Computational and Experimental Investigations of The Efficacy of Dimple Ratios to Characteristics of Flow on Van Vehicle Models

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Abstract:* One of the most critical challenges facing automotive engineers worldwide is to present vehicles with the lowest aerodynamic drag. The method that can be applied to delay separation and to reduce longitudinal wake and vortex formation is passive control, in the form of dimples in the separation area. The research objective focuses on reducing aerodynamic resistance through the analysis of flow pattern characteristics and pressure fields. The test model used is the Reverse Ahmed body, which has a 1:6 ratio to the real Ahmed model. For the flow and pressure field characteristics, the data were obtained through a computational approach. The computational result of aerodynamic resistance was validated by experimental testing. Passive control is applied in 1 line dimple configuration and two zigzag lines with dimple ratios of 0.20, 0.25, and 0.50. The results showed that dimples in the vehicle model reduced longitudinal wake and vortex formation by delaying flow separation, increasing pressure efficiency, and reducing the highest aerodynamic drag by 12.092% for the computational and 8.923% for the experimental approach.

***Index term:* Van Vehicle, Passive Control, Dimple Ratio, Pressure Distribution, Drag Aerodynamics**

I. INTRODUCTION

The challenge facing automotive scientists worldwide is to present a vehicle with the lowest aerodynamic drag. It is related to efforts to save fuel consumption and environmental aspect. Previous research has proven that a 15% reduction in aerodynamic drag can give fuel consumption savings of 5–7% [1].

The vehicle's aerodynamic drag consists of 2 main components; frictional drag, contributing to 20% of total drag [2], and pressure drag, contributing other 80% [3]. These two components are closely related to the characteristics of the flow patterns and the pressure field that occurs on the vehicle's rear wall. When the fluid reaches the top of the vehicle's rear, the flow will lose momentum to move along vehicle's rear parts. As a result, the flow will undergo a separation process and create a backflow, which causes negative pressure on the back wall and triggers backward suction. It will create a pressure difference between the front and rear sides, which is the leading cause of aerodynamic drag that works [4,5]. Apart from flow separation, aerodynamic drag is also caused by a longitudinal vortex on the rear wall. A proportion of the flow that loses momentum to move along with the body shape will be pushed sideward due to differences of flow velocities in mid parts of vehicles. This difference in velocity is a significant factor in the emergence of longitudinal vortices [6]. An in-depth evaluation of the vortex structure that forms around the vehicle body is essential to ensure vehicle stability while driving [7]. Therefore, efforts to reduce the aerodynamic drag acting on the vehicle can be made by delaying flow separation and minimizing vortex formation intensity.

One method that can be applied is passive control at the starting point of the separation process. The application of passive controls is considered more efficient because it does not involve additional energy and tends to be more applicable because it does not require significant modifications to the vehicle body. One of the passive controls that need to be considered to be implemented is a dimple.

Chear and Dol examined the effect of dimple application on Ahmed body on aerodynamic drag through a numerical computational approach with a k-epsilon turbulence model and an upstream velocity of 40 m/s. The dimple ratios used were 0.05, 0.2, 0.3, 0.4, and 0.5, respectively. The results showed a delay in flow separation and the highest reduction in aerodynamic drag obtained at the dimple ratio, DR = 0.4 of 1.95% [8].

Wong and Dol studied the effect of dimple application on simplified vehicle models through a computational simulation approach with the k-epsilon turbulence model at Reynolds number 176,387. The dimple ratios applied were DR=0.05, DR=0.2, DR=0.3, DR=0.4, and DR=0.5. The results showed that dimple geometry could change the kinematics and dynamics of the flow. The maximum turbulent kinetic energy is obtained at DR=0.4, and there is a reduction in aerodynamic resistance compared to the model without the application of dimple [9]. Salam et al. have investigated of characteristics of the flow drag across dimpled square cylinders, computational and experimentally, and have found out that parallel configurations gave higher reduction than the one that zigzag configurations could produce [10]. Sukardin et al. previously studied the distribution of flow through inline dimpled plate and found out that more dimple rows tend to produce more pressure coefficient decreases [11]. Based on the description above, studies on passive control to reduce drag aerodynamics in the form of dimple ratio variations are still limited to certain models. Meanwhile, the van model represented in the Ahmed body reversed model has not been further investigated. The aim of the research is to find the characteristic of the aerodynamics drag on the reverse Ahmed body at various dimple ratios.

II. METHODOLOGY

The test model used is a Reverse Ahmed Body, a modification of the original Ahmed model by changing the flow direction. The designed vehicle has been researched to analyze its flow dynamic [12, 13, 14]. The test model's dimension comparison against the original Ahmed model is 0.17 (1:6). The dimensions are written, length, l=174 mm, height, h=48 mm, and width, w=64.83 mm. The slope of the front geometry is determined to be 25°. Passive control in the form of dimples is placed on the upper side of the vehicle model's rear, which is believed to be the starting location for the flow separation process. This research applies dimple configurations of 1 line and 2-zigzag lines with the dimple ratio of each configuration DR=0.20, DR=0.25, and DR=0.5. The upstream velocity used is 22.2 m/s. Details of the test model are shown in Figure 1.

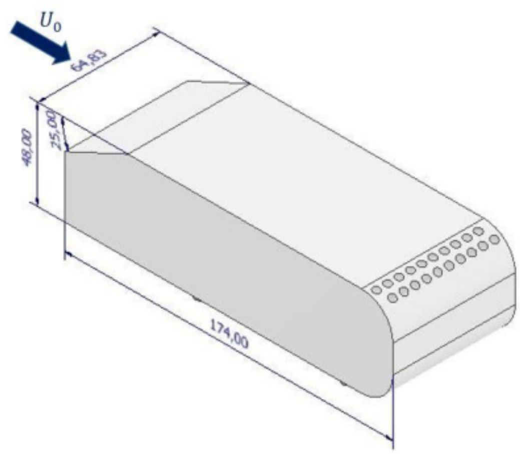


Figure 1 Test model

The research is focused on the analysis of aerodynamic resistance through computational and experimental approaches that are supported by displaying the characteristics of the flow pattern in the form of velocity pathlines and pressure fields on the rear wall of the vehicle model obtained through a computational approach.

Based on various studies, it has been revealed that 80% of the total resistance is caused by low pressure on the rear wall of the vehicle [15]. It is the main reason why the pressure field data collection is determined on the vehicle model's rear wall. For the axes along the model's width, the pressure data are obtained for five grid rows. The ratio of the width of the grid to the width of the rear wall of the vehicle model is written z/w=-1/2, z/w =-1/4, z/w=0, z/w=1/4, and z/w=1/2. The ratios of the grid height to the model height (y/h) are 0.17, 0.33, 0.50, 0.67, and 0.83, respectively, as shown in Figure 2.

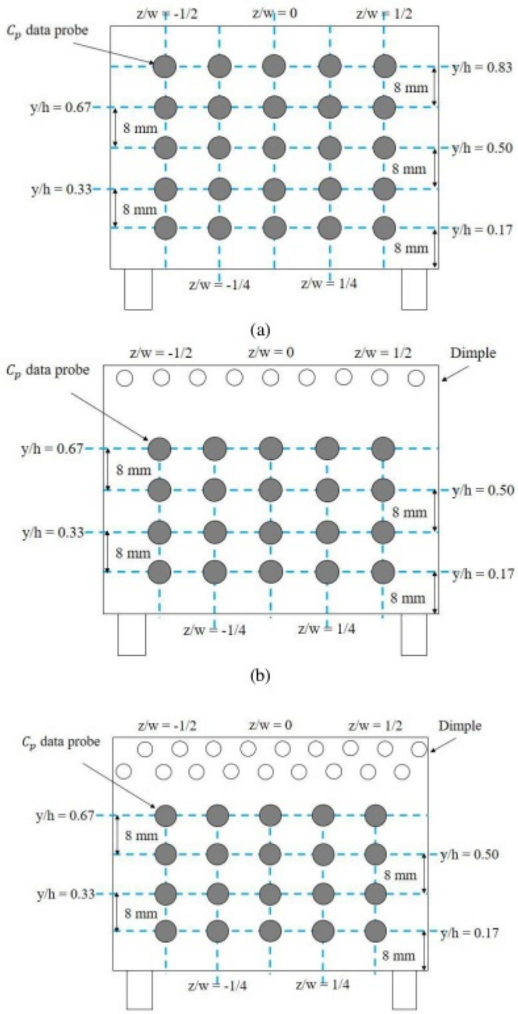


Figure 2 Location of pressure field data collection: (a) Without control, (b) With 1-line dimple, (c) With 2-zigzag dimple lines.

The ratios of the grid height to the model height (y/h) are 0.17, 0.33, 0.50, 0.67, and 0.83, respectively. The pressure value obtained is written in a dimensionless number, the pressure coefficient (Cp), defined in equation 1 [16]:

$$C_p = \frac{P - P_0}{\frac{1}{2}\rho U^2} \qquad (1)$$

After the design process, the vehicle model is then defined into the computational domain, as shown in Figure 3. Hence, the meshing process and defining boundary conditions on the Gambit device, as shown in Figure 4, take parts. Furthermore, the model will go through an iteration process using fluent software tools. The computational conditions are shown in table 1.

TABLE 1: COMPUTATIONAL CONDITION

Fluid	Air	-
Fluid properties	Density Viscosity	1.225 kg/m^3 1.7894 × 10^{-5} kg/m.s
Boundary conditions	Model Outlet Inlet Wall	Wall Pressure outlet Velocity inlet Wall
Upstream velocity (U_0)		2.2 m/s
Reverse Ahmed body 1:6	1-line dimple 2-zigzag lines	DR=0.20 DR=0.25 DR=0.50

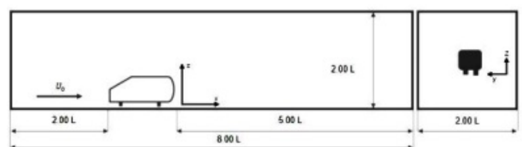


Figure 3 Computational domain

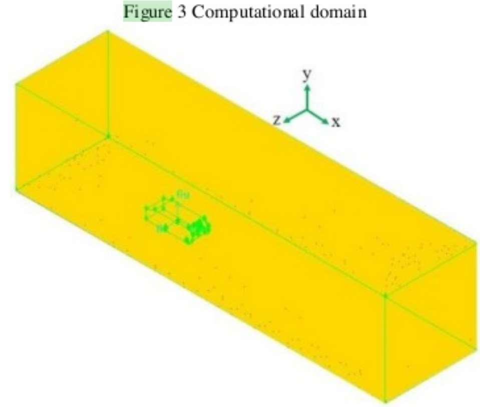


Figure 4 Mesh display.

Figure 5, Hence, The experimental measurement of aerodynamic drag utilizes a load cell device placed around the subsonic wind tunnel. The model is placed in the section via an aluminium support rod connected to the load cell. Drag data is automatically displayed on a computer connected to an Arduino Uno device. Data retrieval duration was determined to be 2 minutes for each model, both without dimple and for models with the application of 1 line and two zigzag dimple passive control, and we get 120 data for each model. The 120 data are averaged and written into dimensionless units using equation 2 [17] to be compared with the results obtained through a computational approach.

$$C_d = \frac{F_d}{\frac{1}{2}\rho U^2 A} \qquad (2)$$

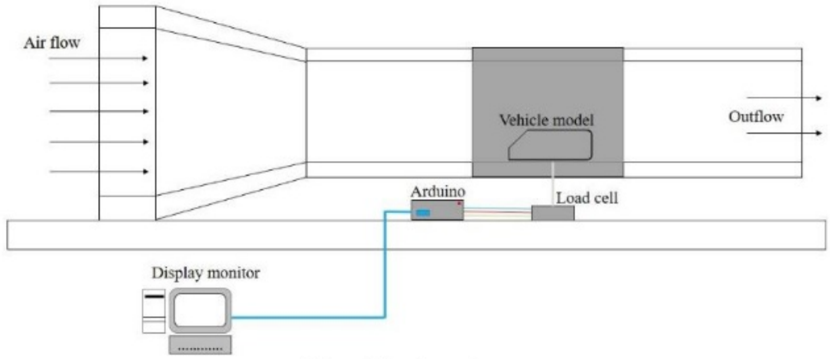


Figure 5 Experimental setup

III. Results And Discussion

A. *The Flow Patten Characteristic*

The flow pattern characteristics comparison of the model without passive control and the model with the application of passive controls in the form of dimples is shown in Figures 6, 7, and 8. For models without passive control, it shows a relatively large wake formation due to the separation process that occurs right on the vehicle model's rear wall. The separation occurs fast enough, causing the fluid flow to lose momentum to move along the shape of the belted body. Apart from forming a backflow right against the back wall, it is also pushed sideward due to the significant differences of flow velocities between the center and sides. This difference in velocity is the main trigger for the appearance of the longitudinal vortex phenomenon.

Models with the application of passive control in the form of dimples have shown delays in flow separation. The separation process tends to move away from the back wall, resulting in backflow formation far away from the rear wall. The longitudinal vortex was also reduced for all models. Visually, it can be seen that the most considerable reduction in longitudinal vortex intensity occurs in the model with the application of zigzag dimple configuration at DR=0.50. For this model, the flow line formed on the rear side tends to be straighter and at the same time has a smaller wake formation structure compared to other models. These results are consistent with Chear and Dol's findings, which revealed that the application of passive control in the form of dimples could delay flow separation and reduce wake formation [8].

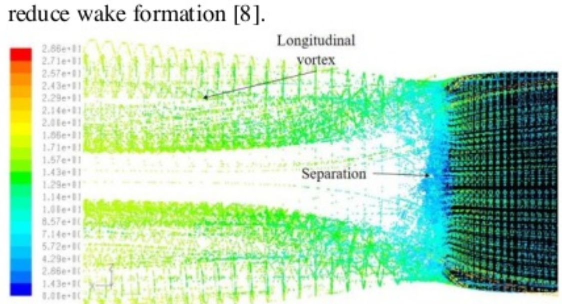
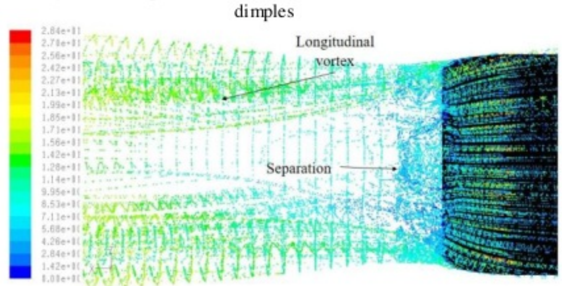
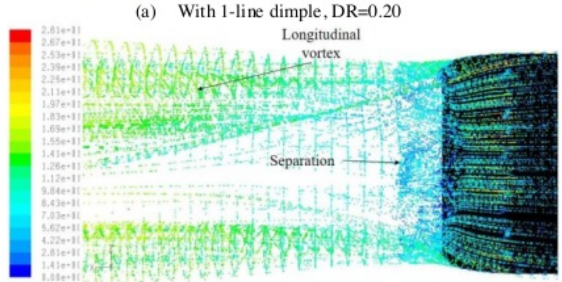


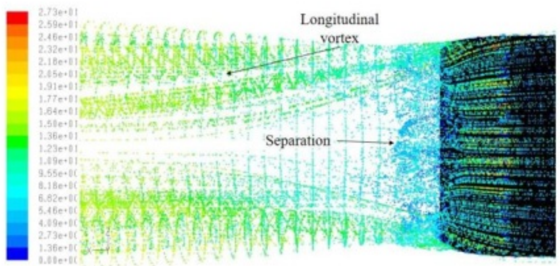
Figure 6 Flow pattern characteristics of each model without dimples



(a) With 1-line dimple, DR=0.20

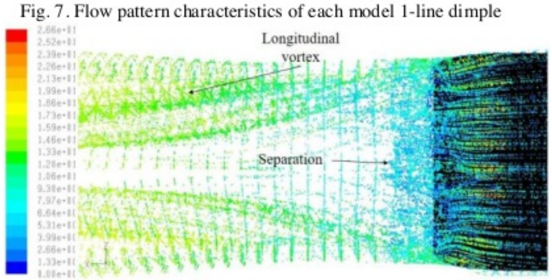


(b) With 1-line dimple, DR=0.25

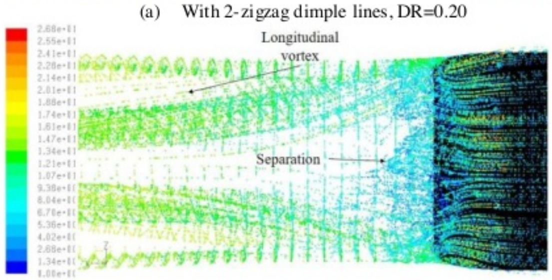


(c) With 1-line dimple, DR=0.25

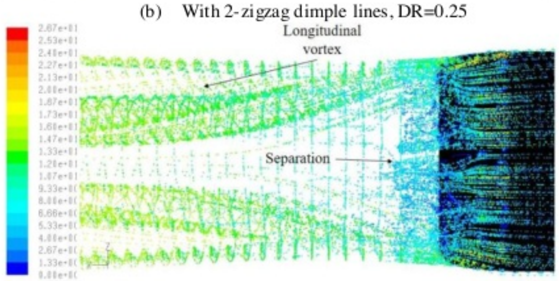
Fig. 7. Flow pattern characteristics of each model 1-line dimple



(a) With 2-zigzag dimple lines, DR=0.20



(b) With 2-zigzag dimple lines, DR=0.25



(c) With 2-zigzag dimple lines, DR=0.50

Fig. 8. Flow pattern characteristics of each model 2-zigzag dimple lines

B. Pressure Field

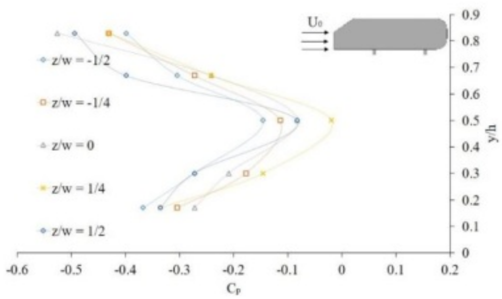
The comparison of the minimum pressure coefficient of the model without dimple and the model with the application of dimple configuration of one line and two zigzag lines in each dimple ratio, DR=0.20, DR=0.25, and DR=0.50 is shown in Table 2. The lowest average minimum pressure coefficient (Cp) of -0.456 has been obtained in the model without control. The minimum pressure coefficient has been obtained at the ratio of the grid height to the model height (y/h) of 0.83. It is because this position is where the flow separation process starts. These findings confirm the flow pattern characteristics shown in Figure 6, where the no-dimple model is the model with the most extensive longitudinal wake and vortex formation compared to other models. This result is correlated with Anderson's findings, which reveal that the pressure field tends to be low in the area where the flow separation occurs [18].

Models with the application of 1 line dimple at DR 0.20, 0.25, and 0.50 respectively, have shown increases in the average minimum pressure coefficient compared to those on the model without the dimples. The increases are sequentially at 15.607%, 16.002%, and 19,903%, where the minimum pressure coefficients on the average of each dimple ratio are at -0.385 for DR=0.20, -0.383 for DR=0.25, and -0.365 for DR=0.50. The model with the application of the two zigzag line dimples also shows a significant increase in pressure efficiency. The increases in average minimum pressure for each dimple ratio have been recorded at 21.623% for DR=0.20, at 21.579% for DR=0.25, and at 22.665% for DR=0.50, whereas the average minimum pressure coefficients have been recorded respectively -0.357, -0.358, and -0.353.

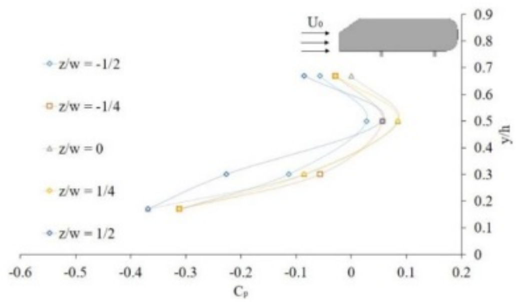
Overall, it was found that the application of passive control in the form of 1 line dimple and zigzag configurations at the respective DR ratios of 0.20, 0.25, and 0.50 on the upper side of the rear of the vehicle model was able to increase the average minimum swallow coefficient. The highest minimum pressure coefficient increase is obtained in a model with a two zigzag line dimple configuration at DR=0.50 of 22.665%. This result correlates with the velocity pathlines shown in Figure 8 (c), which shows that the model with dimple zigzag configuration at DR=0.50 has the smallest wake and longitudinal vortex formation compared to other models.

TABLE 2: THE MINIMUM PRESSURE COEFFICIENT OF EACH MODEL

z/w	Pressure coefficient (C_p)						
	Without dimple	1 line dimples			2-zigzag lines dimples		
		Dimple Ratio (DR)					
		0.20	0.25	0.50	0.20	0.25	0.50
-1/2	-0.399	-0.392	-0.397	-0.338	-0.303	-0.312	-0.309
-1/4	-0.431	-0.348	-0.351	-0.347	-0.357	-0.332	-0.309
0	-0.526	-0.418	-0.423	-0.424	-0.412	-0.418	-0.391
1/4	-0.431	-0.368	-0.351	-0.347	-0.330	-0.332	-0.364
1/2	-0.494	-0.399	-0.394	-0.371	-0.385	-0.394	-0.391
Average	-0.456	-0.385	-0.383	-0.365	-0.357	-0.358	-0.353
Enhancement (%)	-	15.607	16.002	19.903	21.623	21.579	22.665



(a)



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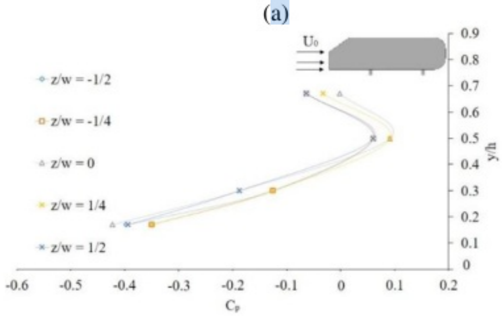
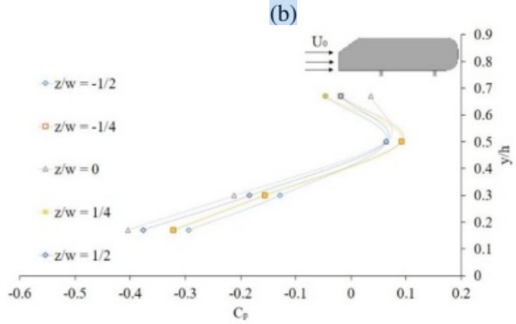
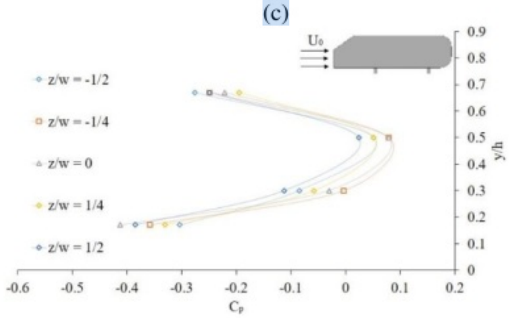


(c)



(d)



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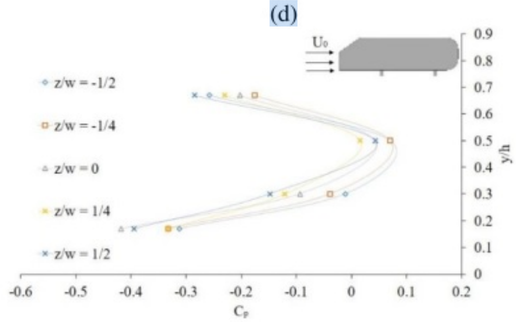
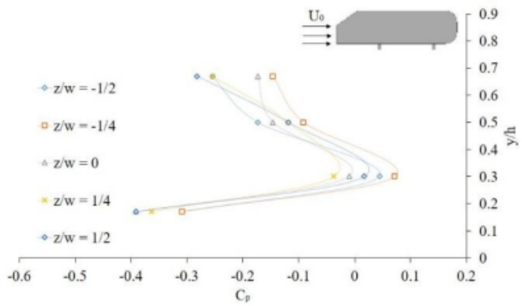


(f)



(g)

Fig. 9. Comparison of the minimum pressure coefficient for each model: (a) Without Dimples, (b) With 1 line dimples, DR=0.20, (c) With 1 line dimples, DR=0.25, (d) With 1 line dimples, DR=0.50, (e) With 2-zigzaglines dimples, DR=0.20, (f) With 2-zigzag lines dimples, DR=0.25, (g) With 2-zigzaglines dimples, DR=0.50.

C. Aerodynamics Drag

Table 3 shows the drag coefficient's values from the numerical computation of the model without dimple and the model with the application of 1-line and two zigzag lines on DR 0.20, 0.25, and 0.50. The highest drag coefficient of 1.439 has been obtained in the model without control. For 1-line dimple model, the drag coefficients for each DR have been recorded at 1.310 for DR=0.20, at 1.302 for DR=0.25, and at 1.293 for DR=0.50. Whereas for a model with two zigzag lines dimple, the drag coefficients of DR 0.20, 0.25, and 0.50 are written as 1.273, 1.279, and 1.265, respectively.

TABLE 3: CD COMPUTATIONAL APPROACH

Model	DR	C_d
Without dimple	-	1.439
	0.20	1.310
With 1 lines dimple	0.25	1.302
	0.50	1.293
	0.20	1.273
With 2-zigzag lines dimple	0.25	1.279
	0.50	1.265

In agreement to the computational approach, the experimental approach also shows that the highest drag coefficient has been obtained in the no-dimple model, at the value of 1.300. For a model with 1-line dimple application, the drag coefficients of each dimple ratio have been recorded at 1.218 for DR=0.20, at 1.207 for DR=0.25, and at 1.192 for DR=0.50. For the model with the application of 2-zigzag dimples configuration, the drag coefficient of the DR 0.20, 0.25, and 0.50 dimple ratios are recorded at 1.185, 1.187, and 1.184, respectively.

TABLE 4: CD EXPERIMENTAL APPROACH

Model	DR	C_d
Without dimples	-	1.300
	0.20	1.218
With 1 lines dimple	0.25	1.207
	0.50	1.192
	0.20	1.185
With 2-zigzag lines dimple	0.25	1.187
	0.50	1.184

A comparison of the aerodynamic drag reduction with computational and experimental approaches is shown in Table 5. For models with the 1-line dimples, the reduction is increased along as dimple ratios enlarge both computationally and experimentally, as shown in Figure 10. For models with 2-zigzag lines configuration, the percentages of the increase in a drag reduction fluctuate both computationally and experimentally. The highest decrease was obtained as well at DR=0.50.

Overall, it shows that dimples on the upper rear part of the vehicle model can reduce the aerodynamic drag of the vehicle model. The highest reduction was obtained in a model with the dimples configuration of 2-zigzag lines at DR=0.50, both computationally and experimentally. The reduction is 12.092% for the computational approach and is 8.923% for the experimental method, where the difference in reduction is 3.169%. These results are consistent with what Chear and Dol revealed that the application of dimples in vehicles could reduce aerodynamic drag while increasing fuel consumption efficiency [8].

TABLE 5: C_D REDUCTION COMPUTATIONAL AND EXPERIMENTAL METHODS

Method	Reduction (%)					
	1 line, DR			2-zigzag lines, DR		
	0.20	0.25	0.50	0.20	0.25	0.50
Computational	8.964	9.520	10.146	11.536	11.119	12.092
Experimental	6.308	7.154	8.308	8.846	8.692	8.923
Difference (%)	2.657	2.367	1.838	2.689	2.426	3.169

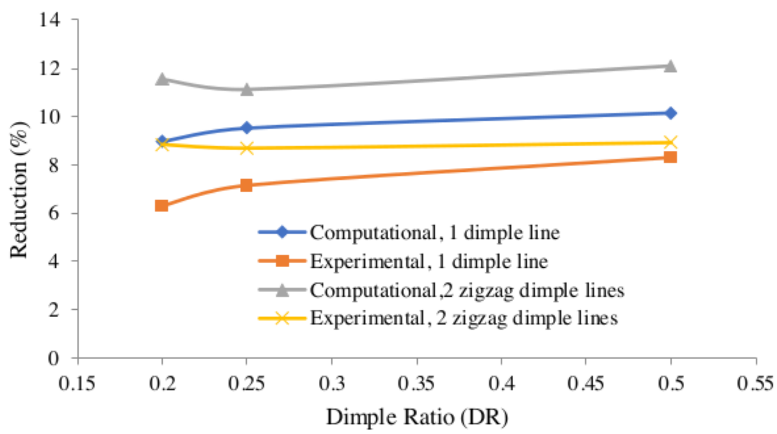


Fig. 10. Reduction comparison

IV. CONCLUSIONS

The application of passive control in the form of dimples on the upper side of the rear of the vehicle model provides significant changes to the characteristics of the flow pattern, the pressure field on the rear wall and aerodynamic drag compared to the model without the dimples. The most significant change was obtained in the model with the application of 2-zigzag lines dimples at DR=0.50, where longitudinal wake and vortex formation was significantly reduced. An average minimum pressure efficiency increase was 22.665%, and the highest aerodynamic drag reduction was 12.092% for computation and 8.923% for the experimental approach.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Mr. MS. Sukardin, main author, conducted CFD and experimental research, wrote the manuscript. Dr. N. Salam organized research promotion, supervised research. Dr. R. Tarakka, corresponding author, conducted research planning, Dr. Jalaluddin, conducted research, and Mr. M. Ihsan, wrote and translated the manuscript. All authors had approved the final version.

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