Final Project Final Submission

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Project title: Visualization of F1 Car Fluid Flow

Table of Contents:

Abstract:

Formula 1 (F1) cars boggle the minds of millions of spectators every year as they hurtle around tight courses at maximum speed. However, behind the pure grunt of the cars is decades of research and development to optimize the aerodynamic characteristics of the cars [18]. The F1 governing body, FIA (Fédération Internationale de l'Automobile), tightly regulates aerodynamics, but their decisions are often contentious [19]. In this paper, we explore the aerodynamic characteristics of F1 cars (new and old) using simulated airflow data, discuss whether the common complaints are valid, and try to understand how F1 cars have evolved. We use OpenFOAM's computational fluid dynamics (CFD) to generate the data that we will be visualizing.

Goals:

We set ourselves lofty goals for this project by electing to generate our own data to answer our questions. We knew that we wanted to compare F1 cars, so we would have to generate multiple datasets for the cars. Ultimately, we found eight F1 cars from throughout the last 50 years to run simulations on, one Porsche 911 to test our simulation methods, and one superbike example. Our data analysis focussed chiefly on the F1 cars. However, we have some example visualizations from the other two that we used for testing and building up enough knowledge to generate meaningful F1 car visualizations (see fig 9.1 and fig 10.1).

As for visualizations, we wanted them to help us answer our questions about F1 car aerodynamics between models of the same year and over time. This meant we would be trying to understand turbulence, vorticity, pressure, etc., using methods such as volume rendering, streamlines, and isosurface extractions on our generated data.

Background and Related Work:

We are certainly not the first people to consider how the aerodynamics of F1 cars affect their performance; in fact, it is one of the primary differentiating factors among F1 teams. As such, there are a plethora of fantastic sources that we can use to understand our visualizations. The sources we found generally fall into three categories: computational fluid dynamics techniques, aerodynamic phenomena description, aerodynamic visualization strategies.

To handle our computational fluid dynamics, we are using two programs. We first have to use MeshLab [14] to modify our 3D models to have a standard coordinate system. Secondly, we have to use OpenFOAM to generate the airflow simulation. To quote the ReScale's (a cloud R&D tech company) documentation [15], "[OpenFOAM is] a C++ toolbox with a large library, allowing for complex models and simulations to be carried out. It also comes with packages to allow parallel computation functionality."

OpenFOAM is a large and flexible solution to CFD and allows us to generate the data we want to visualize. Additionally, there are many tutorials included with OpenFOAM [20] that allow us to see the program's functionality without learning every little detail.

The literature on aerodynamics is dense, thanks to 100 years of research. One of the primary aerodynamic properties of F1 cars is downforce or a net positive force generated in the downward direction[11]. Downforce is created by generating lower pressure below surfaces on the car and higher pressure above[10, 13]. On modern f1 cars, the three main features responsible for producing downforce are the front wing, rear wing, and diffuser[10, 13, 17]. Another essential feature of modern F1 cars is their ability to generate vortices. These vortices, which are generated primarily from the front of the car, allow the air to better adhere to the car's body and direct air away from areas that will cause drag (such as the tires)[10, 11]. These aerodynamics allow engineers to simultaneously reduce drag and funnel air toward important elements such as the rear wing. Uncontrolled vortices, however, can become a source of drag. In modern f1 cars, engineers design endplates to prevent uncontrolled vortices from generating by venting the high-pressure air above the wing[17]. Turbulence is generated when low-pressure/high-speed and high-pressure/low-speed airflow come together[10, 11, 13, 17]. Turbulent air reduces a car's ability to produce downforce and causes drag. In modern F1 cars, the wheels and rear of the car are some of the largest producers of turbulence. This reduces the amount of downforce tailing cars can produce, making it more difficult for drivers to maintain enough grip to overtake leading drivers.

Inspired by some of the techniques we used to visualize the wind flow for Hurricane Katrina for the homework, we decided to use volume visualization, isosurface extraction, and streamline visualization to analyze the turbulence and the direction of velocity[12]. We experimented with multivariate visualization techniques such as layering the isosurfaces with the streamlines and volumes, but the visualizations were hard to analyze, especially with different variables. Our goal was to help users (ourselves included) obtain insight into how velocity and turbulence affect F1 car design, so we instead decided to visualize separate components for our visualizations using the techniques of streamlines, isosurface rendering, and volume visualization[12].

For visualization techniques, we will be referencing The Visualization Handbook from class.

Methods:

There are two sets of methods for the two distinct stages of our project. The first is related to generating the data that we would visualize, and the second relates to the visualizations themselves.

To generate our data, we had to use quite a sophisticated pipeline. We would first pull the STL files (the 3d models) from Thingiverse and save them locally. The models inside the files were often at different resolutions, scales, and orientations, which necessitated that they were transformed to have a common origin, orientation, and scale. After this first transform, it was sometimes necessary to further reduce the model's complexity so that they could be passed into OpenFOAM. To do all of this STL file manipulation, we used MeshLab, a free and open-source tool for 3d mesh manipulations.

After the STL files were correctly oriented and scaled, we could pass the file into OpenFOAM, a command-line program for computational fluid dynamics simulations. OpenFOAM has an extensive range of uses and can be customized to support various fluid dynamic simulations. As such, learning the program was a daunting task. However, they have fantastic examples, and one of them, a fluid flow simulation around a superbike, was a perfect starting point for our visualizations. We used the framework to simulate the superbike, a Porsche 911, and finally, our eight F1 cars. Using this example framework cut down the time it took us to generate these simulations, and it came with the added benefit of out-of-the-box multithreading support. This reduced the time it took us to run the simulations substantially and came with no extra learning curve. The final piece of the puzzle was to understand the initial conditions and the output variables returned by OpenFoam. Thankfully, we found an excellent resource for that from VespaLabs [16].

The fields that we focused on visualizing were the flow velocity, turbulence kinetic energy, and air pressure. These fields are defined as part of the OpenFOAM simulator tool. We tried several visualization techniques we learned this semester, including streamline visualization, Isosurface Extraction Visualization, Volume Visualization, Slicing, Glyphs, and Tensor Glyphs and Multivariate Visualization. The Slicing, Glyphs, Tensor Glyphs, and Multivariate Visualization were not included in the final report because the visualizations did not share any new insights that we had not discovered with the streamline, isosurface, and volume visualization techniques.

Results:

We completed all of our goals. We were able to modify the 10 STL models and run CFD simulations for each of them. You can see all of the images we generated down below in our paper's "Visualizations" section.

One of the hotly debated topics in modern f1 is the restrictions on "ground effects," which refer to aerodynamic elements that seal off the bottom of the car, turning the underside into a very efficient downforce element. In the 1970s, utilizing ground effects became extremely popular, and teams implemented flexible side skirts that sealed off the bottom of the car. These skirts were eventually banned as they would sometimes lose contact with the ground causing a rapid drop in downforce, which frequently resulted in the driver losing control and crashing. To compensate for this, teams relied on more aggressive wings to compensate. These wings, however, become substantial sources of turbulence, causing trailing cars to experience reduced aerodynamic performance. This can clearly be seen from the turbulence visualization, which shows how the turbulence from wings has increased over time. We can also see a general trend in more efficient downforce elements which focus on increasing downforce while minimizing drag. The earliest F1 car we simulated makes no use of wings or diffusers to produce downforce; we can see that by 1968, Mclaren was using large front and rear wings to produce downforce. These cars, however, show no appreciable under the car aerodynamics. Unlike modern f1 cars, the front wing and bodywork doesn't do an excellent job of shuttling air away from the wheels. This means that the wheels produce large amounts of drag, as seen in the pressure visualization. The 1970 Lotus shows a trend toward larger wings producing more downforce. The 1991 Mclaren exhibits several advancements in aerodynamics with a flat underside and rear diffuser, which reduce drag and produce additional downforce. We also see a taller rear wing, which from our visualization produces more downforce than those on the older car, likely due to the decrease in turbulence from being higher up at the car's rear. The bodywork also does a better job of directing air around the rear wheels reducing the drag produced. The modern F1 cars improve on all of these things now using complex front wings to send air around the front tires and a myriad of aerodynamic elements to direct air around the car and towards the rear wing. We can also see the large vortices generated by these elements. The result is less drag and more downforce, evidenced by the high and low-pressure areas above and below the car and relatively small pressure differentials front to back, especially around the wheels. All this comes at the cost of increased turbulence behind the car, however.

Discussion:

We learned a ton implementing this project. We had to thoroughly learn a suite of new software for manipulating STLs and generating CFD simulations, both

MeshLab and OpenFOAM. As for visualization techniques, we strengthened our knowledge of volume rendering, isosurface extraction, streamline visualizations, and contour visualizations.

We exceeded our goals for this project. In our initial description, we did not define the number of cars that we would simulate, and we did not know that we could use the example to speed us up. We also exceeded our visualization goals by finding helpful information, such as vortices, pressure, turbulence, and using the information to comment on the current contentions.

We did not get to our stretch goal of animating the data in ParaView, but maybe if we are selected in the top 6, we will have some additional time to complete it. On the whole, our project was a huge success and a lot of fun.

Visualizations:

Ferrari (2018) F1 Car:

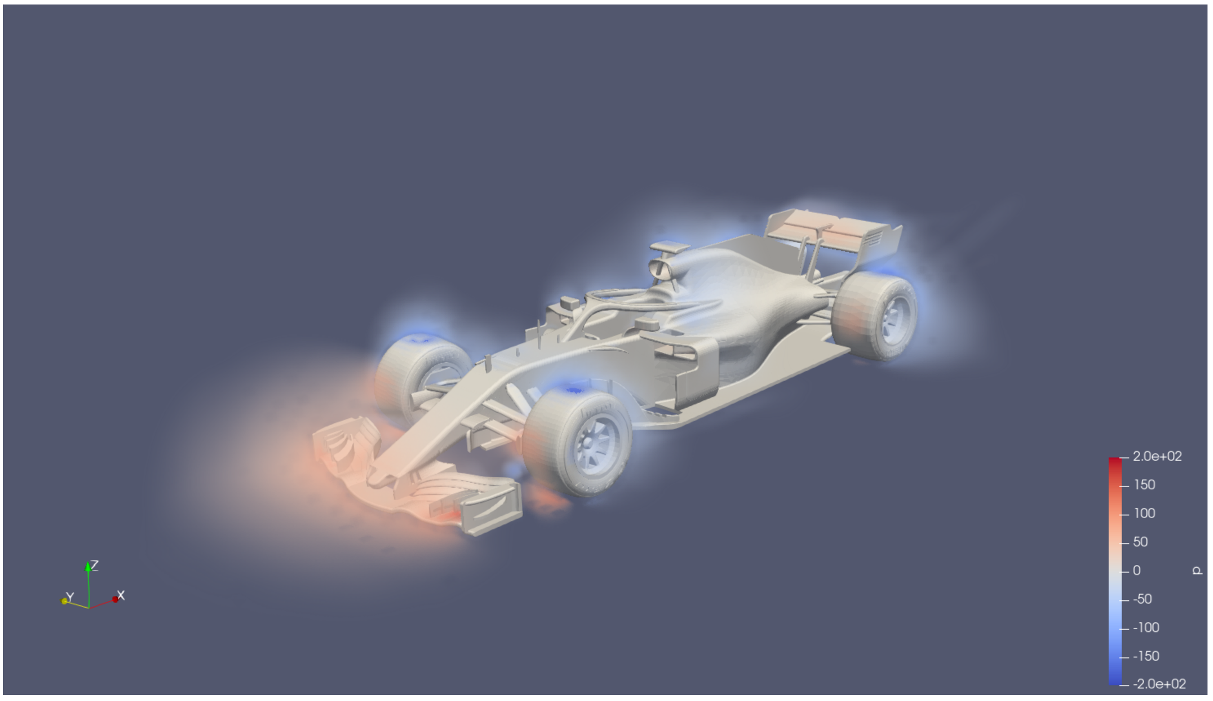

Fig 1.1 Pressure

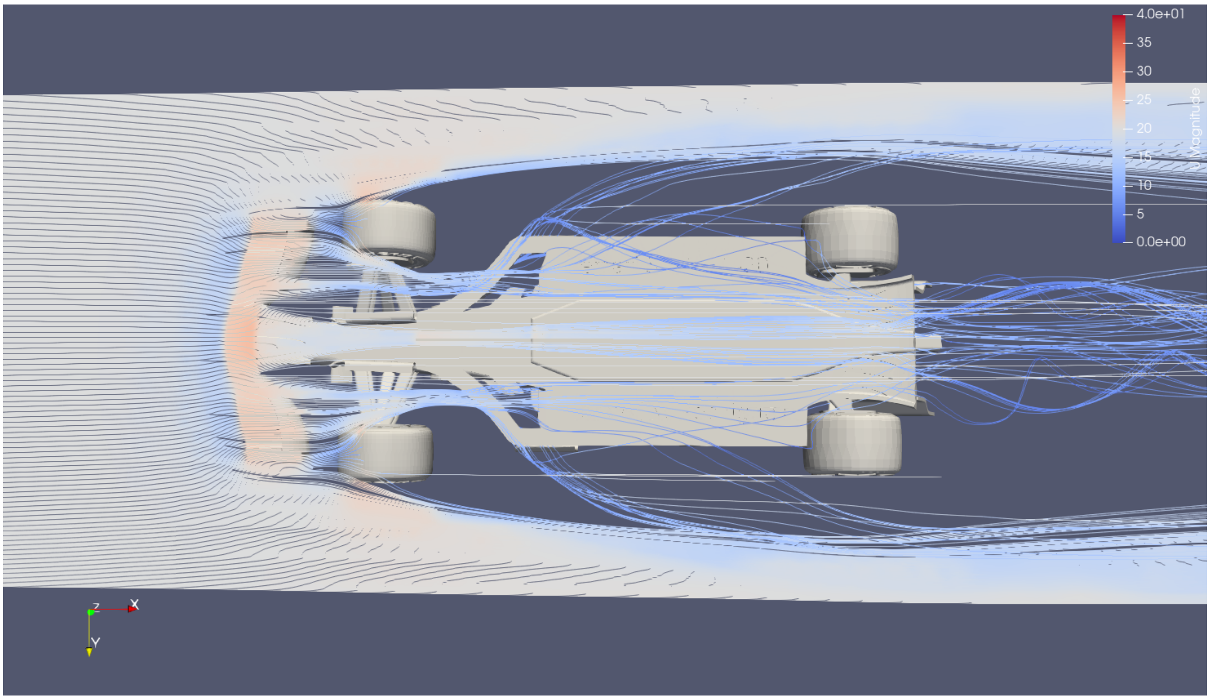

Fig 1.2 Airflow under car

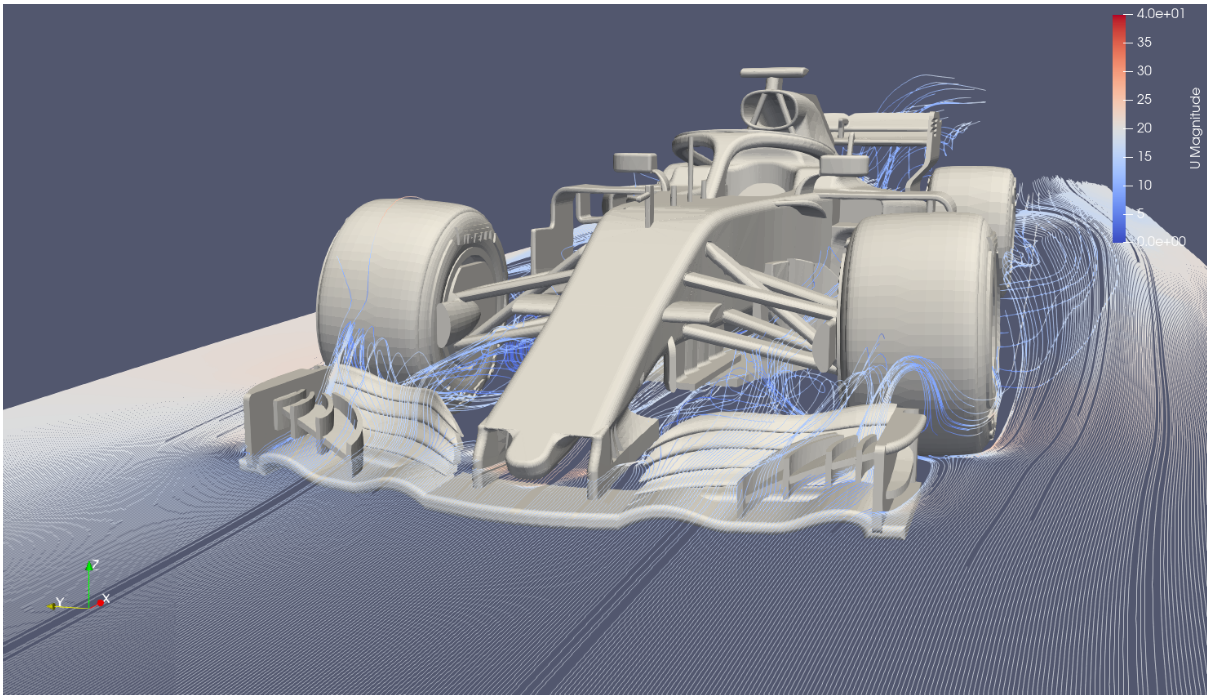

Fig 1.3 Airflow over front wing

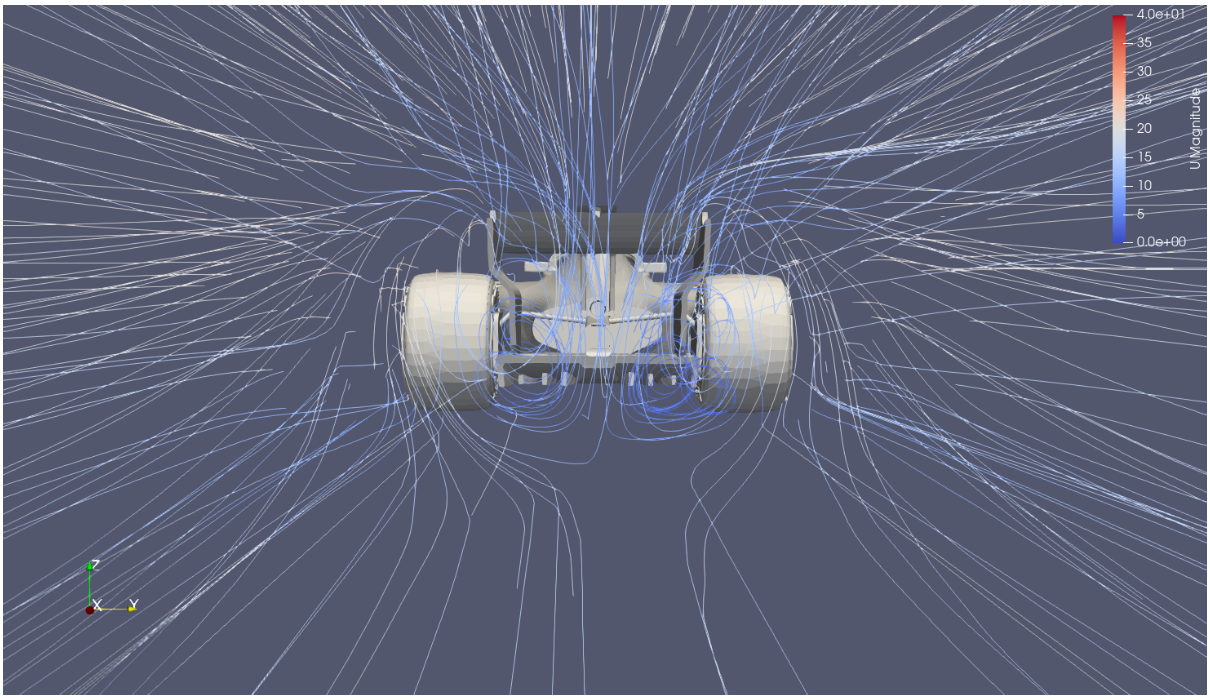

Fig 1.4 Airflow behind car

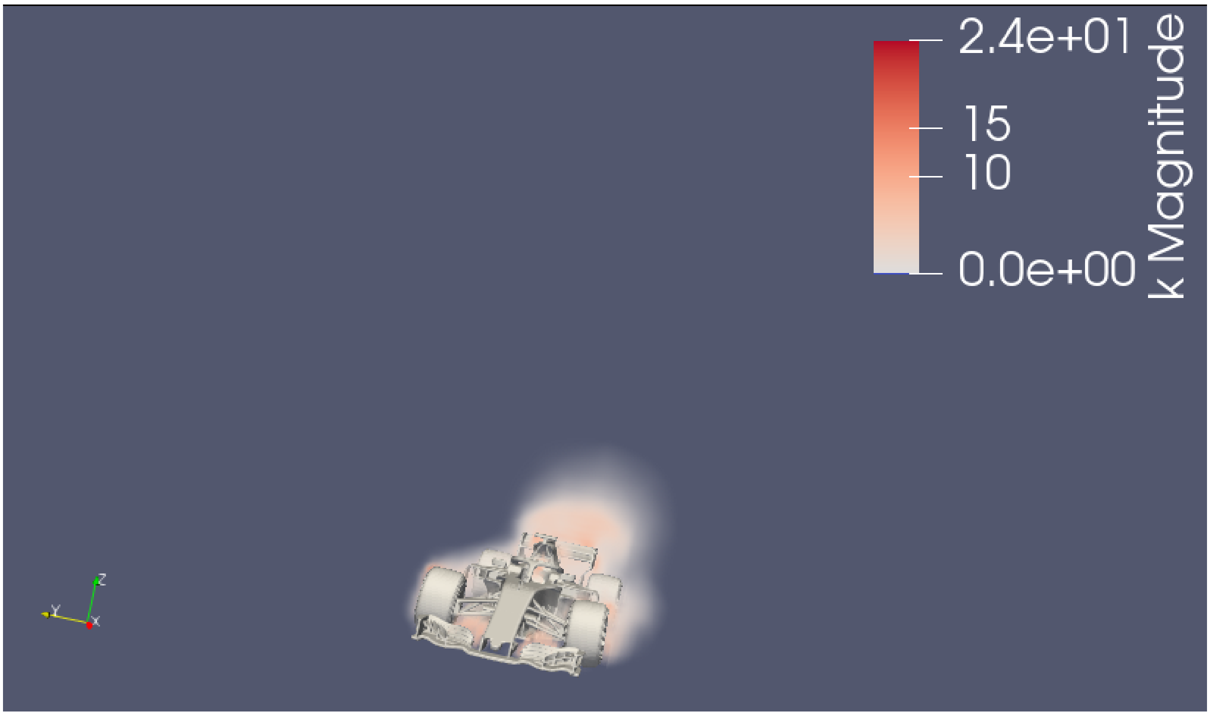

Fig 1.5 Turbulence front car

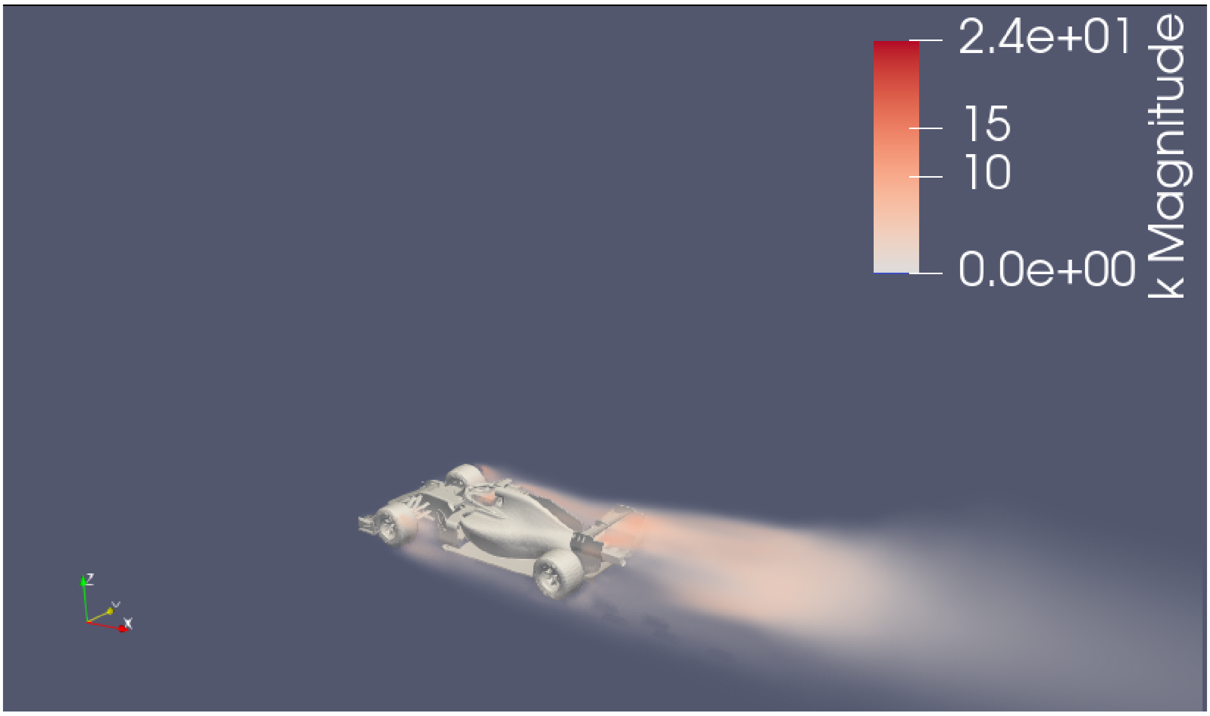

Fig 1.6 Turbulence back/side car

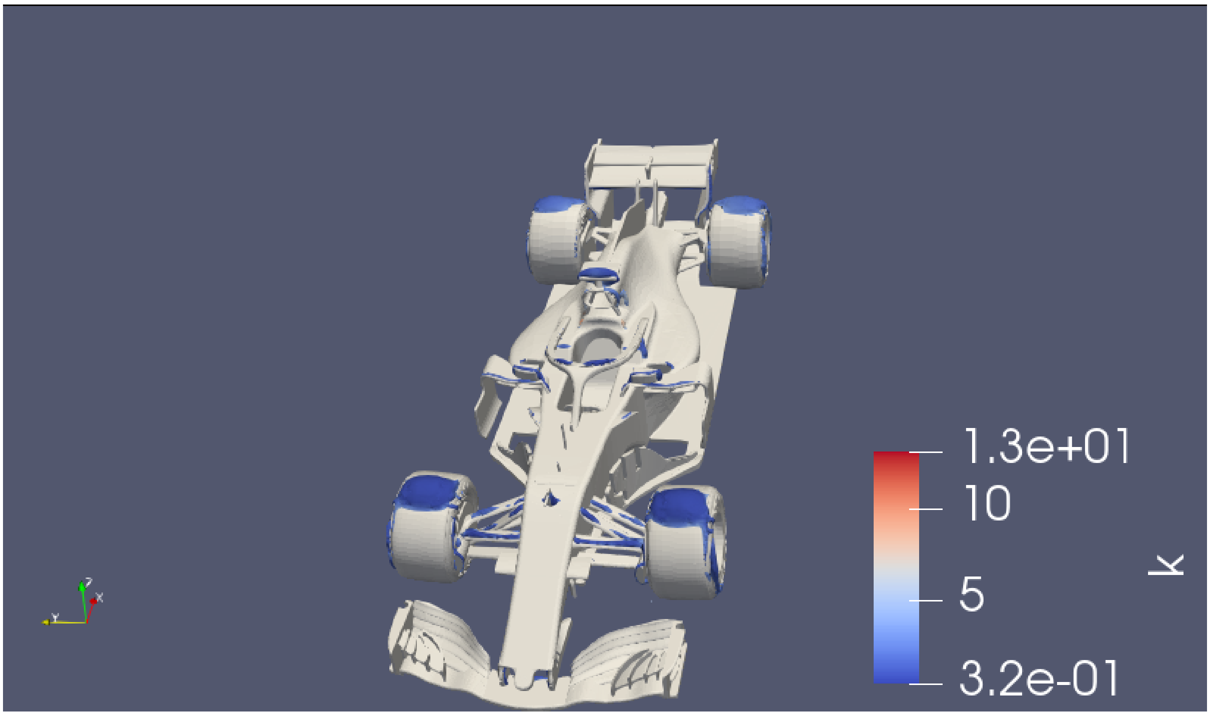

Fig 1.7 Turbulence Isosurface Extraction front car

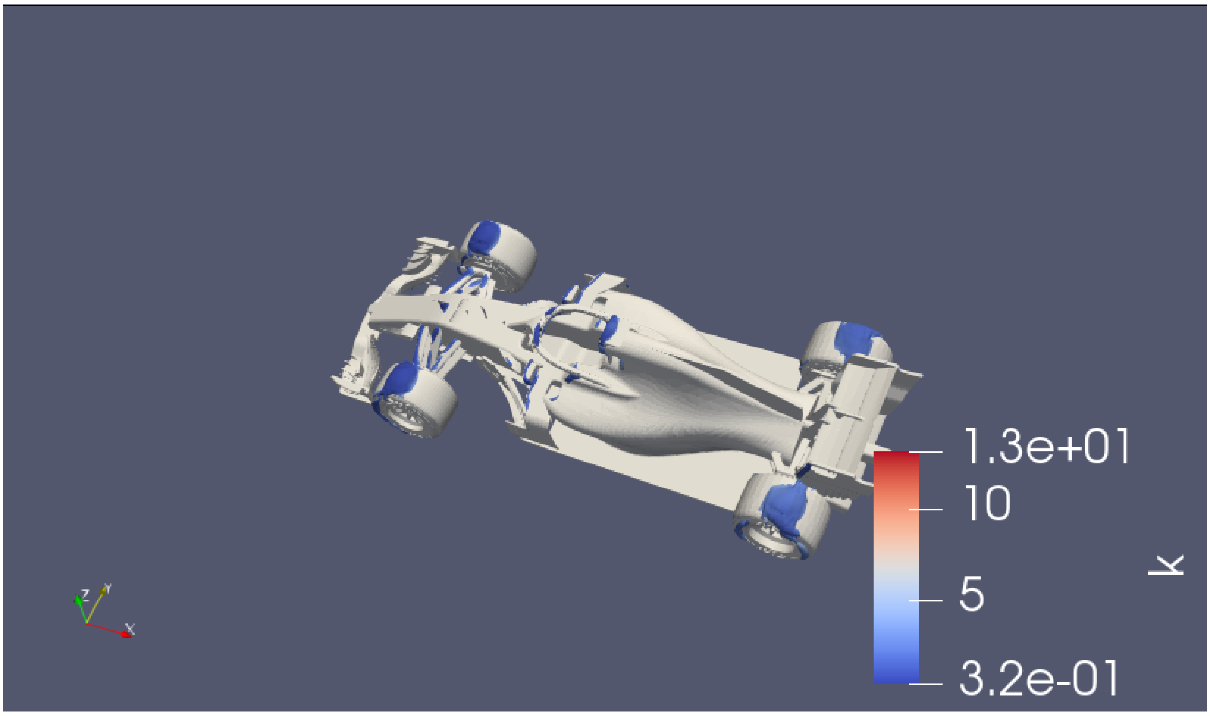

Fig 1.8 Turbulence Isosurface Extraction back/side car

RedBull(2018) F1 Car:

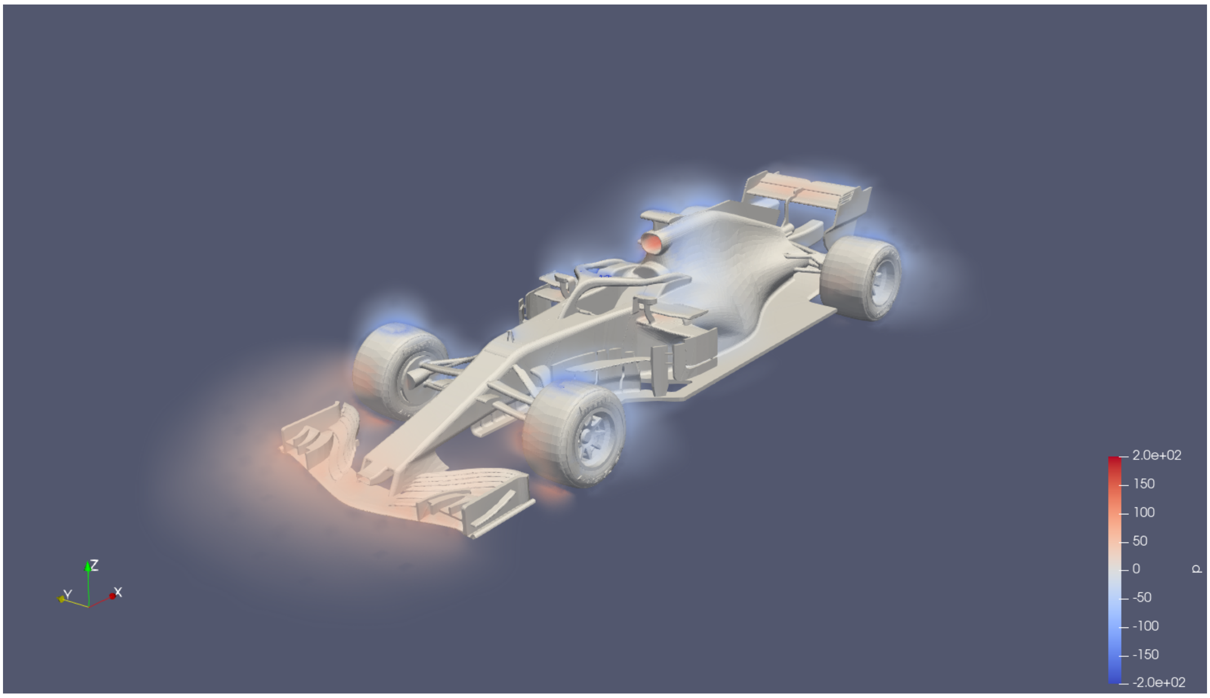

Fig 2.1 Pressure

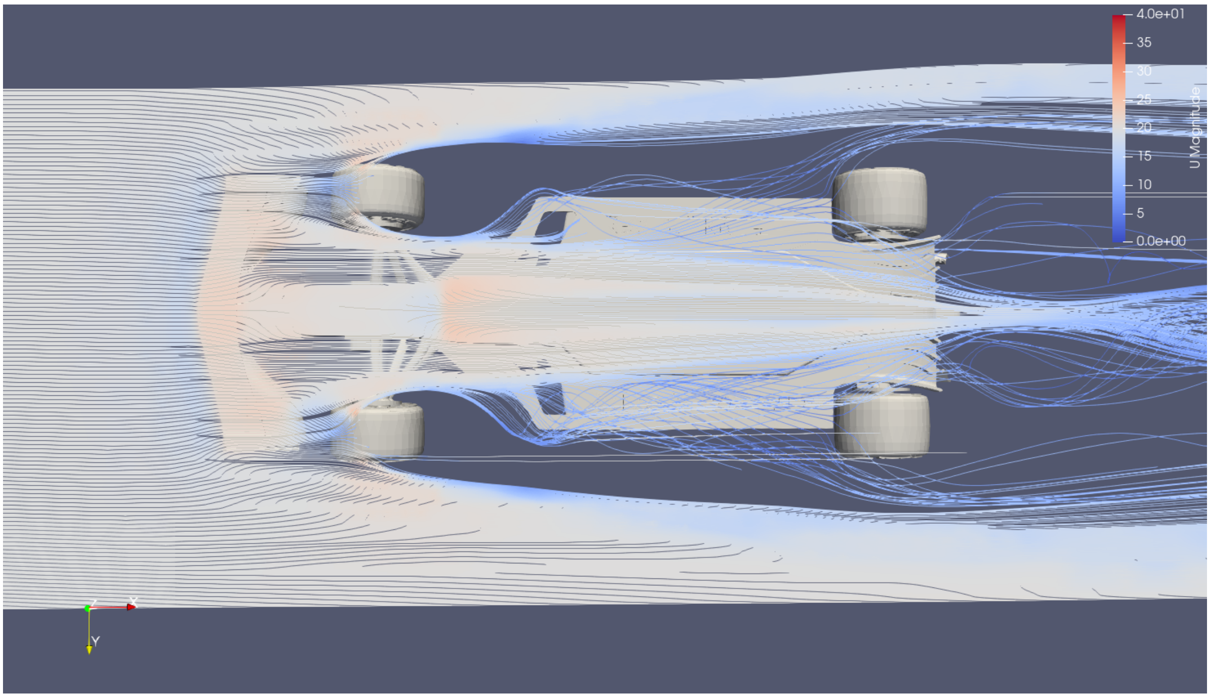

Fig 2.2 Airflow under car

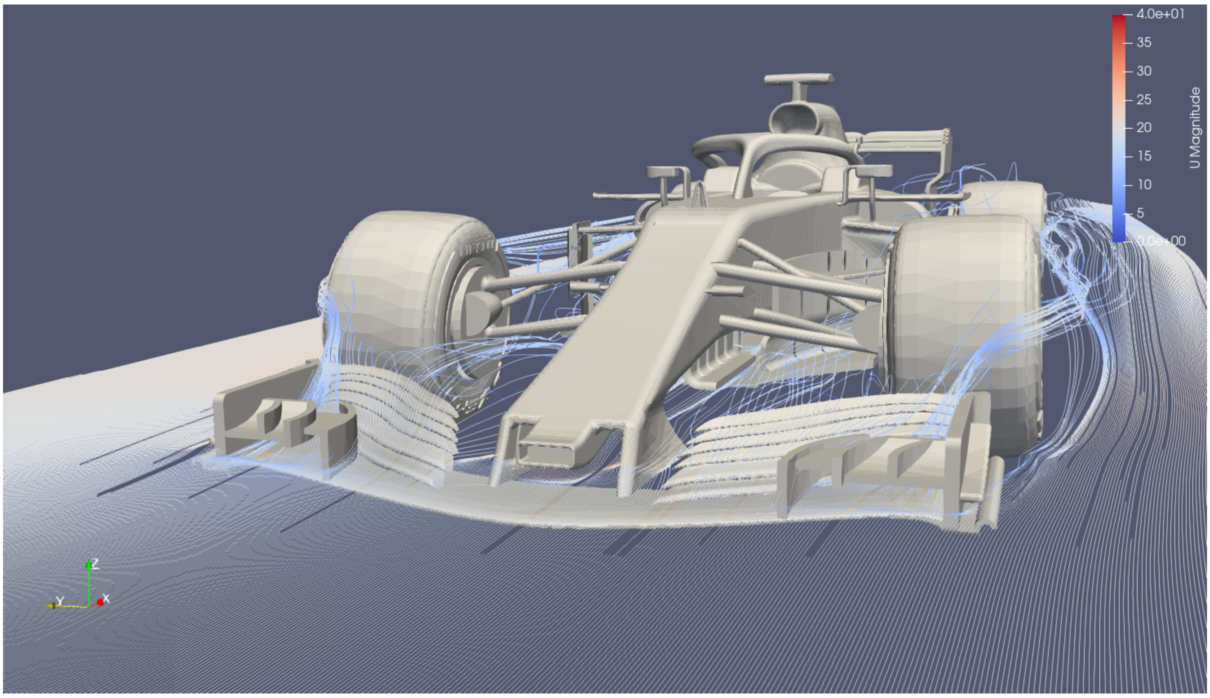

Fig 2.3 Airflow over front wing

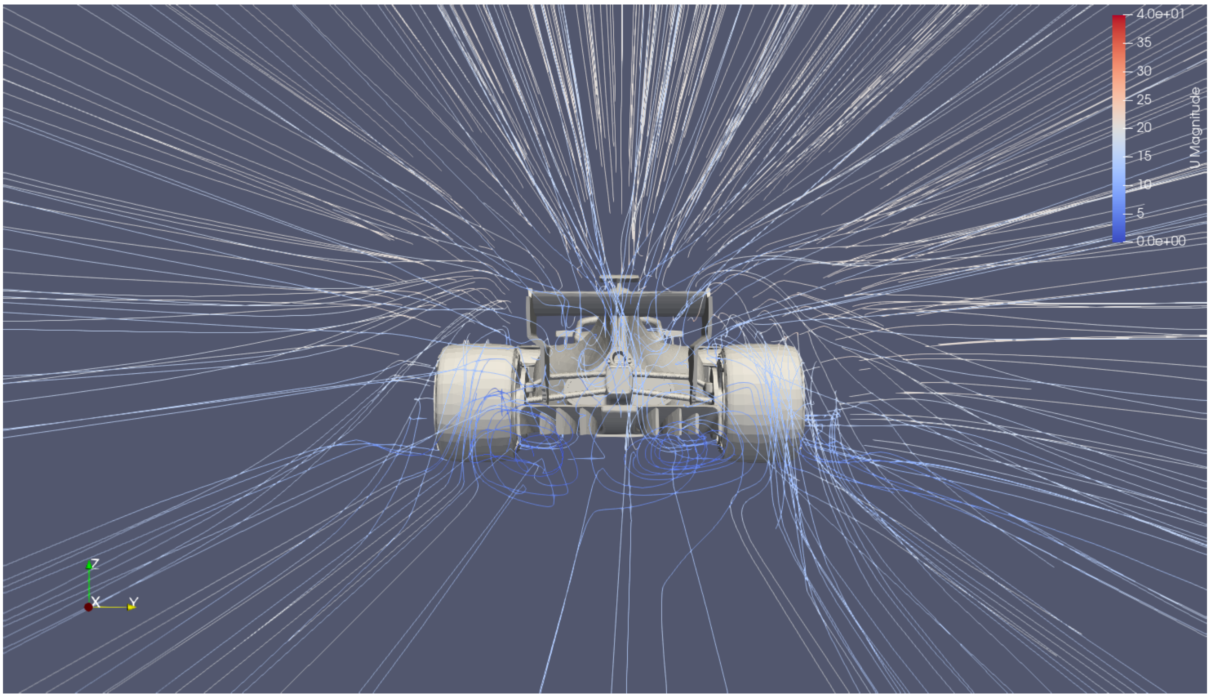

Fig 2.4 Airflow behind car

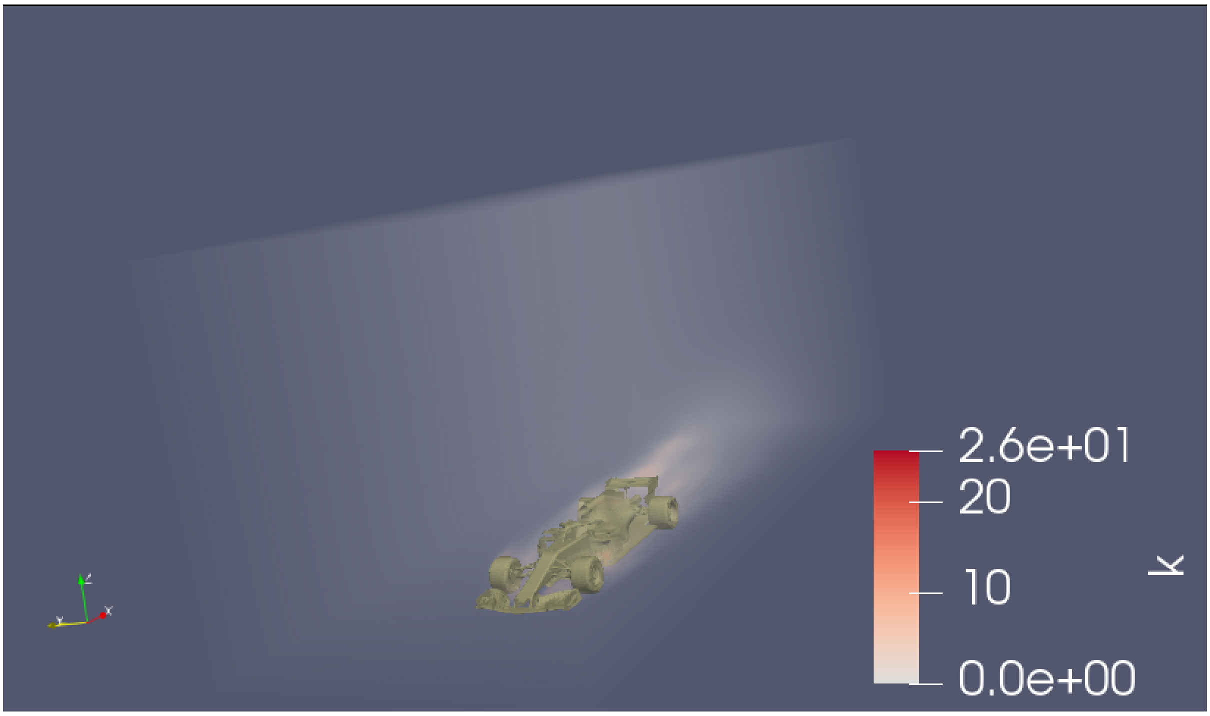

Fig 2.5 Turbulence front car

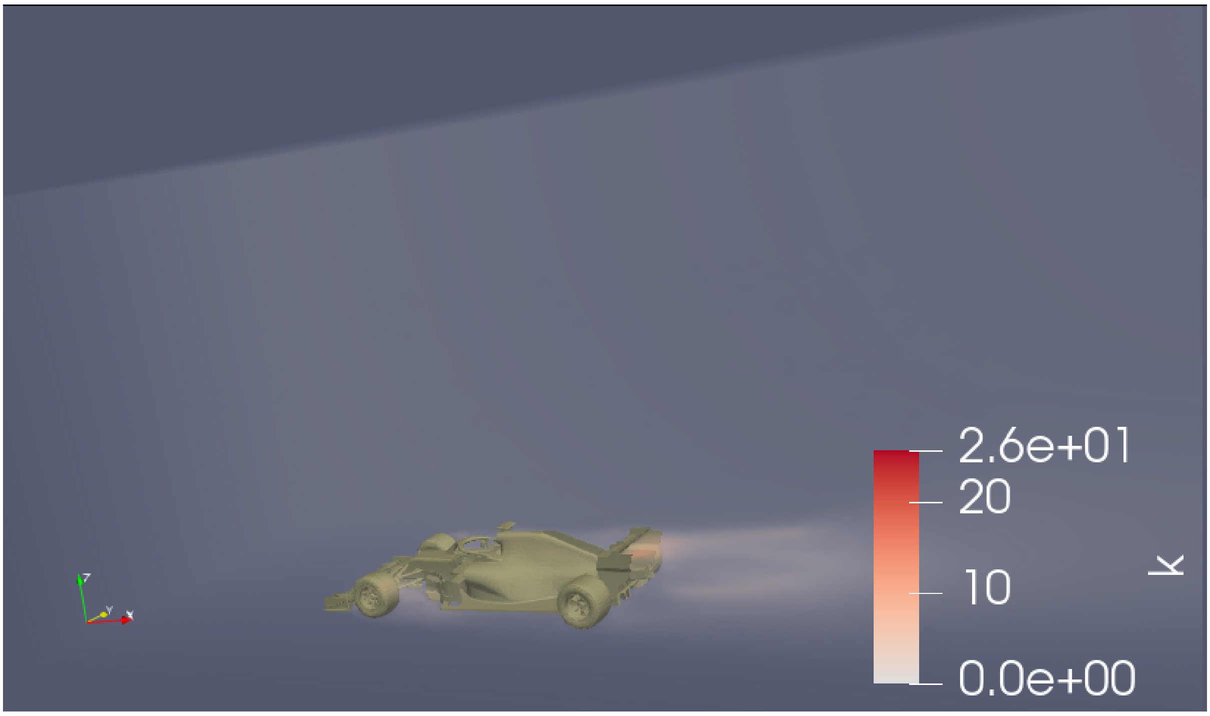

Fig 2.6 Turbulence back/side car

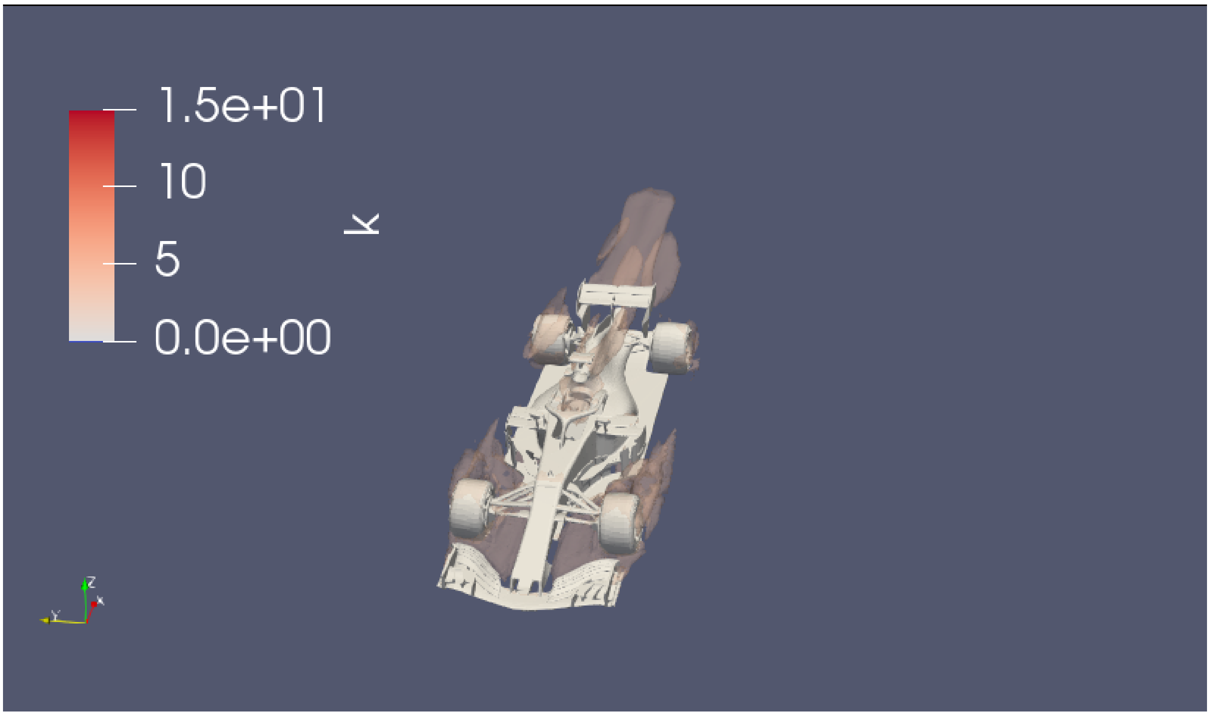

Fig 2.7 Turbulence Isosurface Extraction front car

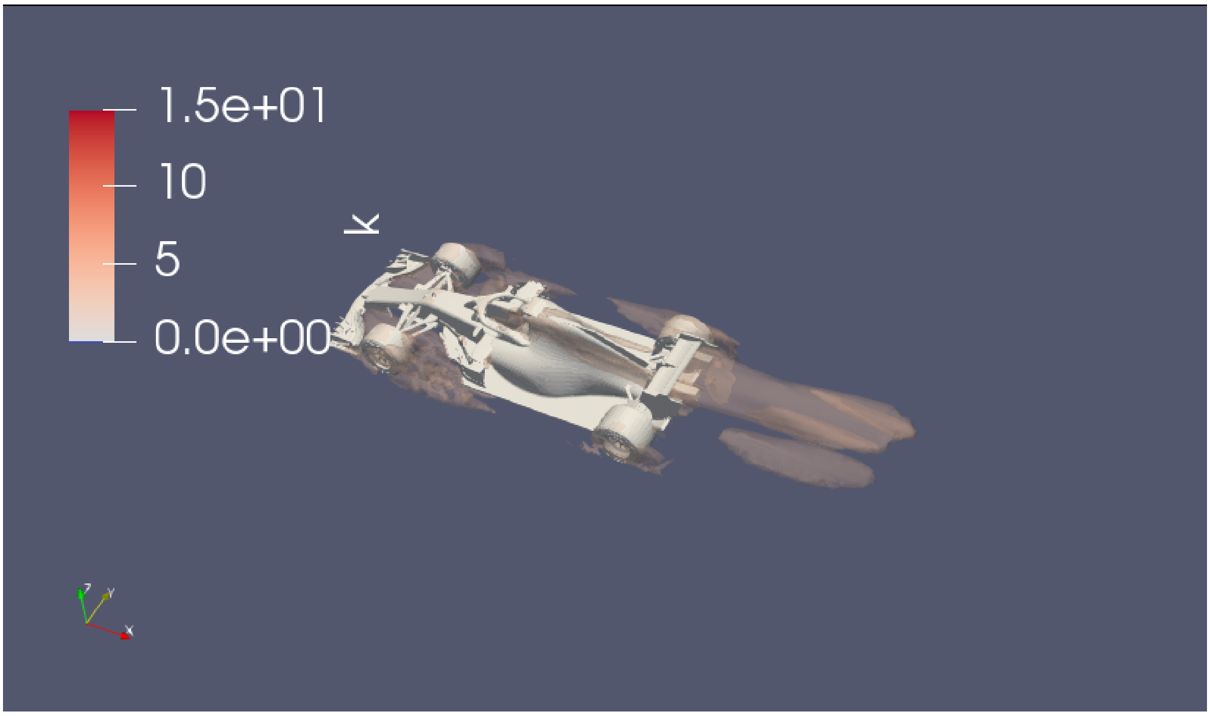

Fig 2.8 Turbulence Isosurface Extraction back/side car

McLaren(1991) F1 Car

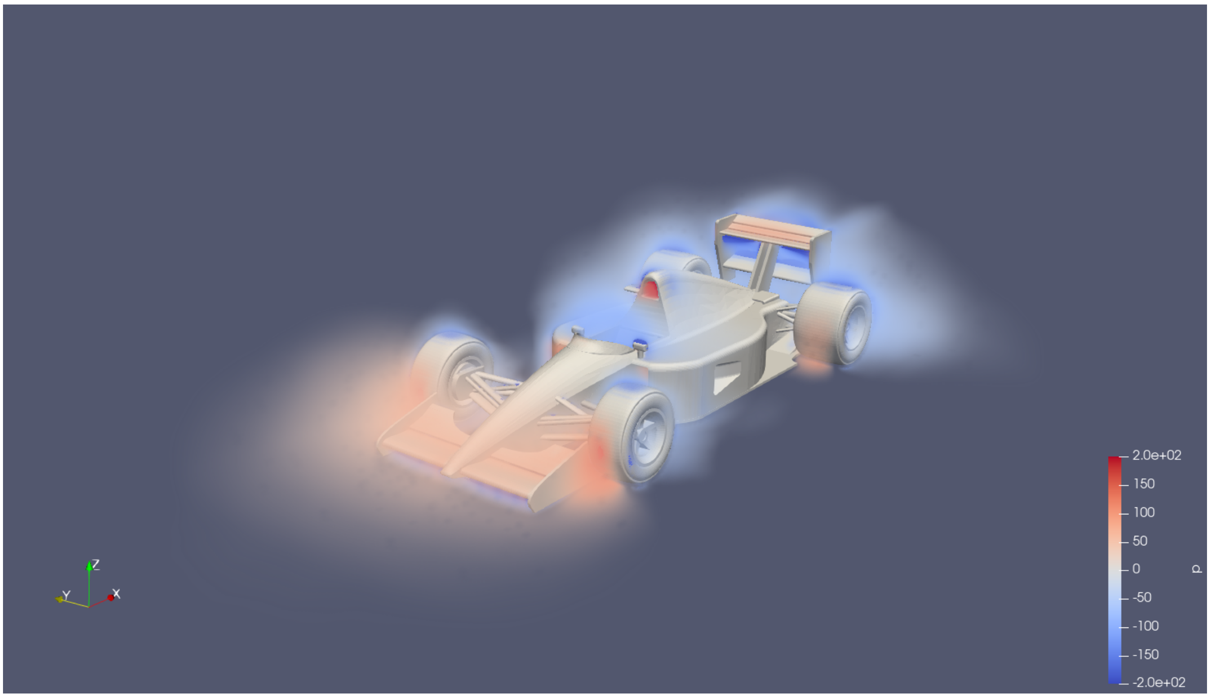

Fig 3.1 Pressure

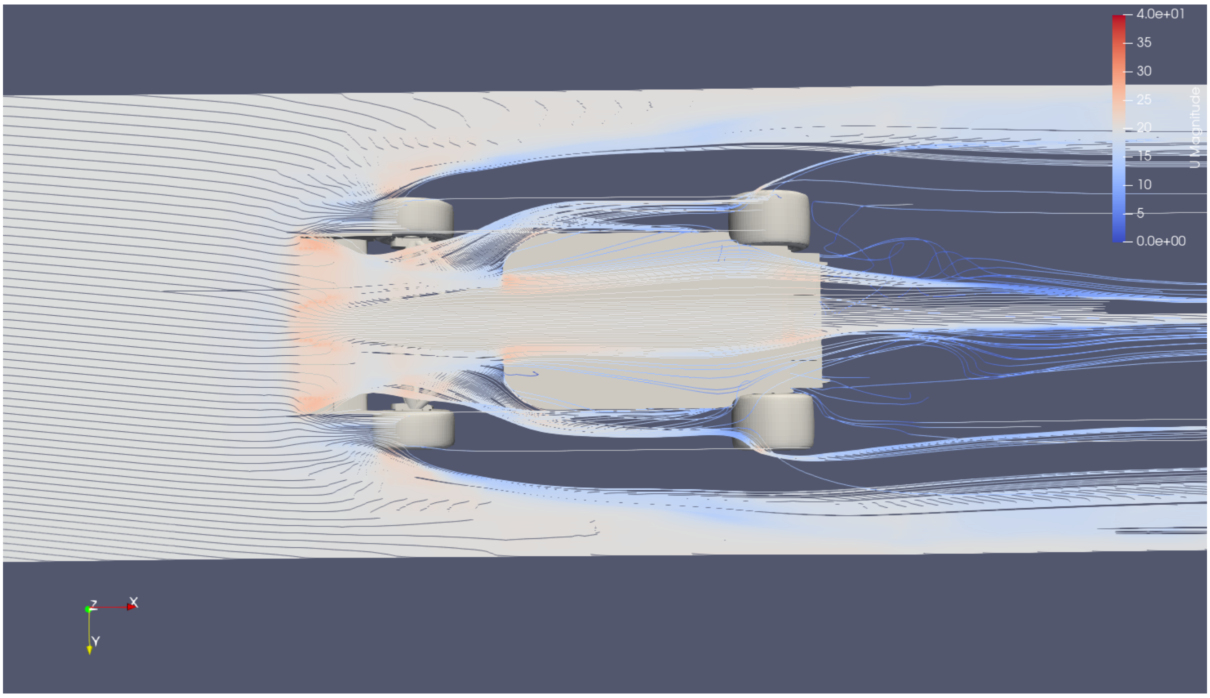

Fig 3.2 Airflow under car

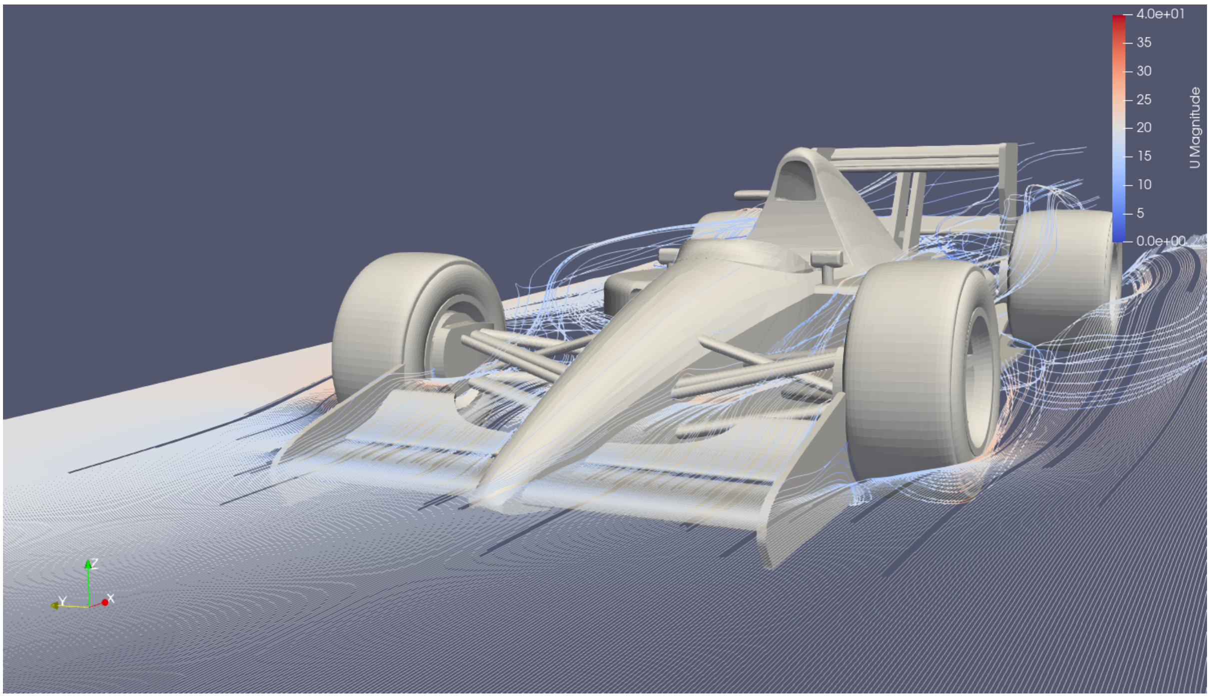

Fig 3.3 Airflow over front wing

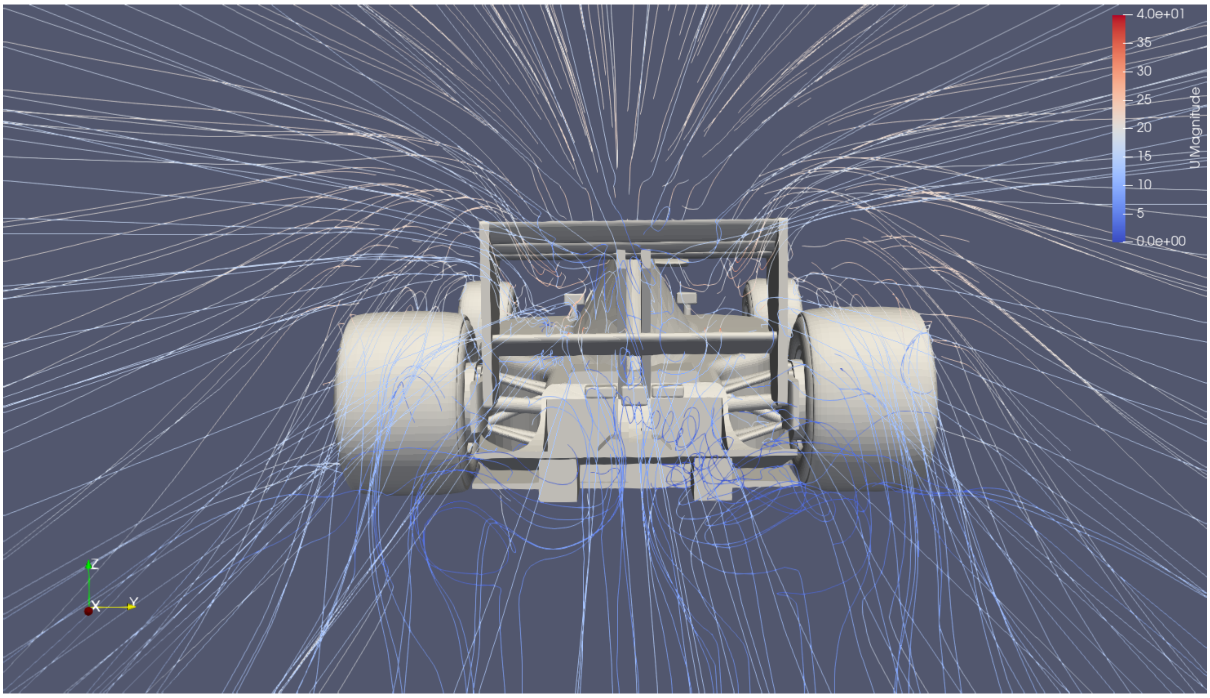

Fig 3.4 Airflow behind car

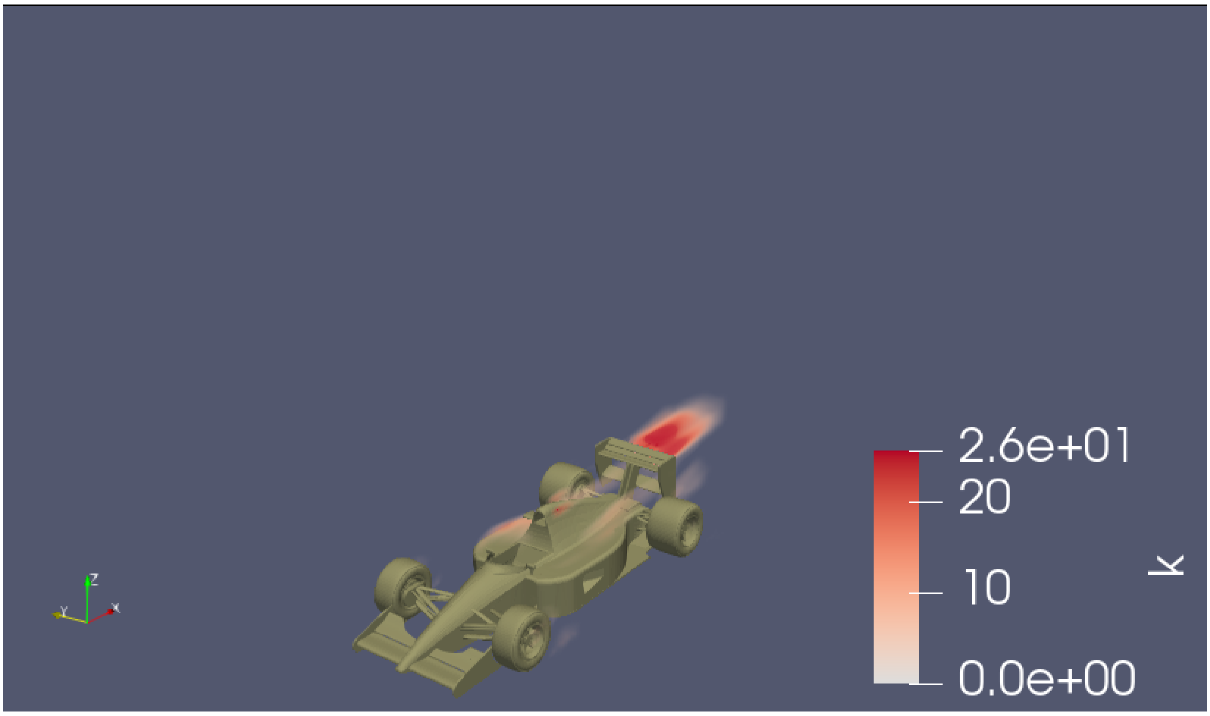

Fig 3.5 Turbulence front car

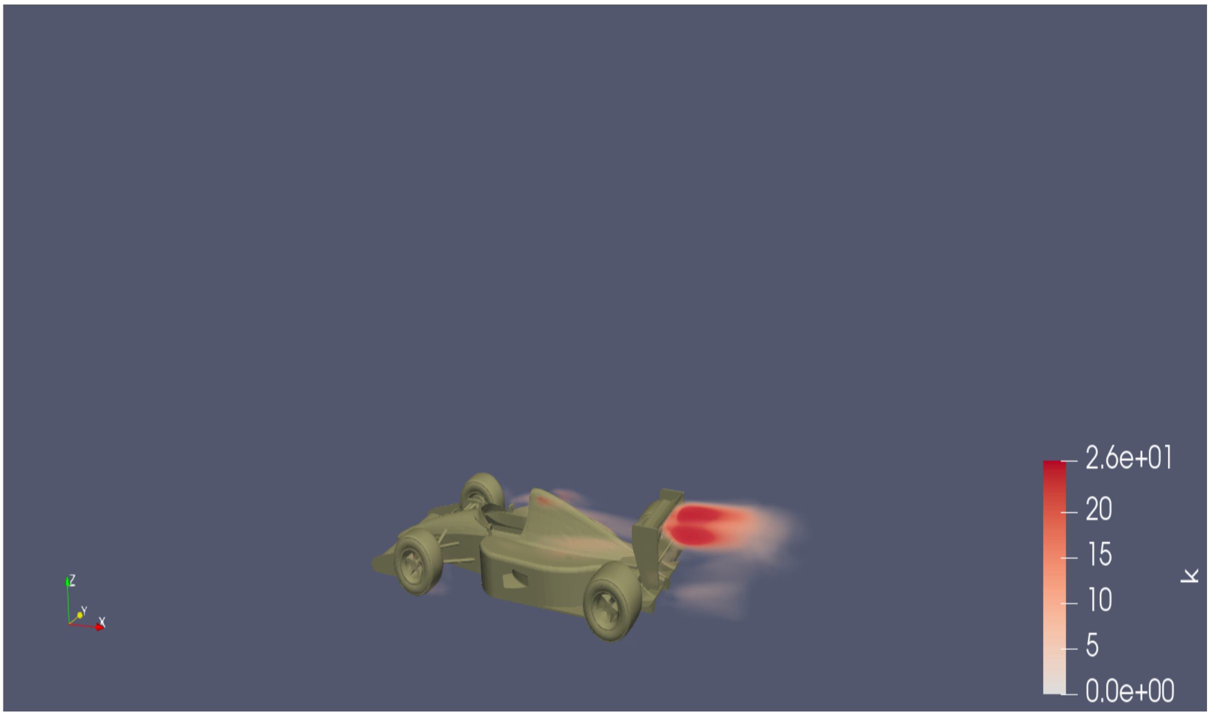

Fig 3.6 Turbulence back/side car

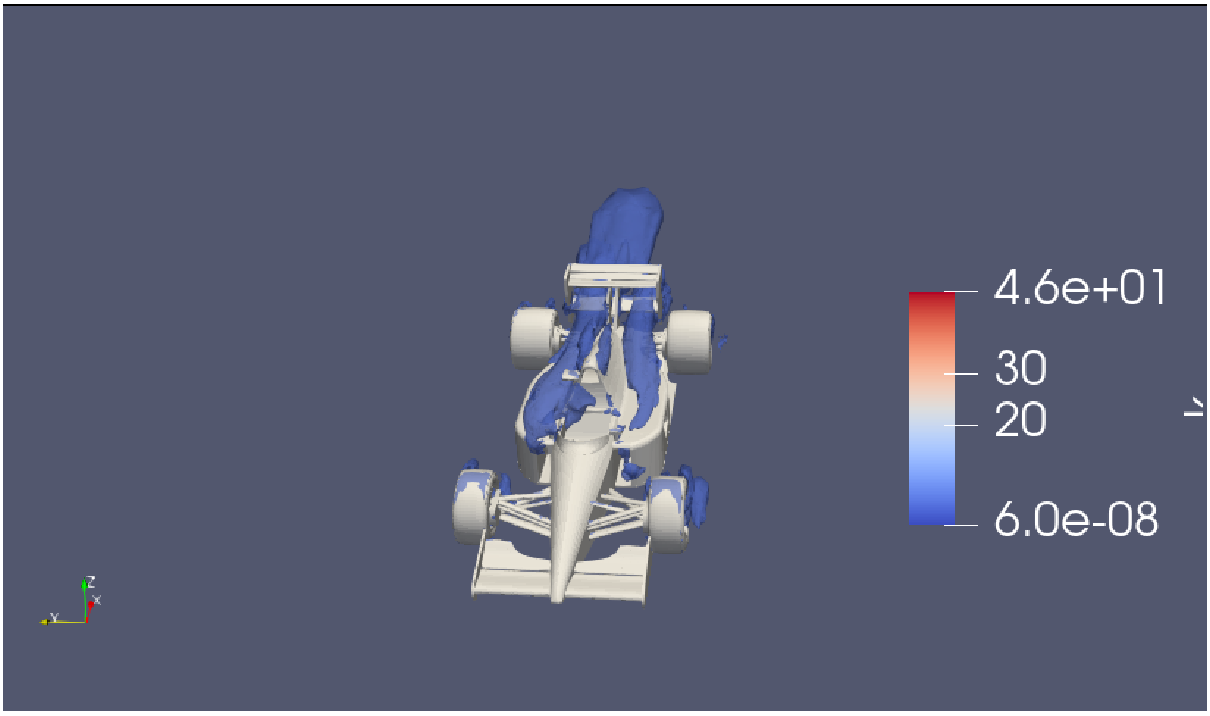

Fig 3.7 Turbulence Isosurface Extraction front car

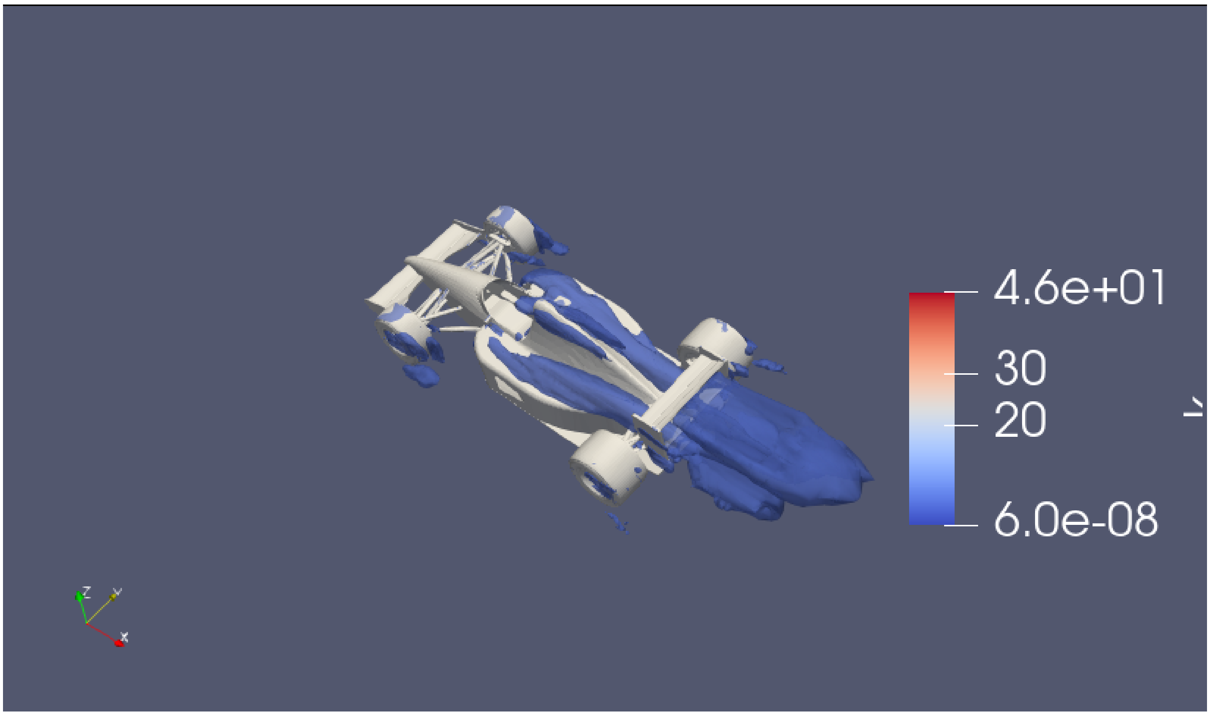

Fig 3.8 Turbulence Isosurface Extraction back/side car

Williams(1991) F1 Car:

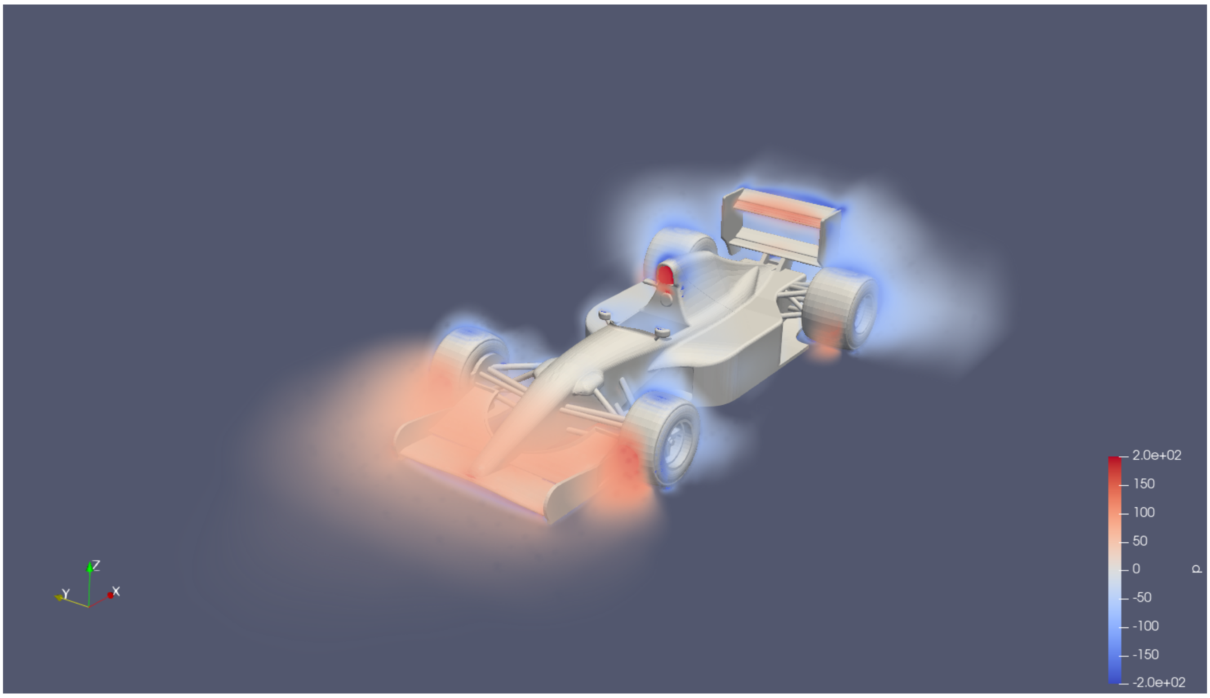

Fig 4.1 Pressure

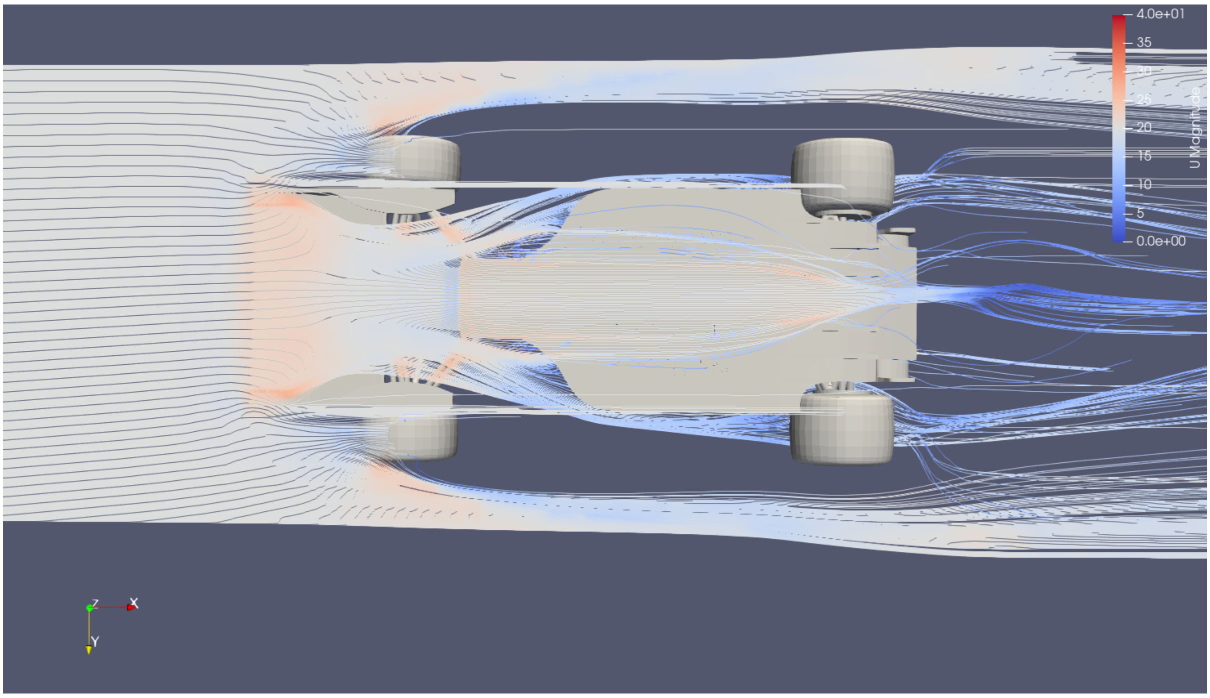

Fig 4.2 Airflow under car

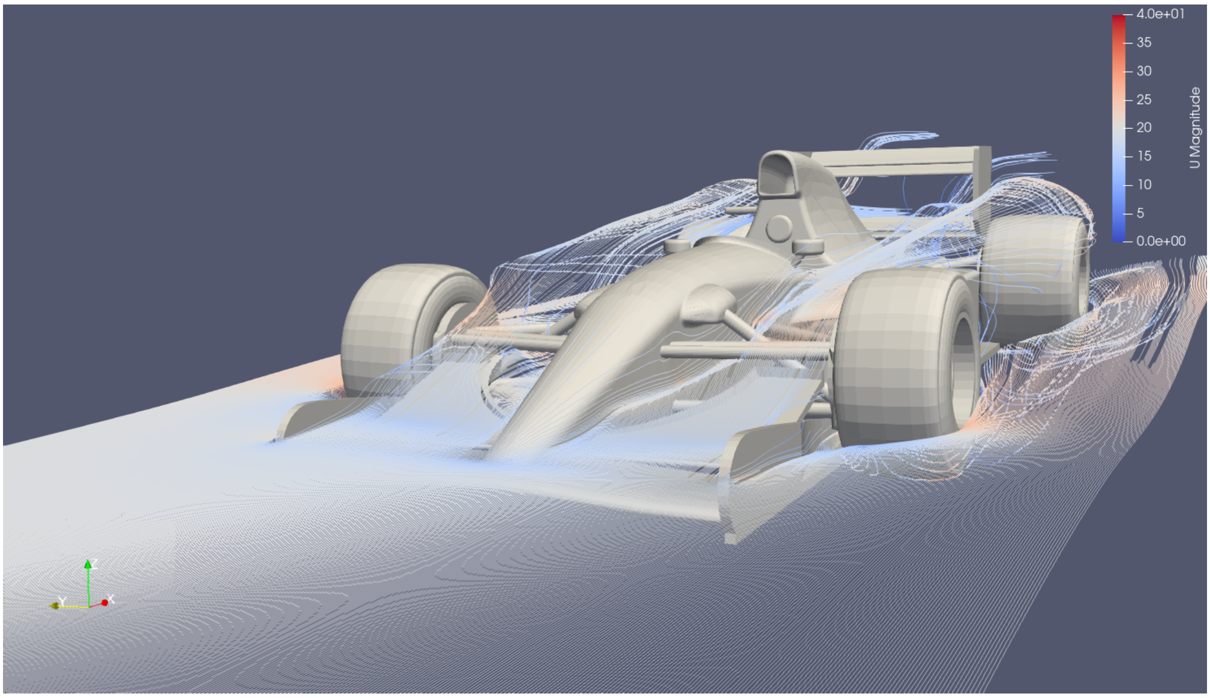

Fig 4.3 Airflow over front wing

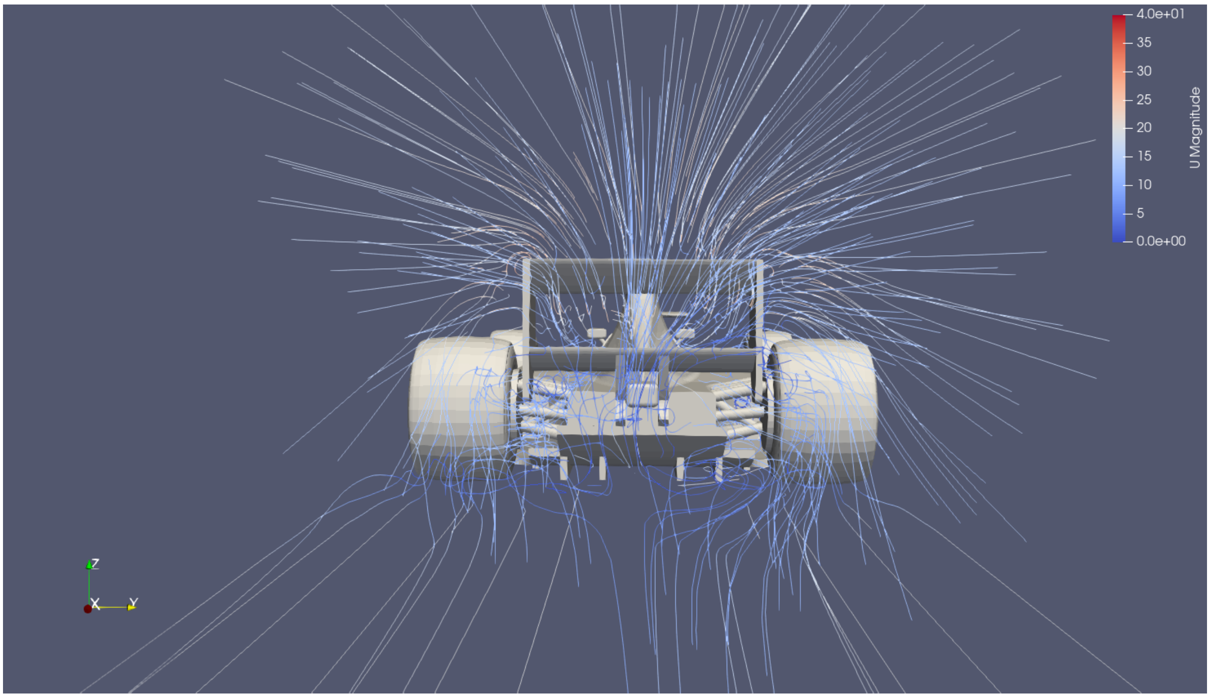

Fig 4.4 Airflow behind car

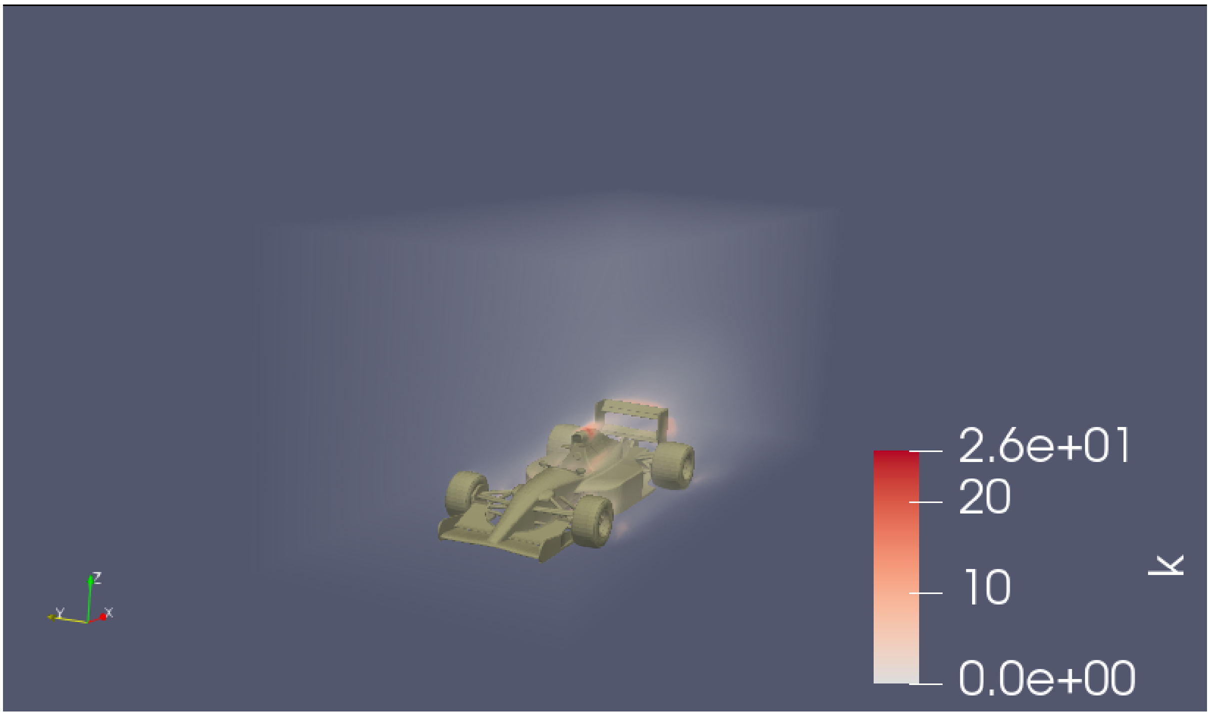

Fig 4.5 Turbulence front car

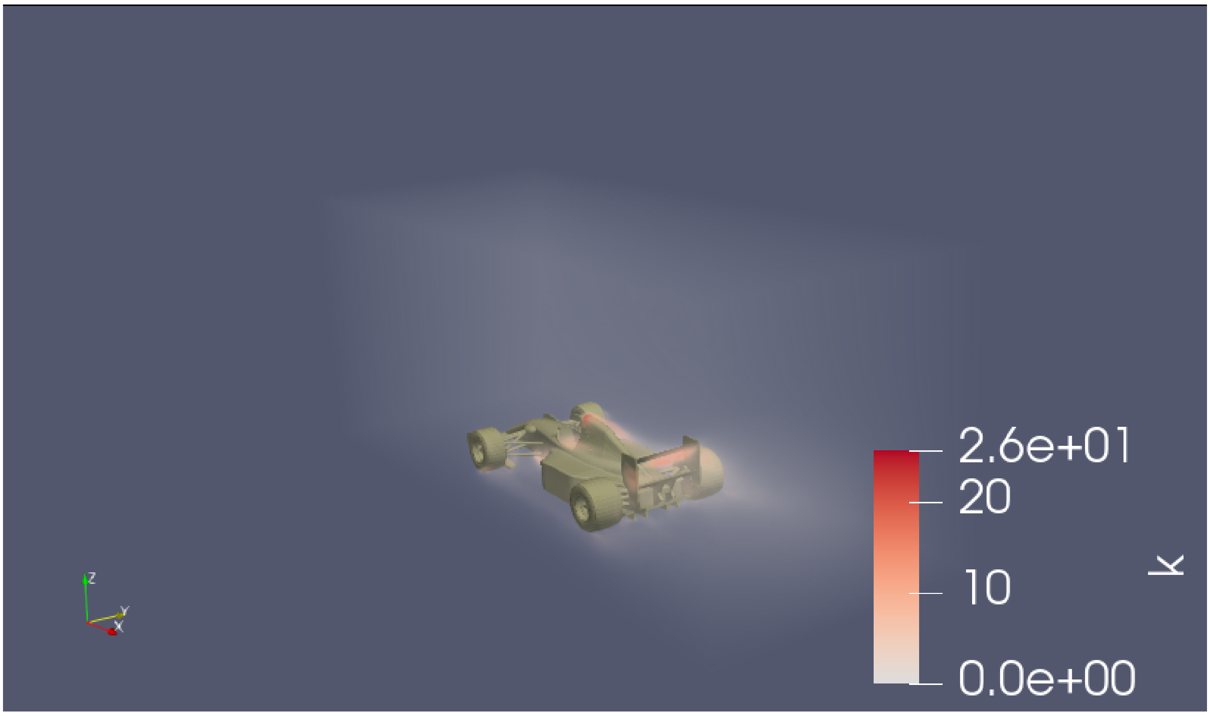

Fig 4.6 Turbulence back/side car

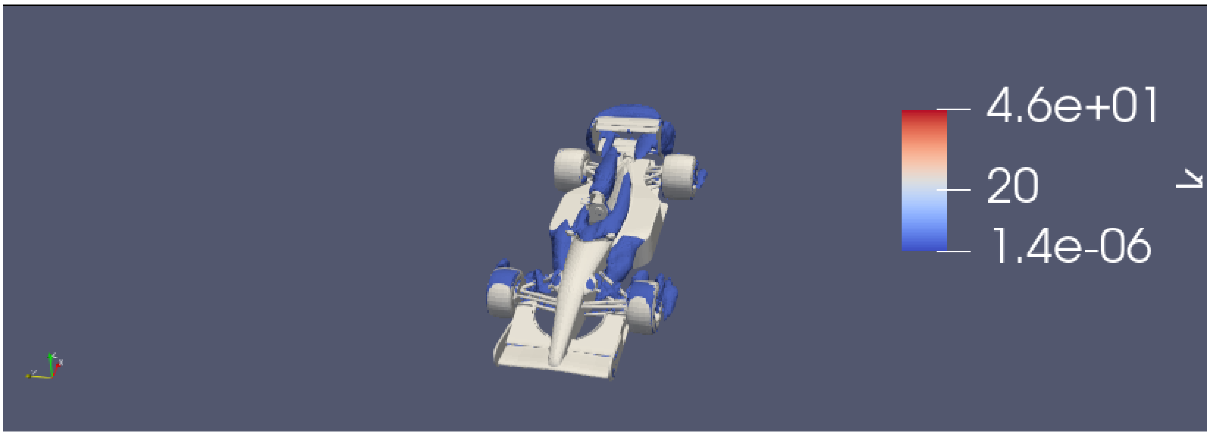

Fig 4.7 Turbulence Isosurface Extraction front car

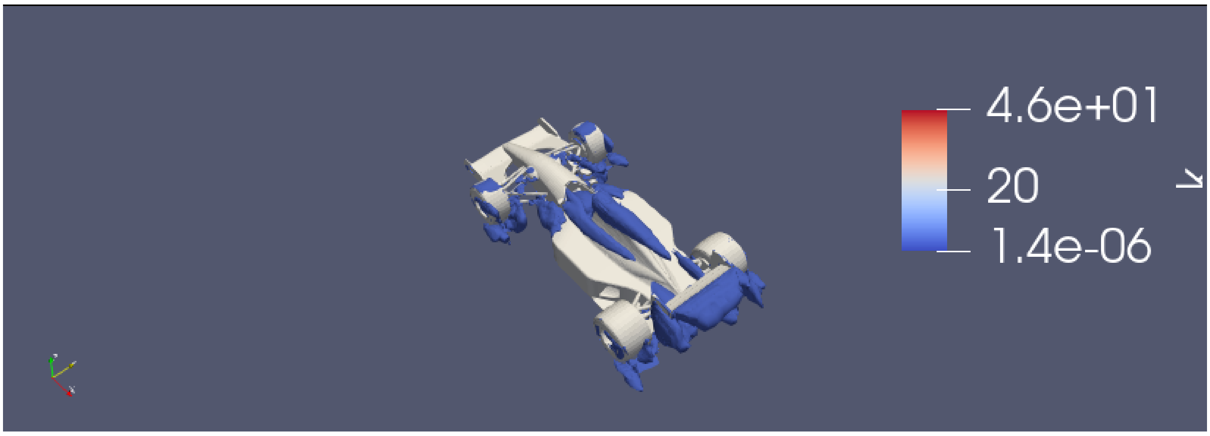

Fig 4.8 Turbulence Isosurface Extraction back/side car

Ferrari (1970) F1 Car:

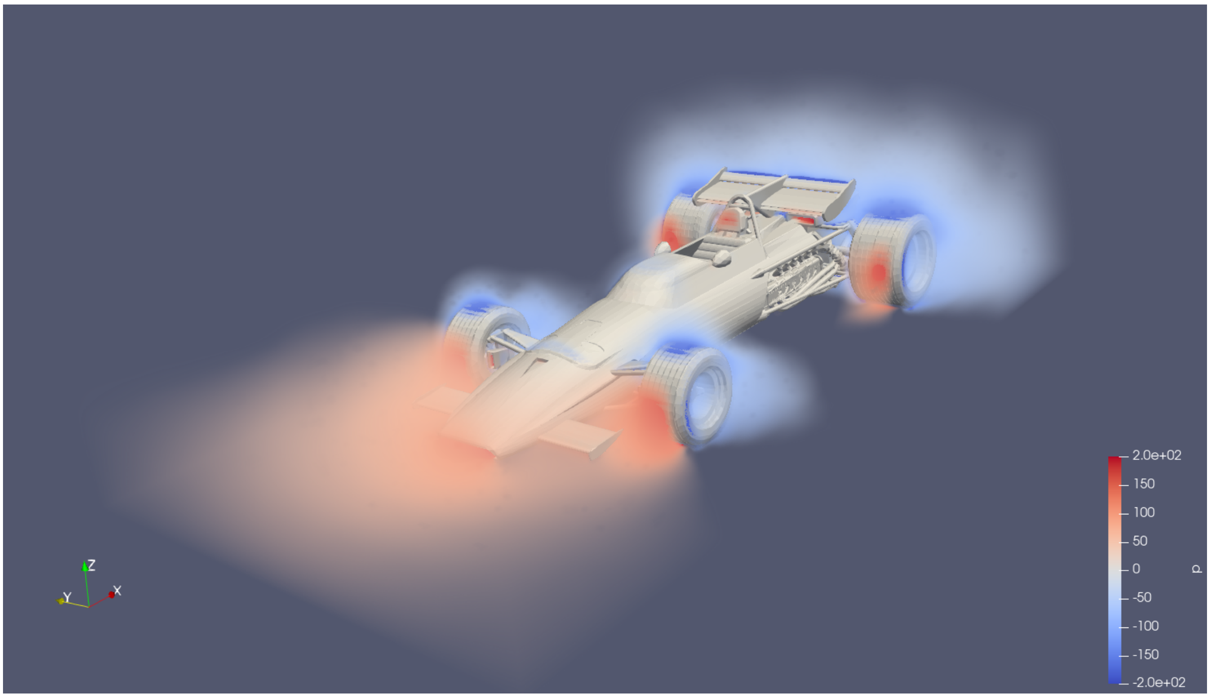

Fig 5.1 Pressure

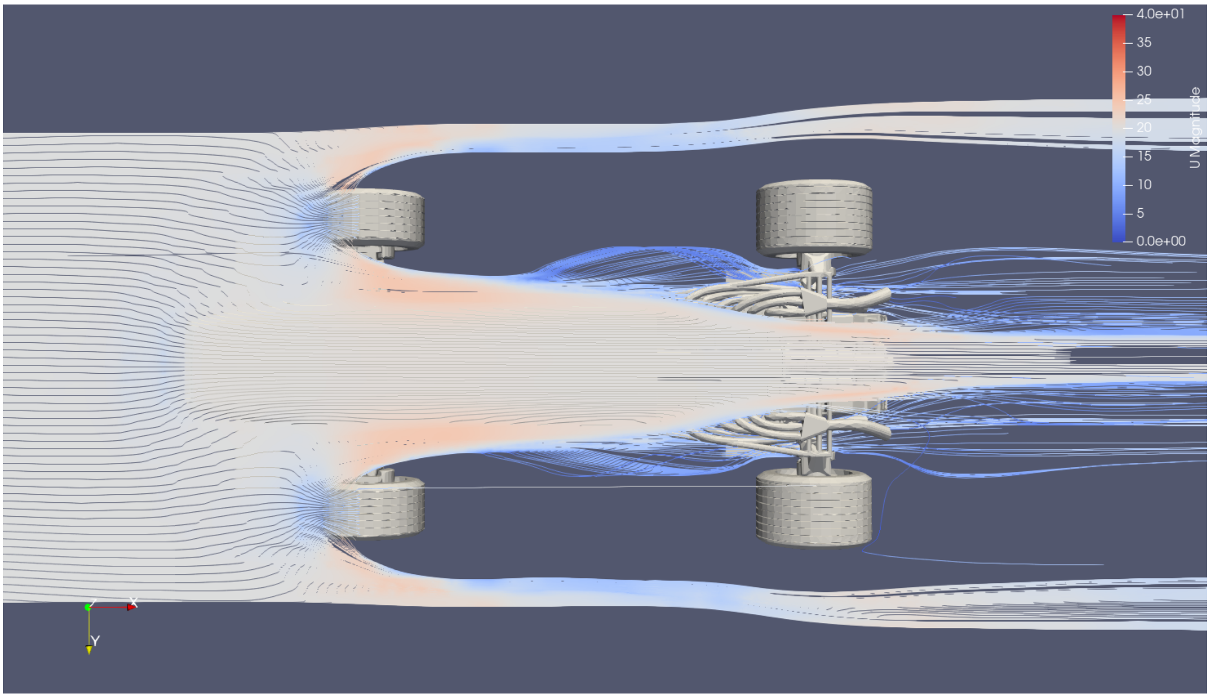

Fig 5.2 Airflow under car

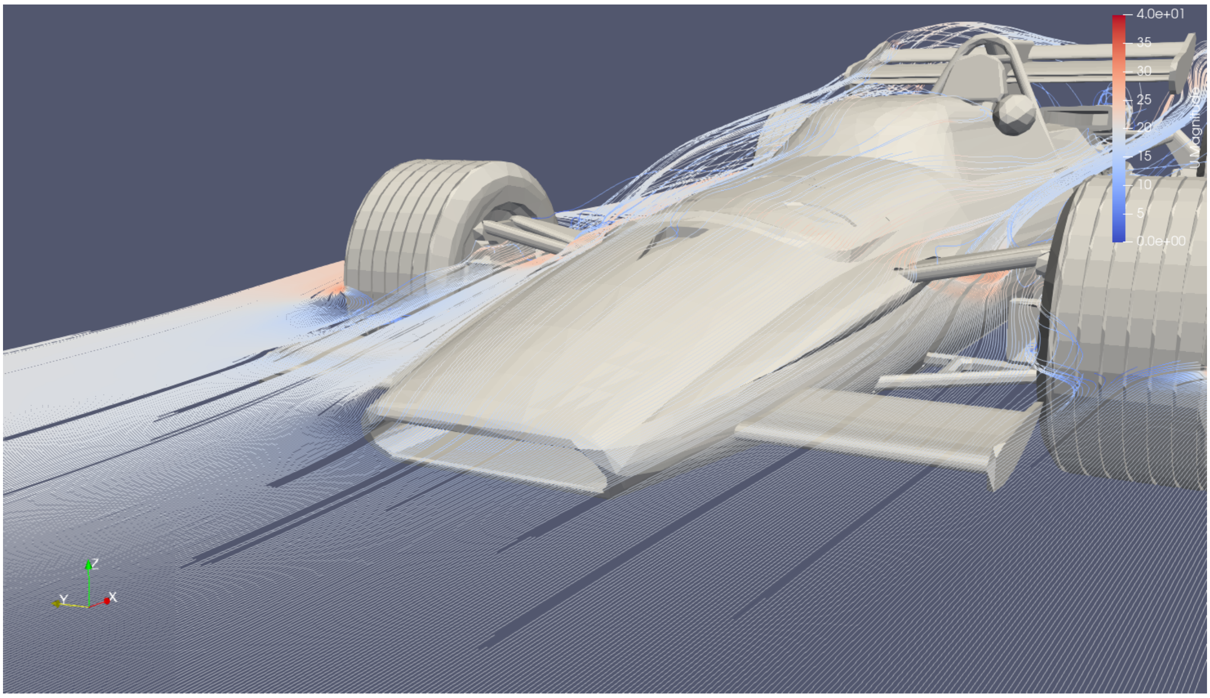

Fig 5.3 Airflow over front wing

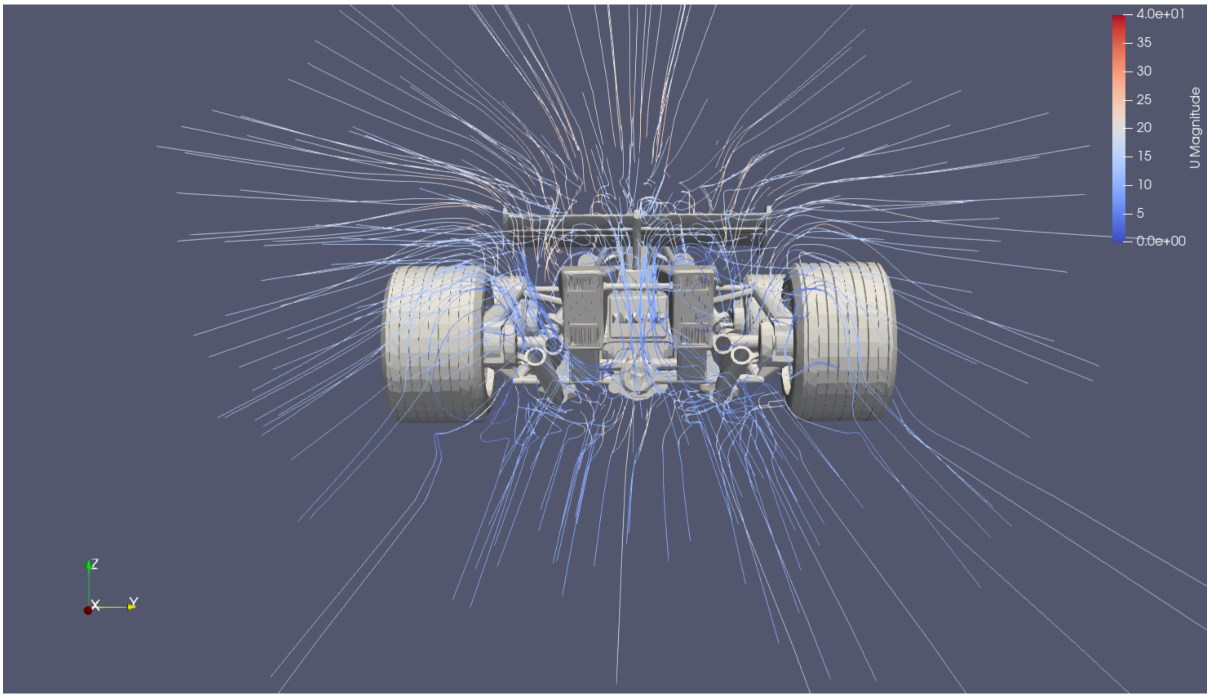

Fig 5.4 Airflow behind car

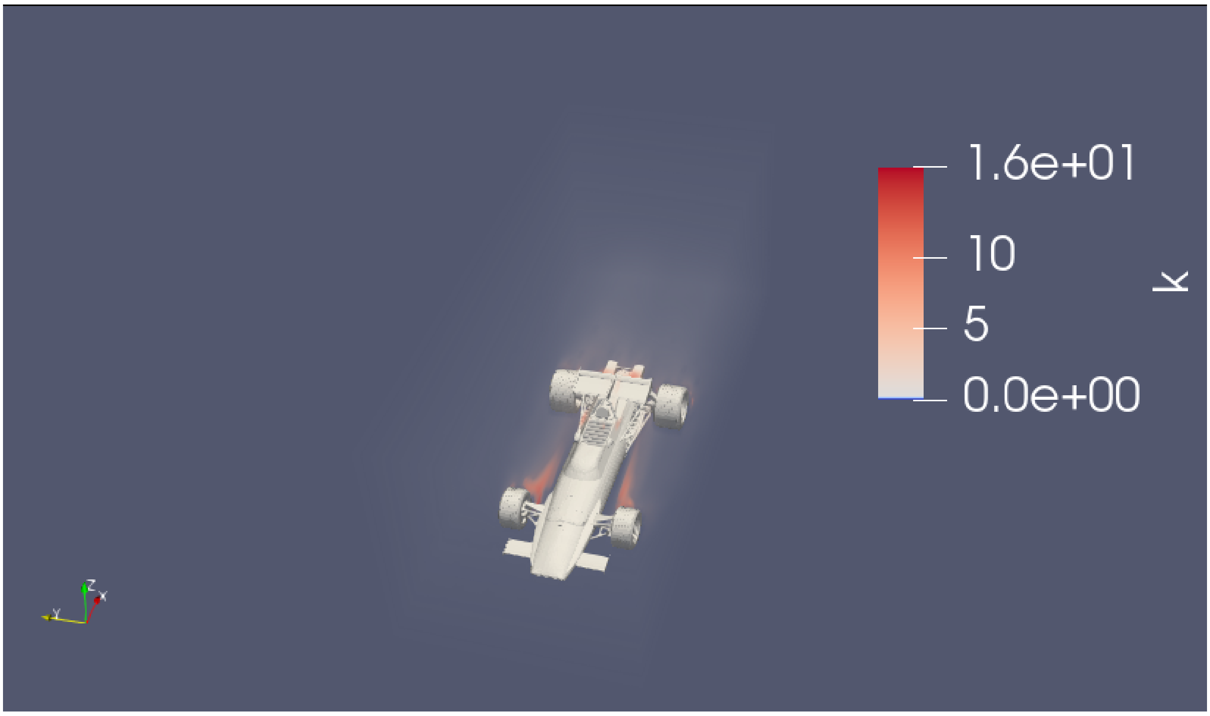

Fig 5.5 Turbulence front car

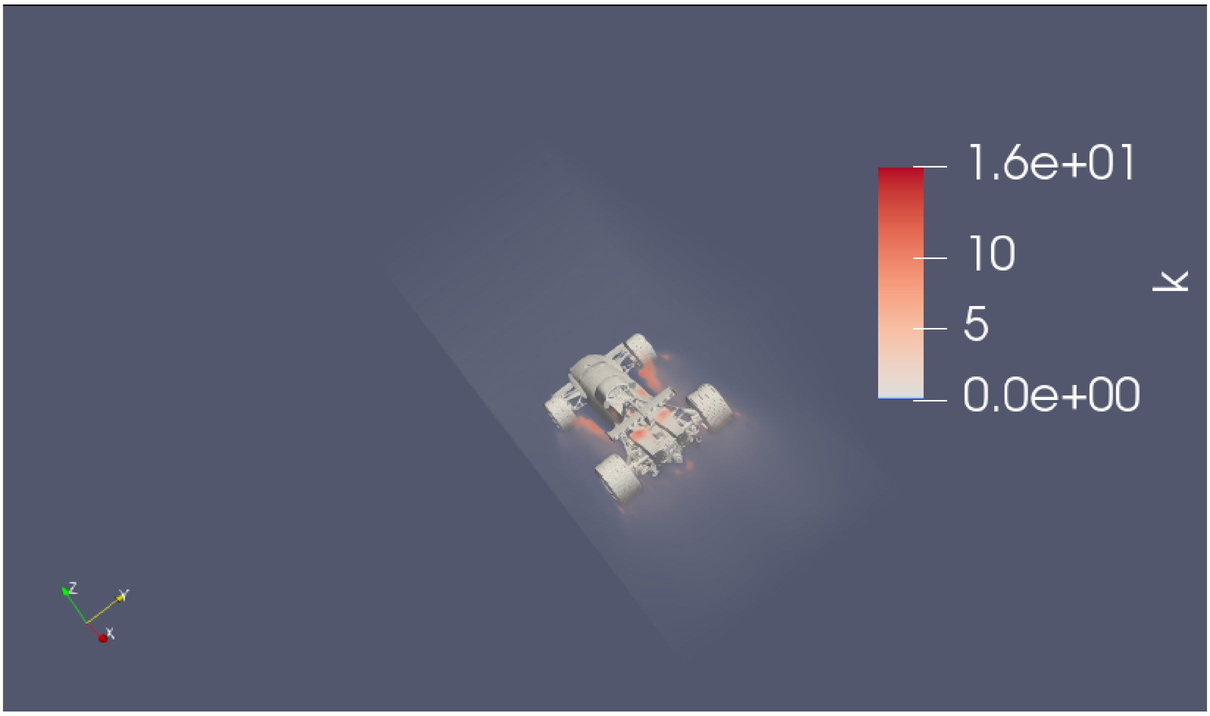

Fig 5.6 Turbulence back/side car

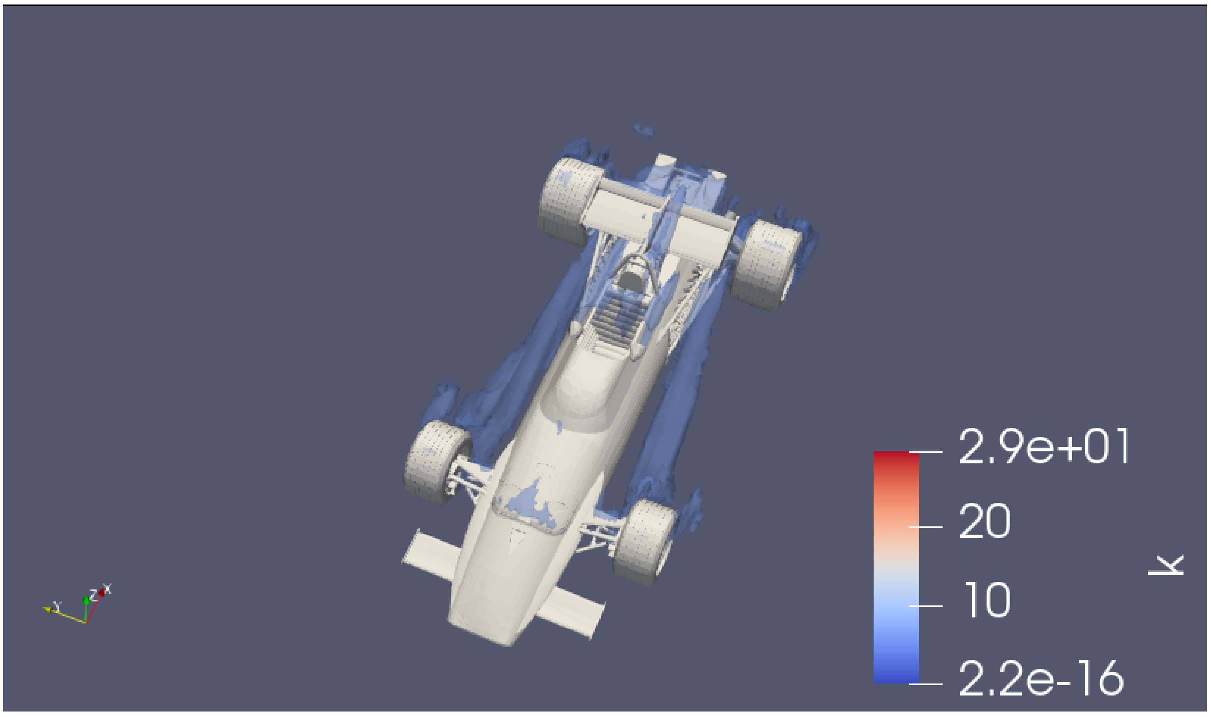

Fig 5.7 Turbulence Isosurface Extraction front car

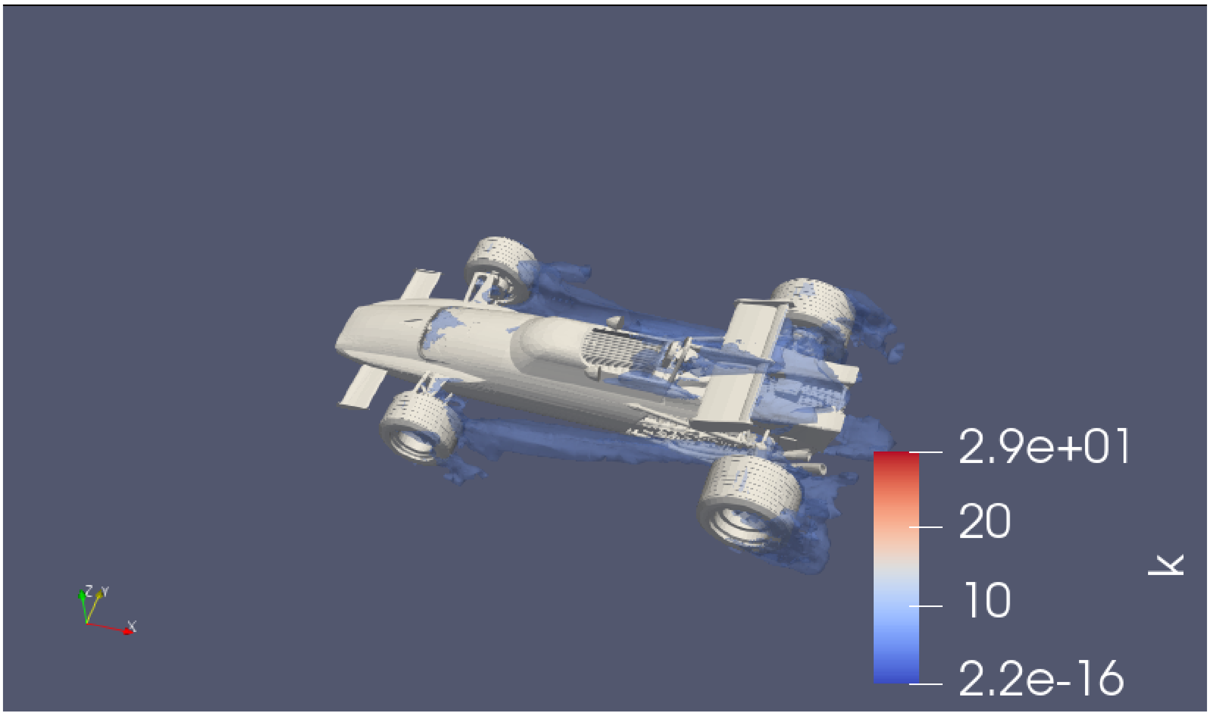

Fig 5.8 Turbulence Isosurface Extraction back/side car

Lotus (1970) F1 Car:

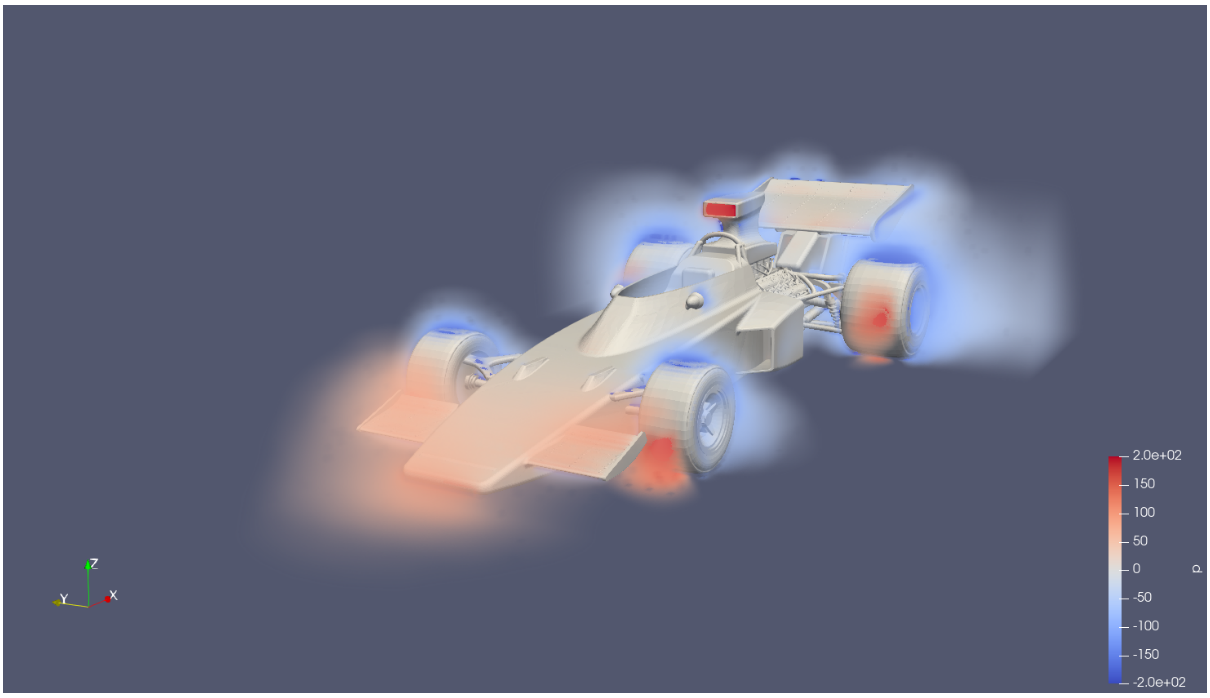

Fig 6.1 Pressure

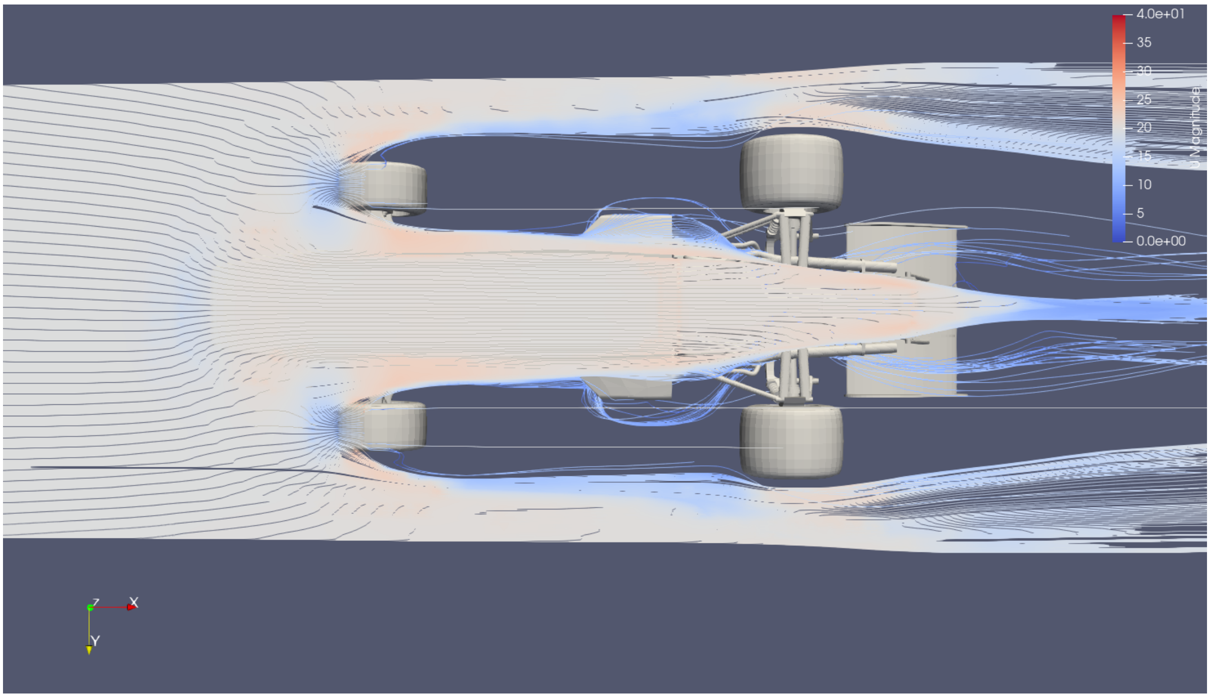

Fig 6.2 Airflow under car

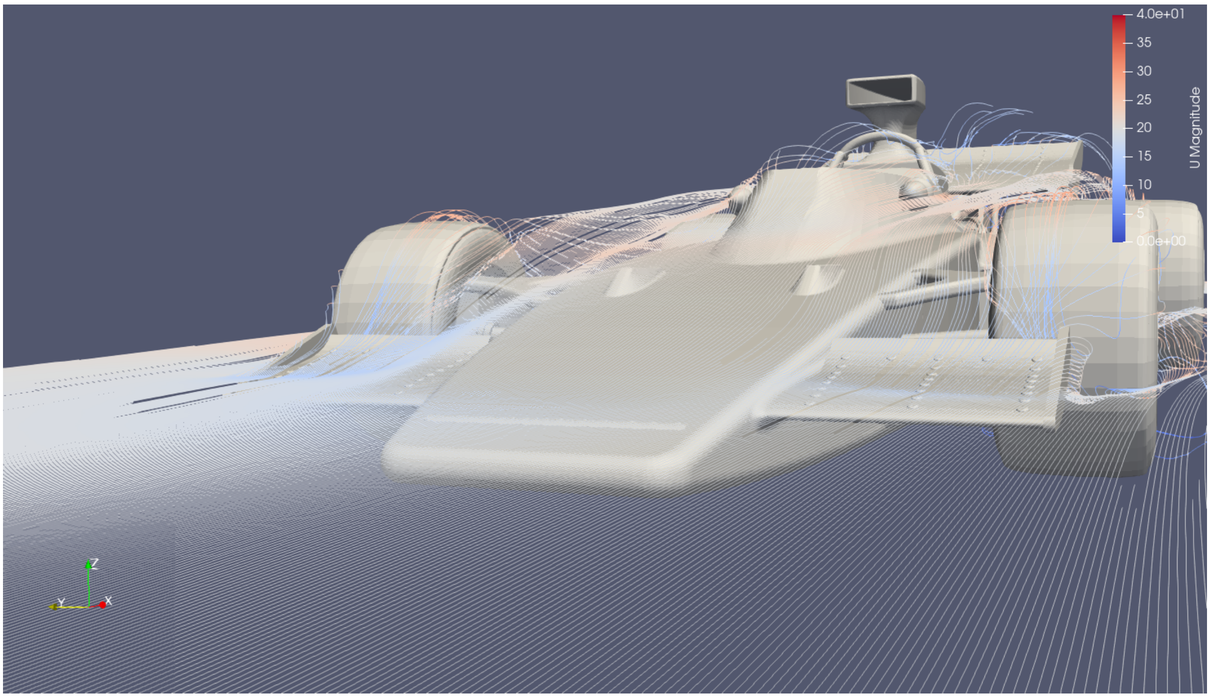

Fig 6.3 Airflow over front wing

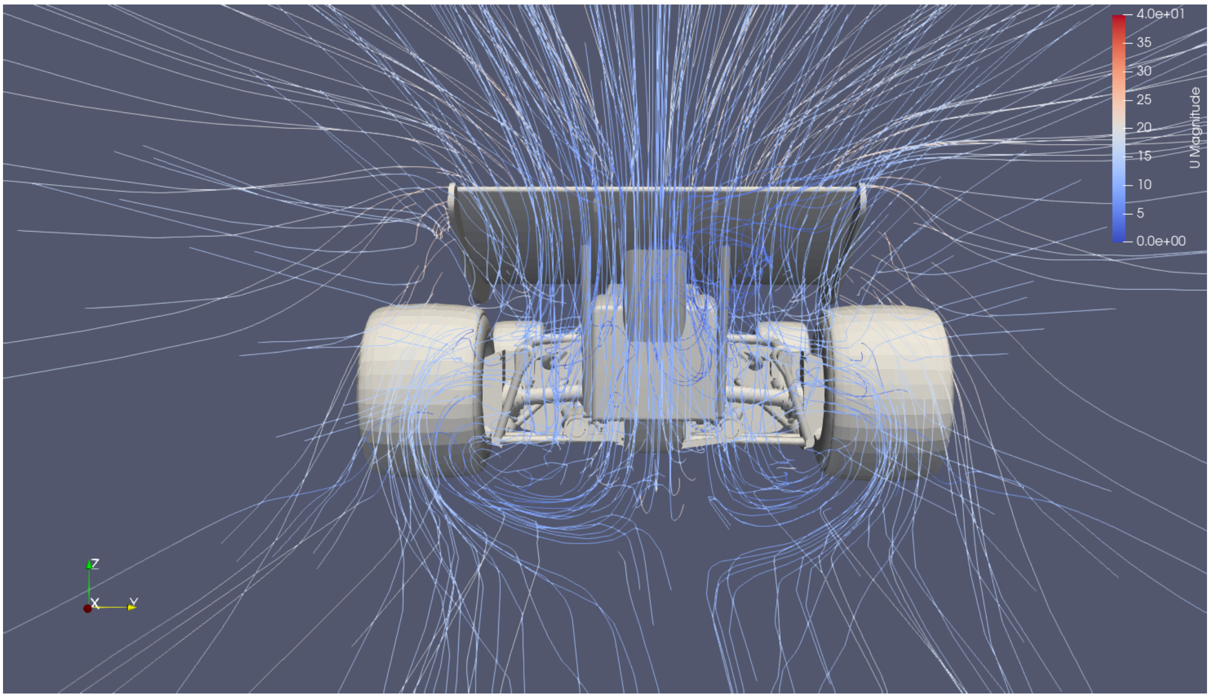

Fig 6.4 Airflow behind car

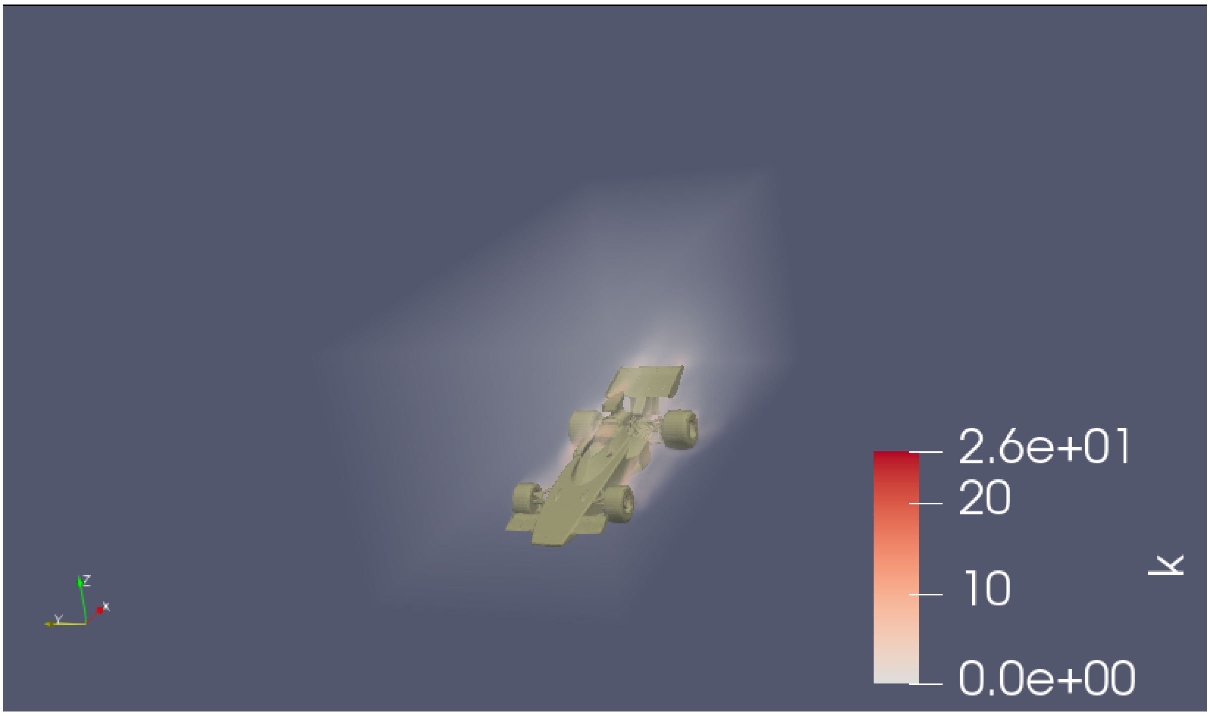

Fig 6.5 Turbulence front car

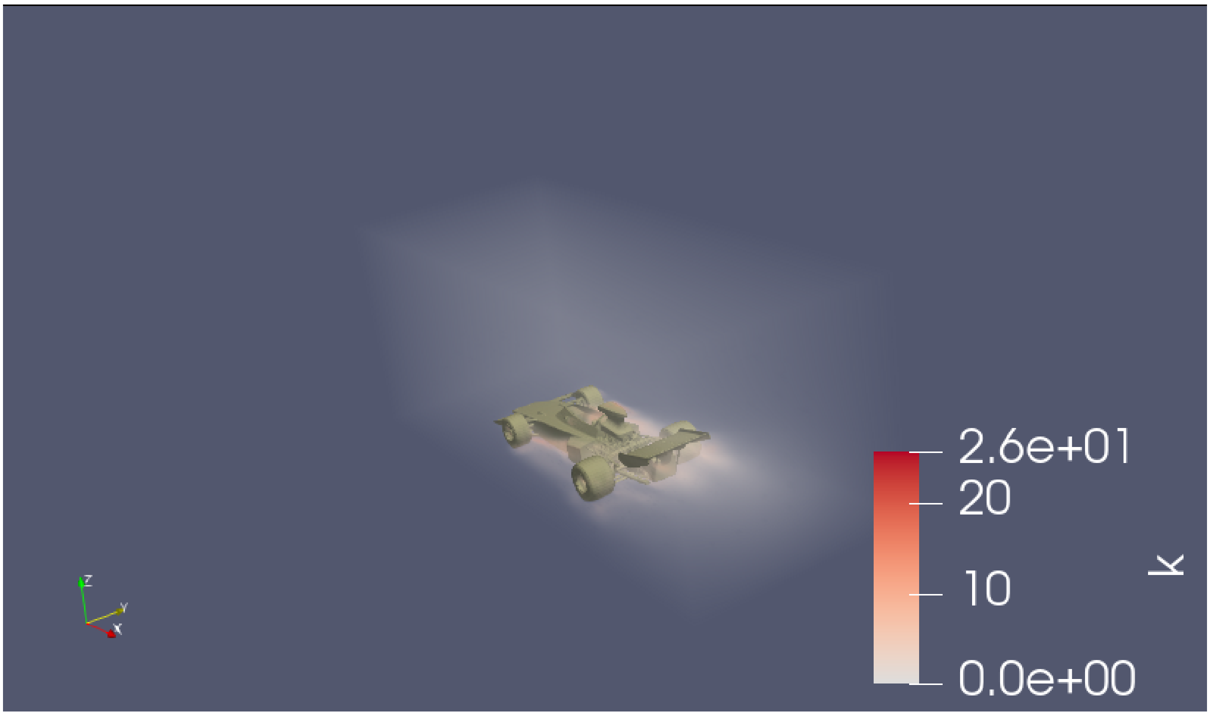

Fig 6.6 Turbulence back/side car

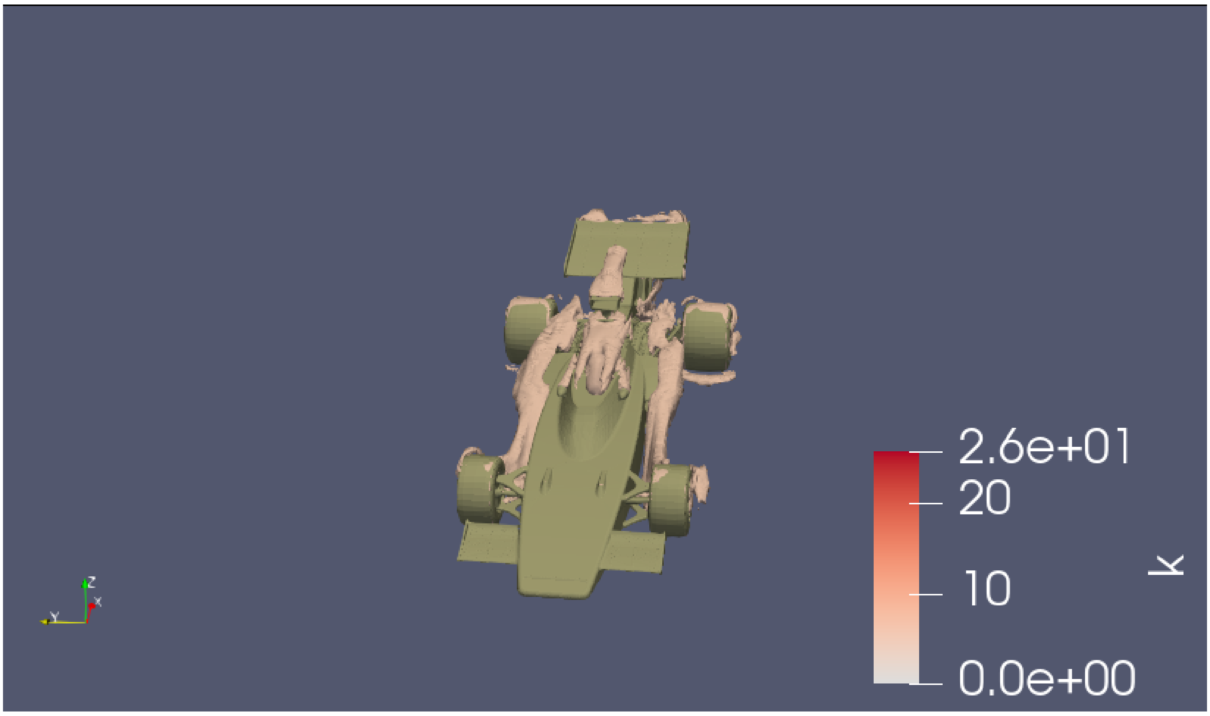

Fig 6.7 Turbulence Isosurface Extraction front car

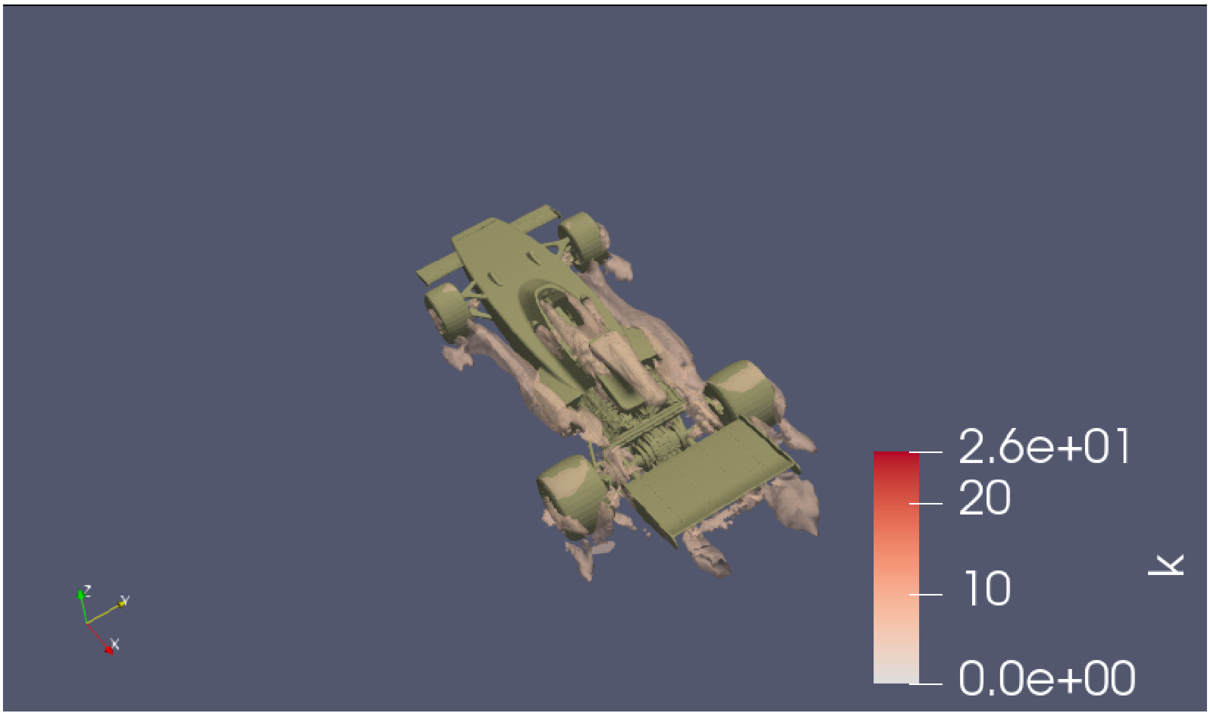

Fig 6.8 Turbulence Isosurface Extraction back/side car

McLaren(1968) F1 Car:

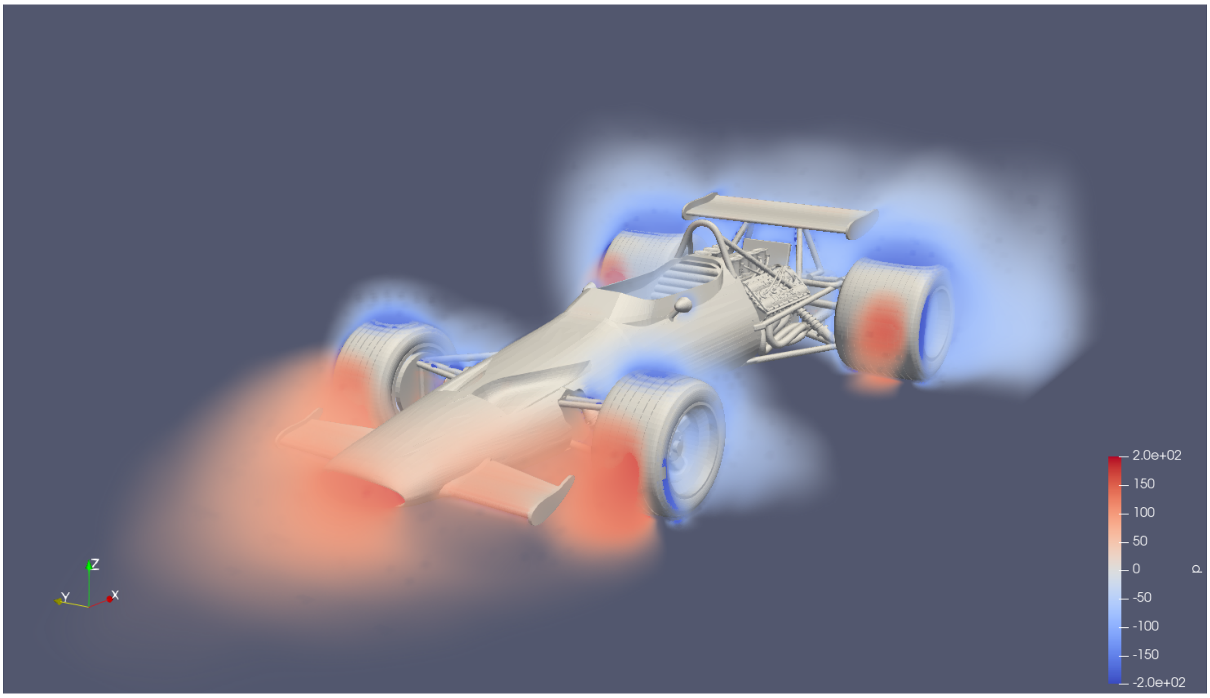

Fig 7.1 Pressure

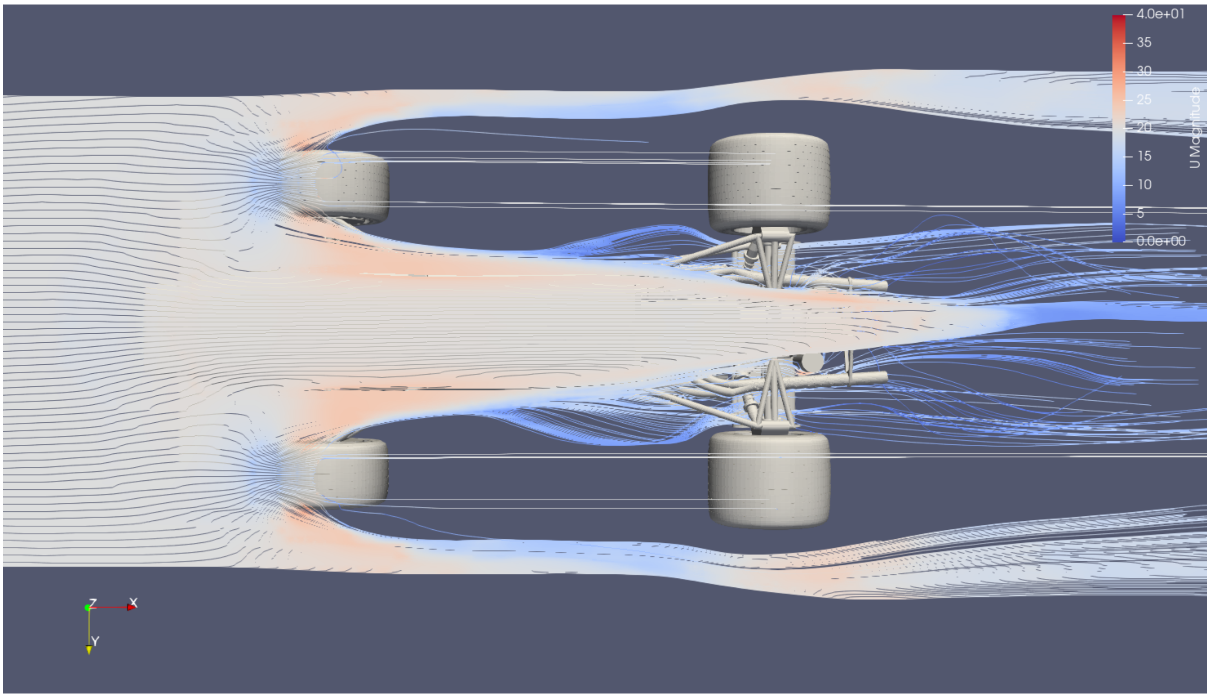

Fig 7.2 Airflow under car

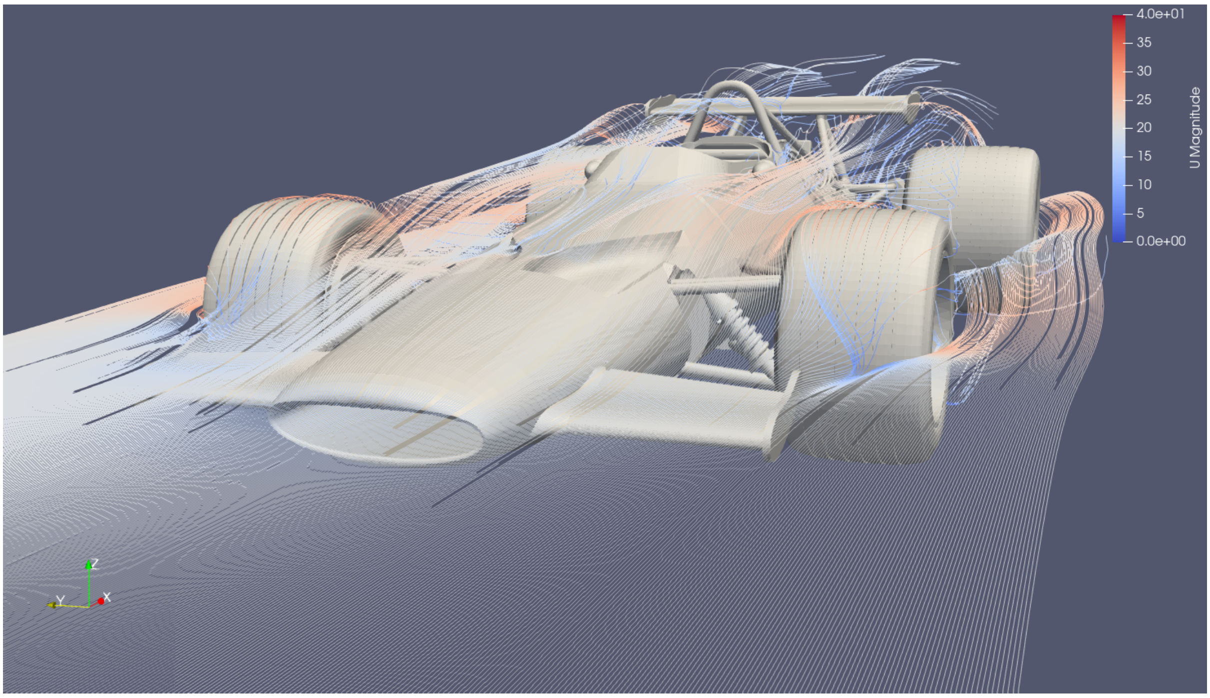

Fig 7.3 Airflow over front wing

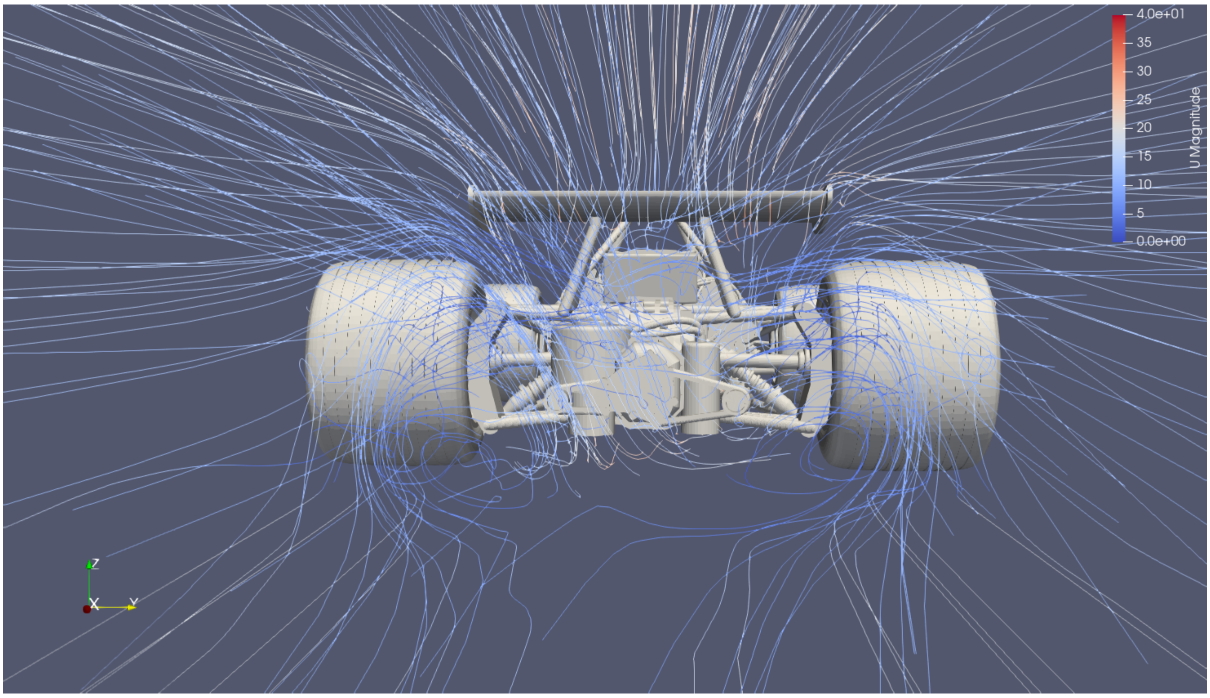

Fig 7.4 Airflow behind car

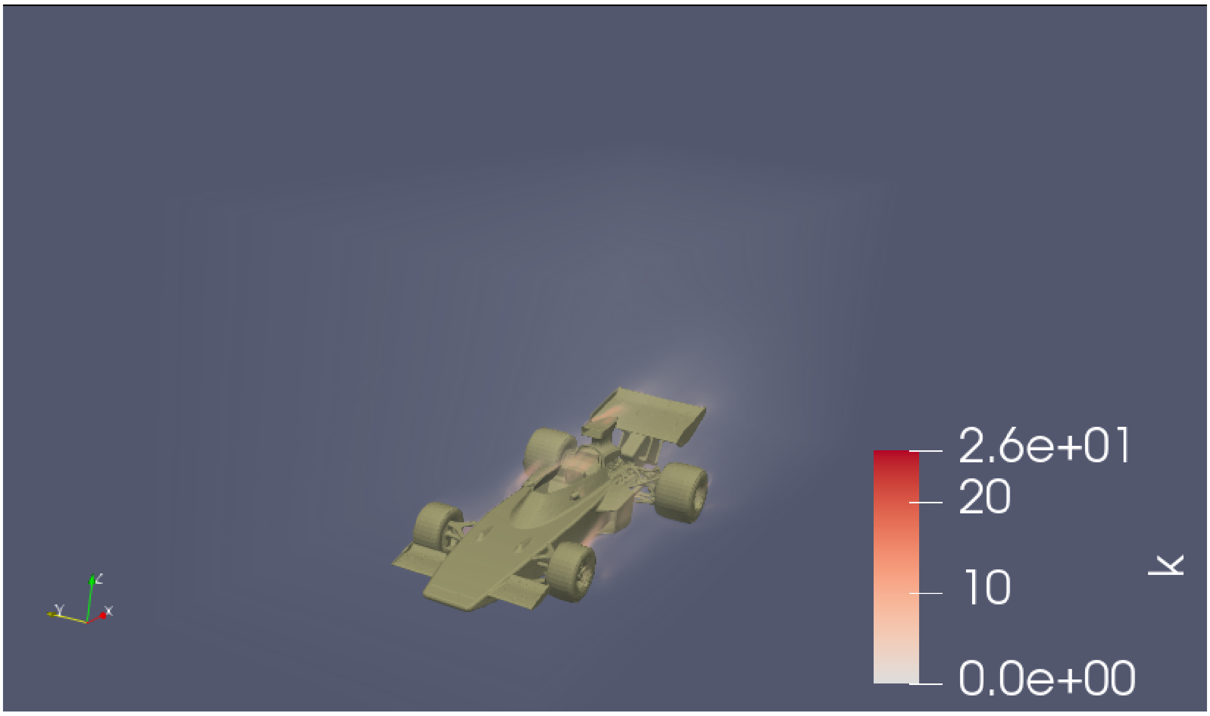

Fig 7.5 Turbulence front car

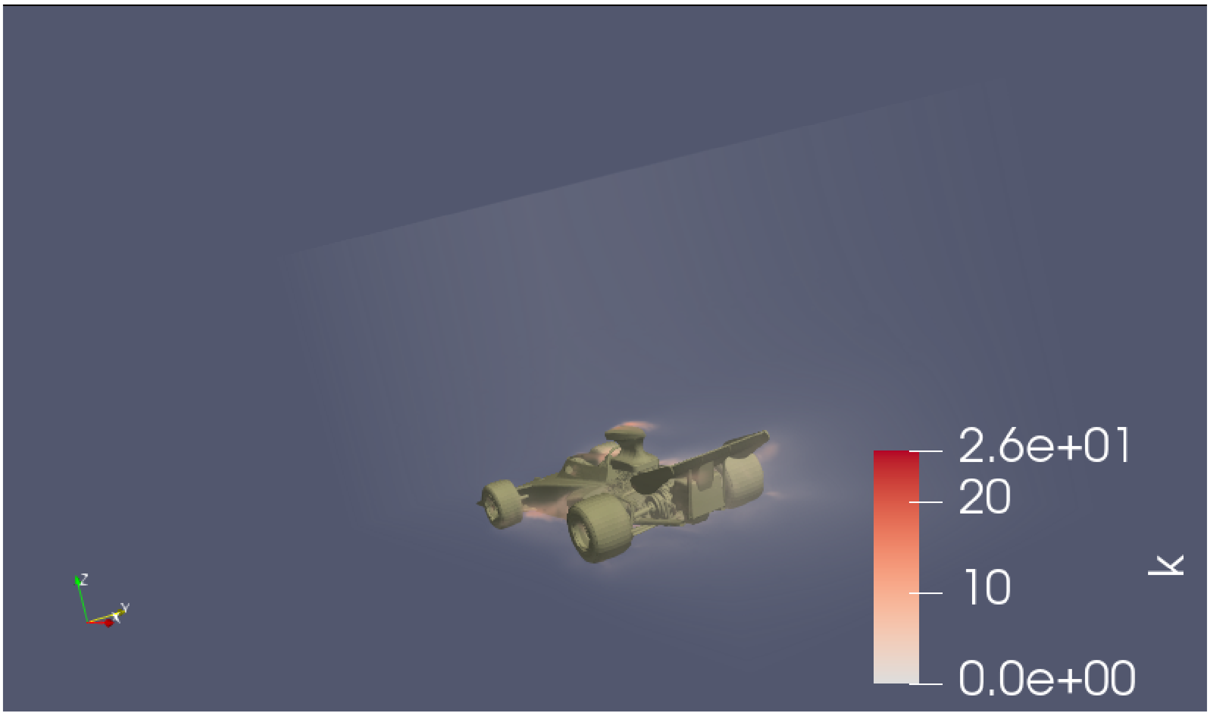

Fig 7.6 Turbulence back/side car

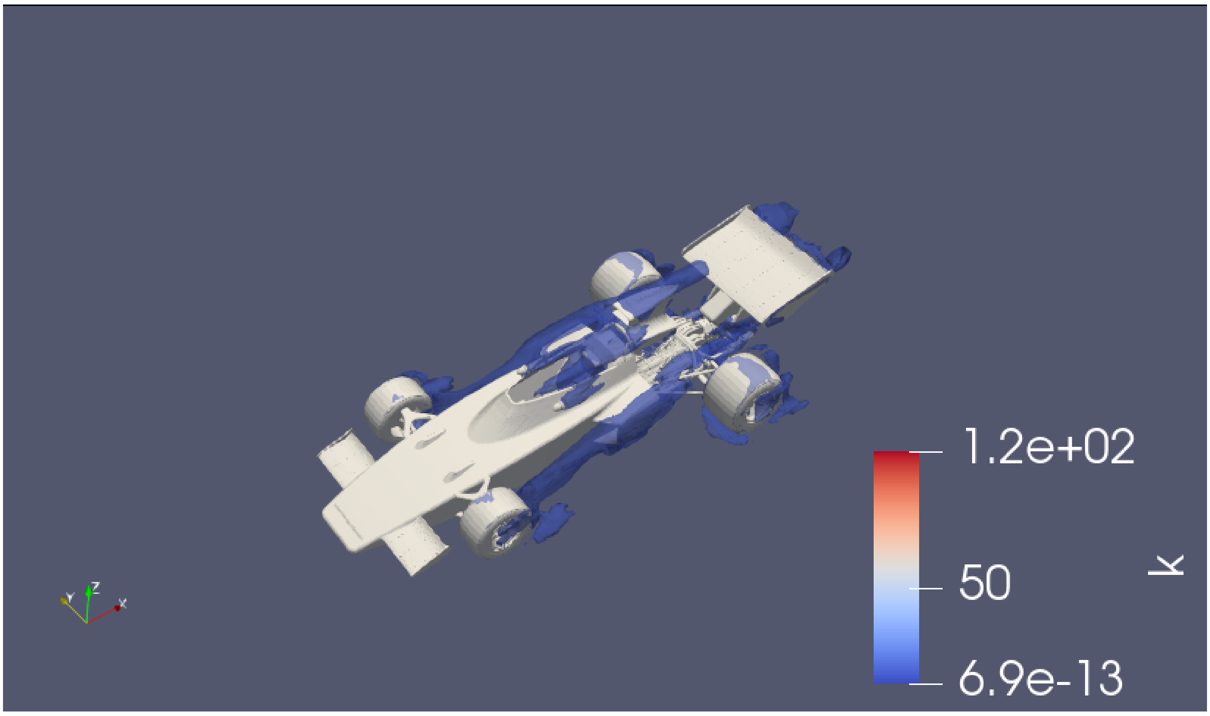

Fig 7.7 Turbulence Isosurface Extraction front car

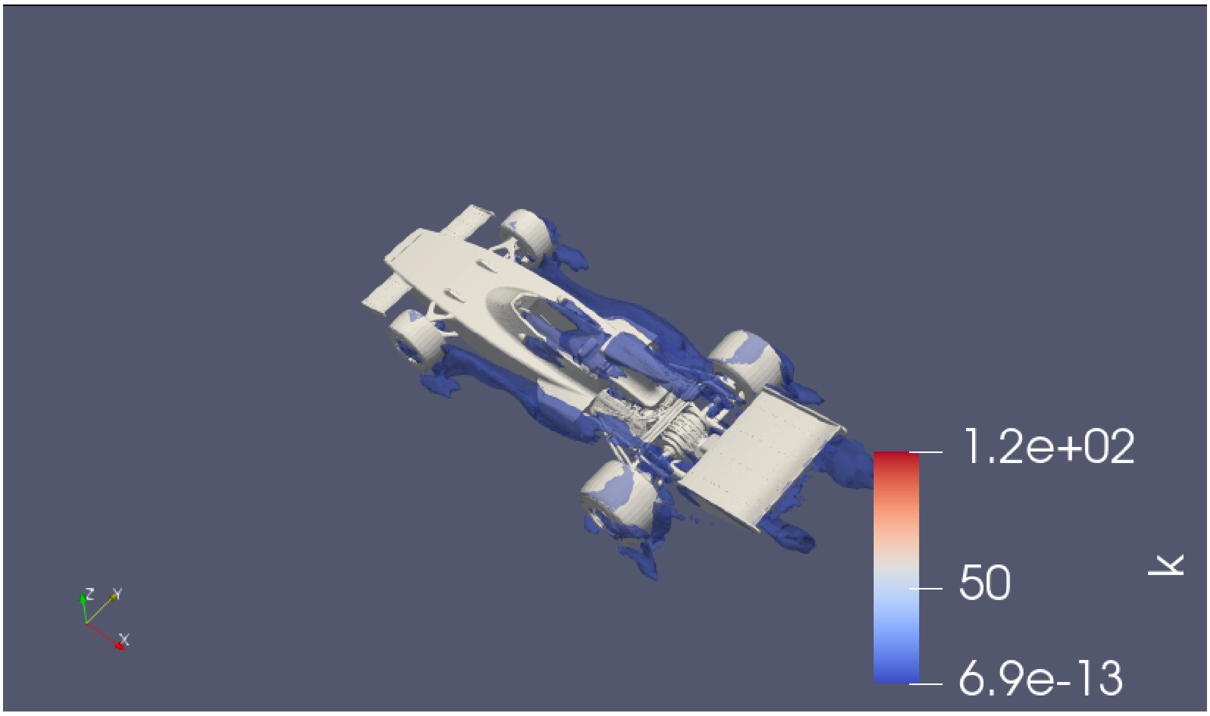

Fig 7.8 Turbulence Isosurface Extraction back/side car

Honda (1965) F1 Car

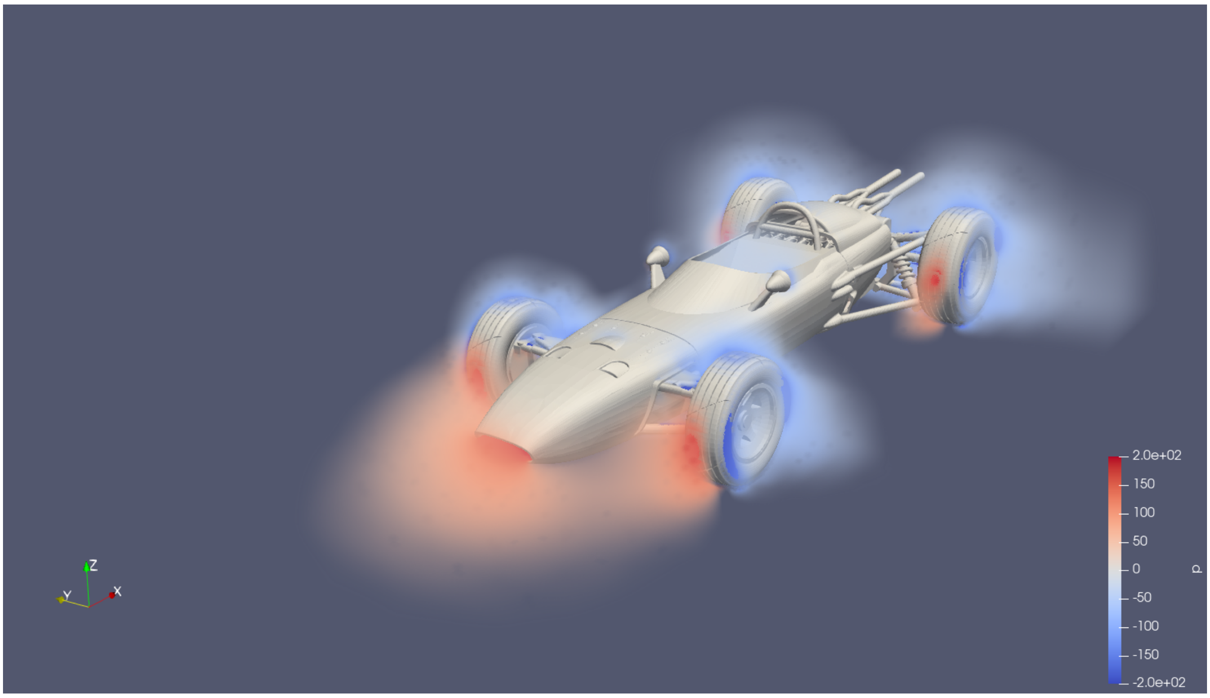

Fig 8.1 Pressure

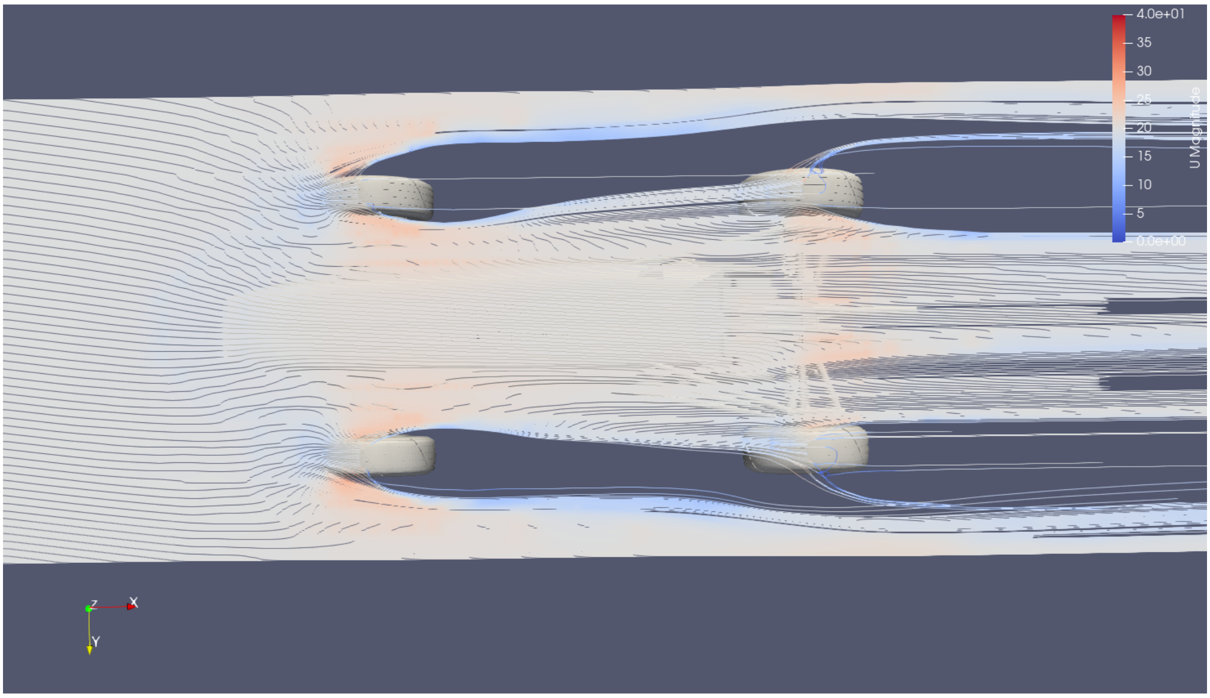

Fig 8.2 Airflow under car

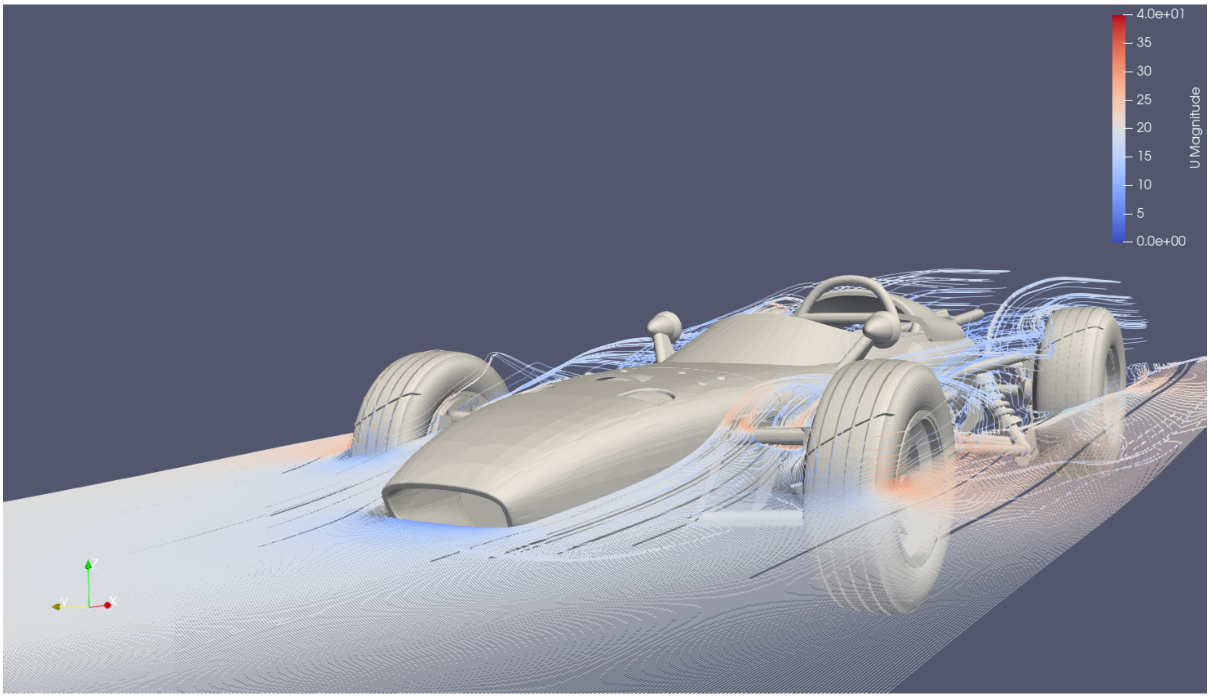

Fig 8.3 Airflow over front wing

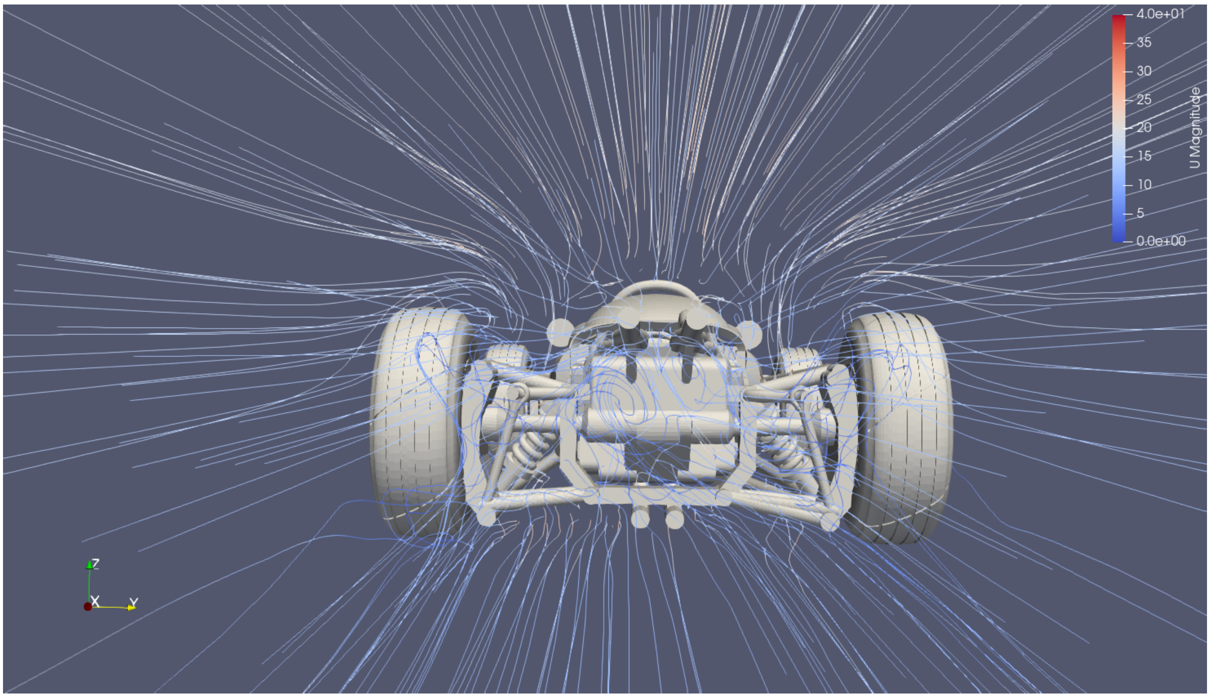

Fig 8.4 Airflow behind car

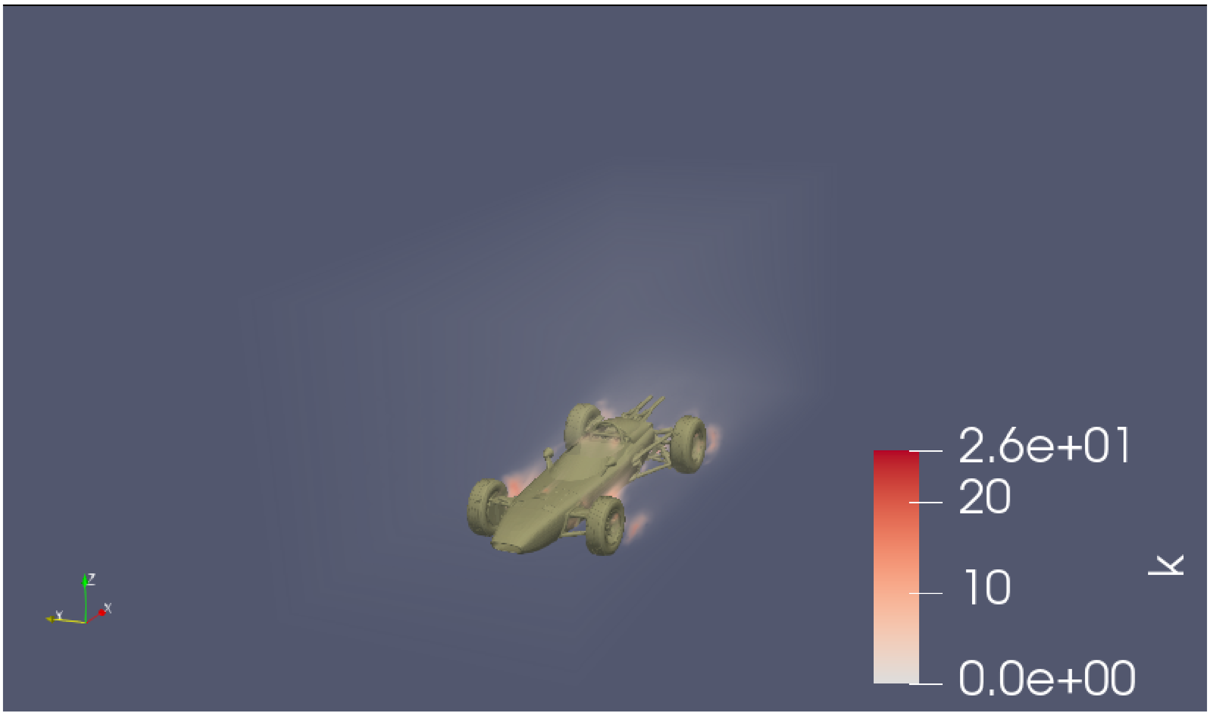

Fig 8.5 Turbulence front car

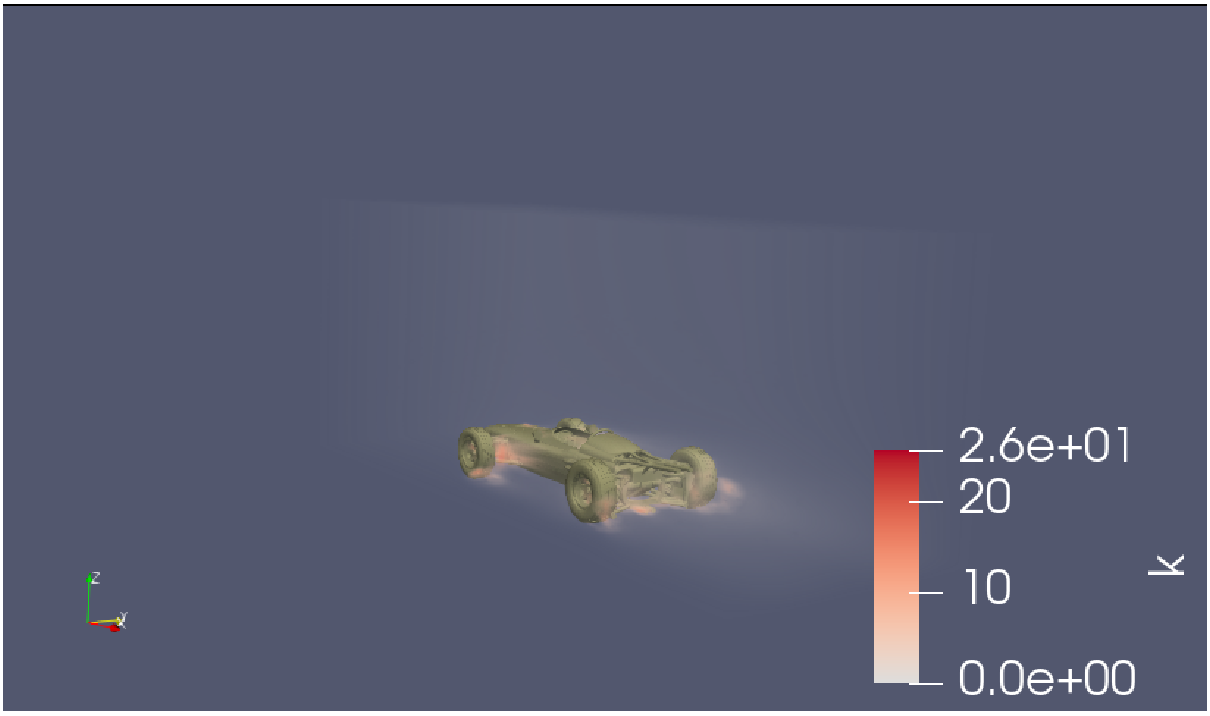

Fig 8.6 Turbulence back/side car

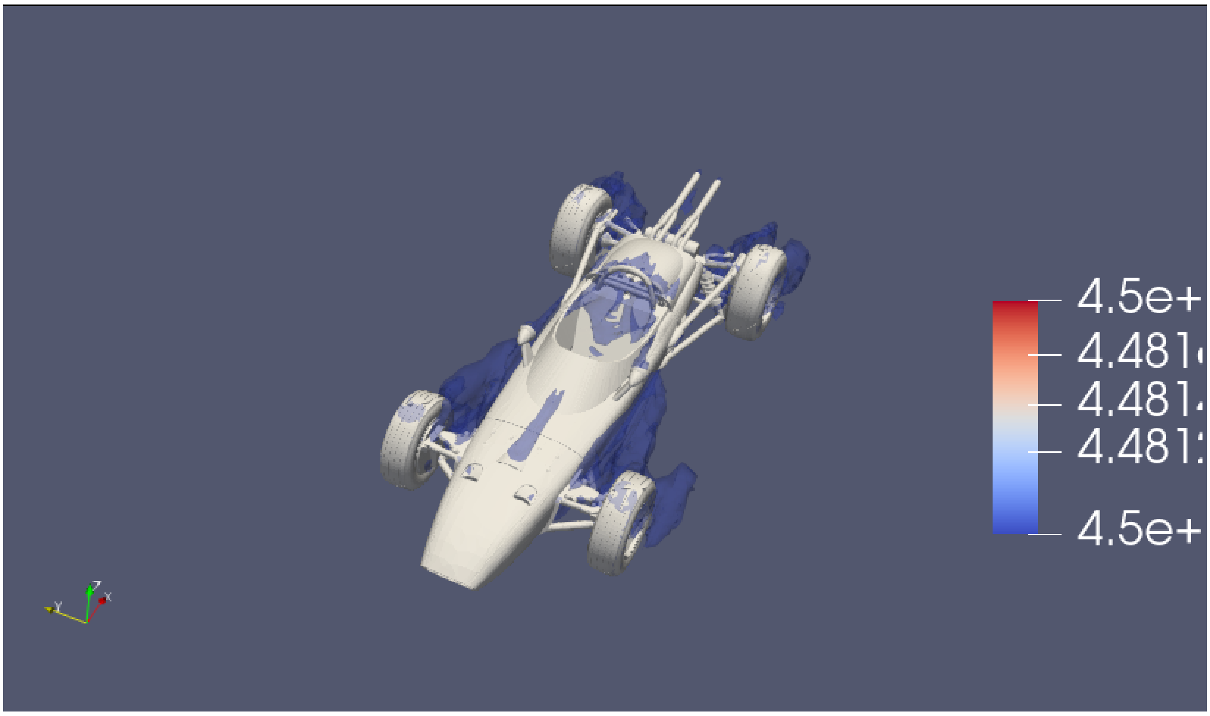

Fig 8.7 Turbulence Isosurface Extraction front car

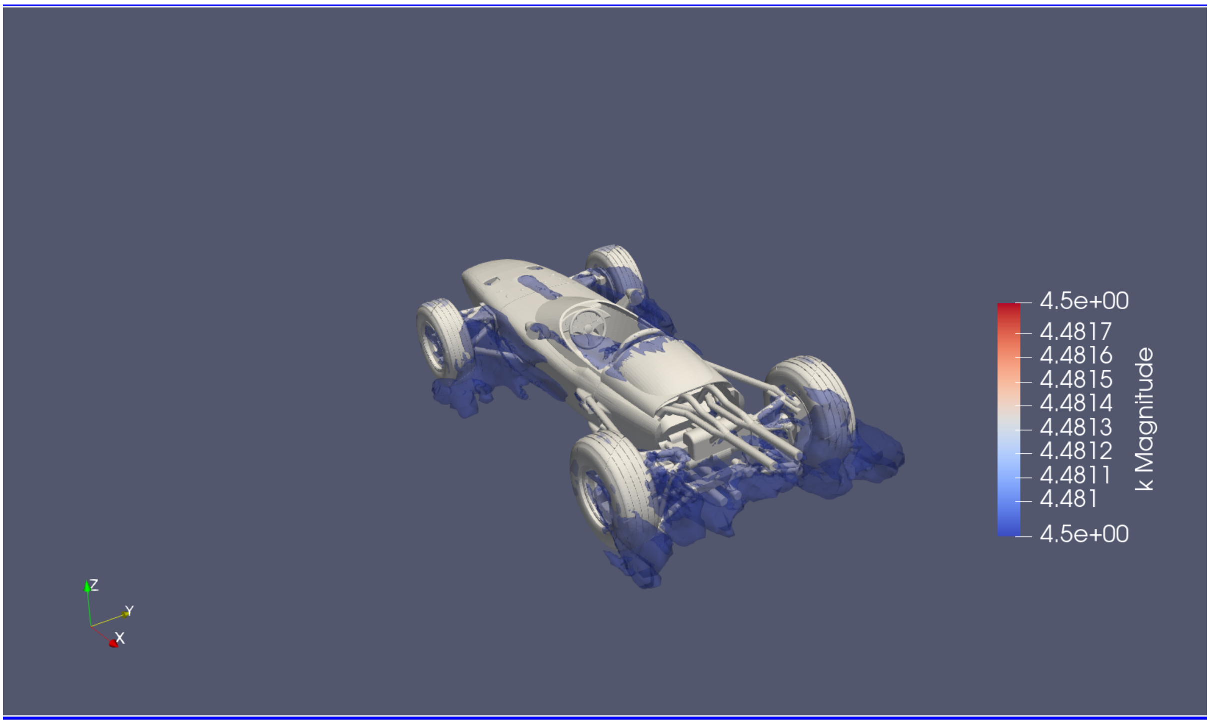

Fig 8.8 Turbulence Isosurface Extraction back/side car

Porsche 911:

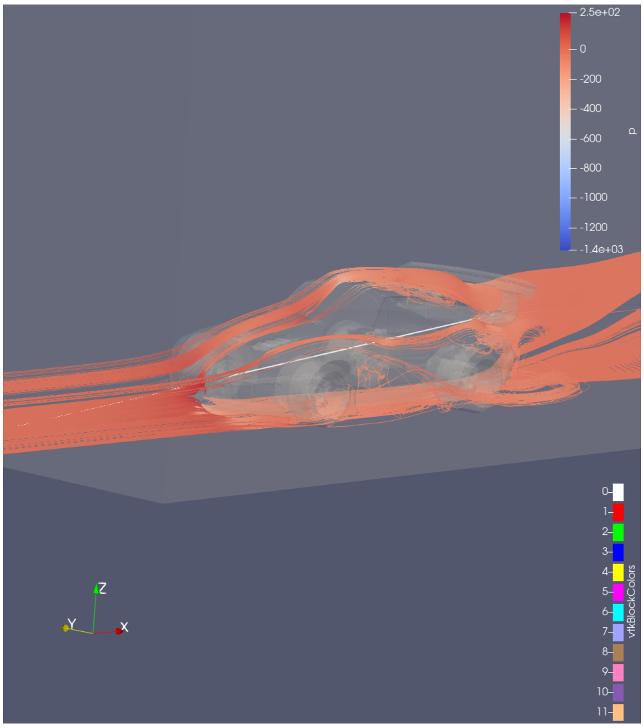

Fig 9.1 Streamline Test

Superbike:

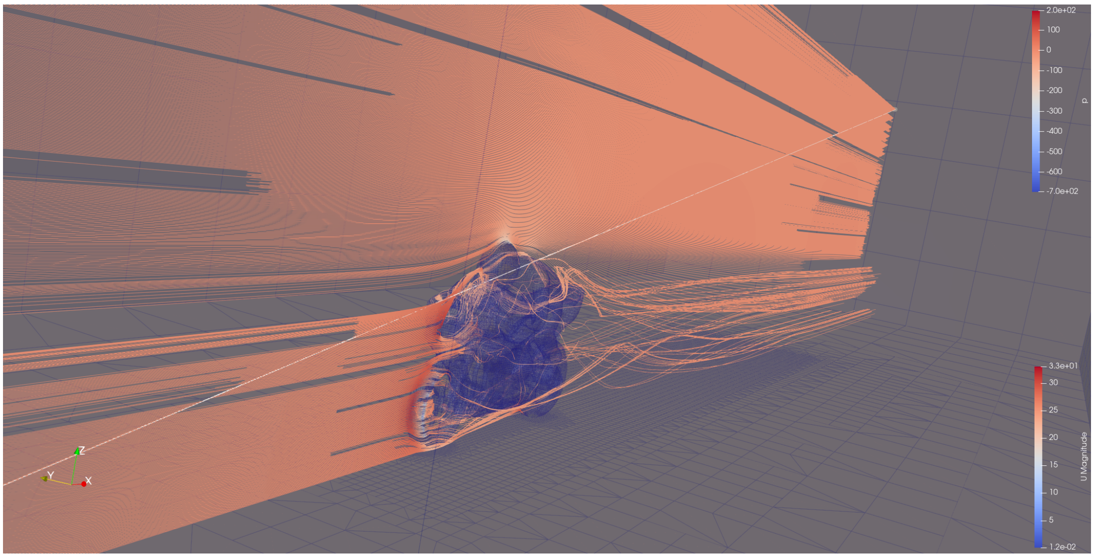

Fig 10.1 Streamline Test

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