Exploring the New Changes to the 2022 Formula 1 Car

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Abstract

This paper explores the aerodynamics of Formula 1 (F1) race cars through analysis of the current literature and an independent 2D computational study. Based on the proposed 2022 design changes to the front wing should produce less vortices, the upper body will be simplified, and the rear wing will be angled. The paper will explore how the reliance on down force has affected the sport and why the proposed changes will allow for closer racing. The paper also explores different rear wings and their role in the creation of turbulent air.

1 Overview of a Formula 1 Car

What makes a race car fast? Some cars are meant to muscle their way through the air with powerful engines while other cars use their sleek design to get to the finish line first. In both cases, race cars are able to accelerate quickly and reach high top speeds. However, when race cars enter a course with curves and sharp turns, understanding and exploiting aerodynamics becomes vital. Using this understanding to develop an efficient race car can result in unintuitive designs. The sport of Formula 1 is a great example of race cars which are designed to maximize their aerodynamic capabilities. At first glance, the cars might appear bulky, too wide, and not fast enough to compete at a high level. However, the design of the cars is highly engineered to produce fast and competitive races.

At the front of a Formula 1 car, there is a wide front wing (Figure 1A). This wing is designed to apply a large amount of down force to the car. Down force describes the downward lift created when the car is moving at fast speeds. In essence, air molecules push against the front wing, when the car is moving at high speeds, forcing the car to shift lower to the ground [The21]. When the car drives around a corner, it has increased grip because there is more vertical stress on the tires [Kat06]. However, by gaining this grip and speed around corners, the cars lose speed when going down a straight portion of the track. This is because the front wing is so wide, the car ends up having to push more air out

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Figure 1: Side of Formula 1 car [F1T21]

of the way than if the front wing wasn't there [The21]. Optimizing this tradeoff to produce an efficient race car on all parts of the track is an important design consideration.

Another important element of a Formula 1 car is the barge board (Figure 1B). On both sides of the car there is a horizontal extruded surface which serves as a platform for the upper bodywork. The main purpose of this barge board is to slow down air when it enters the side pods. It also limits the amount of drag on the side of the car. The side pods are an external piece of the car which serve to cool down the engine by allowing air to enter the car and flow to the engine [The21].

A final notable part of the car is the rear wing (Figure 1C). This wing serves two important roles. Just like the front wing, the rear wing creates down force which helps the car have increased speed on corners. However, this wing has the added ability to open up, thereby creating less drag and increasing the car's speed on the straight parts of the track [AN17]. The Fédération Internationale de l'Automobile (FIA), the governing body for world motor sport including Formula 1, has implemented this strategy of opening up the front wing in order to promote closer racing. However, regulations dictate that this wing can only be opened when a car is within 1 second of the car in front of it [The21].

2 Literature Review

The most important aspect of motorsport, the car's velocity, is influenced by grip and downforce. Drivers feel the most comfortable with more grip as they are able to drive faster and more consistently. On the F1 cars, downforce is mainly generated by the front wing, rear wing, and bodywork. On the 2017 F1 car, the underbody provides the most efficient downforce because it makes use of ground forces while also only providing 15.6 percent drag. The underbody provides 44.5 percent of the overall downforce for the car. The front wing meanwhile provides 13.7 percent of the overall drag with 26.3 percent of the downforce. The rear wing provides 20.3 percent of the drag and 27.5 percent of the downforce. The remaining drag is mainly caused by the tires (around 30 percent of the total drag) [Rav18].

An important point to note is that even though the front wing is the cause of a lot of drag it also helps limit the amount of drag the front tires produce. The shape of the ends of the wing are designed to push air above the front tires. This allows for the car to experience less drag, and additionally forces the car behind to experience turbulent air [4].

The underbody of the car is angled so that the rear of the car is higher than the front. This allows the front of the underbody to produce more downforce than the rear because the ground clearance is lower in the front. At the front, the air pressure is very low allowing for the down force from ground effects to be high. However, near the rear of the car the ground clearance is higher and the benefit from ground effects is gone. Throughout these low pressure areas, the flow's speed is higher because the flow is pushed into a smaller area. This relationship can be explained by the continuity equation which states that the air flow entering the system must be equal to the air flow exiting the system [Rav18].

Just like the underbody, the front wing also makes use of ground forces. The front accelerates the flow by forcing it into a smaller area. This causes a low pressure area under the car and causes the car to be suctioned down to the ground [Rav18]. However, the rear wing generates down force directly from the air flow which is why it has so much drag. Despite this large drag coefficient, the rear wing is vital to the support of the car. Without it, drivers would struggle to keep the rear from slipping off the track [The21].

The benefits provided by the underbody also come with the creation of turbulent air and vortices. At the very rear of the car, the F1 car has a part called a diffuser. The diffuser is meant to generate additional downforce. As mentioned previously, as air moves through the bottom of the car the pressure increases. The diffuser is meant to increase the speed of the air flow to provide another drop in pressure and push the car down to the track. This is why, at high speeds, F1 cars scrape the ground and make sparks. The underbody and front wing effectively force the air flow into a tighter space which creates a drop in pressure [Rav18].

However, the diffuser and the underbody create a lot of turbulent air and vortices. While the diffuser creates downforce it also causes the air flow to speed up and shoot diagonally upward from the bottom of the car. This turbulent air then interacts with the car behind. The diffuser also creates the Venturi vortex. This vortex is created from a difference in pressure between the side of the diffuser and the underbody [Rav18].

In conclusion, analysis shows that Formula 1 cars are designed to leverage aerodynamics to their advantage. F1 cars create so much turbulent air in their wake that it prevents drivers behind them from overtaking and causes the race to be less exciting. However, the 2022 season brings in massive regulation changes which will hopefully shift the aerodynamics of Formula 1 cars toward closer racing.

3 The Reason for the Changes of Formula 1 Cars

An important restriction in Formula 1 is the cost cap. The sport is expensive and teams require sponsors in order to continue competing. Some teams, like Mercedes or Mclaren, have large amounts of money and are able to build cars that give them a competitive advantage over some of the less well-funded teams. In order to make the sport fairer, the FIA have implemented a 145 million dollar cost cap forcing teams to spend below or equal to that amount. While this has brought teams to a more level playing field, it still has not totally made the sport as competitive as it could be. Teams like Haas or Williams are not able to fight for the win because they can not spend as much money as other teams [The21].

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This is where the new regulation changes are entering the sport. In an effort to make it more competitive, the FIA is massively changing the design of the cars for the 2022 season. The goal is to create cars that might be slower, but are much more evenly matched. The hope is that this will bring in new fans and keep the sport interesting. Another important goal is a massive shift in the aerodynamic regulations making F1 cars produce less turbulent air. This will allow F1 cars to stay closer to one another on the curved parts of the track. Formula 1 is currently the fastest sport in the world. The top speed reached by a Formula 1 car is around 223 mph while the top speed of a car from Nascar is around 200 mph [6]. F1 undergoing this shift can serve as an example to other motorsport events of how to increase competition and use aerodynamics effectively [The21].

So, returning to the obvious question: what makes a race car fast? The basics of what makes a race car fast are grip, acceleration, and the car's top speed. Grip is defined as the friction between the tire and surface of the race track. However, it basically measures how fast a car can go around a turn before it starts to slide. As mentioned, the more down force you have the more grip you are going to have. However, the type of tire used is also massively important [The21].

The current manufacturer of tires in Formula 1 is a company called Perelli. Based on strategy and conditions, the teams have a choice between five different tire compounds: softs, mediums, hards, intermediates, and wets. The soft tire is fastest because it is the stickiest but it also has the shortest life span. The opposite can be said for the hard tire with a very long life. While not related to the aerodynamics of the Formula 1 car, the different tire compounds demonstrate the intricacy of the sport and the strategy that goes into each design and race [F1T21].

The next important piece to understand about Formula 1 dynamics is the

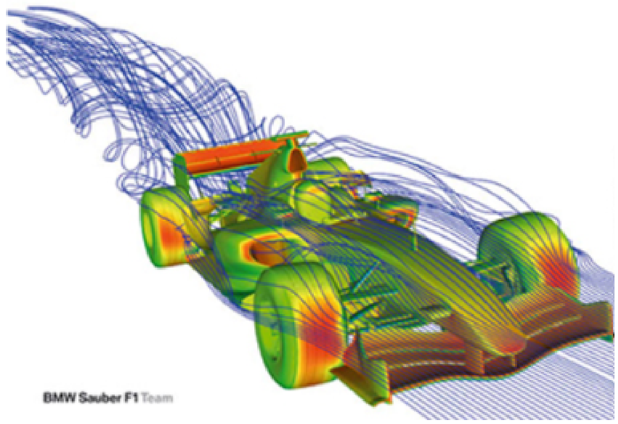

Figure 2: Simulation of flow reacting with Formula 1 car [AN17]

difference between a slipstream and what fans call “dirty air.” When a Formula 1 car is driving through a track at high speeds, air hits the front wing and is pushed over the car until it hits the back wing. At this point the friction created by the car along with the angle of the rer wing forces most air to be turbulent and flow upward. This creates a small pocket behind a Formula 1 car where the air density is low and the air is turbulent [The21].

On a straight part of the track this creates an advantage for the car behind allowing for overtaking, the term used for when a car passes another on the track. This is called a slipstream. However, on the curved parts of the track this creates a massive disadvantage of the car because of the loss of air resistance. Based on the design of Formula 1 cars, the large front and rear wings provide more downforce which in turn allows for faster cornering speeds. This does, however, force the car to rely on the downforce created by the front wing. So, when a car is in front pushing most of the air out of the way the second car loses down force. This loss of down force on turns is called “dirty air” because teams and drivers want air that isn't interrupted by the car in front [The21].

This has become a big issue in the past few seasons because cars that were behind another car would catch up on the straight parts of the track but the loss of down force on the curved parts of the track caused the cars behind to fall back. Competitively this is good for the top teams because once they qualify in or near the front it is difficult for them to be overtaken. However, from the perspective of the fans, dirty air makes the sport less exciting [The21].

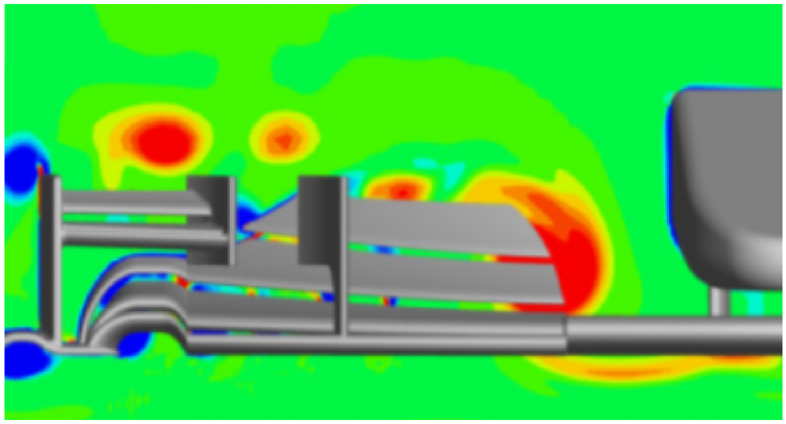

Figure 3: Simulation of vortices created by 2017 Formula 1 front wing [The21]

4 Overview of the New Changes

4.1 Y250 Vortex and the Front Wing

For all the reasons discussed above, the FIA has decided to change the design of the 2022 car. Starting from the front, the front wing is smaller and starts directly from the nose. The current design of the front wing in particular creates a vortex sometimes referred to as a Y250 vortex. This vortex is caused by the air flow past the neutral, horizontal part of the front wing and the inner flaps of the front wing. This vortex causes the car to be faster because it directs air under the barge board. However, it hurts the car behind because the turbulent air travels back to the front wing of the following car [Rav18].

In Figure 3, the Y250 vortex can be seen on the right. Previously, the 2017 F1 car had a more complicated front wing which caused the creation of more vortices which can be seen on the left. These vortices bypassed the front tire which forced the turbulent air to interact with the car behind. This caused the flow to be unsteady for both the car in front and behind which is why it was eventually removed resulting in the vertical side pieces of the wing to be added [Rav18].

Now, the FIA is removing the horizontal part of the wing in an effort to get rid of the Y250 vortex. This will allow Formula 1 cars to make less turbulent air and to receive less turbulent air when following another car. In 2022 the wing will start straight from the base of the nose. This should provide for more exciting and closer racing [The21].

4.2 Changes to Tires

The next major difference is the size of the tires. Formula 1 has consistently used 13 inch tires but in 2022 it will be changing to 18 inches. While it might

Figure 4: 2021 and 2022 Formula 1 Front Wings [F1T21]

not seem to make a huge difference, the tires are being introduced in order to help drivers maintain tire temperatures. Many tracks are twisty, resulting in heavy friction forces being applied to the tires. In order for a car to turn the tire must have a nonzero slip angle. However, if the tire exceeds a maximum slip angle the car can slide. In addition, increasing the load or weight of the car can cause the amount of slip angle to increase because the tire is subject to more lateral force [Kat06].

This slip created by the forces of the car on the tire causes the tire to increase in temperature. On some circuits tire temperatures are easy to manage. However, on most circuits this friction force can cause the tires to overheat past a reasonable temperature forcing drivers to slow down or risk sliding off the track. With larger wheels, tire temperatures will not change as frequently, allowing drivers to feel more comfortable in the car without the need to conserve tire temperatures [The21].

However, these increases in tire sizes are making the car heavier and therefore slower. While it might not seem a big price to pay, a 5 percent increase in weight is important, especially since the rest of the car is becoming lighter. Each new tire is supposed to be about 14 kg heavier than the previous tire which makes the weight of the 2022 car increase by an overall 38 kg. Because of this increase in car weight, the car will be slower overall. This will then provide a lower downforce amount on the tires which will decrease the stress the tires experience. The large reliance on down force has caused many tires to puncture in the 2021 season and previous seasons [The21].

4.3 Changes to Rear Wing

The final major area of change between the 2021 and 2022 car is the rear wing. On the 2021 car, the rear wing had vertical walls on the outside of the wing called straight endplates. The 2022 car no longer has these endplates in order to reduce turbulent air. Additionally, the angle of the rear wing will be altered. The 2022 rear wing is slanted more to allow for the cars behind to not lose as much downforce [The21].

This design shift leads to another important question: is the rear wing even necessary? The rear wing produces a substantial amount of drag and little down force compared to the front wing. Further, in the 24 hour race at Le Mans, the French company Peugeot made a car without a rear wing. The car instead uses downforce from the diffuser and underbody while also maintaining the drag coefficient required to race at Le Mans [F1T21]. Is it possible that there is a more efficient design that does not include a rear wing at all?

However, studies show that the rear wing is important. In fact, it's central to how the sport works. The Drag Reduction System (DRS) is a critical way teams are able to overtake. Making lead cars experience more drag causes the race to be even more exciting. Further, the rear wing provides extra stability to the car and important grip to the rear tires [The21].

All of the new changes discussed here aim to assist the FIA in their goal of making racing more competitive. Combined, the changes represent a massive alteration to the aerodynamics of the car and the expense of manufacturing. This should then give all teams the liberty to be creative with their remaining budget.

5 Do the Aerodynamic Changes Produce Less Turbulent Air

Based on the upcoming design changes to F1 cars, an initial numerical study exploring the impact of the rear wing was completed. With the use of a 2D Computational Fluid Dynamics (CFD) program called Flowsquare, it is possible to devise a study to gain insight into how the angle or length of rear wings affect the airflow behind the car. In Formula 1, teams often use an experimental setup in which full-sized cars are placed in a machine called a wind tunnel in order to test their aerodynamic capabilities. As seen in Figure 2, the car is placed on a flat surface with a fan to replicate the air speed that the car would usually be going at. In order to test the car, teams have sensors. There are three types of sensors. The first is a control sensor associated with making sure the car's features are operational like the acceleration pedal. The next is the monitoring sensor focused on the health of the car. Finally, instrumentation sensors measure the performance of the car and are used around the engine. These sensors are

Figure 5: Formula 1 car in a wind tunnel [Els21]

required by the FIA for safety but many teams also rely on them in order to make sure the car is working correctly [The21].

However, this form of experimental testing is expensive. If it is realized that there are drawbacks to the current design after experimental testing, an entirely new piece must be manufactured and replaced. By first using computational methods, design changes (both subtle and radical) can be easily explored for a small fraction of the cost. Here, Flowsquare is used to test the capabilities of different wings and their effect on air.

5.1 Computational Study

Flowsquare is a program which uses a Boundary Condition (BC) file and a Grid text file. The BC file serves as an image for what the program is testing. For example, if you wanted to test the aerodynamics of a rock in water you would draw a rock in the BC file which the program then uses during the test. The Grid text file is used to show the properties of the fluid, temperature, domain size, and numerical solve parameters. It dictates what the program is going to run and is important to understand in order to run experiments.

Flowsquare is a program which uses the Navier-Stokes equations and continuity equation in order to find values for velocity, pressure, and other values which dictate how the flow operates. Because of the complexity of these partial differential equations, the program needs many hours in order to complete a simulation which is why it is important to review the Grid Text File carefully before starting the experiment.

For this computational study, first, a basic model of a car with a small rear wing was simulated. The car was placed in the program and an inlet boundary through which air entered moving towards the car was created. As in the wind tunnel, this set up simulates the velocity encountered by the car racing without requiring the car to move. The velocity of the fluid, air, was 40 m/s to the

Figure 6: Car used in the Small Rear Wing experiment.

right. The density was set to 1.2 kg/m3 in order to represent air at standard temperature and pressure (STP). The dynamic viscosity was 2E-5 kg/m-s. This is a measure of how much force is needed to break up the fluid. For example, honey has a higher viscosity than air because it is harder to separate. It is also important to note that the simulation assumed air to be an incompressible and Newtonian fluid in order to simplify the experiment and get clearer results.

In actual races, temperature, density, and elevation are all huge factors which affect strategy and the drivers performance. However, because the simulation is running with a 4th order solution using the Lax-Wendroff method to improve the accuracy of results, it takes approximately 8 hours to run. Therefore, when compared to changes in the rear wing, testing small differences in temperature or density was decided to be of low importance. The numbers used for these parameters were kept constant for the entire experiment.

The car used for the first simulation is shown in Figure 6. Figure 7 shows a screenshot of the program at 0 steps. In the program, steps are equivalent to times meaning that this screenshot is before the program started. As shown, the car boundary is parallel with the ground facing the oncoming air as if it were in a wind tunnel. Also, the black arrow shows the direction of the air. Currently, the arrows are all parallel with each other and the air is all flowing at the same speed. This means that the air is currently laminar with no disruptions or mixing in the air flow.

When a flow is laminar, fluid particles move in parallel streamlines to each other. When a flow transitions to turbulent, it experiences constant random mixing throughout the fluid. A turbulent fluid is much harder to predict and follow as the molecules have so many possibilities as to where they could travel.

Figure 8 is taken 100 steps into the program. Each time step accounts for a small amount of time where at 100 time steps 0.0055 s have passed. In this screenshot, the air flow is still laminar everywhere except for behind the car. In this time frame, a small air pocket is forming where the air has 0 speed. In the program, blue is shown to represent that the fluid is moving at 0 m/s. If we then move to the end of the program, at 20000 steps, there is now a large space where the fluid has no speed. On the edges of this zone, the air flow is moving but has a lower velocity than before. In Figure 9, it is seen that the car is causing a significant drop in air speed behind it which shows that it is

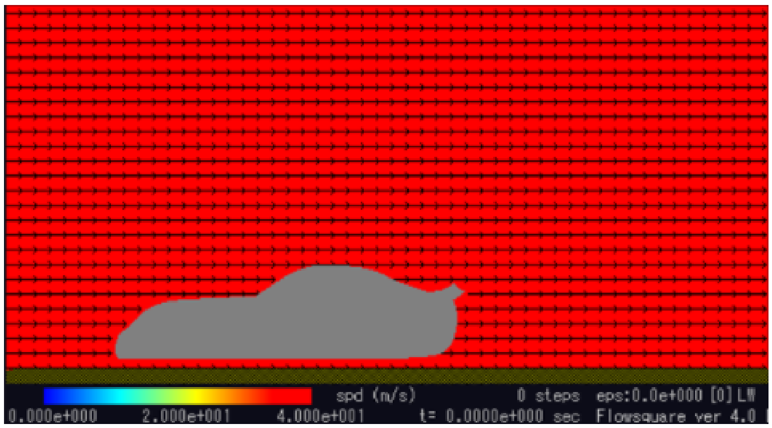

Figure 7: Low Rear Wing simulation at 0 steps.

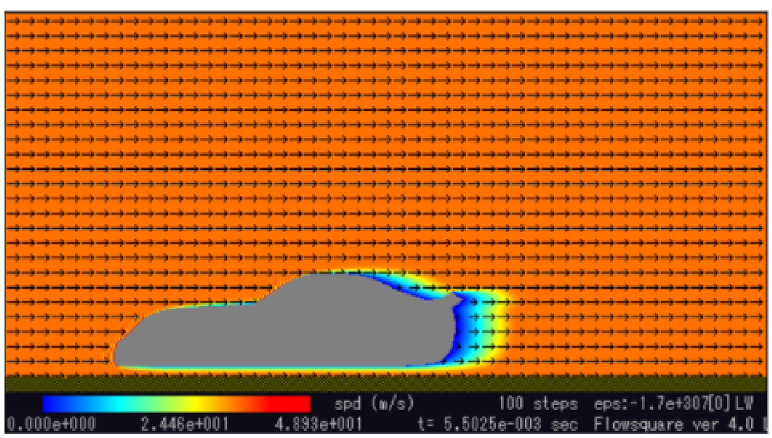

Figure 8: Low Rear Wing simulation at 100 steps.

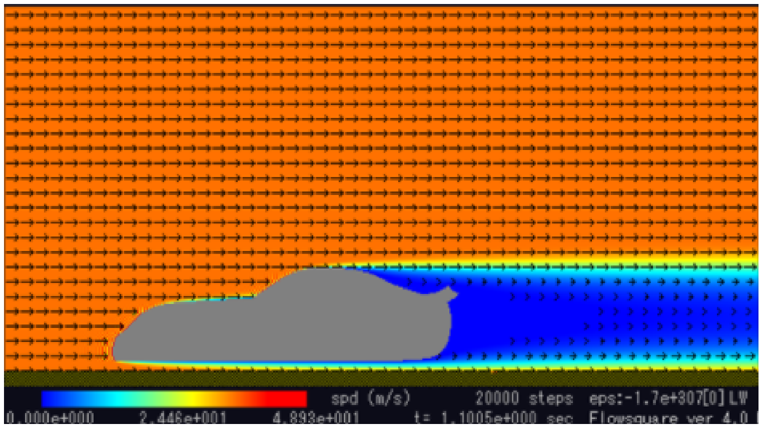

Figure 9: Low Rear Wing simulation at 20000 steps.

pushing the air up and over itself.

Finally, we can also notice that the arrows, the indicators of the direction of the fluid, disappear for a short time before returning. If we now imagine placing a car behind this one, the second car would obviously be experiencing little drag and little down force.

Figure 10 shows the beginning of the program running with a longer rear wing. Already the rear wing is providing more drag and is causing a taller area where the fluid has no speed. At the end of the program, Figure 11, the rear wing has increased the area where the fluid does not have speed.

Clearly, the increase in wing length has caused more air to lose speed and therefore would cause a car behind to feel a loss of drag and downforce. However, the next important thing to look at is the effect wing length and angle have on the turbulent air produced by the rear wing.

Figure 12 shows the model of the car when the wing is straight. In order to ensure the rear wing stays the same length, a ruler held up to the screen was used. The wing is approximately 1.5 cm long. As shown before, this wing will cause a large amount of drag and will block the airflow from reaching the space directly behind the car.

In Figure 13, the program shows the possible vortices created when the rear wing is vertical. The slowest vortex is shown by darker blue where the highest is red. On the middle of the car and on the front of the car there is a faster, thin red vortex created. Also, right at the top of the rear wing a red vortex is created however it quickly diminishes back to a darker shade of blue. When the wing is straight, the vortex created is very small and thin.

In Figure 14, the rear wing is then placed at an angle. The length is still the same. Surprisingly, there is a very similar vortex created from both wings. Both rear wings produce the same type of vortex over the car and behind the car. Surprisingly, there is not a huge difference between the rear wings. However, the program was not able to be run at higher flow speeds so the results could change

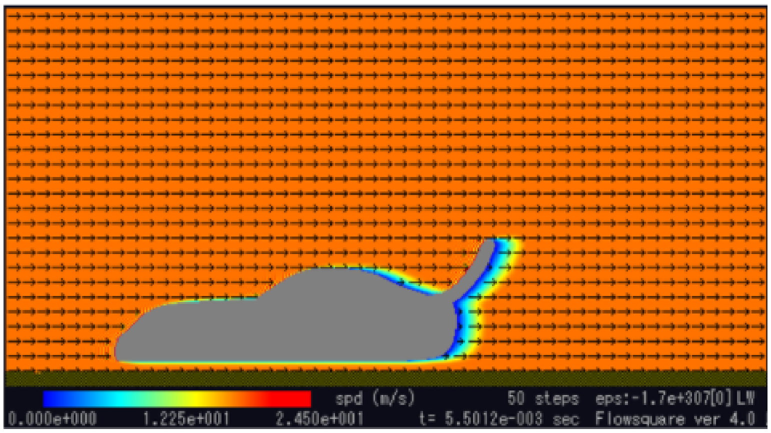

Figure 10: High Rear Wing simulation at 50 steps.

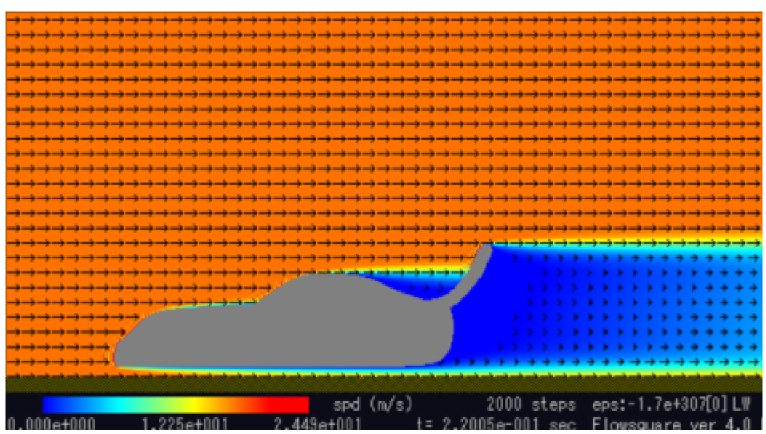

Figure 11: High Rear Wing simulation at 2000 steps.

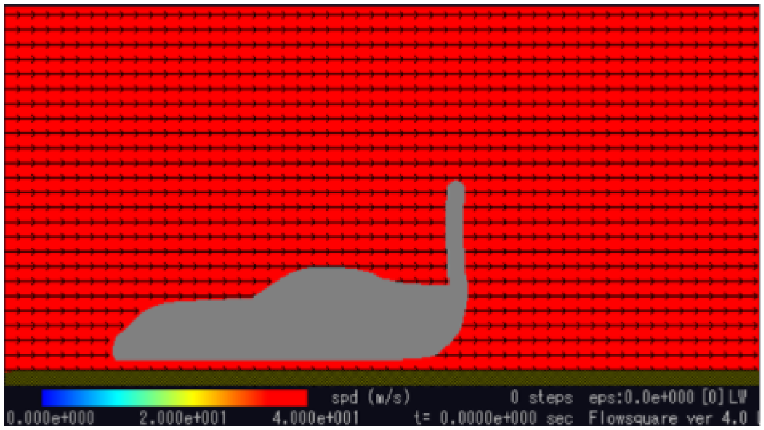

Figure 12: Straight Rear Wing simulation at 0 steps

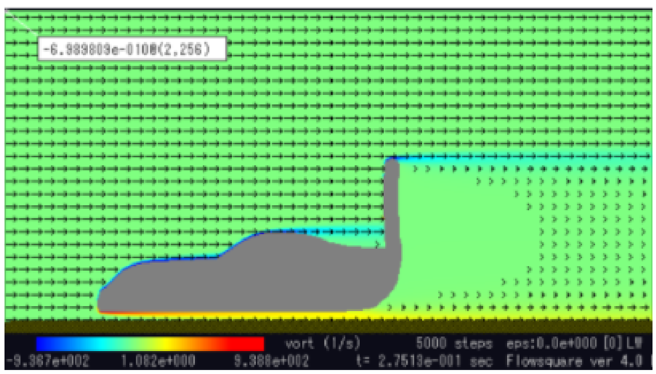

Figure 13: Straight Rear Wing simulation at 5000 steps.

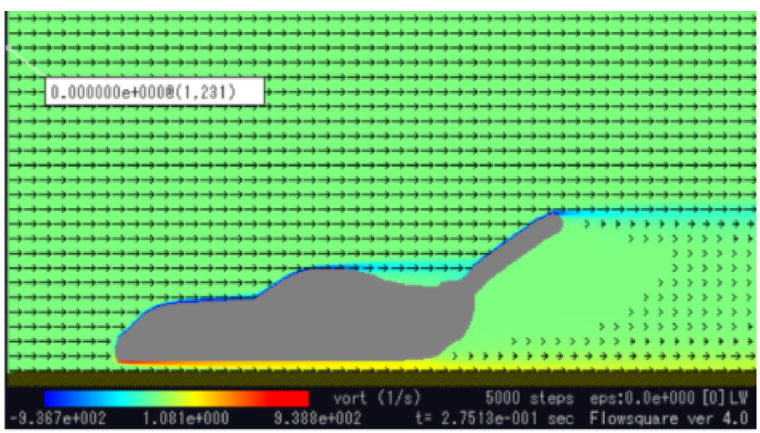

Figure 14: Angled Rear Wing simulation at 5000 steps

when brought up to the speeds Formula 1 cars experience. Also, many tracks have been experiencing high temperatures which would affect the viscosity of the air. In doing so, the creation of more turbulent air and vortices is likely. Therefore, the results are very dependent on temperature, density, and viscosity.

6 Analysis of Computational Results

It is important to note the drawbacks of the simulation used. Because the simulation was in 2D, it was impossible to add end plates to the wings to see how this would affect turbulent air or vortices. Also, features like the tires, bargeboard, and front wing have massive effects on the air flow before it hits the rear wing. Because of this, the flow isn't as laminar as it hits the front wing like the program suggests. Simulations are expensive. In order to get better and more accurate results, better programs and more access to computational resources are needed. The simulation used had air flow that was not as fast as Formula 1 cars. This limitation was due to the simulation being unable to run at higher flow speeds without glitches or crashes.

Also, the simulation was run at ideal conditions with the flow, temperature, viscosity, and density staying constant throughout the experiment. However, Formula 1 tracks can reach up to 7 km long. This means that Formula 1 cars experience different conditions throughout the track. Therefore, it would be very beneficial to test how different speeds of flow, different temperatures, and different density values affect the experiment. Also, it would be important to experiment how constantly changing the flow would affect the experiment because that is what F1 cars experience. Finally, it would be important to gather observational or experimental data against which to validate the computational results.

7 Conclusions

Formula 1 cars have a huge reliance on downforce. It provides a huge increase in grip which allows drivers to take corners at higher speeds providing for faster lap times. Recently, this huge reliance on down force has made it increasingly difficult for drivers to overtake one another because leading cars push air flow over the cars behind them. Additionally, the front wing, rear wing, tires, and underbody each shed vortices which affect the driver behind.

However, 2022 is bringing changes which should allow for closer racing. With the addition of a front wing that begins design at the base of the nose, several vortices should be eliminated. Plus, by decreasing the angle of the rear wing and by removing the side plates, the loss of downforce should be decreased. And finally, by removing the barge board the front car should experience more drag while the rear car doesn't lose as much downforce.

Numerical results from simulations of the rear wing support the claim that a lowered rear wing will provide the car behind with more downforce. However, the simulation also shows that with the rear wing placed at a lower angle might cause more turbulence for the car behind. In total however, the changes should provide for closer racing with the trade off of decreased individual car speed.

How does this relate to other motorsport events? With the reliance of downforce and grip, Formula 1 is one of the fastest motorsport events currently held. If other organizations want to make their sport faster, it would be advantageous to increase the amount of downforce cars gain from the underbody while also keeping a low rear wing. This would provide drivers with more speed around corners while the low rear wing would allow for close racing between drivers. Plus, if other motorsport events lowered the cars to allow for more ground effects to give down force, the cars would be even faster around corners.

However, these types of additions are expensive and put more stress on the teams trying to compete. For the most part, if organizations were trying to make their cars faster, these would be important additions but many motorsport teams don't have the budget teams in Formula 1 do. So, while important, the increase in downforce is expensive and isn't necessary to make a sport exciting. Also, by making advancement in the designs it can cause a lot more vortices or turbulent air to be made as shown by the complex front wing incorporated by F1 cars in 2017.

It is important to note that Formula 1 changes almost every year. For example, Formula 1 cars used to use a V10 engine but now use a V6 turbo hybrid engine. Plus, as teams create new designs to try and beat their competitors, certain parts or designs are banned from the sport. Because the sport is always changing, solutions to turbulent air and vortices will continue to change and progress with time.

In the future, it would be especially good to investigate how different front wings affect the car. It would be important to see how the length, width, distance from the ground, angle, and shape used affect the front wing. While we know that currently the wing is designed to push air up and around the car, it would be important to see if changing the wing to allow for more drag to the leading car affects the downforce of the car behind.

8 Appendix: Input Files for Computational Study

8.1 Large Rear Wing

———- Control File for Flowsquare ver 4.0 (Use SI Unit) ———- ———— ————- General Control Data ———————— 01:cmode 0 // Simulation mode, 0:non-reac, 1:premixed, 2:non-premixed, 3:Euler, 4:analysis 02:nx 512 // No. grid points 03:ny 256 // No. grid points 04:lx 9.0 // Domain x-size 05:ly 4.5 // Domain y-size 06:sts 0 // Start time step (new simulation starts from sts=0) 07:latts 2000 // End time step 08:cflfac 8 // Delta t factor (more is better, but typically 10-1000) —————- Numerical Scheme, Smoothing and Accuracy ————— 09:iorder 3 // 0: low order, 1: high order, 2:2nd+LW, 3:4th+LW 10:nfil 1 // Interval time steps for filtering 11:wfil 0.1 // Relaxation

Figure 15: Angled Rear Wing simulation at 5000 steps

parameter for filtering 12:omega 1.8 // Relaxation parameter for Poisson Eq (for cmode=0-2) 13:peps 1.0E-1 // Convergence limit for Poisson Eq (for cmode=0-2) 14:loopmax 1 // Maximum no. of iteration for Poisson Eq (for cmode=0-2) 15:wdrho 1.0 // Factor for d(rho)/dt (0¡=wdrho¡=1.0, 1 is ideal for cmode=12) ————— General BC and Global IC (White) —————- 16:perikey 0 // 0: no peri, 1: x-peri, 2: y-peri, 3: all peri 17:pres0 1.0E+05 // Pressure in Pa (atmospheric: 1.0E+05 Pa) 18:uin0 20 // Initial u 19:vin0 0 // Initial v 20:rho0 1.2 // Initial density (for cmode=0,3) 21:temp0 0 // Initial temperature (for cmode=1,2) 22:scalar0 0 // Initial Mixture fraction (for cmode=2) ——————— BLUE Local BC and/or IC (optional) ———— 23:uin1 20 // U 24:vin1 0 // V 25:rho1 1.2 // Density (for cmode0,3) 26:temp1 0 // Temperature (for cmode1,2) 27:scalar1 0 // Mixture fraction (for cmode2) ————— RED Local BC and/or IC (optional) ————— 28:uin2 20 // U 29:vin2 0 // V 30:rho2 0 // Density (for cmode0,3) 31:temp2 0 // Temperature (for cmode1,2) 32:scalar2 0 // Mixture fraction (for cmode2) ———- PINK Local BC and/or IC (pure air flow, optional) ———- 33:uin3 20 // U 34:vin3 0 // V 35:temp3 0 // Temperature ———— BLACK Wall Boundary Condition (optional) ——— ——— 36:tempw 0 // Temperature (0: free, for cmode1,2) ———— GREEN Moving Boundary Condition (optional) ————- 37:imb 1 // 0:one-time, 1:periodic 38:umb 20 // U of moving boundary 39:vmb 0 // V of moving boundary 40:tempmb 0 // Temperature (0: free, for cmode1,2) ————- YELLOW Scalar Boundary Condition (optional) ————- 41:scalarT 0 // Local scalar value which might be used as tracer ———- Transport Properties Thermochemical Conditions ——— 42:mu 2E-5 // Dynamic viscosity of mixture 43:R 0 // Specific gas constant J/kg K (for cmode=1,2) 44:diff 0 // Diffusivity of mixture (for cmode=1,2,yellow BC) 45:Tu 0 // Unburnt temperature (for cmode=1) 46:Tb 0 // Burnt (flame) temperature (for cmode=1,2) ——————- Chemical Reaction (for cmode=1) ——————- 47:krate 0 // Rate onstant 48:Trate 0 // Activation temperature 49:nrate 0 // Rate rho*k*exp(-Ta/T)*Tn 50:cF 0 // Progress variable at which flame locates (optional for vis) —————— Non-Premixed Reacting Flow (for cmode=2) ————— 51:Xst 0 // Stoichiometric mixture fraction at which flame locates 52:sigma 0 // Relaxation parameter for density change (0¡=sigma¡=1, 1 is ideal) ———————— Display and Output ————————— 53:box 1 // Pixel size of one grid point 54:nfig 50 // Interval time steps for figure output (0:off) 55:nfile 5000 // Interval time steps for dump file output (0:off) 56:bcdisp 1 // Display wall boundary (0:off, 1:on) 57:idisp 4 // 0:off,1:rho,2:u,3:v,4:spd,5:vrt,6:T,7:rate,8:c/xi,9:P 58:cmax 0 // Scale (max). 0:auto scale 59:cmin 0 // Scale (min). 0:auto scale 60:icolor 0 // 0:Jet,1:Rainbow,2:Nishiki,3:Gray,4:Gray(inv),5:Hot,6:Sea,7:Leaf 61:icont 0 // (Reaction front) contour line (0:off,1:blck,2:red,3:grn,4:bl,5:wht) 62:linewidth 0 // Line width of contour line (1, 3, 5 or 7) 63:ivec 1 // Velocity vector (0:off,1:blck,2:red,3:grn,4:bl,5:wht) 64:ndiv 10 // Interval grid points between displayed vectors (0:auto) 65:vecsize 2 // Pixel size of vector arrow (0:auto) —————— Lagrangian Trajectory (optional) ——————- 66:lagkey 0 // 0:off,1:x, 2:y,3:x-x,4:y-y 67:lagcolor 0 // 0:black, 1:white 68:lagsize 0 // Pixel size of particles 69:nlagra 0 // Interval time steps of restart (¿=100) 70:npart 0 // No. particle (¿=1000) ———————— Body Force (optional) ————————— 71:gfx 0 // X-body force 72:gfy 0 // Y-body force 73:dref 0 // Reference density. 1:max, 2:middle, 3:min density as reference ——————- Initial Perturbation (optional) ——————- 74:pmode 0 // Mode of perturbation 0:off, 1:single mode, 2:multi, 3:multi (random amp.) 75:umag 0 // Velocity amplitude (m/s) 76:nwave 0 // Number of waves in x-direction ————————— Others ————————- 77:nwait 0 // Wait time ———————————————————— End of file

8.2 Angled Rear Wing

9 Appendix: Input Files for Computational Study

9.1 Large Rear Wing

———- Control File for Flowsquare ver 4.0 (Use SI Unit) ———- ————————- General Control Data ———————— 01:cmode 0 // Simulation mode, 0:non-reac, 1:premixed, 2:non-premixed, 3:Euler, 4:analysis 02:nx 512 // No. grid points 03:ny 256 // No. grid points 04:lx 9.0 // Domain x-size 05:ly 4.5 // Domain y-size 06:sts 0 // Start time step (new simulation starts from sts=0) 07:latts 20000 // End time step 08:cflfac 8 // Delta t factor (more is better, but typically 10-1000) —————- Numerical Scheme, Smoothing Accuracy ————— 09:iorder 3 // 0: low order, 1: high order, 2:2nd+LW, 3:4th+LW 10:nfil 1 // Interval time steps for filtering 11:wfil 0.1 // Relaxation parameter for filtering 12:omega 1.8 // Relaxation parameter for Poisson

Figure 16: Angled Rear Wing simulation at 5000 steps

Eq (for cmode=0-2) 13:peps 1.0E-1 // Convergence limit for Poisson Eq (for cmode=0-2) 14:loopmax 1 // Maximum no. of iteration for Poisson Eq (for cmode=0-2) 15:wdrho 1.0 // Factor for d(rho)/dt (0¡=wdrho¡=1.0, 1 is ideal for cmode=12) ——————– General BC and Global IC (White) ——————— 16:perikey 0 // 0: no peri, 1: x-peri, 2: y-peri, 3: all peri 17:pres0 1.0E+05 // Pressure in Pa (atmospheric: 1.0E+05 Pa) 18:uin0 40 // Initial u 19:vin0 0 // Initial v 20:rho0 1.2 // Initial density (for cmode=0,3) 21:temp0 0 // Initial temperature (for cmode=1,2) 22:scalar0 0 // Initial Mixture fraction (for cmode=2) ——————– BLUE Local BC and/or IC (optional) ——————– 23:uin1 40 // U 24:vin1 0 // V 25:rho1 1.2 // Density (for cmode0,3) 26:temp1 0 // Temperature (for cmode1,2) 27:scalar1 0 // Mixture fraction (for cmode2) ——————– RED Local BC and/or IC (optional) ——————– 28:uin2 40 // U 29:vin2 0 // V 30:rho2 0 // Density (for cmode0,3) 31:temp2 0 // Temperature (for cmode1,2) 32:scalar2 0 // Mixture fraction (for cmode2) ———- PINK Local BC and/or IC (pure air flow, optional) ———- 33:uin3 40 // U 34:vin3 0 // V 35:temp3 0 // Temperature ————— BLACK Wall Boundary Condition (optional) ————— 36:tempw 0 // Temperature (0: free, for cmode1,2) ————— GREEN Moving Boundary Condition (optional) ————- 37:imb 1 // 0:one-time, 1:periodic 38:umb 40 // U of moving boundary 39:vmb 0 // V of moving boundary 40:tempmb 0 // Temperature (0: free, for cmode1,2) ——— ——- YELLOW Scalar Boundary Condition (optional) ————- 41:scalarT 0 // Local scalar value which might be used as tracer ———- Transport Properties Thermochemical Conditions ———— 42:mu 2E-5 // Dynamic viscosity of mixture 43:R 0 // Specific gas constant J/kg K (for cmode=1,2) 44:diff 0 // Diffusivity of mixture (for cmode=1,2,yellow BC) 45:Tu 0 // Unburnt temperature (for cmode=1) 46:Tb 0 // Burnt (flame) temperature (for cmode=1,2) ———— ————- Chemical Reaction (for cmode=1) ——————- 47:krate 0 // Rate onstant 48:Trate 0 // Activation temperature 49:nrate 0 // Rate rho*k*exp(-Ta/T)*Tn 50:cF 0 // Progress variable at which flame locates (optional for vis) ——————— Non-Premixed Reacting Flow (for cmode=2) ——————— 51:Xst 0 // Stoichiometric mixture fraction at which flame locates 52:sigma 0 // Relaxation parameter for density change (0¡=sigma¡=1, 1 is ideal) —————————— Display Output —————————— 53:box 1 // Pixel size of one grid point 54:nfig 50 // Interval time steps for figure output (0:off) 55:nfile 5000 // Interval time steps for dump file output (0:off) 56:bcdisp 1 // Display wall boundary (0:off, 1:on) 57:idisp 4 // 0:off,1:rho,2:u,3:v,4:spd,5:vrt,6:T,7:rate,8:c/xi,9:P 58:cmax 0 // Scale (max). 0:auto scale 59:cmin 0 // Scale (min). 0:auto scale 60:icolor 0 // 0:Jet,1:Rainbow,2:Nishiki,3:Gray,4:Gray(inv),5:Hot,6:Sea,7:Leaf 61:icont 0 // (Reaction front) contour line (0:off,1:blck,2:red,3:grn,4:bl,5:wht) 62:linewidth 0 // Line width of contour line (1, 3, 5 or 7) 63:ivec 1 // Velocity vector (0:off,1:blck,2:red,3:grn,4:bl,5:wht) 64:ndiv 10 // Interval grid points between displayed vectors (0:auto) 65:vecsize 2 // Pixel size of vector arrow (0:auto) ————————— Lagrangian Trajectory (optional) ——————- 66:lagkey 0 // 0:off,1:x, 2:y,3:x-x,4:y-y 67:lagcolor 0 // 0:black, 1:white 68:lagsize 0 // Pixel size of particles 69:nlagra 0 // Interval time steps of restart (¿=100) 70:npart 0 // No. particle (¿=1000) ————————— Body Force (optional) ——————— ———— 71:gfx 0 // X-body force 72:gfy 0 // Y-body force 73:dref 0 // Reference density. 1:max, 2:middle, 3:min density as reference ——————- Initial Perturbation (optional) ——————- 74:pmode 0 // Mode of perturbation 0:off, 1:single mode, 2:multi, 3:multi (random amp.) 75:umag 0 // Velocity amplitude (m/s) 76:nwave 0 // Number of waves in x-direction ————————————— Others ——————————————- 77:nwait 0 // Wait time ————————————— ——————————————————— End of file

9.2 Short Rear Wing

10 Appendix: Input Files for Computational Study

10.1 Large Rear Wing

————- Control File for Flowsquare ver 4.0 (Use SI Unit) ————- ————— —————- General Control Data ————————— 01:cmode 0 // Simulation mode, 0:non-reac, 1:premixed, 2:non-premixed, 3:Euler, 4:analysis 02:nx 512 // No. grid points 03:ny 256 // No. grid points 04:lx 9.0 // Domain x-size 05:ly 4.5 // Domain y-size 06:sts 0 // Start time step (new simulation starts from sts=0) 07:latts 2000 // End time step 08:cflfac 8 // Delta t factor (more is better, but typically 10-1000) ——————- Numerical Scheme, Smoothing Accuracy ——————— 09:iorder 3 // 0: low order, 1: high order, 2:2nd+LW, 3:4th+LW 10:nfil 1 // Interval time steps for filtering 11:wfil 0.1 // Relaxation parameter for filtering 12:omega 1.8 // Relaxation parameter for Poisson Eq (for cmode=0-2) 13:peps 1.0E-1 // Convergence limit for Poisson Eq (for

Figure 17: Angled Rear Wing simulation at 5000 steps

cmode=0-2) 14:loopmax 100 // Maximum no. of iteration for Poisson Eq (for cmode=0-2) 15:wdrho 1.0 // Factor for d(rho)/dt (0¡=wdrho¡=1.0, 1 is ideal for cmode=12) ———————— General BC and Global IC (White) ————————- 16:perikey 0 // 0: no peri, 1: x-peri, 2: y-peri, 3: all peri 17:pres0 1.0E+05 // Pressure in Pa (atmospheric: 1.0E+05 Pa) 18:uin0 100 // Initial u 19:vin0 0 // Initial v 20:rho0 1.2 // Initial density (for cmode=0,3) 21:temp0 0 // Initial temperature (for cmode=1,2) 22:scalar0 0 // Initial Mixture fraction (for cmode=2) ———————— BLUE Local BC and/or IC (optional) ———————— 23:uin1 0 // U 24:vin1 0 // V 25:rho1 1.2 // Density (for cmode0,3) 26:temp1 0 // Temperature (for cmode1,2) 27:scalar1 0 // Mixture fraction (for cmode2) ———————— RED Local BC and/or IC (optional) ———————— 28:uin2 0 // U 29:vin2 0 // V 30:rho2 0 // Density (for cmode0,3) 31:temp2 0 // Temperature (for cmode1,2) 32:scalar2 0 // Mixture fraction (for cmode2) ————- PINK Local BC and/or IC (pure air flow, optional) ————- 33:uin3 0 // U 34:vin3 0 // V 35:temp3 0 // Temperature ——————— BLACK Wall Boundary Condition (optional) ——————— 36:tempw 0 // Temperature (0: free, for cmode1,2) ——————— GREEN Moving Boundary Condition (optional) ————- 37:imb 1 // 0:one-time, 1:periodic 38:umb 0 // U of moving boundary 39:vmb 0 // V of moving boundary 40:tempmb 0 // Temperature (0: free, for cmode1,2) ——— ——- YELLOW Scalar Boundary Condition (optional) ————- 41:scalarT 0 // Local scalar value which might be used as tracer ————- Transport Properties Thermochemical Conditions ———— 42:mu 2E-5 // Dynamic viscosity of mixture 43:R 0 // Specific gas constant J/kg K (for cmode=1,2) 44:diff 0 // Diffusivity of mixture (for cmode=1,2,yellow BC) 45:Tu 0 // Unburnt temperature (for cmode=1) 46:Tb 0 // Burnt (flame) temperature (for cmode=1,2) ————

———- Chemical Reaction (for cmode=1) ————— 47:krate 0 // Rate onstant 48:Trate 0 // Activation temperature 49:nrate 0 // Rate rho*k*exp(-Ta/T)*Tn 50:cF 0 // Progress variable at which flame locates (optional for vis) ———— Non-Premixed Reacting Flow (for cmode=2) ———— 51:Xst 0 // Stoichiometric mixture fraction at which flame locates 52:sigma 0 // Relaxation parameter for density change (0¡=sigma¡=1, 1 is ideal) ——————— Display Output ——————— 53:box 1 // Pixel size of one grid point 54:nfig 50 // Interval time steps for figure output (0:off) 55:nfile 5000 // Interval time steps for dump file output (0:off) 56:bcdisp 1 // Display wall boundary (0:off, 1:on) 57:idisp 4 // 0:off,1:rho,2:u,3:v,4:spd,5:vrt,6:T,7:rate,8:c/xi,9:P 58:cmax 0 // Scale (max). 0:auto scale 59:cmin 0 // Scale (min). 0:auto scale 60:icolor 0 // 0:Jet,1:Rainbow,2:Nishiki,3:Gray,4:Gray(inv),5:Hot,6:Sea,7:Leaf 61:icont 0 // (Reaction front) contour line (0:off,1:blck,2:red,3:grn,4:bl,5:wht) 62:linewidth 0 // Line width of contour line (1, 3, 5 or 7) 63:ivec 1 // Velocity vector (0:off,1:blck,2:red,3:grn,4:bl,5:wht) 64:ndiv 10 // Interval grid points between displayed vectors (0:auto) 65:vecsize 2 // Pixel size of vector arrow (0:auto) ————— Lagrangian Trajectory (optional) ————— 66:lagkey 0 // 0:off,1:x, 2:y,3:x-x,4:y-y 67:lagcolor 0 // 0:black, 1:white 68:lagsize 0 // Pixel size of particles 69:nlagra 0 // Interval time steps of restart (¿=100) 70:npart 0 // No. particle (¿=1000) —————— Body Force (optional) ————— 71:gfx 0 // X-body force 72:gfy 0 // Y-body force 73:dref 0 // Reference density. 1:max, 2:middle, 3:min density as reference ————— Initial Perturbation (optional) ————— 74:pmode 0 // Mode of perturbation 0:off, 1:single mode, 2:multi, 3:multi (random amp.) 75:umag 0 // Velocity amplitude (m/s) 76:nwave 0 // Number of waves in x-direction ——————— Others ——————— 77:nwait 0 // Wait time ————————————— End of file

10.2 Straight Rear Wing

11 Appendix: Input Files for Computational Study

11.1 Large Rear Wing

Control File for Flowsquare ver 4.0 (Use SI Unit) ——- ——————- General Control Data —————— 01:cmode 0 // Simulation mode, 0:non-reac, 1:premixed, 2:non-premixed, 3:Euler, 4:analysis 02:nx 512 // No. grid points 03:ny 256 // No. grid points 04:lx 9.0 // Domain x-size 05:ly 4.5 // Domain y-size 06:sts 0 // Start time step (new simulation starts from sts=0) 07:latts 20000 // End time step 08:cflfac 8 // Delta t factor (more is better, but typically 10-1000) ————- Numerical Scheme, Smoothing Accuracy ——— 09:iorder 3 // 0: low order, 1: high order, 2:2nd+LW, 3:4th+LW 10:nfil 1 // Interval time steps for filtering 11:wfil 0.1 // Relaxation parameter for filtering 12:omega 1.8 // Relaxation parameter for Poisson Eq (for cmode=0-2) 13:peps 1.0E-1 // Convergence limit for Poisson Eq (for cmode=0-2) 14:loopmax 1 // Maximum no. of iteration for Poisson Eq (for cmode=0-2) 15:wdrho

Figure 18: Angled Rear Wing simulation at 5000 steps

1.0 // Factor for d(rho)/dt (0¡=wdrho¡=1.0, 1 is ideal for cmode=12) ——————— General BC and Global IC (White) ——————- 16:perikey 0 // 0: no peri, 1: x-peri, 2: y-peri, 3: all peri 17:pres0 1.0E+05 // Pressure in Pa (atmospheric: 1.0E+05 Pa) 18:uin0 40 // Initial u 19:vin0 0 // Initial v 20:rho0 1.2 // Initial density (for cmode=0,3) 21:temp0 0 // Initial temperature (for cmode=1,2) 22:scalar0 0 // Initial Mixture fraction (for cmode=2) ——————— BLUE Local BC and/or IC (optional) ——————— 23:uin1 40 // U 24:vin1 0 // V 25:rho1 1.2 // Density (for cmode0,3) 26:temp1 0 // Temperature (for cmode1,2) 27:scalar1 0 // Mixture fraction (for cmode2) ——————— RED Local BC and/or IC (optional) ——————— 28:uin2 40 // U 29:vin2 0 // V 30:rho2 0 // Density (for cmode0,3) 31:temp2 0 // Temperature (for cmode1,2) 32:scalar2 0 // Mixture fraction (for cmode2) ————- PINK Local BC and/or IC (pure air flow, optional) ————- 33:uin3 40 // U 34:vin3 0 // V 35:temp3 0 // Temperature ——————— BLACK Wall Boundary Condition (optional) ——————— 36:tempw 0 // Temperature (0: free, for cmode1,2) ——————— GREEN Moving Boundary Condition (optional) ————- 37:imb 1 // 0:one-time, 1:periodic 38:umb 40 // U of moving boundary 39:vmb 0 // V of moving boundary 40:tempmb 0 // Temperature (0: free, for cmode1,2) ————- YELLOW Scalar Boundary Condition (optional) ————- 41:scalarT 0 // Local scalar value which might be used as tracer ————- Transport Properties and Thermochemical Conditions ——————— 42:mu 2E-5 // Dynamic viscosity of mixture 43:R 0 // Specific gas constant J/kg K (for cmode=1,2) 44:diff 0 // Diffusivity of mixture (for cmode=1,2,yellow BC) 45:Tu 0 // Unburnt temperature (for cmode=1) 46:Tb 0 // Burnt (flame) temperature (for cmode=1,2) ——————— Chemical Reaction (for cmode=1) ——————- 47:krate 0 // Rate onstant 48:Trate 0 // Activation temperature 49:nrate 0 // Rate rho*k*exp(-Ta/T)*Tn 50:cF 0 // Progress variable at which flame locates (optional for vis) ——————— Non-Premixed Reacting Flow (for cmode=2) ——————— 51:Xst 0 // Stoichiometric mixture fraction at which flame locates 52:sigma 0 // Relaxation parameter for density change (0¡=sigma¡=1, 1 is ideal) ——————— Display Output ——————— 53:box 1 // Pixel size of one grid point 54:nfig 50 // Interval time steps for figure output (0:off) 55:nfile 5000 // Interval time steps for dump file output (0:off) 56:bcdisp 1 // Display wall boundary (0:off, 1:on) 57:idisp 4 // 0:off,1:rho,2:u,3:v,4:spd,5:vrt,6:T,7:rate,8:c/xi,9:P 58:cmax 0 // Scale (max). 0:auto scale 59:cmin 0 // Scale (min). 0:auto scale 60:icolor 0 // 0:Jet,1:Rainbow,2:Nishiki,3:Gray,4:Gray(inv),5:Hot,6:Sea,7:Leaf 61:icont 0 // (Reaction front) contour line (0:off,1:blck,2:red,3:grn,4:bl,5:wht) 62:linewidth 0 // Line width of contour line (1, 3, 5 or 7) 63:ivec 1 // Velocity vector (0:off,1:blck,2:red,3:grn,4:bl,5:wht) 64:ndiv 10 // Interval grid points between displayed vectors (0:auto) 65:vecsize 2 // Pixel size of vector arrow (0:auto) ——————— Lagrangian Trajectory (optional) ———————- 66:lagkey 0 // 0:off,1:x, 2:y,3:x-x,4:y-y 67:lagcolor 0 // 0:black, 1:white 68:lagsize 0 // Pixel size of particles 69:nlagra 0 // Interval time steps of restart (¿=100) 70:npart 0 // No. particle (¿=1000) —————————— Body Force (optional) ——————————— 71:gfx 0 // X-body force 72:gfy 0 // Y-body force 73:dref 0 // Reference density. 1:max, 2:middle, 3:min density as reference ———————- Initial Perturbation (optional) ———————- 74:pmode 0 // Mode of perturbation 0:off, 1:single mode, 2:multi, 3:multi (random amp.) 75:umag 0 // Velocity amplitude (m/s) 76:nwave 0 // Number of waves in x-direction ————————————— Others ————————————- 77:nwait 0 // Wait time ————————————————————————————— End of file

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