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Computational and Experimental Investigations on 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 the manufacture of vehicles with the lowest aerodynamic drag. Therefore, this research aims to reduce aerodynamic resistance by analyzing the flow pattern characteristics and pressure fields. The method applied to delay separation and reduce longitudinal wake and vortex formation is the passive control in the form of dimples in the separation area. Furthermore, this research was carried out using a 1: 6 ratio of the Reverse to Real Ahmed body model. The computational approach was used to obtain the flow and pressure field characteristics with its aerodynamic resistance validated by experimental testing. Passive control was applied in a dimple configuration and two zigzag lines with 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 for the computational and experimental approaches by 12.092% and 8.923%, respectively.**

***Index Term*—van vehicle, passive control, dimple ratio, pressure distribution, drag aerodynamics**

I. INTRODUCTION

Globally, automotive engineers face the challenge of manufacturing vehicles with the lowest aerodynamic drag to save fuel consumption and reduce environmental pollution. Preliminary studies have proven that a 15% reduction in aerodynamic drag saves fuel consumption by 5–7% [1].

The vehicle's aerodynamic drag consists of 2 main components, namely frictional [2] and pressure [3] drags, which contribute to 20% and 80% of total drag, respectively. 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. For instance, when the fluid reaches the top of the vehicle's rear, the flow loses the momentum to move along its rear parts. As a result, it undergoes a separation process and creates a backflow, which causes negative pressure on the back wall and triggers backward suction. This also creates a pressure difference between the front and rear sides, which is the leading cause of aerodynamic drag [4,5]. Apart from flow separation, aerodynamic drag also occurs due to a longitudinal vortex on the rear wall. Furthermore, when in motion, the proportion that loses the momentum to move along with the body shape is 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]. Therefore, an in-depth evaluation of the vortex structure that forms around the vehicle body is essential to ensure stability while driving [7]. In addition, efforts need to be carried out to reduce the aerodynamic drag acting on the vehicle by delaying flow separation and minimizing vortex formation intensity.

One of the functional methods applied is the passive control at the starting point of the separation process. The application of this process is considered more efficient

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because it does not involve additional energy. It is also widely applied because it does not require significant modifications to the vehicle body. However, one of the passive controls that need to be considered during the implementation process is a dimple.

Chear and Dol examined the effect of dimple application on Ahmed's 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 with the highest reduction in aerodynamic drag obtained at a 0.4 dimple ratio 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 has the ability to change the kinematics and dynamics of the flow. The maximum turbulent kinetic energy is obtained at DR=0.4, with a reduction in aerodynamic resistance compared to the model without the application of dimple [9]. Salam et al. carried out a research to determine the characteristics of the flow drag across dimpled square cylinders, using computational and experimental processes. The result showed that parallel configurations have a higher reduction than the zigzag [10]. Sukardin et al. previously studied the distribution of flow through the inline dimpled plate and found out an increase in dimple rows produces more pressure with a decrease in coefficient [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 has not been further investigated. Therefore, this study aims to determine 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, which is modified by changing the flow direction. The designed vehicle was 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) with the length, height, and width in values of 174mm, 48mm, and 64.83mm, respectively. The front geometry slope is determined to be 25°, with passive control in the form of dimples placed on the upper side of the vehicle model's rear as the starting location for the flow separation process. This research applies dimple configurations of 1 and 2-zigzag lines at ratios of 0.20, 0.25, and 0.50, respectively. The upstream velocity used is 22.2 m/s. Details of the test model are shown in Fig. 1.

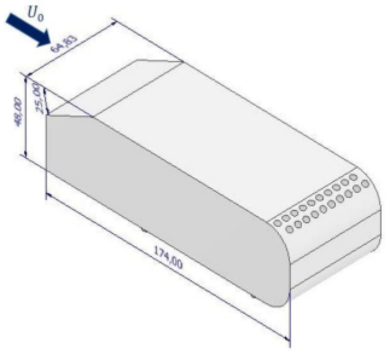
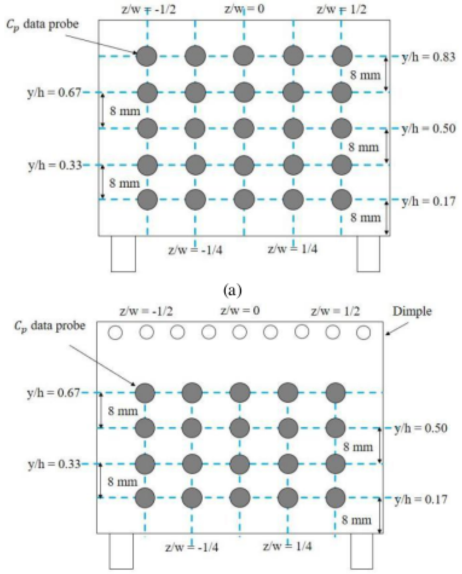


Figure 1. Test model

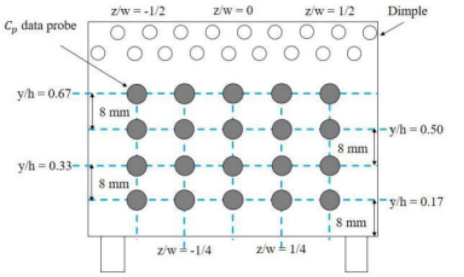
This research is focused on the analysis of aerodynamic resistance through computational and experimental, which are supported by displaying the characteristics of the flow pattern in the form of velocity pathlines and pressure fields on the rear wall of the vehicle model obtained through a computational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

According to numerous studies, 80% of a vehicle's total resistance is caused by its rear wall [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 from five grid rows. The ratio of the grid width to the rear wall of the vehicle model is written as z/w=-1/2, z/w =-1/4, z/w=0, z/w=1/4, and z/w=1/2. The grid height ratios to the model height (y/h) are 0.17, 0.33, 0.50, 0.67, and 0.83, respectively, as shown in Fig. 2.



(a)

(b)



(c)

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, with the pressure coefficient (Cp), defined in equation 1 [16].

$$C_p = \frac{P - P_0}{\frac{1}{2}\rho U^2} \tag{1}$$

After the design process, the vehicle model is defined into the computational domain, as shown in Fig. 3. Furthermore, the meshing process and defining boundary conditions on the Gambit device are shown in Fig. 4. The model goes through an iteration process using fluent software tools. The computational conditions are shown in Table I.

TABLE I. 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)		22 m/s
Reverse Ahmed body 1:6	1-line dimple 2-zigzag lines	DR=0.20 DR=0.25 DR=0.50

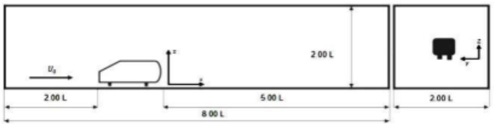


Figure 3. Computational domain

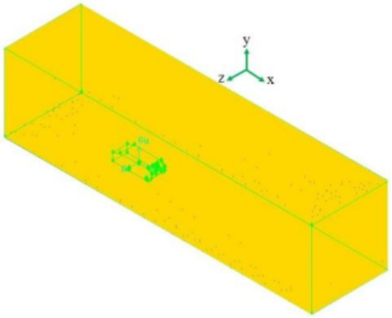


Figure 4. Mesh display.

Fig. 5 shows the experimental measurement of aerodynamic drag, which utilizes a load cell device placed around the subsonic wind tunnel. The model is placed in the section via an aluminum 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. For those without dimples with the application of 1 line and two zigzag dimple passive control, a total of 120 data were obtained with the average written into dimensionless units using equation 2 [17]. This is compared with the results obtained through a computational approach.

$$C_d = \frac{F_d}{\frac{1}{2}\rho U^2 A} \tag{2}$$

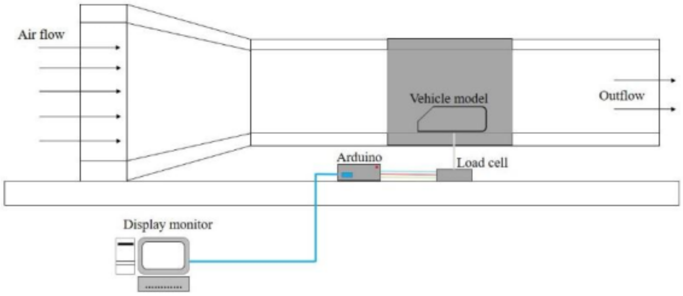


Figure 5. Experimental setup

III. RESULTS AND DISCUSSION

A. The Flow Patten Characteristic

The flow pattern characteristics comparisons of the model with and without passive controls in the form of dimples are shown in Figs. 6, 7, and 8. Those without passive control show a relatively large wake formation due to the separation process right on the vehicle model's rear wall. The separation occurs fast enough, causing the fluid flow to lose momentum and move along the belted body's shape. Apart from forming a backflow right against the back wall, it is also pushed sideward due to the significant differences in 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. This process tends to move away from the back wall, leading to backflow formation far from the rear wall. The longitudinal vortex was also reduced for all models. Visually, 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 with a smaller wake formation structure compared to others. These results are consistent with Chear and Dol's research, which stated that the application of passive control in the form of dimples delays flow separation and reduces wake formation [8].

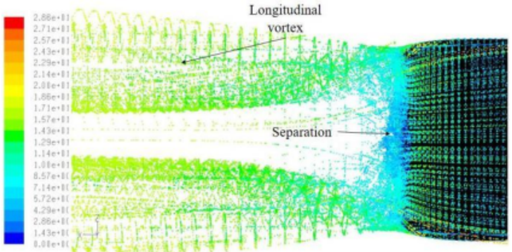
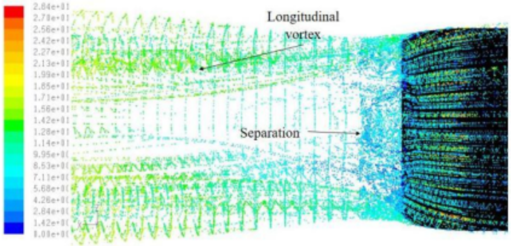
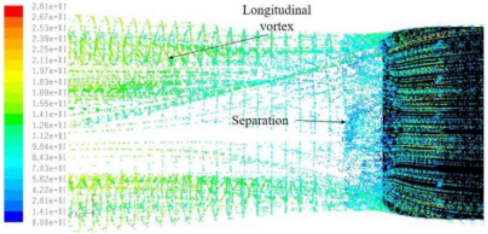


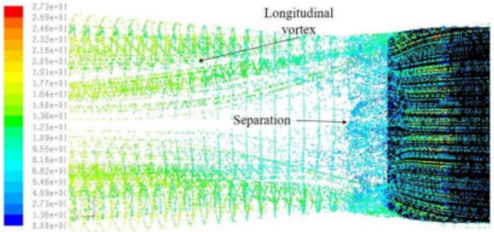
Figure 6. Flow pattern characteristics of each model without dimples



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

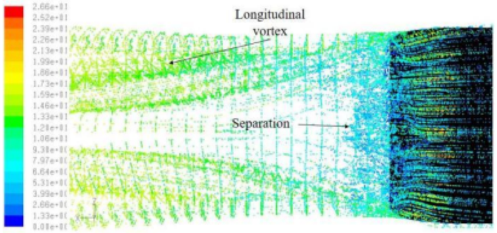


(b) With 1-line dimple, DR=0.25

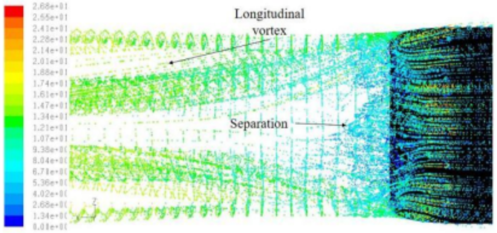


(c) With 1-line dimple, DR=0.25

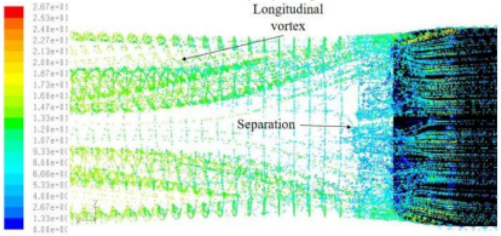
Figure 7. Flow pattern characteristics of each model 1-line dimple



(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

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

B. Pressure Field

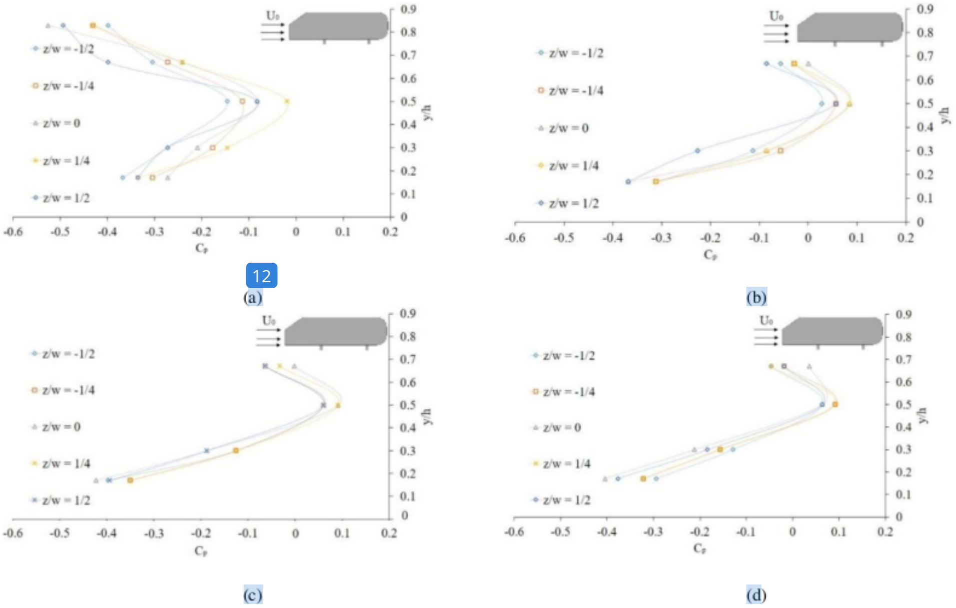
The comparison of the minimum pressure coefficient of the models without and with dimples of one and two zigzag lines in each dimple ratio of 0.20, 0.25, and 0.50 are shown in Table II. The lowest average minimum pressure coefficient (Cp) of -0.456 at grid height (y/h) of 0.83 was obtained in the model without control. This 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 has the most extensive longitudinal wake and vortex formation compared to others. This result correlates with Anderson's findings, which stated 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 have shown an increase in the average minimum pressure coefficient compared to those without dimples. The increases are sequential 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 two zigzag line dimples' application also shows a significant increase in pressure efficiency. The increases in average minimum pressure for each dimple ratio are 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 Fig. 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.

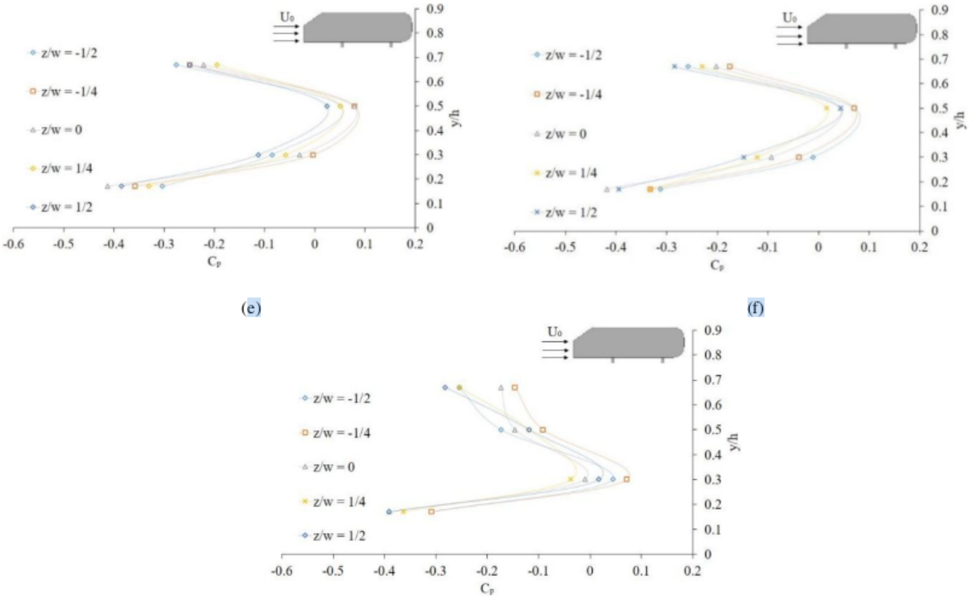
TABLE II. THE MINIMUM PRESSURE COEFFICIENT OF EACH MODEL

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) (b)

(c) (d)



(e)

(f)

(g)

Figure 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 III shows the drag coefficient's values from the model's numerical computation without and with dimple 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 was obtained in the model without control. For a 1-line dimple, the drag coefficients for each DR were recorded at 1.310, 1.302, and 1.293 for 0.20, 0.25, and 0.50, respectively. Meanwhile, 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 III. CD COMPUTATIONAL APPROACH

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

In agreement with the computational approach, the experimental approach also shows that the highest drag coefficient was obtained in the no-dimple model at the value of 1.300. For a 1-line dimple application model, the drag coefficients of each dimple ratio were recorded at 1.218, 1.207, and 1.192 for 0.20, 0.25, and 0.50. For the model with the 2-zigzag dimples configuration application, 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 IV. CD EXPERIMENTAL APPROACH

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

A comparison of the aerodynamic drag reduction with computational and experimental approaches is shown in Table V. There is a significant decrease in models with the 1-line dimples as its ratios enlarge both computationally and experimentally, as shown in Fig. 10. For models with a 2-zigzag lines configuration, the increase in percentages in a drag reduction fluctuates computationally and experimentally. The highest decrease was obtained at DR=0.50.

Overall, it shows that dimples on the upper rear part of the vehicle model reduce the vehicle model's aerodynamic drag. 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 reductions are 12.092% and 8.923% for the computational and experimental method, with a reduced value of 3.169%. These results are consistent with Chear and Dol research, which stated that dimples in vehicles reduce aerodynamic drag while increasing fuel consumption efficiency [8].

TABLE V. 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

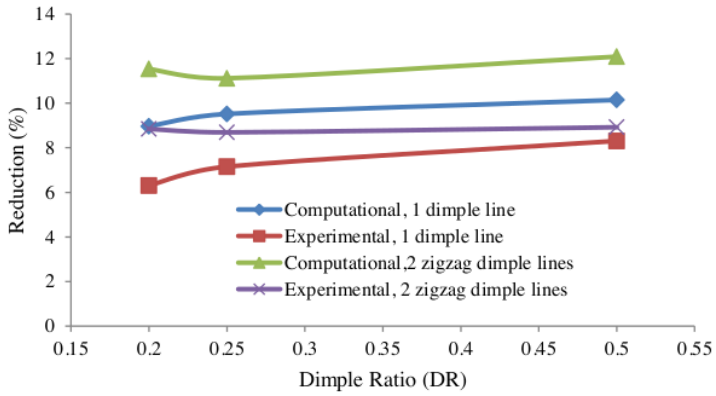


Figure 10. Reduction comparison

IV. CONCLUSION

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

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

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

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