Assignment 2

Backstep Channel – Analysis of heat transfer and flow parameters

Heat and Mass Transfer – ME306

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1. Project Objectives

The key objective of the project is to observe fully turbulent flow in a backstep channel in order to inspect the variations in non-dimensional flow and heat transfer parameters. Using the information on temperature and velocity fields of the channel, we will calculate local and average heat transfer coefficient, Nusselt number, as well as the friction coefficient. We know that no-slip condition is an important factor in channel flows, and it has a great impact on the near wall region of the channel. That is why, all of the parameters will be observed in this critical area, where changes in velocity and boundary layer play crucial role in developing flow fields.

Since this is flow inside the channel with heat flux on the bottom wall, we can expect interesting findings, especially since this is turbulent flow where chaotic motion and turbulent eddies enhance these effects.

In this paper, we will go through key steps and methodology required for heat trasnefr and flow analysis. All the resulting graphs will be discussed and elaborated, and the explanation of their physical meaning will be provided for clarity. Finally, we will end this paper by reflecting on the key findings and how they matter in everyday world of flow simualtion analysis.

The program used for this project is Paraview, which is a post-processing software that allows extraction and calculation of main flow parameters. Additional key plots will be generated using XMGrace plotting tool.

2. Introduction

Internal convection and the efficiency of heat transfer depends mainly on heat transfer coefficient which is often not easy to obtain. In practice, experimental studies and observations have showed that it depends on not only the flow regime, but also the type of the fluid and its physical properties, as well as geometry of the channel and its surface roughness. In the backstep channel with flow separation due to sharp expansion, along with the no-slip condition, we will see how the critical parameters change along the bottom wall of the channel. Therefore, the flow over the bottom wall will be identical to flow over flat plate with imposed heat flux on it.

Development of the fluid flow through changes in velocity and thermal boundary layers is imperative to determine how efficient the heat transfer really is, and also how viscosity affects the friction coefficient of the flow.

Heat transfer ceofficient will be determined using the following relation:

$$h = \frac{q}{T_S - T_\infty}$$

where q is the heat flux, T_S is the wall surface temperature and T_∞ and the temperature in the far field of the flow.

Nusselt number, which is basically a non-dimensional heat transfer coefficient, is calculated by:

$$N_u = \frac{hL_c}{k}$$

where h is heat transfer coefficient, L_c is the characteristic length and k is thermal conductivity.

Lastly, finding friction coefficient requires calculating shear stress, and then use it for obtaining friction coefficient.

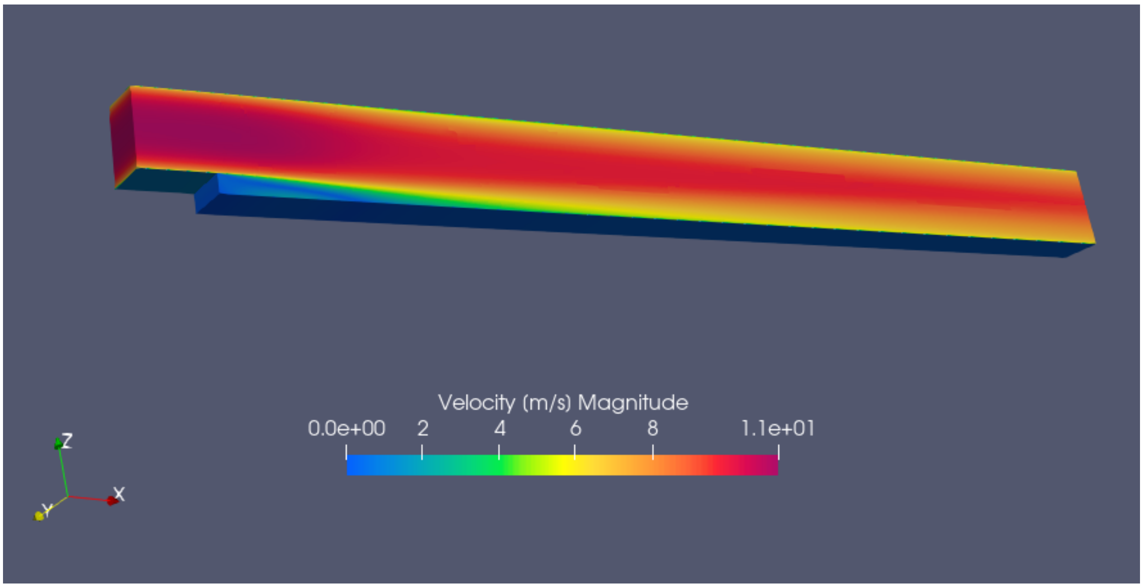
$$\tau_w = \mu \frac{dV}{dz}$$

For shear stress, we need the gradient of velocity with respect to z-axis, as that is the direction of the velocity boundary layer.

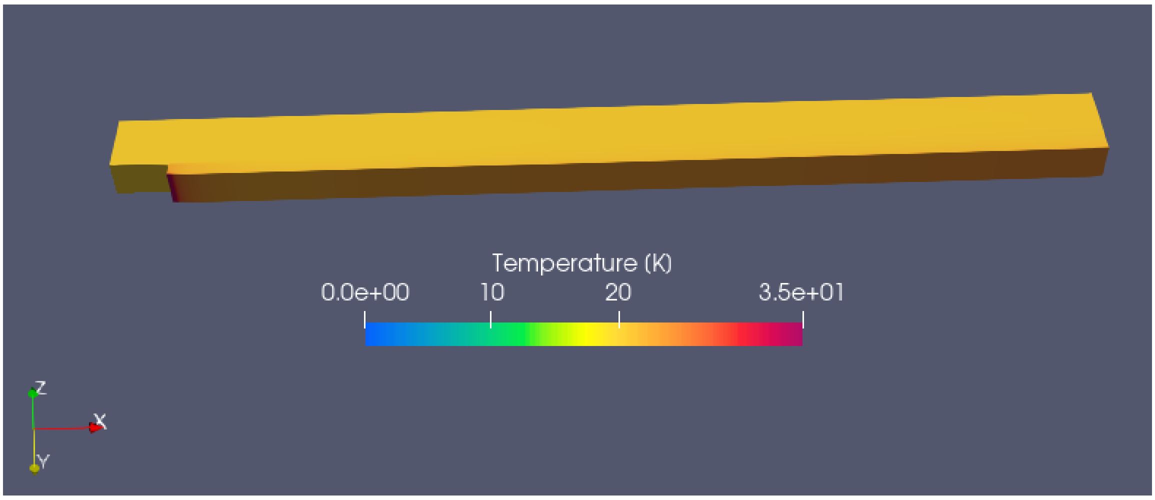
$$c_f = \frac{\tau_w}{\frac{1}{2}\rho U^2}$$

For the friction coefficient, besides the shear stress, we also require the flow density and the upstream velocity of the fluid.

Domain of the backstep channel is defined by two files, one representing the interior of the channel, and the other for boundary conditions. The complete configuration is shown below:



Picture 1 – Backstep channel, velocity field.



Picture 2 – Backstep channel, velocity field.

3. Methodology

In order to extract the necessary data, we will use several filters in Paraview including, *Cell Data to Point Data*, *Slice, Clip*, *Integrate Variables*, *Calculator*, *Gradient*, and most important, *Plot over line*.

Local values are obtained by applying *Plot over line near the wall region*, and the averages are calculated using *Integrate variables* filter.

3.1. Heat transfer coefficient (h)

In order to get both local and average heat transfer coefficient, we need to make sure that correct parameters are found. The explanation for each is provided in the following text.

Heat Flux

To obtain heat transfer coefficient, we first need to get the value of the heat flux imposed on the surface. There are two main ways to do this: first requires calculating the temperature gradient $\frac{dT}{dz}$ and multiplying it by thermal conductivity k. However, since we already have the information on the heat flux in the control file for the backstep case, we can use that value instead. The correct location of the control file will be provided at the end of this paper. Thus, the value of heat flux we will use for both calcualtions is:

$$q = 0.1$$

Bulk Temperature (Average interior temperature)

Extracting both local and average heat transfer coefficient requires using correct temperature values. In both cases, it is crucial to use the bulk temperature as it represents more accurately the average temperature of the interior domain. It is given by:

$$T_B = \frac{\int_A \rho T_\infty V_x dA}{\int_A \rho V_x dA}$$

To calculate it in Paraview, we open the interior file, and then apply the *Slice* filter so that the plane perpendicular to the flow (x-axis) is selected. Then, we apply a calculator to get the numerator of the above equation. We label it as „A“ and set it equal to:

$$A = \rho T_\infty V_x$$

Then, for the denominator, it is just the product of density and x-component of velocity:

$$B = \rho V_x$$

After this is done, we can find A and B in the data array, in the information tab. Next step is to apply *Integrate Variables* filter to both, which sums up all the point values in the given slice. We then read these values from the spreadsheet view and divide A by B to get the bulk temperature which results to:

$$T_B = 20.01$$

This value is needed for both calculating local and average heat transfer coefficient.

Average Surface Temperature (T_S)

For otaining the h_{avg}, it is necessary to obtain the average surface temperature over the bottom wall. For this purpose, we need to get information on the wall area. Coordinates for the bottom wall can be read from the domain file:

```
%-------------------------------------------%
%
%     14----------15---------------------16
%     /|          /|                     /|
%   11----------12---------------------13 |
%    | |  (1)   | |         (2)        | |
%    | 6 - - - - | 7- - - - - - - - - - -|10
%    |/         |/|                    |/|
%    1----------2---------------------5 |
%               | |         (3)        | |
%               | 8--------------------|-9
%               |/                     |/
%               3---------------------4
%
%-------------------------------------------%
%  Nodes (cells), boundary cells and sides  %
%-------------------------------------------%
  180000 10000 290000

%----------%
%  Points  %
%----------%
16
  1  -0.1444          0.0          0.038
  2   0.0             0.0          0.038
  3   0.0             0.0          0.0
  4   2.28            0.0          0.0

  5   2.28            0.0          0.038
  6  -0.1444          0.1          0.038
  7   0.0             0.1          0.038
  8   0.0             0.1          0.0

  9   2.28            0.1          0.0
  10  2.28            0.1          0.038
  11 -0.1444          0.0          0.19
  12  0.0             0.0          0.19

  13  2.28            0.0          0.19
  14 -0.1444          0.1          0.19
  15  0.0             0.1          0.19
  16  2.28            0.1          0.19
```

Thus, the bottom wall temperature is:

$$A = 2.28 * 0.1 = 0.228$$

Picture 3 – Backstep channel, domain and point coordinates.

To obtain the average surface temperature, we have to select only the bottom wall using the *Clip* filter, which requires an origin point and the normal point. In this case, the plane is normal to z-axis, so we enter:

$$Origin(0,0,0)\ and\ Normal(0,0,1)$$

Next, we again apply the *Integrate Variables* filter, and divide the resulting value by area to get the average surface temperature:

$$T_{S,avg} = \frac{5.28574}{0.228} = 23.62$$

Now that we found all the critical parameters, we can proceed to calculating local and average heat trasnfer coefficient.

3.1.1. Local heat transfer coefficient

Local value of h is calculated as:

$$h = \frac{q}{T_S - T_\infty} = \frac{q}{T_S - T_B}$$

where $T_\infty$is again the bulk temperature, and for the surface temperature we now use the one from the data array, after opening the boundary file. After calculating it as in above relation, we apply *Plot Over Line* filter near the bottom wall which is why there is no need for averaging the interior temperature. The coordinates for the plotting line are:

$$P_1(0,0,0)\ and\ P_2(2.28,0,0)$$

The resulting plot and its interpretation will be provided in the Results section.

3.1.2. Average Heat Transfer Coeffcient

Calculating average h is done by the same relation as the local, only this time, we substitute the surface temperature by the average surface temperature we found above. The calculation is as follows:

$$h_{avg} = \frac{q}{T_{S,avg} - T_B} = \frac{0.1}{23.62 - 20.01} = 0.0277$$

Now we can proceed with finding local and average Nusselt number.

3.2. Nusselt Number ($\boldsymbol{N_u}$)

If the previous steps for local and average heat transfer coefficient were done correctly, then finding the same for Nusselt number should not be hard work.

3.2.1. Local Nusselt Number

Continuing working on the same branch as for the local h, we simply add a new Calculator filter, and enter the following expression:

$$N_U = \frac{h_{local} * L}{k} = \frac{h_{local} * 2.28}{2.2e - 5}$$

We note the length of the bottom wall is 2.28, and use the information on the physical conductivity. We again plot it using *Plot Over Line* to see the resulting function.

3.2.2. Average Nusselt Number

Average value is found by simply substituting the local value of h, by its already calculated average:

$$N_U = \frac{h_{avg} * L}{k} = \frac{0.0277 * 2.28}{2.2e - 5} = 2870{,}7$$

Large value tells as that convective heat transfer dominates most of the wall area.

3.3. Skin Friction Coefficient

Skin friction coefficient c_f requires similar approach as h, as it depends on wall shear stress τ_w, and the upstream velocity of the flow V_x. That is why we first must find the values of local and average shear stress, as well as the bulk average velocity.

Local Shear Stress

We know that wall shear stress depends on the velocity gradient. To get it we apply a *Gradient* filter to the velocity vector in the interior file. This will result in having all of the nine gradients from the velocity gradient tensor, and for our specific case we will only require the one in z–direction, as that is the direction of velocity boundary layer development.

Next we calculate the following:

$$\tau_w = \mu \frac{dV}{dz}$$

Where μ is the fluid viscosity, and the gradient to be selected is refered by number 2 in the data array.

Bulk Velocity (Average Upstream Velocity)

Bulk velocity measure the average velocity of the flow in the channel, which is exactly what we need for $c_{f,avg}$. Similarly to bulk temperature, the expression for bulk velocity is:

$$V_B = \frac{\int_A \rho V_x dA}{\int_A \rho dA}$$

We apply the same steps as for finding the bulk temperature, including slicing the channel, and calculating the two integrals by using the *Integrate Variables* filter.

Next, we divide the obtained values and the resulting bulk velocity is:

$$V_B = 8.34$$

Reynolds Number

In order to calculate the average skin friction coefficient, we can use the relation between R_e and c_f. For that reason, we also find the Reynolds number which results to:

$$R_e = \frac{\rho UL}{\mu} = \frac{1 * V_B * 2.28}{2.2e-5} = 8.64 * 10^5$$

This also concludes that the flow is fully turbulent, since it is well above the critical value of $5 * 10^5$.

3.3.1. Local Skin Friction Coefficient

To get the local c_f we must open the interior file and as before apply *Cell Data to Point Data* filter to it. Then, we proceed with finding the velocity gradient in z-direction by applying the *Gradient* filter, necessary for calculating wall shear stress. The filter will result in calculating all the nine tensor components, and we will need the one indexed with number 2.

After we obtain τ_w, we can then move to calculating bulk velocity. The procedure is same as for calculalting bulk temperature. Now that we obtained all the parameters, we simply calculate the local c_f by *Plot Over Line*.

$$c_f = \frac{\tau_w}{\frac{1}{2}\rho U^2}$$

3.3.2. Average Skin Friction Coefficient

We will obtain the average value of c_f by using the following expression:

$$c_f = \frac{0.074}{R_e^{\frac{1}{5}}}$$

Which will give us the average value in case of fully turbulent flow. As we already calculated Reynolds number, we simply plug in the values and the resulting average coefficient is:

$$c_{f,avg} = 4.8 * 10^{-3}$$

Now we can proceed with showing the results.

4. Results

In this section, we will go through the resulting plots of the local parameter values, and also their averages are provided in a separated table as well.

4.1. Heat Transfer Coefficient

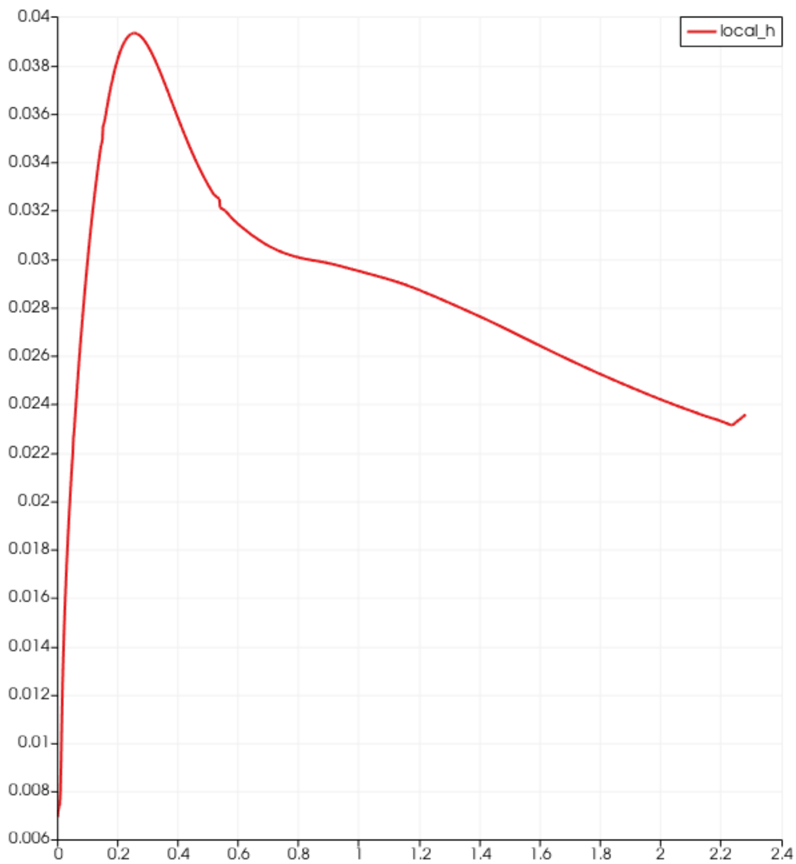


Figure 1 – Local heat transfer coefficient plotted in Paraview.

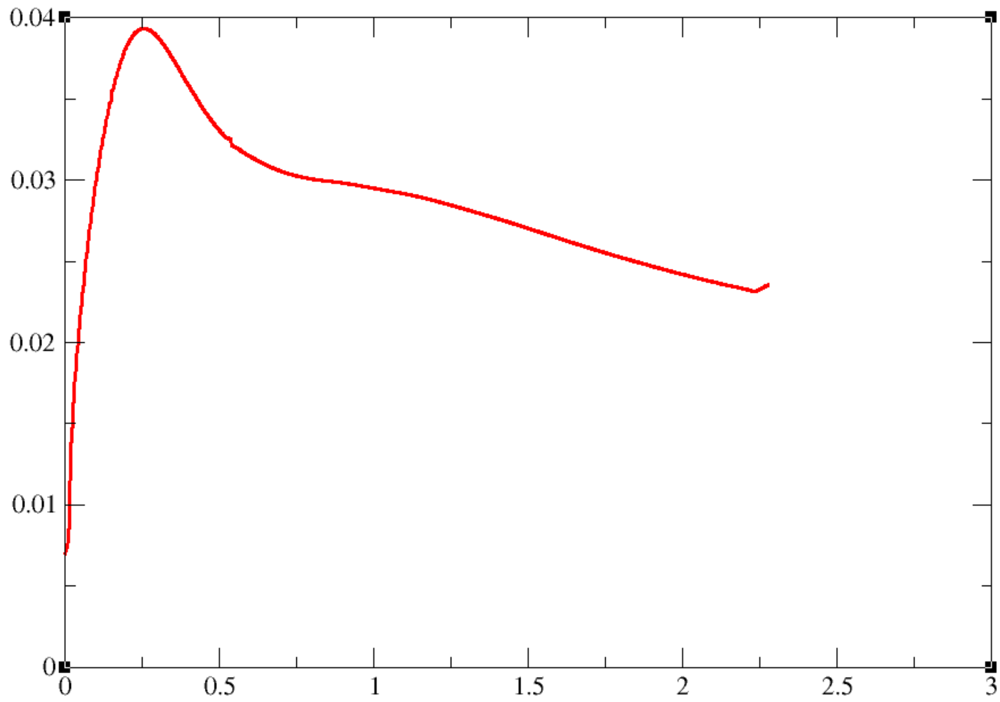


Figure 2 – XMGrace plot of local heat transfer coefficient.

We can see on the plot that, heat transfer coefficient starts off with very small values and also on a short entrance length of the channel. This is the region where separation bubble is present and the stagnation of the flow inside of it results in these small values.

As the flow is being reattached to the original streamlines, we notice a rapid increase of h. This is due to the fact that velocity increases at the point of reattachment due to mixing of the original and newly formed flow streams. Thanks to efficient mixing due to turbulent eddies, thermal boundary layer gets thinner and the temperature gradient is significantly steep which results in more efficient heat transfer. Higher velocity gradients in this region ocurr thanks to high shear stress at the wall which is necessary for effective heat transfer. Higher the velocity gradients are, the more turbulent kinetic energy will be present to enhance the heat transfer.

After the peak value is hit, there will be less and less turbulent kinetic energy responsible for effective heat transfer. In the region where h decreases on the graph, we observe that shear stress stabilizes and the fluid continues to flow in a less disorderly manner. At this point, velocity boundary layer starts to get its fully developed shape, and the amount of heat transfer is now more ordered and reduced thanks to having smaller changes in velocity gradients.

4.2. Nusselt Number

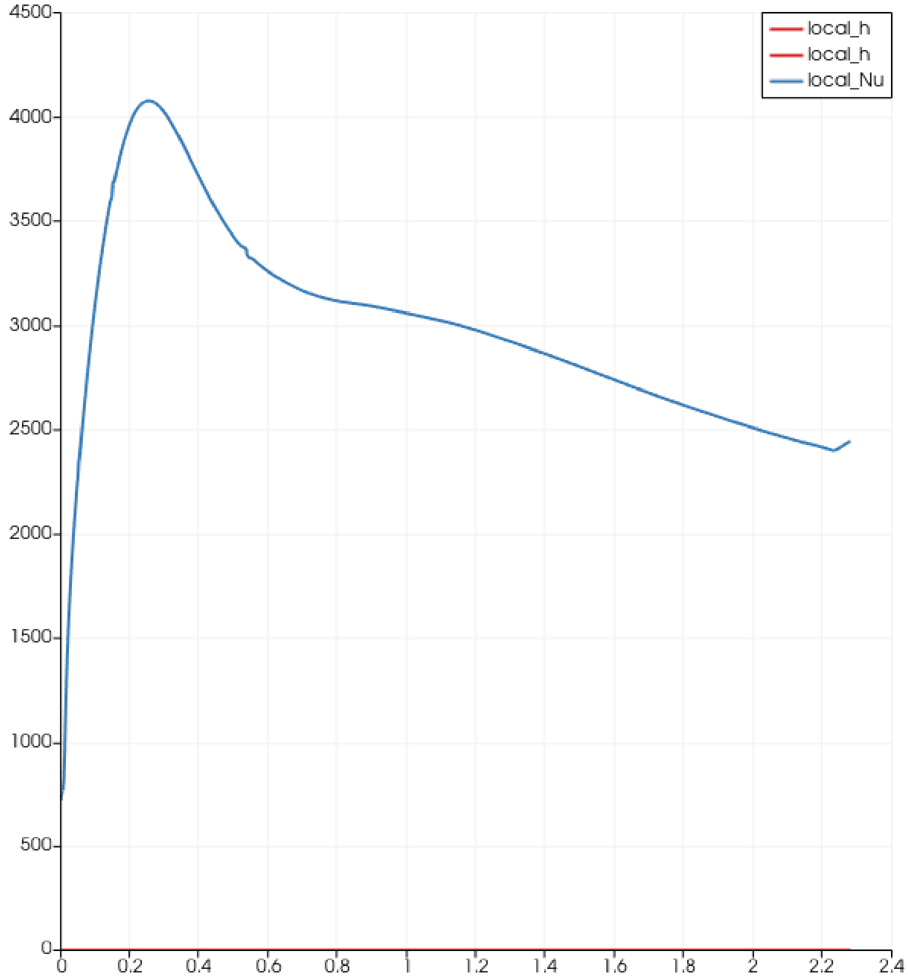


Figure 3 – Local Nusselt number plotted in Paraview.

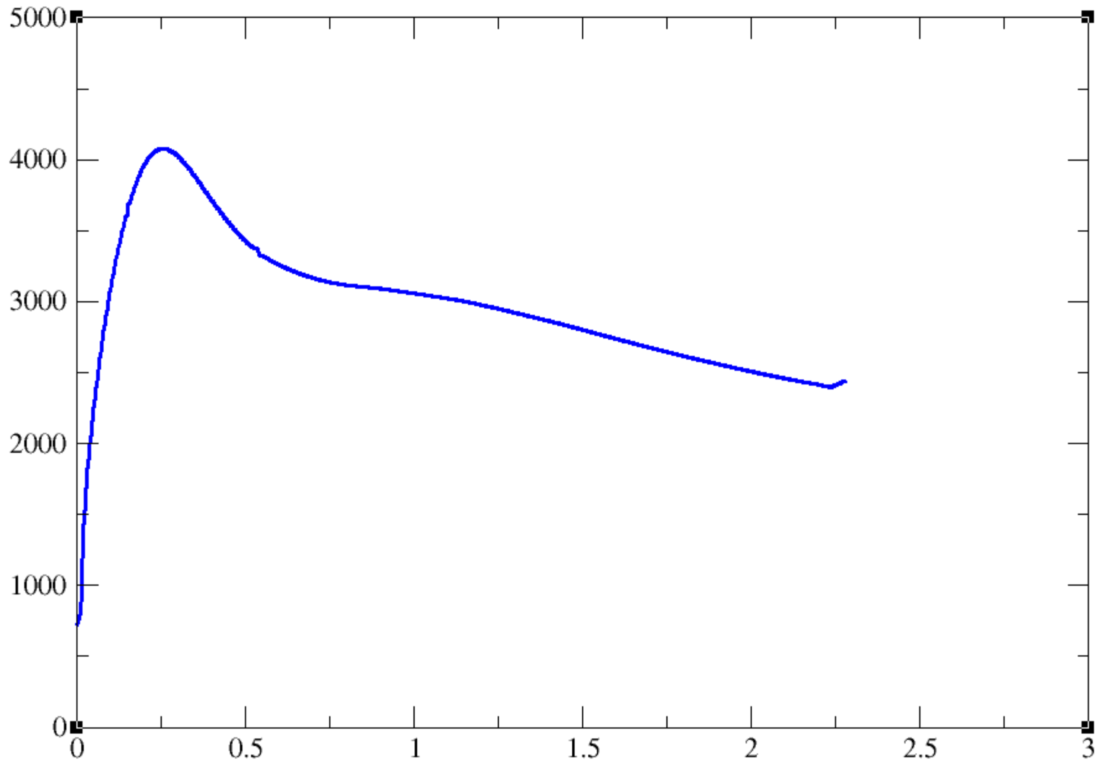


Figure 4 – XMGrace plot of local Nusselt number.

Nusselt number is a non-dimensional heat transfer coefficient which is used to demonstrate the efficiency of convection heat transfer over heat transfer by conduction.

Seeing how in our case, the range on which it is present reaches a bit over 4000, tells us how heat transfer in the basckstep channel is in large capacity due to convective heat transfer.

The high peak in the graph above confirms that the most effective heat transfer occurs at the point of flow reattachemnt where the velocity gradients are at its peak. Moving across the channel after this point, the flow starts to stabilize and the velocity profile is being more developed. Since there are no further changes in shear stress, we will have less turbulent mixing and the heat transfer will start to occur in a more predictable way.

What this tells us about heat transfer is that, convection dominates the regions where velocity is changing rapidly which can be said about the entrance length where separation bubble diminishes and turbulent eddies accelerate the flow increasing its heat transfer capabilities.

Just like in the case with the heat transfer coefficeint, as the thermal and velocity boundary layers become fully developed, there will be less vortices and eddies responsible for generating turbulent kinetic energy, and therefore gradients of velocity and temperature will change more subtly, resulting in stable heat transfer by convection.

4.3. Skin Friction Coefficient

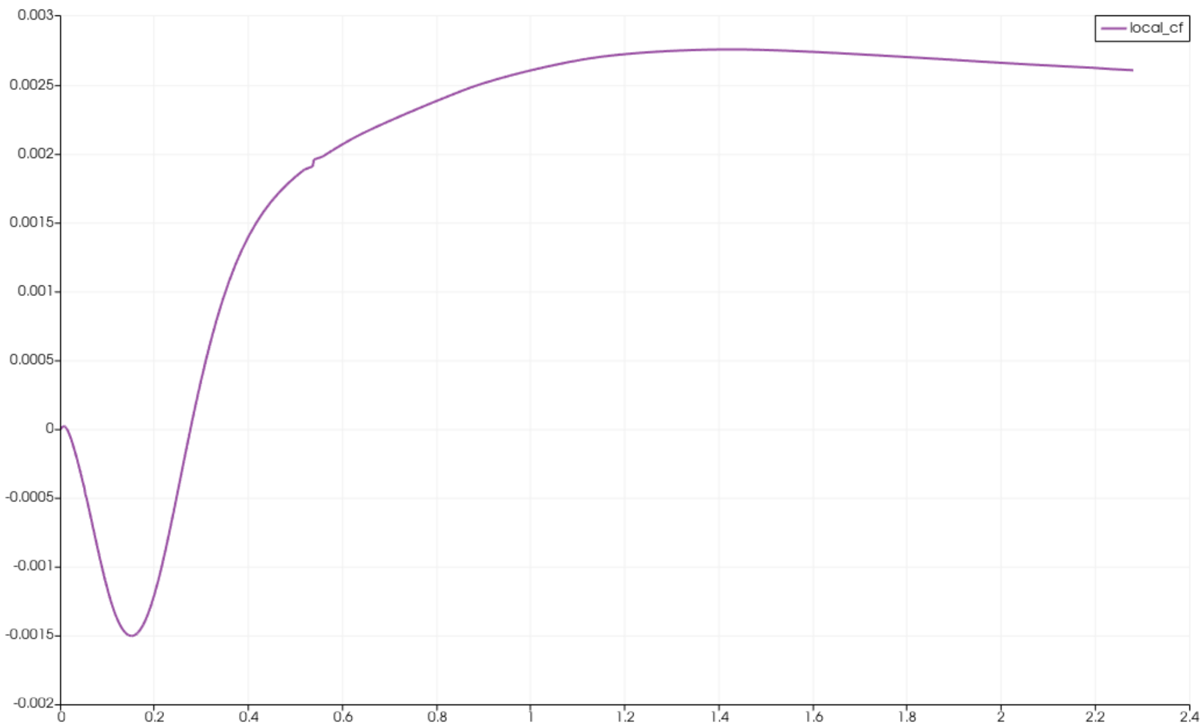


Figure 5 – Local skin friction coefficient plotted in Paraview.

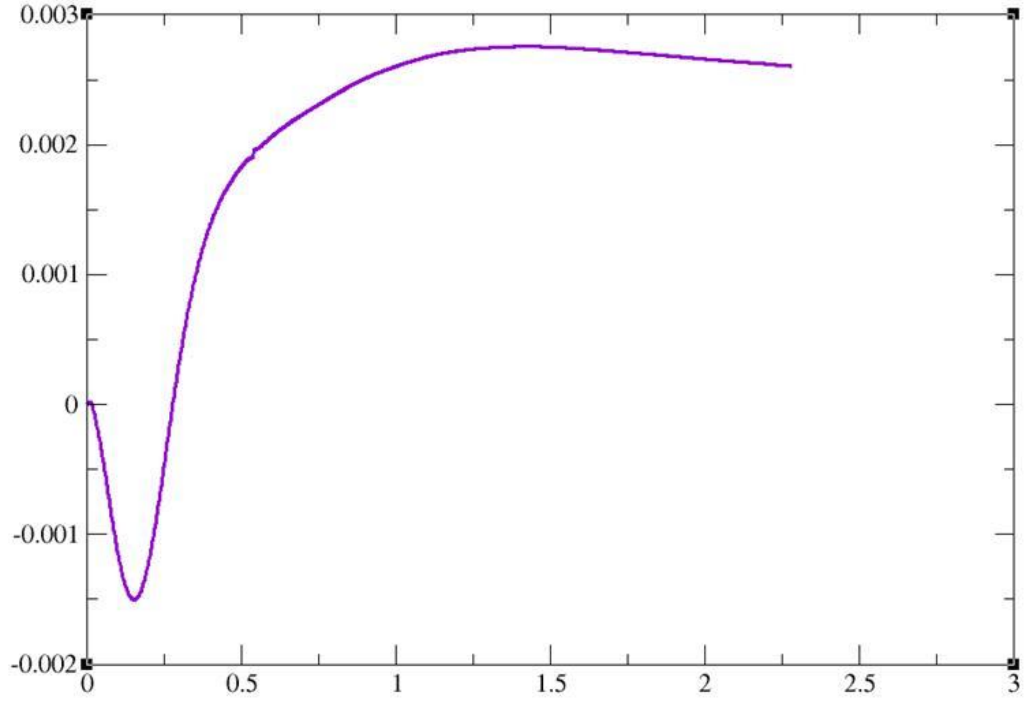
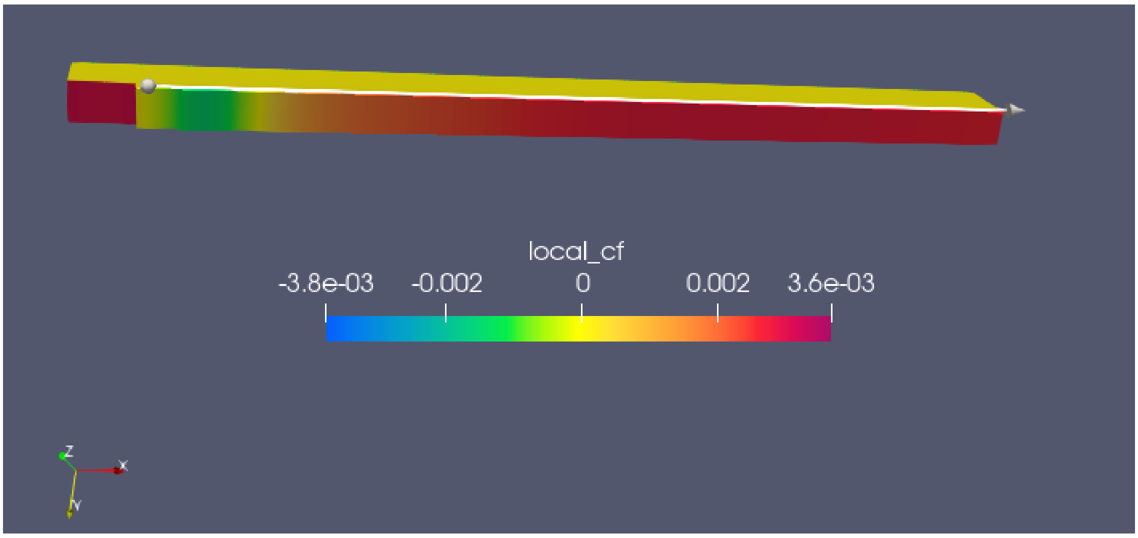


Figure 6 – XMGrace plot of local skin friction coefficient.

Uniform heat flux on the bottom wall results in higher surface temperature and hence the layer of the fluid near the wall will have larger temperature. This leads to a decrease in fluids viscosity meaning the viscous forces resisting the flow will also decrease, leading to a decrease in shear stress which inevitably results in smaller c_f values. This can be clearly observed in the Figure 7 where the region of lowest shear stress perfectly correlates with the decrease in friction coefficient seen in Figure 6. Similarly, slight increase in shear stress can be related to the increase of friction coefficient in the area of flow reattachment.

As the flow progresses downstream, there will be a gradual thickening of thermal boundary layer thanks to diffusion of heat. Viscosity of the fluid also grows stronger and the shear stress of the flow increases resulting of c_f recovery, as well as its expanded growth. Stabilization of the flow velocity profile and full development of its temperature boundary layer will result in stable and predictable increase of skin friction coefficient.

Final c_f values will reach values around 0.0025 which is well in the expected range of 0.002 – 0.01, typical for turbulent channel flows with uniform heat flux.



Picture 4 – Local skin friction coefficient field, indicating low values at the entrance region, and rapid increase thanks to flow development.

Vizualization above shows that c_f has lowest values at the entrance region. Orange hues represent the transitional region where the shear stress increases due to increase in velocity gradients. Moving downstream in the flow, it slightly increases and then stabilizes thanks to having a fully developed thermal boundary layer, where there are no additional changes in fluid viscosity.

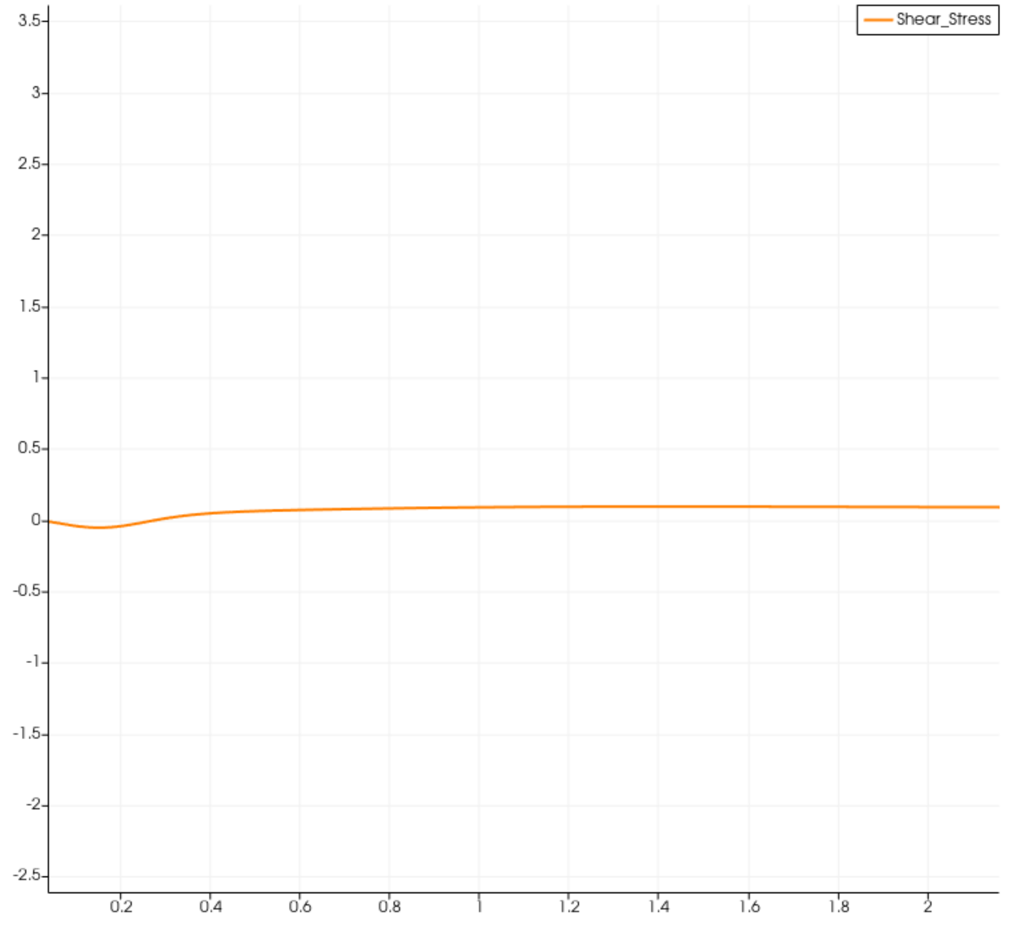


Figure 7 – Local shear stress with minimum values in the region of flow separation where stagnation results in low velocity gradients..

4.4. Average Parameter Values

Below are shown average values of h, N_u, and c_f:

Parameter	h	N_u	c_f
Average value	0.0277	2870,7	0.0048

The average values are all within the range of local values, and serve as a rough estimate of the overall flow behaviour.

5. Discussion

We saw that every step in the calculations required analytical approach, and reasonable assumptions of the fluid flow which are crucial to avoid making unecessary errors.

First source of error is not chosing the rigth file to work on, for a specific purpose. For example, extracting velocity gradient from the boundaries file would not give a full picture of the velocity changes, as those are detected in the z-direction of the flow and extracted from the interior domain file.

Also, for using the *Clip* and *Slice* filter, chosing the correct orientation of the normal axis is important to ensure that gradients and other properties are compuoted in the correct direction. If done incorrectly, it could lead to unaccurate or unnatural behaviour of the flow.

Last but not least, it should be stressed that for calculations of heat transfer coefficient and skin friction coefficient, it is the averages of temperature and velocity fields that should be used, expressed as T_{bulk} and V_{bulk}, and not their immediate data array values. This is probably the easiest error to be done, and should be given special attention before going deeper into the simulation.

Even if it may not be obvious enough, an analysis such as this can bring great benefits to the world of real life engineering and physics solutions.

Since heat transfer coefficient quantifies the efficiency of heat transfer, it provides an invaluable insight into optimizing various cooling and heating systems that rely on convective heat transfer. These include electronics cooling, managing thermal loads in aerospace industry, and improving the efficiency of general energy generating systems such as solar panels, nuclear reactors etc.

Evaluation of Nusselt number helps to understand the power of convection over conduction, which is often a crucial piece of information in systems involving turbulence flow for optimizing flow design.

Finally, skin friction coefficient is an important scaling factor in aerodynamics, as it helps to understand the resistance exerted by the fluid, leading to increased values of drag force. It represents an irreplacable parameter for optimizing vehicle aerodynamics, various pipeline systems and similar configurations that involve fluid flow.

6. Conclusion

In this paper, we worked to simulate the key fluid flow and heat transfer parameters: heat transfer coefficient (h), Nusselt number (N_u), and skin friction coefficient (c_f).

We saw that extracting these parameters from Paraview requires attentive approach, with a series of steps and various filters, and overall solid knowledge of the software. Understanding the resulting plots and calculated average values is not possible without a good insight into the no-slip condition, and how it affects the development of velocity and thermal boundary layers, responsible for shear stress and its variations along the channel.

We found that both h and N_u start of at low values in the separation region where the fluid motion is mostly stagnant. As the fluid streams reattach, there is a visible increase in these coefficients thanks to an increase in velocity gradients and therefore shear stress which heavily influences the increase in velocity and thermal boundary layers.

As for c_f, it starts of in the negative region where the values of shear stress are at its minimum. As it continues to grow, so does the skin friction coefficient, where there is less turbulent mixing and the viscosity of the fluid increases as well.

Flow simulations that involve data extraction and calculation are key for understanding the efficiency of heat transfer and ways to optimize it in various systems.

7. Table of Pictures and Figures

8. Literature and Sources

Heat and Mass Transfer by Yunus A.Cengel and Afshin J.Ghajar, fourth edition.

What is the integral of temperature over space called? (n.d.). Physics Stack Exchange. https://physics.stackexchange.com/questions/370908/what-is-the-integral-of-temperature-over-space-called

Effect of Bottom Wall Heating on the Turbulent Fluid Flow in an Asymmetric Rectangular Diffuser: an Experimental Study (S. Bhattacharjee, A. Mandal† , R. Debnath, S. Majumder and D. Roy)

https://www.jafmonline.net/article_1860_01705ea1d90c23c8e9acda93efddaef2.pdf

Software used:

- Paraview 5.13.2.
- XMGrace

Link to GitHub repository containing the Backstep Case and its documentation:

https://github.com/MelihaDelalic/T-Flows