | |
|  |  | time (s) | Iterations |
| 0.0000001 | 0.01121 | 370.686 | 3818889 |
| 0.000001 | 261.891 | 2707750 |
| 0.001 | 0.45362 | 4598 |
| 0.01 | 0.057257 | 488 |
| 0.1 | 0.018143 | 68 |
| 0.2 | 0.014165 | 43 |
| 0.4 | 0.014496 | 47 |
| 0.8 | 0.018322 | 79 |
| 1 | 0.014437 | 96 |
| 10 | 0.087152 | 788 |
| 1000 | 2.63056 | 27579 |
| 10000 | 20.1965 | 210781 |
| 25000 | 47.8102 | 501020 |
| 27457 | 52.7434 | 550259 |
| 27458 | 52.8759 | 550279 |
| 27459 | 0.07287 | 0.461225 | 4680 |
| 27460 | 0.457621 | 4680 |
| 50000 | 0.837793 | 8521 |
| 100000 | 1.64398 | 17041 |
| 1000000 | 16.5132 | 170263 |
| 10000000 | 162.003 | 1688566 |

## Part 7

Part 7 gets to the real problem of the assignment that is determining the fully-developed value of the temperature gradient at the bottom wall and the thermal development length. This was done using an inflow boundary condition of . When plotting the gradient at the bottom wall against x, the fully-developed value was taken to be the value to which the solution converges at steady state, that is once it has stopped changing. This is of course when the gradient of the gradient reaches zero and the point at which this happens is then the development length. For this experiment the value of the gradient of the gradient was considered zero once it was less than because the outputted values only carried four digits of significance, and values afterwards were less reliable, oscillating before finding zero. So the steady state point was approximated by the first instance where this is true. Figure 3, below, shows the solution for a mesh size of with the channel on the domain .



Figure 3: Solution on [0, 200] x [0,1]

Looking at the image it looks as though it reaches a steady state near or after cell in the direction. To see more accurately where we do in fact reach the steady state solution Figure 4, below, shows the gradient along the bottom wall and the gradient of that gradient.

|  |  |
| --- | --- |
|  |  |

Figure 4: Temperature Gradients

Looking at these plots we can see more accurately that the solution reaches a steady state at , to three decimal places. So, we can now conclude that the fully-developed value for the temperature gradient given the initial conditions mentioned above is . And staying consistent with the stopping criteria above, the thermal development length is about channel widths.

We will now try to define both the gradient value and development length more generally for the initial condition above. First, we will look at the effects of changing the width of the channel. For this experiment a constant 500 cells per grid point was used to keep the resolution of each solution consistent. That is with cells were used, and from there scaled accordingly. As we will see, because the gradient is decreases as the channel gets wider the stopping criteria must also adjust, so for each width the stopping criteria will also be divided by the new ratio. Table 6 below, summarizes the results of the experiment while all of the plots of the gradient can be found in the Appendix.

Table 6: Development Length and Gradient along bottom wall

|  |  |  |
| --- | --- | --- |
| Width | Dev. Length | Gradient |
| 0.25 | ~7 | 19.08 |
| 0.5 | ~24 | 9.541 |
| 1 | ~75 | 4.771 |
| 2 | ~200 | 2.385 |
| 4 | ~550 | 1.188 |
| 8 | ~1080 | 0.9365 |

From this we can hypothesize that the development length very loosely increases by a factor of about 2.5 when doubling the width. Now this does not align with the theoretical data that suggests it simply doubles as the width doubles. To that end, I do believe that the numerical solution may be a lot closer than 3/2 simply because it is difficult to accurately determine where the flow becomes fully developed, especially with poor resolution.

As for the gradient, I believe we can conclude that as the channel becomes wider or narrower the gradient changes linearly with that factor. To further explore how these parameters change, the Reynolds number and Prandtl number were differed as above.

Table 7: Development Length and gradient along Bottom Wall

|  |  |  |
| --- | --- | --- |
|  | Dev. Length | Gradient |
| 35 | ~100 | 4.771 |
| 70 | ~200 | 4.771 |
| 140 | ~400 | 4.771 |

These results were much easier to interpret as it is clear that by doubling the Reynolds number or Prandtl number the development length also doubles and has no effect on the gradient. It was also found that by doubling the temperature everywhere, by doubling the upper wall boundary condition and the Eckert number, this had no effect on the development length but simply doubled the value of the gradient at the bottom wall. From all of the summarized results we can conclude that the gradient along the bottom wall and development length for the initial conditions given looks of the order:

# Appendix

Table 8: Efficiency Results

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Mesh |  |  | time (s) | Iterations |
| 25 x10 | 0.0000001 | 0.01121 | 370.686 | 3818889 |
| 0.000001 | 261.891 | 2707750 |
| 0.00001 | 31.9382 | 332201 |
| 0.0001 | 4.21625 | 43578 |
| 0.001 | 0.45362 | 4598 |
| 0.01 | 0.057257 | 488 |
| 0.1 | 0.018143 | 68 |
| 0.2 | 0.014165 | 43 |
| 0.4 | 0.014496 | 47 |
| 0.8 | 0.018322 | 79 |
| 1 | 0.014437 | 96 |
| 10 | 0.087152 | 788 |
| 1000 | 2.63056 | 27579 |
| 10000 | 20.1965 | 210781 |
| 20000 | 38.1666 | 400817 |
| 25000 | 47.8102 | 501020 |
| 26250 | 50.9847 | 526070 |
| 26875 | 51.7797 | 538596 |
| 27200 | 52.2057 | 545109 |
| 27350 | 53.1083 | 548115 |
| 27425 | 53.3168 | 549618 |
| 27440 | 52.6586 | 549919 |
| 27450 | 52.7947 | 550119 |
| 27455 | 52.8345 | 550219 |
| 27457 | 52.7434 | 550259 |
| 27458 | 52.8759 | 550279 |
| 27459 | 0.07287 | 0.461225 | 4680 |
| 27460 | 0.457621 | 4680 |
| 27500 | 0.453407 | 4687 |
| 30000 | 0.504438 | 5113 |
| 50000 | 0.837793 | 8521 |
| 100000 | 1.64398 | 17041 |
| 1000000 | 16.5132 | 170263 |
| 10000000 | 162.003 | 1688566 |
|  | | | | |
| 50 x 20 | 0.1 | 0.00288149 | 0.024301 | 51 |
| 0.15 | 0.019776 | 41 |
| 0.16 | 0.018789 | 39 |
| 0.2 | 0.029272 | 56 |
| 0.4 | 0.042014 | 104 |
| 0.8 | 0.07105 | 193 |
| 1 | 0.083972 | 232 |
| 1000 | 9.53208 | 29484 |
| 10000 | 0.0314212 | 1.20986 | 3661 |
| 100000 | 11.9689 | 36568 |
| 1000000 | 119.528 | 363178 |
|  | | | | |
| 100 x 40 | 0.09 | 0.00072508 | 0.069731 | 51 |
| 0.1 | 0.069492 | 53 |
| 0.2 | 0.08574 | 67 |
| 0.4 | 0.200536 | 162 |
| 1 | 0.473619 | 400 |
| 100 | 9.53842 | 8142 |
| 1000 | 92.6391 | 79328 |
| 5000 | 357.24 | 309990 |
|  | | | | |
| 200 x 80 | 0.03 | 0.00018155 | 0.583916 | 123 |
| 0.04 | 0.438977 | 92 |
| 0.05 | 0.441127 | 92 |
| 0.1 | 0.552037 | 117 |
| 0.2 | 0.923047 | 198 |
| 0.4 | 1.66082 | 356 |
| 1 | 3.69493 | 789 |
| 10 | 26.3183 | 5754 |
|  | | | | |
| 400 x 160 | 0.03 |  | 3.00516 | 162 |



Figure 5: Gradient Solutions for various channel Widths

|  |  |
| --- | --- |
|  |  |

Figure 6: Gradient Solution for Various RE PR