JEMMME (Journal of Energy, Mechanical, Material, and Manufacturing Engineering)
Vol.4, No. 1, May 2019

ISSN 2541-6332 | e-ISSN 2548-4281
Journal homepage: http://ejournal.umm.ac.id/index.php/JEMMME

Effect of Tapper Ratio on a Car Rear Spoiler Performance

Harianto[a], Yosua Heru Irawan[b], Eka Yawara[c], Husni Bakhtiar[d]
[a,b,c,d] Department of Mechanical Engineering, Institut Teknologi Nasional Yogyakarta
Jl. Babarsari, Caturtunggal, Depok, Sleman, Yogyakarta
Telephone: (0274) 485390

e-mail: harianto@itny.ac.id, yhirawan@itny.ac.id, ekayawara@itny.ac.id, husnibakhtiar75@gmail.com

Abstract

The increasing development of car modification and the lack of understanding on the function of using spoilers or rear wings on vehicles, underlies the research on the aerodynamic forces acting on cars. The influence of this aerodynamic device will produce a compressive force to the bottom of the vehicle or called downforce, where this force is greatly influenced by the CL (lift coefficient) value. The purpose of this study was to determine the effect of variations in the tapper ratio on the value of downforce and drag force on on single-element type spoilers made using a NACA 6412 airfoil. The research was conducted using the Computational Fluid Dynamic method using ANSYS Fluent software with steady state pressure based solver. In this study five variations of the tapper ratio were used, namely: 1:1; 1:0.5; 1:0.7; 0.5:1; and 0.7:1. The fluid properties used are adjusted to the climate and weather in general air conditions and at air flow speeds of 100 km/h. Based on the research conducted, it can be concluded that the highest lift coefficient value was achieved in the 1:1 tapper ratio variation which was equal to CL = -0.2275 and CD = 0.0195. The highest downforce value is achieved in the 1:1 tapper ratio variation that is equal to L = -107,529 N and the largest drag force value is also achieved in the 1: 1 tapper ratio variation that is equal to D = 9.2269 N. The best CL/CD results are obtained at the 1:05 tapper ratio variation with a value of 12.82.

***Keywords**: coefficient drag; coefficient lift; downforce; dragforce spoiler; tapper ratio*

1. INTRODUCTION

Aerodynamics has an important role in the design of modern cars (1,14). In this case, aerodynamics has become one of the main studies in car design for the last 40 years with the aim of increasing the grip of tires on the road without adding mass to the vehicle (15). As a result, the car can reach the same downforce with a heavier car but with a lighter mass. This will result in better and faster acceleration.

The lift force is a force caused by the Bernoulli Effect, where the air moving faster the pressure that arises will decrease. This means that the air velocity on the upper surface is faster than the air velocity on the lower surface of the airfoil. The pressure difference on the surface where the upper surface has a pressure smaller than the bottom surface. This pressure difference causes lift force on a moving airfoil.

Drag force is a force that works in the horizontal direction and in the opposite direction to the direction of movement of the vehicle. The aerodynamics of a vehicle depend on the design and shape of the vehicle. This is because the design of the vehicle will determine the air resistance that occurs in a vehicle and the amount of drag for each vehicle shape is different from one another. Skin friction drag is caused by surface shear stresses on objects that come in contact with fluid. Skin friction drag occurs due to viscous friction that occurs in the boundary layer. The smoothness of the skin or surface will greatly affect this prisoner. While the friction drag is caused by pressure on an object moving past the fluid. The shape of an object affects the pressure drag that occurs on the object.

The influence of Aerodynamics will produce a downward force or also called downforce, where the force is greatly influenced by the CL (lift coefficient) value (2,3,11). The influence of downforce is very large in the process of vehicle design especially modern racing cars. The CL value will increase along with the increase in angle of attack and the magnitude of the Taper Ratio, and will decrease to a certain degree due to the stall phenomenon. When lift is produced, it will also produce drag or the presence of CD (drag coefficient) (4,13). Maximizing the application of down-force on the car will optimize performance when the car turns at turns. This is a challenge to create a design that produces optimum downforce value and minimizes CD.

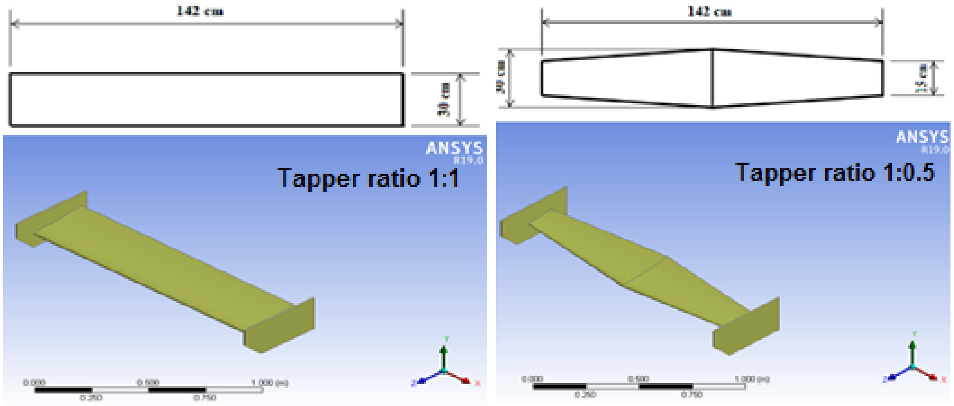
The aspect that needs to be reviewed in the development of vehicle design is to reduce drag force and also lift force or even create a negative lift (downforce) (5,6,7). In vehicles with high speed, aerodynamics is very influential and is responsible for the instability of the car at high speeds because the resulting lift force is usually greater in the car with a rear drive rather than the front drive (1,8,9). For high-speed cars the first anticipation to deal with instability in vehicles is to reduce drag force and lift force or even create negative lifts (downforce) using inverted wings (1,12). The air will move faster on the upper airfoil surface than at the bottom surface. The difference in speed produced on the surface of the airfoil creates a low pressure on the upper surface and a higher pressure on the bottom surface. The result of this pressure difference will produce downforce in the airfoil (1,10).

Tapper ratio is the ratio of the length of the chord to the tip and the length of the chord at the base of the wing. Tapper ratio has an effect on induced drag. Based on the lifting line theory for wings without sweep angles and without twist, the elliptic wing planform gives a minimum drag. To obtain a single element spoiler with maximum performance, the right tapper ratio is needed to produce the right ratio of lift force and drag force.

In this study, a single element rear wing/spoiler will be made with a tapper ratio variation to determine the lift coefficient value and the drag coefficient value using a NACA 6412 airfoil. The fluid flow that passes through rear wings construction will be simulated using ANSYS Fluent software. The purpose of this study was to determine the effect of variations in the tapper ratio on the value of downforce and drag force on a vehicle.

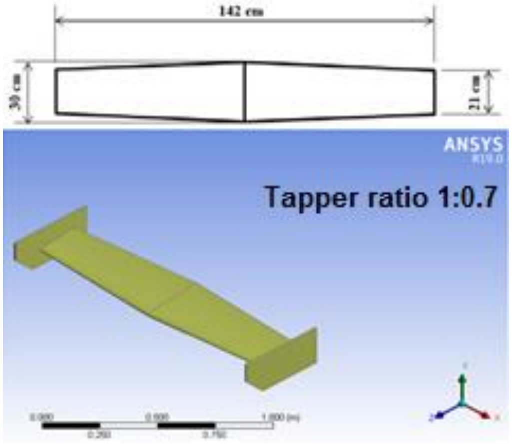
2. RESEARCH METHOD

The research method was carried out by varying the rear wings/spoiler model with five variations of the tapper ratio, namely 1:1; 1:0.5; 1:0.7; 0.5:1; 0.7:1. The simulation is carried out with an air speed 100 km/h, air temperature 288.16 K, dynamic viscosity 1.78 × 10^{-5} kg/m.s and the density of air 1.225 kg/m^3 . The research model is shown in the Figure 1, in this study only rear wings/spoiler were simulated, not using vehicles. The following is a picture along with specifications of the varying tapper ratio on the rear wings/spoilers.

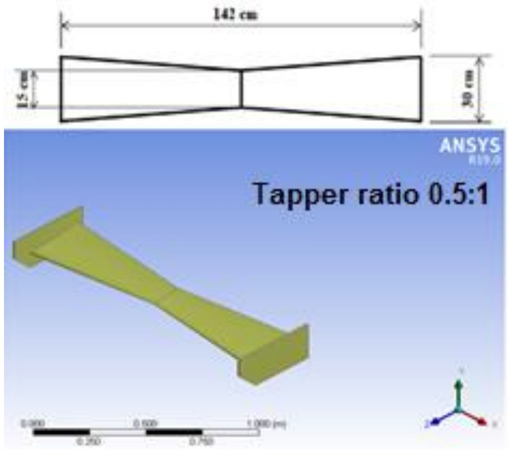


(a) (b)

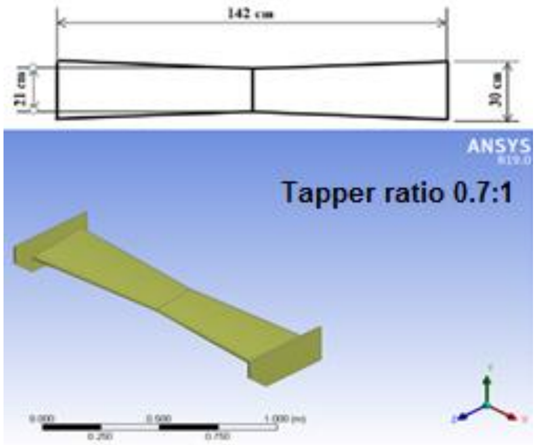
Figure 1. Simulation model with 5 tapper ratio variations. (a) Tapper ratio 1:1; (b) Tapper ratio 1:0.5; (c) Tapper ratio 1:0.7; (d) Tapper ratio 0.5:1; (e) Tapper ratio 0.7:1



(c)



(d)



(e)

Figure 1. Simulation model with 5 tapper ratio variations. (a) Tapper ratio 1:1; (b) Tapper ratio 1:0.5; (c) Tapper ratio 1:0.7; (d) Tapper ratio 0.5:1; (e) Tapper ratio 0.7:1 (continued)

Simulations are carried out on these single-element models by varying the taper ratio values to get the lift coefficient value and the drag coefficient value. The lift coefficient value will be compared with the drag coefficient value in consideration of choosing the best tapper ratio variation. From these data the ratio of lift coefficient values with drag coefficient is calculated which will be calculated using ANSYS Fluent software to calculate downforce and drag force.

The solution method in this case use steady state pressure based solver. To model the turbulent flow that occurs, a realizable k-epsilon turbulent model is used. Boundary conditions in this case consist of 4 types, namely: inlet (surface to define wind speed), outlet (surface to define pressure outlet), symmetry (surface to define the surface of the test section or computational domain surface), wall (spoiler surface part will be simulated). In this case, the number of iterations specified is 1000 iterations using the hybrid initialization method.

For observing the flow field in a model with five variations of the tapper ratio, two views or two planes are made. First is the plane on the side of the symmetry and the second is the observation plane at the base. The two planes are used to observe the two sides of the airfoil because of differences in the contour between the symmetry and the base due to the installation of the end plate on the base.

3. RESULTS AND DISCUSSION

3.1 Visualization results at tapper ratio of 1:1

Figure 2 represents the flow velocity that occurs on the surface and around the airfoil on the symmetry side and base side. Where in the tapper ratio 1:1, the airfoil produces the maximum CL value. On the symmetry side of the upper surface of the airfoil produces a low speed which is represented by light blue on the upper edge of the leading edge which ranges from v = 34.65 km/h and turns green on most of the upper surface of the airfoil to trailing edge around v = 83.45 km/h. At the base side the air velocity is the same as the symmetry side marked with light blue on the side of the leading edge and turns green to the trailing edge. On the symmetry side of the lower surface of the airfoil produces a red color which is a higher speed value at the leading edge which ranges from v = 129.8 km/h and changes gradually to yellow in the trailing edge worth v = 111.3 km/h. While at the base of the airfoil under the surface, it shows the same speed with the symmetry side which is marked in red but the red color on the base side is not as wide as the symmetry because of the end plate. This is a phenomenon where there are high and low speed flows on one part of the airfoil. This is due to the flow separation that occurs because of the large drag value generated from the viscosity of the boundary layer.

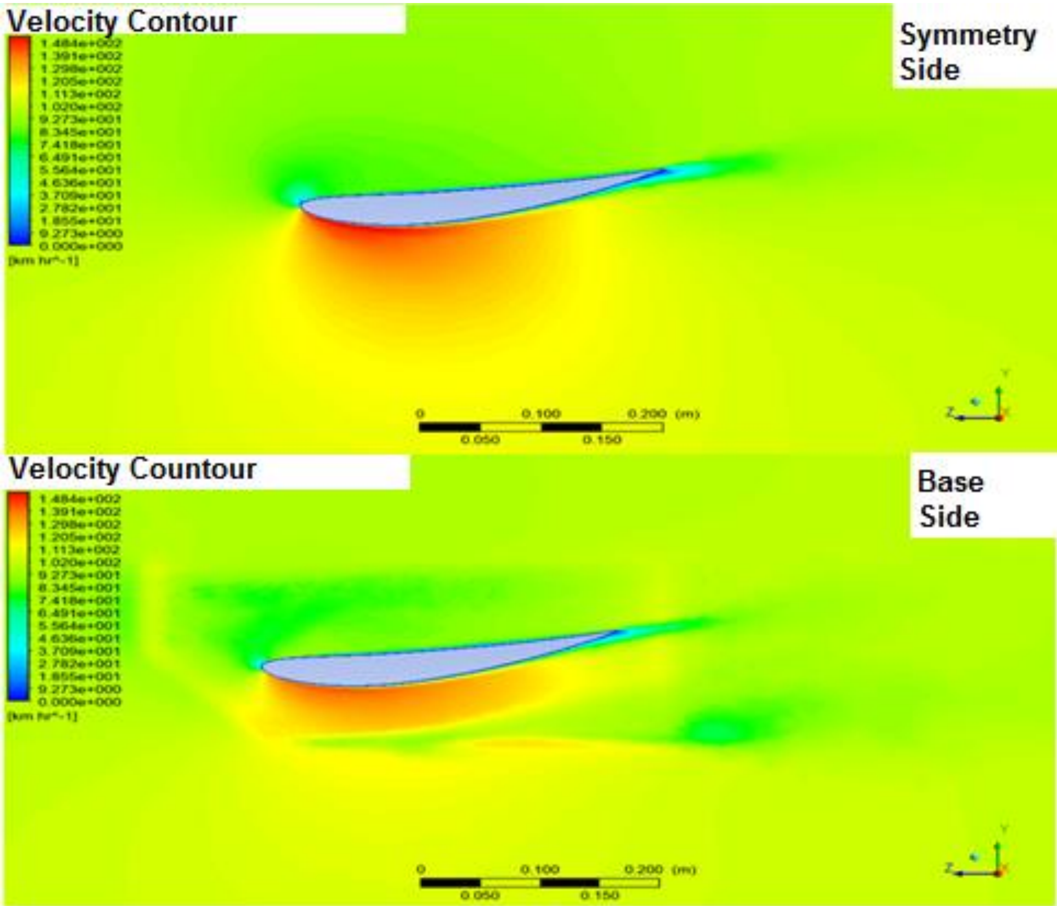


Figure 2. Velocity contour at tapper ratio of 1:1

Figure 3 presents the pressure generated from an airfoil with tapper ratio of 1:1 on the symmetry side and base side. On the symmetry side the high pressure on the upper surface of the red leading edge ranges from P = 288.7 Pa and changes color gradually to yellow to the trailing edge which ranges from P = 188.45 Pa. On the base of the upper surface of the airfoil it looks red as well as the symmetry side but slightly different on the base side which turns greenish yellow to the trailing edge which has a pressure ranging from P = 84.33 Pa. Then on the symmetry side of the bottom surface of the blue leading edge is P = - 528.8

Pa and changes gradually to light blue which ranges from P = 256.3 Pa and changes to green to the trailing edge which is P = -51.91 Pa. At the base side there is a slight difference in the lower part of the airfoil which is shown in blue which tends to be slightly and continued in light blue to the end of the end plate. The pressure on the upper side of the airfoil is higher than the pressure on the lower side of the airfoil, indicating a force of downforce occurring on this airfoil.

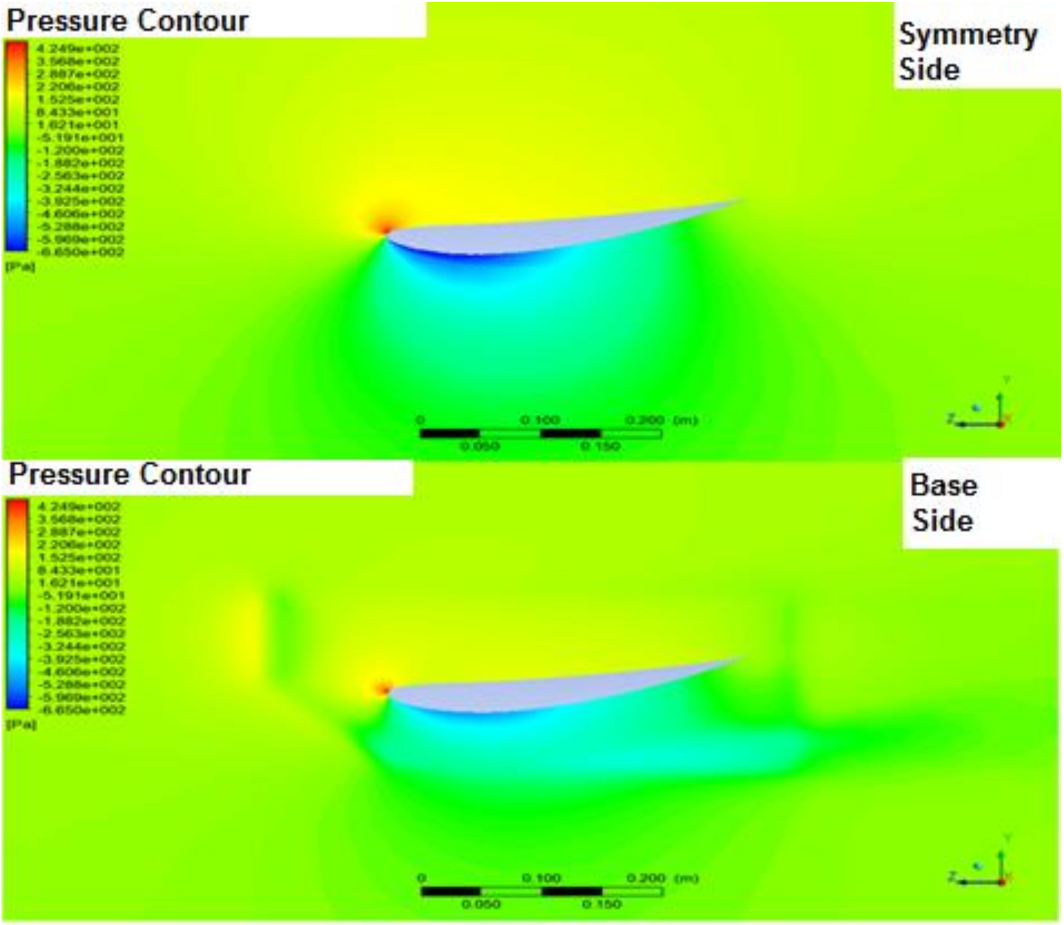


Figure 3. Pressure contour at tapper ratio of 1:1

3.2 Visualization results at tapper ratio of 1:0.5

Figure 4 shows the flow velocity on two sides, which is the symmetry and base side that occurs on the surface and around the airfoil with a 1:0.5 tapper ratio variation. Where the tapper ratio variation results in a lower CL value than the 1:1 tapper ratio variation. On the symmetry side the upper surface edge of the leading edge of the airfoil produces a low speed represented by light blue ranging from v = 54.91 km / h and changing gradually until light green until the trailing edge ranges from v = 82.36 km/h. At the base where there is a slight difference in air flow on the side of the leading edge which is more light blue compared to the symmetry side which ranges from v = 54.91 km/h. The lower surface side of the airfoil produces a red color which is a high velocity value in the leading edge around v = 137.3 km/h and changes gradually to yellow towards the trailing edge worth v = 100.7 km / hr. And there is a color difference in the end plate, this is because the base side of the rear wings has an end plate with the air velocity symbolized in yellow, which ranges from 109.8 km h. This is a phenomenon where there are high and low speed flows on one part of the airfoil. At the base where there is a slight difference in air flow on the side of the leading edge which is more light blue compared to the symmetry side which ranges from v = 18.34 km/h. This is due to the flow separation that occurs because of the large drag value generated from the viscosity of the boundary layer.

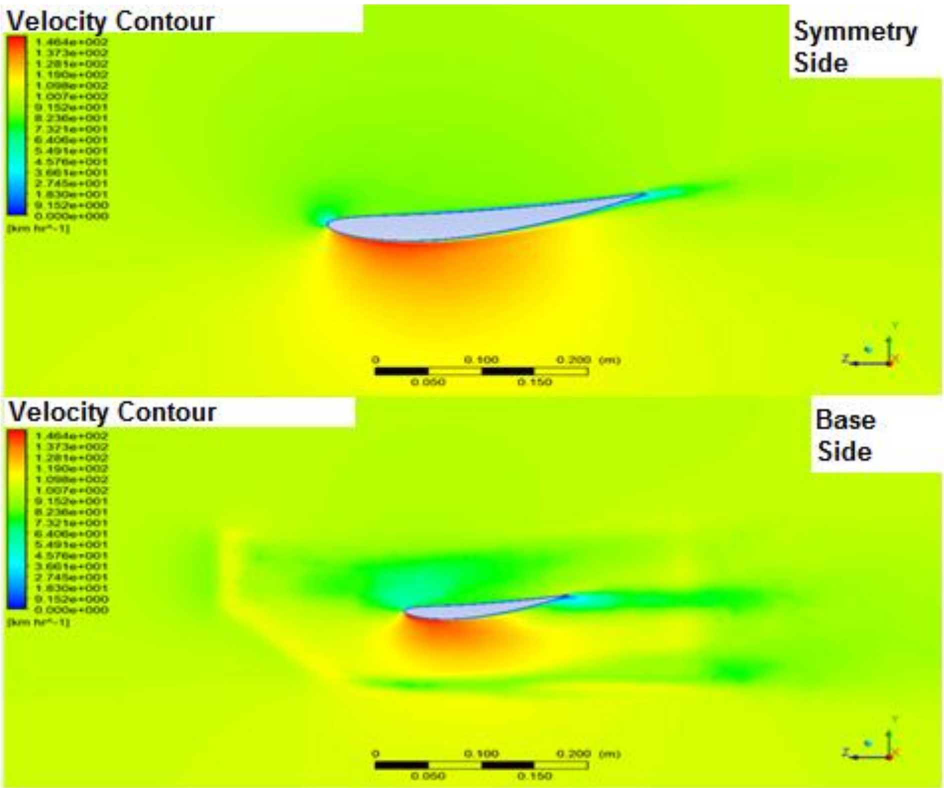


Figure 4. Velocity contour at tapper ratio of 1:0.5

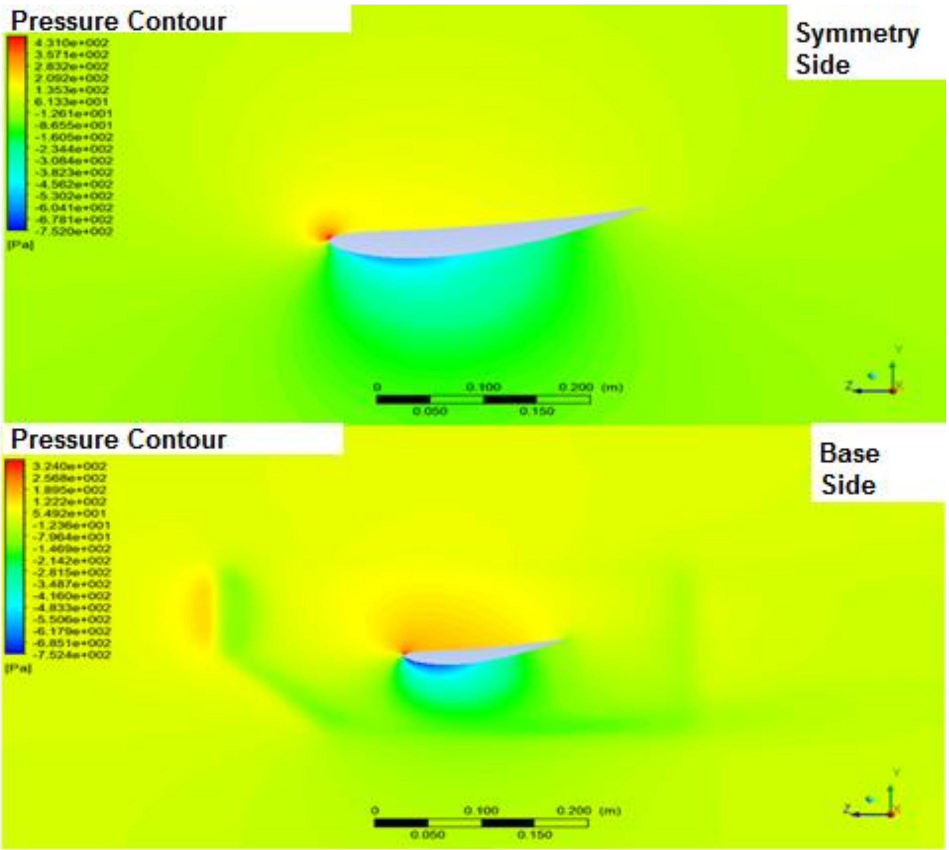


Figure 5. Pressure contour at tapper ratio of 1:0.5

Figure 5 presents the pressure generated from an airfoil with a variation of 1: 0.5 tapper ratio with two different sides, namely the symmetry side and the base side. On the side of symmetry it produces high pressure right at the top of the airfoil on the side of the red leading edge around P = 209.2 Pa and turns yellow to the trailing edge which ranges from P = 120.3 Pa. At the base side there is a pressure difference with the symmetry side at the top of the leading edge which is shown in red which spreads widely on this side of the base plane which ranges from P = 135.3 Pa. On the symmetry side the lower surface of the light blue leading edge is P = -308.4 Pa and changes gradually to green to the trailing edge which is worth P = -160.5 Pa.

While on the base side it produces dark blue at just below the airfoil which ranges from P = - 550.6 Pa. Then change color to light blue at the bottom of the middle side of the airfoil which ranges from P = - 348.7 Pa. And green on the bottom leading to the trailing edge which ranges from P = - 146.9 Pa. It is seen on the end of the green plate which indicates the low pressure around the end plate which ranges from P = - 146.9 Pa. There is a pressure difference between the symmetry and the base which ranges from ΔP = 73.9 Pa. The end plate at the base side functions to maximize downforce. The pressure on the upper side of the airfoil higher than the lower side of the airfoil shows downforce in this type of tapper ratio variation.

3.3 Visualization results at tapper ratio 1:0.7

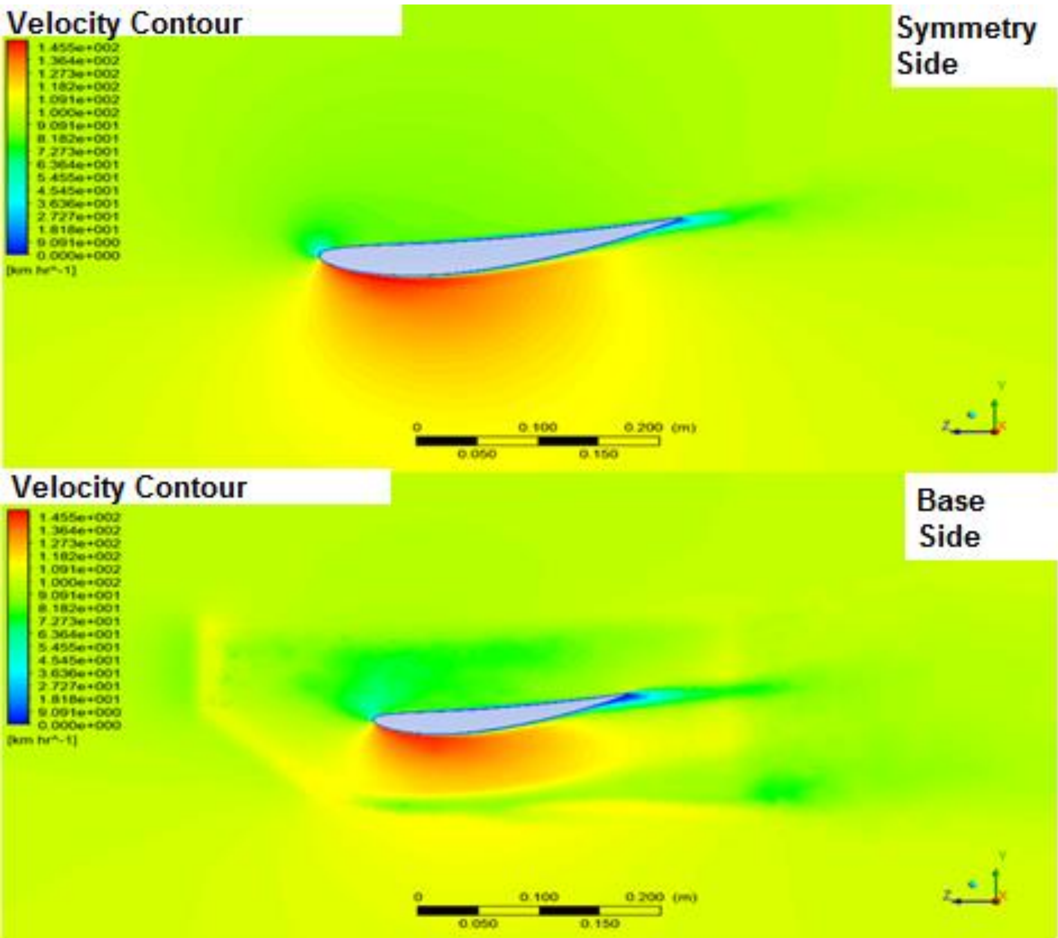


Figure 6. Velocity contour at tapper ratio of 1:0.7

Figure 6 represents flow velocities that occur on the surface and around the airfoil with a variation of tapper ratio 1:0.7 with two different sides, namely the symmetry side and the base side. Where the tapper ratio variation results in a lower CL value than the 1:1 tapper ratio variation and higher than the 1:0.5 tapper ratio variation. On the symmetry side the upper surface of the leading edge of the airfoil produces a low velocity represented by light blue ranging from v = 63.64 km/h and turns green around v = 90.91 km/h. At the base at the top of the light blue leading edge is more widespread than the symmetry side which ranges from v = 63.64 km/h. And change to green which ranges from v = 81.82 km/h. On the symmetry side of the airfoil under surface produces a red color which is a very high speed value in the leading edge around v = 127.3 km/h and changes gradually to yellow towards the trailing edge worth v = 109.1 km/h. And at the bottom of the leading edge on the base side is red but at the base side it looks red on the underside of the leading edge which is more irregular because on this side the frontal area is smaller compared to the symmetry side. At the base there is an end plate which indicates a low air velocity which is shown in green around the end plate which ranges from v = 72.73 km/h. This is a phenomenon where there is a high and low speed flow on one part of the airfoil which is a result of flow separation due to the large drag value generated from the viscosity of the boundary layer.

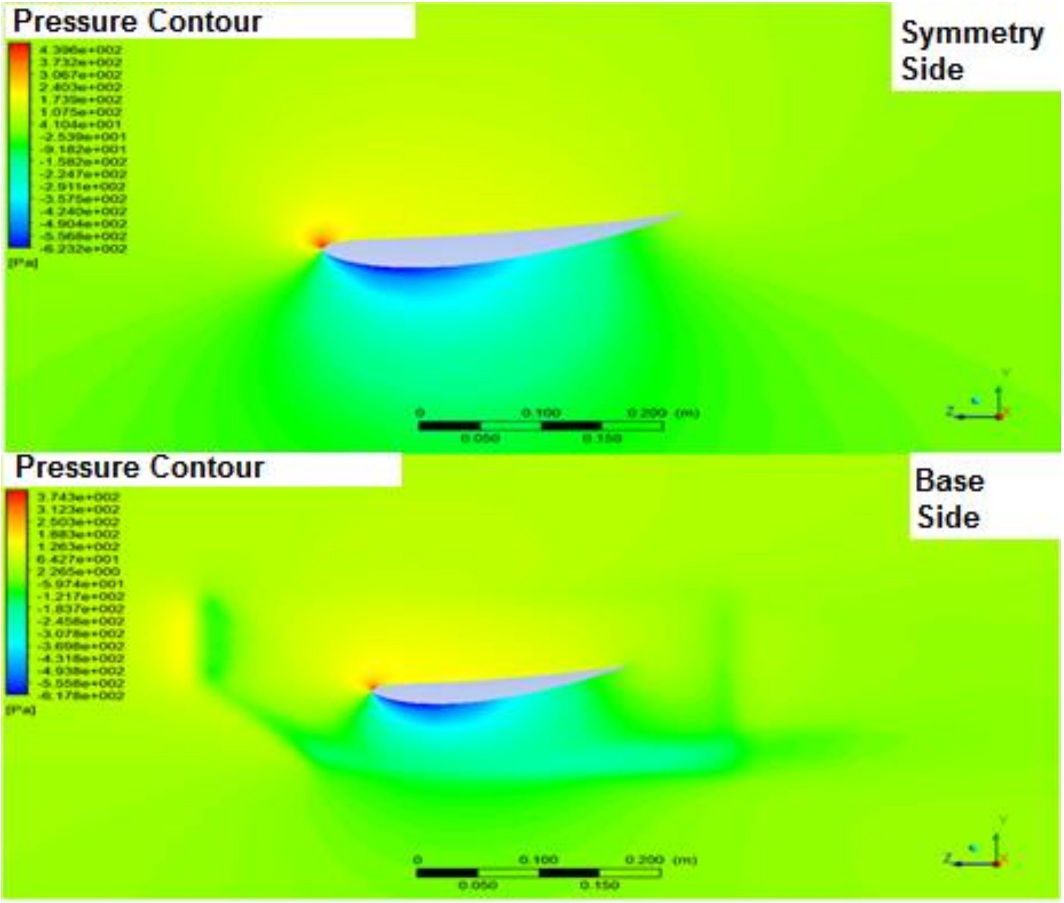


Figure 7. Pressure contour at tapper ratio of 1:0.7

Figure 7 shows the pressure generated from an airfoil with a variation of tapper ratio 1:0.7 on the symmetry side and base side. On the symmetry side it produces a high pressure on the upper part of the airfoil on the side of the red leading edge around P = 239.7 Pa and turns yellow to the trailing edge which ranges from P = 107 Pa. On the upper base side the leading edge has the same color as the symmetry side and has the same large pressure. On the symmetry side of the surface under the leading edge the pressure is lower than the pressure above the leading edge, which is dark blue, P = - 490.3 Pa changes gradually to light blue which is P = - 291.2 Pa and turns green the value of the trailing edge is P = -25.73 Pa.

On the lower base of the airfoil there is a difference in color, namely light blue which is dominant at the bottom of the airfoil to the lower end of the end plate which ranges from P = - 224.8 Pa. While the end plate looks green around the front and back ends which range from P = - 25.73 Pa. And the pressure at the lower end of the end plate is light blue which ranges from P = - 291.2 Pa. The end plate at the base side functions to maximize downforce. The pressure on the upper side of the airfoil higher than the lower side of the airfoil shows downforce in this type of tapper ratio variation.

3.4 Visualization results at tapper ratio 0.5:1

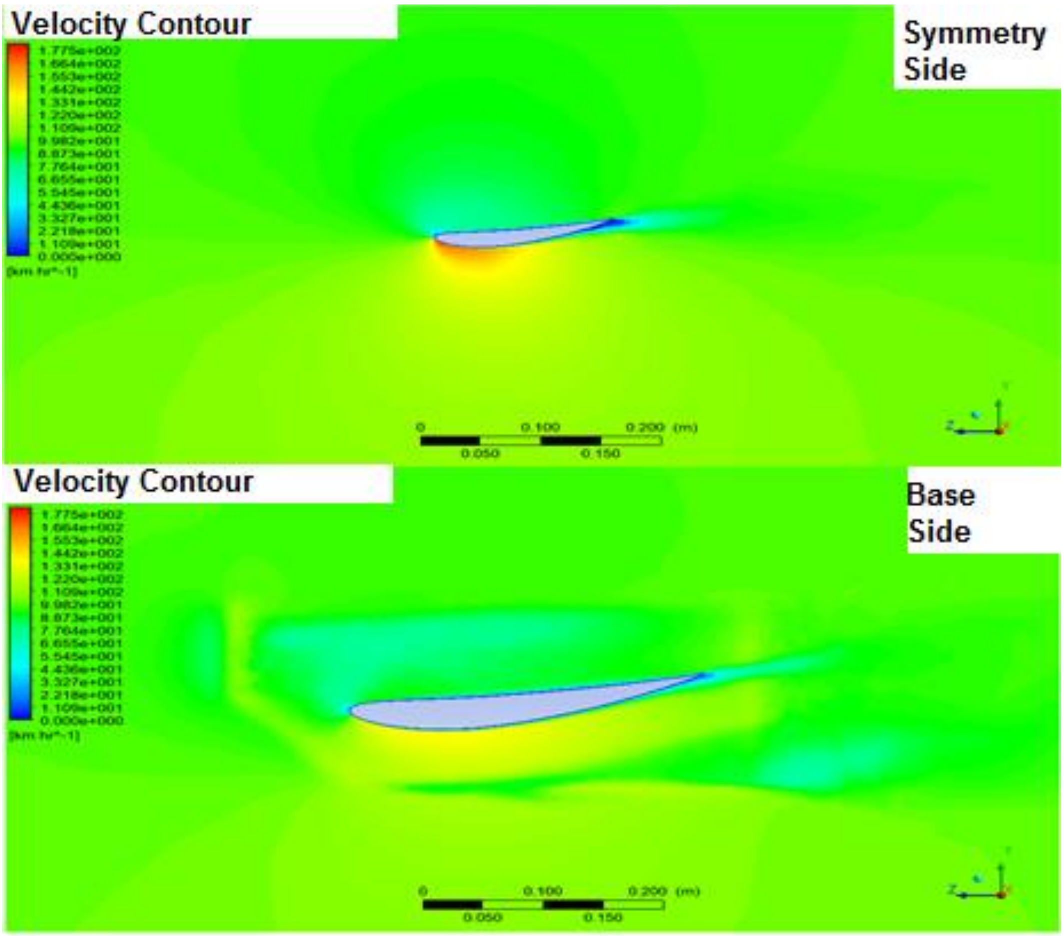


Figure 8. Velocity contour at tapper ratio of 0.5:1

Figure 8 represents flow velocities that occur on the surface and around the airfoil with variations in the tapper ratio 0.5:1 side of the symmetry and base side. Where the tapper ratio variation produces a CL value that is almost the same as the 1:0.5 tapper ratio variation but slightly lower. On the symmetry side of the surface of the leading edge of the airfoil produces a low speed which is represented by a light blue centered on the end of the airfoil which ranges from v = 66.55 km/h and changes gradually to green to the trailing edge around v = 99.82 km/ h. At the base of the edge of the airfoil on the upper edge of the leading edge, there is a difference in color, which on the base of the light blue color is irregular and not centered but has the same airspeed. On the symmetry side of the airfoil under surface produces a red color which is a high speed value ranging from v = 155.3 km/h and changes gradually until yellow in the middle of the airfoil which ranges from v = 133.1 km/h and turns blue to trailing edge direction worth v = 22.18 km/h. At the bottom base of the leading edge there is a difference with the symmetry side where the lower base side is indicated in yellow which ranges from v = 122 km/h to the trailing edge. This is a phenomenon where there are high and low speed flows on one part of the airfoil. This is due to the flow separation that occurs because of the large drag value generated from the viscosity of the boundary layer.

Figure 9 shows the pressure generated from an airfoil with variations in the tapper ratio 0.5:1 on the symmetry side and base side. On the side of symmetry it produces high pressure at the top of the airfoil on the side of the leading edge shown in red ranging from P = 317.1 Pa and turns yellowish red towards the trailing edge which ranges from P = 99.88 Pa. At the base of this side there are differences with the symmetry side. At the base of the red color above the leading edge it does not spread and the yellow dominance is greater which indicates a lower pressure compared to the symmetry side which ranges from P = 208.5 Pa. On the lower surface symmetry the leading edge pressure is lower than the pressure above the leading edge of the light blue value P = -551.8 Pa and changes gradually to green towards the trailing edge which is worth P = - 117.3 Pa.

And at the bottom of the airfoil at the base of the pressure is higher than the pressure on the symmetry side which is marked with green which ranges from P = - 17.53 Pa. At the base side it looks green on the edge of the pressure end plate P = 8.727 Pa. The end plate at the base side functions to maximize downforce. The pressure on the upper side of the airfoil higher than the lower side of the airfoil shows downforce in this type of tapper ratio variation. Pressure flows from high pressure to low pressure, resulting in a downforce that occurs and makes the lift coefficient value very large.

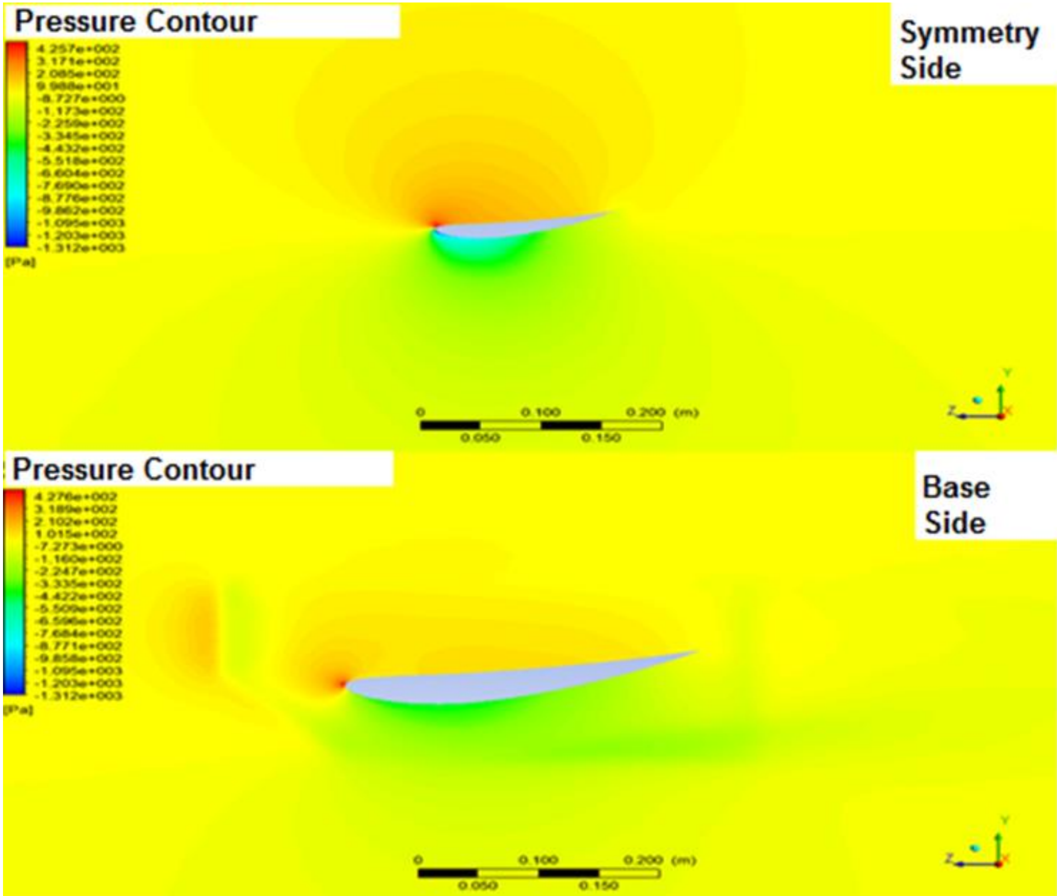


Figure 9. Pressure contour at tapper ratio of 0.5:1

3.5 Visualization results at tapper ratio 0.7:1

Figure 10 represents the flow velocity that occurs on the surface and around the airfoil with a variation of the tapper ratio 0.7:1 side of the symmetry and base side. Where the tapper ratio variation produces a CL value that is almost the same as the tapper ratio variation of 1:0.7 but slightly lower. On the symmetry side the upper surface of the leading edge of the airfoil produces a low speed represented by light blue ranging from v = 60 km/h and changes gradually to green until the trailing edge ranges from v = 90 km/h. At the base of the airfoil end of the upper edge of the leading edge, there is a difference in the speed of flow which on the upper side of the leading edge of light blue is greater and is continued in green indicating a slightly higher speed compared to the symmetry which ranges from v = 70 km/h. On the symmetry side of the airfoil under surface produces a red color which is a very high speed value in the leading edge around v = 150 km/h and changes gradually until yellowish red in the center v = 125 km/h. And turn yellowish green towards the trailing edge worth v = 125 km/h. At the bottom base side the leading edge speed is slightly lower than the symmetry side which is marked with yellowish red which ranges from v = 135 km/h. And turns greenish yellow to the trailing edge which ranges from v = 115 km/h. And it looks green around the end plate which has air velocity around v = 80 km/h. This is a phenomenon where there are high and low speed flows on one part of the airfoil. This is due to the flow separation that occurs because of the large drag value generated from the viscosity of the boundary layer.

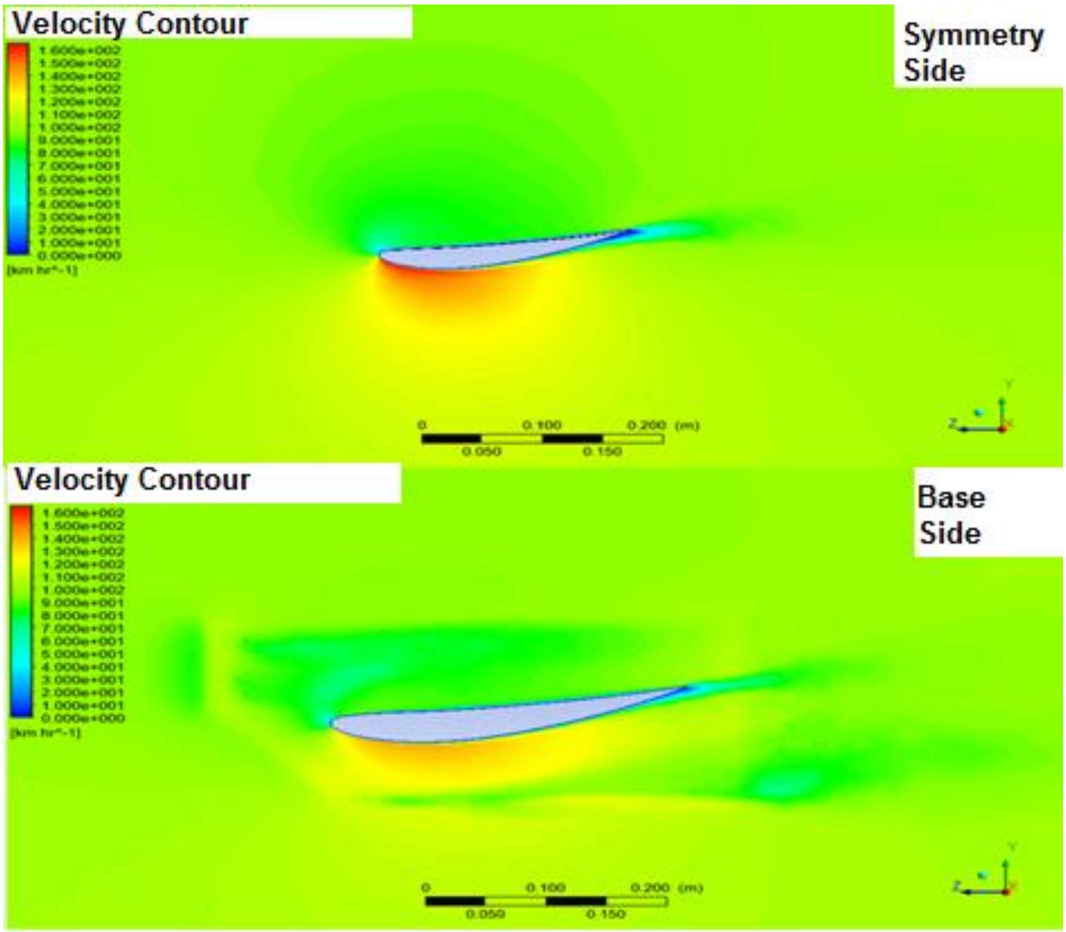


Figure 10. Velocity contour at tapper ratio of 0.7:1

Figure 11 represents the pressure generated from an airfoil with a variation of tapper ratio 0.7:1 on the symmetry side and base side. On the symmetry side it produces a high pressure at the top of the airfoil on the side of the red leading edge around P = 258.8 Pa and turns yellowish red in the middle which reaches P = 175.1 Pa. And yellow on the trailing edge which ranges from P = 15.68 Pa. At the base of this side there are differences with the symmetry side. At the base of the red leading edge, which tends to be small, P = 245.8 Pa. And turned yellow to trailing edge which ranged from P = 91.36 Pa. On the symmetry side of the surface under the leading edge the pressure is lower than the pressure above the leading edge which is dark blue and is continued with light blue which is worth P = - 622.7 Pa and turns green to the direction of the trailing edge P value = - 76.03 Pa. At the lower base of the airfoil the higher pressure is compared to the pressure on the symmetry side marked in light blue which is P = - 410.8 Pa and changes gradually to green which is P = - 159.7 Pa. At the base, green is seen around the end plate which has a value of P = - 76.03 Pa. The end plate at the base side functions to maximize downforce. The pressure on the upper side of the airfoil higher than the lower side of the airfoil shows downforce in this type of tapper ratio variation. Pressure flows from high pressure to low pressure, resulting in a downforce that occurs and makes the lift coefficient value very large.

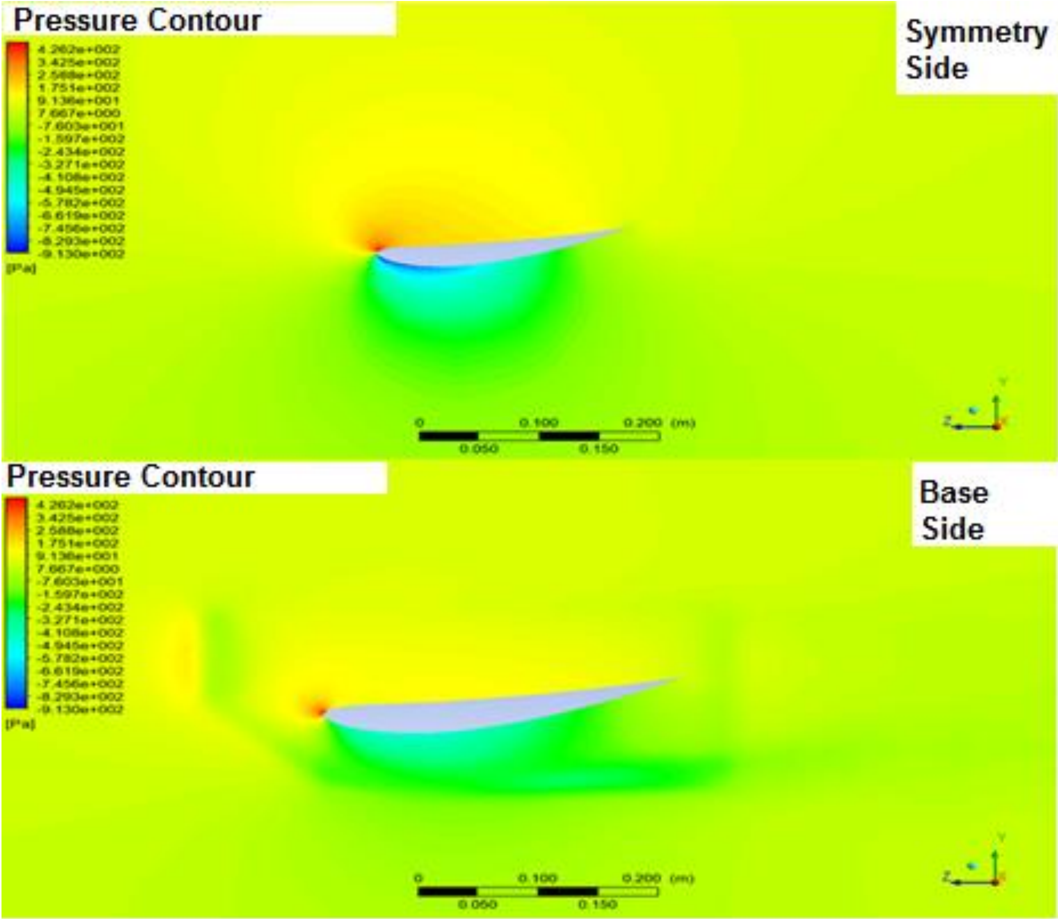


Figure 11. Pressure contour at tapper ratio of 0.7:1

3.6 Calculation results for dragforce and downforce

Table 1. Comparison of simulation results

Tapper Ratio	***Angle of Attack (º)***	**CL**	**CD**	**CL/CD**	**Drag Force (N)**	**Down force (N)**
1:1	**-8**	**-0,2275**	**0,0195**	**11,67**	**9,2226**	**-107,53**
1:0.5	**-8**	**-0,1782**	**0,0139**	**12,82**	**6,5862**	**-84,22**
1:0.7	**-8**	**-0,2003**	**0,0162**	**12,35**	**7,6415**	**- 94,66**
0.5:1	**-8**	**-0,1717**	**0,0142**	**12,17**	**6,7046**	**- 81,14**
0.7:1	**-8**	**-0,1951**	**0,0162**	**12,11**	**7,6401**	**- 92,18**

The Table 1 is a comparison of the results of the lift coefficient, drag coefficient, downforce and maximum drag forces that can be generated by each variation of the tapper ratio with an angle of attack - 8º. The best comparison between CD and CL of all variations is the variation of the tapper ratio 1:0.5 which ranges from 12.82. The highest lift coefficient and drag coefficient values are found in the 1:1 tapper ratio variation ranging from 0.2275 and 0.0195. The highest downforce and drag forces values are found in the 1:1 tapper ratio variation - 107.53 N and 9.2226 N.

4. Conclusion

Based on the research conducted, it can be concluded that the effect of variations in tapper ratio with angle of attack - 8º using NACA 6412 airfoils on lift coefficient and drag coefficient showed that the results were different. Conversely, if the surface area is smaller, the lift coefficient value will be smaller and the drag coefficient value will be smaller. After doing a simulation with various variations of the tapper ratio, the highest lift coefficient value was achieved in the 1:1 tapper ratio variation which was equal to CL = -0.2275 and CD = 0.0195. The highest downforce value is achieved in the 1:1 tapper ratio variation that is equal to L = -107,529 N and the largest drag force value is also achieved in the 1: 1 tapper ratio variation that is equal to D = 9.2269 N. The best CL/CD results are obtained at the 1:05 tapper ratio variation with a value of 12.82.

References

1. Katz J. Race Car Aerodynamics Designing for Speed Engineering and Performance. 1995. p. 279.
2. Tsai CH, Fu LM, Tai CH, Huang YL, Leong JC. Computational aero-acoustic analysis of a passenger car with a rear spoiler. Applied Mathematical Modelling. 2009;33(9):3661–3673.
3. Hai-Tao B. Study the effect of rear spoiler on car aerodynamics characteristics. IGCSE 2011 - 6th International Conference on Computer Science and Education, Final Program and Proceedings. 2011;460–463.
4. Nadia O, Norwazan AR, Khalid AJ, Zulkiffli AK, Fuad MN. Experimental and Numerical Analysis of Lift and Drag Force of Sedan Car Spoiler. Applied Mechanics and Materials. 2012;165:43–47.
5. Pachpund S, Madhavan J, Pandit G, Chimner T. Development of CFD Methodology for Drag Force Prediction on Passenger Car with Rear Mounted Spoiler. SAE Technical Paper Series. 2012;1.
6. Sunanda A, Nayak MS. Analysis of NACA 2412 for Automobile Rear Spoiler Using Composite Material. International Journal of Emerging Technology and Advanced Engineering. 2013;3(1):236–242.
7. Beigmoradi S, Jahani K, Keshavarz A, Bayani Khaknejad M. Aerodynamic Noise Source Identification for a Coupe Passenger Car by Numerical Method Focusing on the Effect of the Rear Spoiler. SAE Technical Paper Series. 2013;1.
8. Febrianto N, Sardjito, Ahlis N. Studi Perbandingan Karakteristik Airfoil NACA 0012 dengan NACA 2410 Terhadap Koefisien Lift dan Koefisien Drag pada Berbagai Variasi Sudut Serang dengan CFD. 2014;(April).
9. Mashud M, Das RC. Effect of rear end spoiler angle of a sedan car. AIP Conference Proceedings. 2017;1851.
10. Kumar MVS, Rao BA, Mallaiah G. Design, Analysis and Manufacturing of a Car Rear Spoiler for Drag Reduction. International Advanced Research Journal on Sciences, Engineering and Technology. 2017;4(6):89–96.
11. Cakir, Mustafa, "CFD study on aerodynamic effects of a rear wing/spoiler on a passenger vehicle" (2012). Mechanical Engineering Masters Theses. Paper 1.
12. Deressa KK, Sureddy KK. Design and analysis of a new rear spoiler for SU vehicle mahindra bolero using CFD. International Research Journal of Engineering and Technology. 2016;03(06):914–24.
13. Chandra R, Riyad M. CFD Analysis of Passenger Vehicle at Various Angle of Rear End Spoiler. Procedia Engineering. 2017;194:160–5.

14. Blocken B, Toparlar Y. Journal of Wind Engineering A following car influences cyclist drag: CFD simulations and wind tunnel measurements. Journal of Wind Engineering and Industrial Aerodynamic. 2015;145:178–86.
15. Thabet S, Thabit TH. CFD Simulation of the Air Flow around a Car Model (Ahmed Body). International Journal of Scientific and Research Publications. 2018;8(7):517–25.