Fluid Flow Resistance Through Hemispherical Dimpled Plates in Parallel and Zigzag Configurations

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Abstract – *The application of hemispherical dimples in parallel and zigzag configurations on flat plates flowed with fluids is one of the rarest forms used in structural and transport engineering. It has been particularly studied on aircraft wing, turbine blade, golf balls and vehicle bodies with dents. For this reason, a study on resistance force on hemispheric dimpled in parallel and zigzag configuration on flat plates has been performed. The test piece has been made of acrylic in a total of 9 pieces with length of 30 cm, width 10 cm and thickness of 0.5 cm and dimpled ratio DR = 0.5. Dimples are arranged in rows numbered from 1 to 8. All the specimens are treated in 7 equal flow velocity rates from 8 m/s to 20 m/s. The study, which has taken place in laminar flow region with Reynolds number (Re) of 1.29×10^5 to 3.23×10^5, indicates that the use of hemispherical dimples in parallel and zigzag configuration reduces the resistance coefficient (C_d). For example, in the same Re=2.26×10^5 without dimples obtained C_d has been 0.0517 whereas on plates with dimples in parallel configuration, the smallest resistance coefficient obtained on 2 rows dimples has been of 0.0472. Dimpled plates in zigzag configuration have obtained C_d=0.0487 for single line dimple configuration. When compared with the plates without dimples, the percentage of resistance reduction coefficient for dimpled plates in zigzag configuration is 5.88%, while for dimpled plate in parallel configuration is 8.65%. This result shows that the use of parallel configuration is better than zigzag configuration.*

***Keywords**: Resistance Coefficient (C_d), Reynolds Number (Re), Dimpled Plates, Parallel and Zigzag Configuration*

Nomenclature

A	Sectional area of plates
C_d	Drag coefficient
$F_{d_{th}}$	Theoretical drag force
$F_{d_{act}}$	Actual drag force
l	Length of plate
w	Width of plate
h	Length of plate
H	Depth of dimple
Re_L	Reynolds number
U_0	Incoming air flow velocity to wind tunnel
ρ	Air density
υ	Kinematic air viscosity
L_x	Distances between dimples on the x-axis
L_z	Distances between dimples on the z-axis
N	Number of dimple rows
x/D	Ratio of distance in x-axis to diameter of dimple
z/D	Ratio of distance in z-axis to diameter of dimple

I. Introduction

Various applications of dimpled plate arrangement can be found on the surface of aircraft wing and on the surface of high-speed vehicles. When fluid flows through a flat plate, energy losses due to the resistance force generated by the influence of the boundary layer and by the separation of streams will occur. In the first category, the resistance is caused directly by viscous effects. Therefore, the tangential stress is called viscous resistance or friction resistance. In the second category, although indirectly caused by viscosity, resistance is caused by the influence of pressure, i.e. normal forces, and it is called shape resistance or pressure resistance. This is one of the problems on the transportation industry in improving system efficiency and stability. Turbulent flow through arrays of dimples on a channel with a low Reynolds number at four depths (h) i.e. 0.05 mm, 0.10 mm, 0.15 mm and 0.2 mm indicates that near wall turbulent fluctuations can be significantly effective by the shape and the depth of dimples [1]. The use of bump or concave dimples on the wing of the aircraft has been proven to be useful as a factor in decreasing drag pressure and delaying flow separation. Optimizing placements of multiple dimples on the wing trailing edge is useful to keep the boundary layer attached. Optimizations in terms of size, shape and design of dimples have been conducted in order to improve wing efficiency. Research on utilizing concave, convex and composite concave and convex semi-spherical configurations have been performed in order to determine the maximum effectiveness that can be achieved in delaying the layer separation boundary on the trailing edge [2]. Dimples surface with a submicron-scale

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roughness has undergone surface hydrophobicity.

Dimpled formations can reduce skin friction by reducing shear stress on walls and reducing drag profiles by about 3-5% consistently [3]. The integration of the wall-friction coefficient in the flow direction indicates a total drag increment of 3.54% in a single groove [4]. A numerical simulation approach of the turbulent boundary layer passes through the bump has been performed in order to obtain the effect of the longitudinal curve surface to the wall pressure fluctuations. The fluctuation of the pressure wall significantly increases near the trailing edge on the bump where the boundary layer obtains a very adverse pressure gradient [5]. Dimpled configuration of 1.0 mm in diameter with dimpled ratio of 0.2, located on 30% - 60% and 75% - 95% of axial chord lengths on each side of suction has effectively reduced total pressure loss [6]. On characterization of the turbulent boundary layer passes through the surface of the flat plate having dimpled compared with no dimpled, it has been found out that the friction factor of plate with dimples has been higher on about 30% - 80% compared to the one of the flat plate.

The friction factor of the plate also depends on Reynolds number value [7]. When a sphere is embedded in a turbulent boundary layer, the distribution of flow velocity fluctuation, the sectional streamline pattern, the vorticity contour, the flow velocity field, the turbulent kinetic energy and the correlation of the Reynolds pressure can be obtained using PIV data. The large gap of the ratio affects the flow structure of the wake-boundary layer interaction and reattachment location variation of the flow separation[8]. Dimpled passive control can trigger instability that causes significant momentum transport on the application of semi-spherical concave dimples with dimpled ratio (RD) 0.1 and dimpled depth equivalent to twice the thickness of the boundary layer.

The shear layer developing as the flow separation through the first two dimple lines gets unstable and it forms coherent vortex layers. As the vortex evolves through the plates or dimpled series, the flow dynamics become different significantly with remarkable change of momentum transport across the boundary layer [9]. From the analysis on the use of vortex generators in order to improve and control flow characteristics, dimples application have been found out to be useful [10]-[11]. A further improvement has been proposed by incorporating the use of a novel surface modification in the form of dimples inspired by golf ball designs which help to reduce the wake region induced by boundary layer separation [12]. The surface modifications by considering different types and shapes of dimples could help to reduce pressure drag when airfoil reaches a variety of angle. This happens because wake formation initializes due to boundary layer separation. Application of dimples on aircraft wing works in the same way as vortex generators could help to increase the overall aerodynamic characteristics which in turn could enhance the aerodynamic characteristics and maneuverability. The enhancement includes the reduction in drag and stall phenomenon where the airfoil containing dimples will have relatively less drag than the airfoil without dimples. Dimples application on the aircraft wing could create vortices which could delay the boundary layer separation resulting in decreasing of pressure drag and the increasing in the stall angle. Additionally, wake reduction can lead to acoustic emission reduction [13].

Dimples could behave as protrusions on the surface of the wing which could generate vortices resulting in a reduction of flow separation on the suction side of the wing. This can delay and reduce the chord-wise boundary layer growth rate. An experimental analysis on dimple effect carried out on a symmetrical wing has proved the reduction of drag and delaying the flow separation on the upper surface of aircraft wing [14]. Computational and experimental analyses of dimple effect have been studied on aircraft wing using NACA 6321 airfoil. Analyses have been conducted on aerofoil with circle, heart, elliptical type dimples which have been tested under the inlet velocity in different angles of attack. The experiment has showed that the flow separation can be delayed by using dimples on the aerofoil on the aircraft where flow separation in turn reduced the drag. The research which aimed to reduce the take off distance by attaining the high coefficient of the lift at the higher angle of attack has proved that raised pressure drag in wake area at the higher angle of attack has been attained by applying dimples that influence flow separation [15]. Another research has focused on studying the influence of dents on flat plates over the drag coefficient. A total of seven dent configuration, defined by three parameters of dents (depth, main radius, diameter) has been studied for flow conditions of 5 m/s to 40 m/s. The study has been conducted with the help of computational fluid dynamics (CFD) simulations in ANSYS FLUENT where a pre-processing stage such as meshing has been performed in ANSYS Work Bench. Necessary mesh refinement near the plate wall has also been performed to predict the skin friction components. Reynolds Averaged Navier-Stokes (RANS) formulation [21][22] has been used in the simulation with the two-equation SST k-omega turbulence model. The results have showed the drag reduction of nearly 30% by providing dents on the flat plate with flow condition of 10 m/s to 40 m/s [16]. The research on the effect of dimple pattern on the suppression of boundary layer separation on a low-pressure turbine blade has indicated that dimples provide a passive means of controlling boundary layer separation. Determining the optimum and the exact dimple pattern, by advances in the parameterization, in order to totally reduce the boundary layer separation will enormously improve turbine efficiency and it will allow for potentially significant improvements in aircraft mission effectiveness and capabilities [17]. Despite many works have proven that dimple application is useful in reducing energy loss due to fluid flow resistance on bodies such as cars and aircrafts, research works, on determining the formation and number of dimpled lines that could give the optimum reduction of energy loss, have not been available yet. In this regard, hypotheses of the research are parallel dimple configuration is predicted to be more optimum in reducing the energy loss of fluid flow when compared to zigzag dimple configuration. It is also predicted that there is a particular number of dimple lines which could optimally reduce the energy loss. Following this introduction and subsequent part of methodology, the paper is presenting the results of the research starting with the discussion of parallel dimple configuration, zigzag dimple configuration and followed by the comparison analysis of the two types of configuration. The discussion ends with the verification of the hypotheses which confirms the aforementioned ones.

II. Methodology

The flat plate test piece is added with the dimples in parallel and zigzag configuration on the top surface. The given treatment is to change the number of rows of dimples toward the x axis (L_x/D) by 8 (eight) variation levels (1, 2, 3, 4, 5, 6, 7 and 8) of rows and without dimpled, in order to set distances of dimples to z axis (L_z/D) to be constant, dimpled ratio DR=0.5 with hemi-spherical shape. Each dimple sequence is installed in parallel and zigzag configuration, then flowed in 7 equal flow velocity rates (U_0) which are8 m/s, 10 m/s, 12 m/s, 14 m/s, 16 m/s, 18 m/s and 20 m/s. The flat plate test is manufactured from acrylic material with a thickness of 5 mm while Dimple configuration is formed using a CNC machine with dimensions of 300 mm length (l), 100 mm width (w) and 5 mm thickness (h).

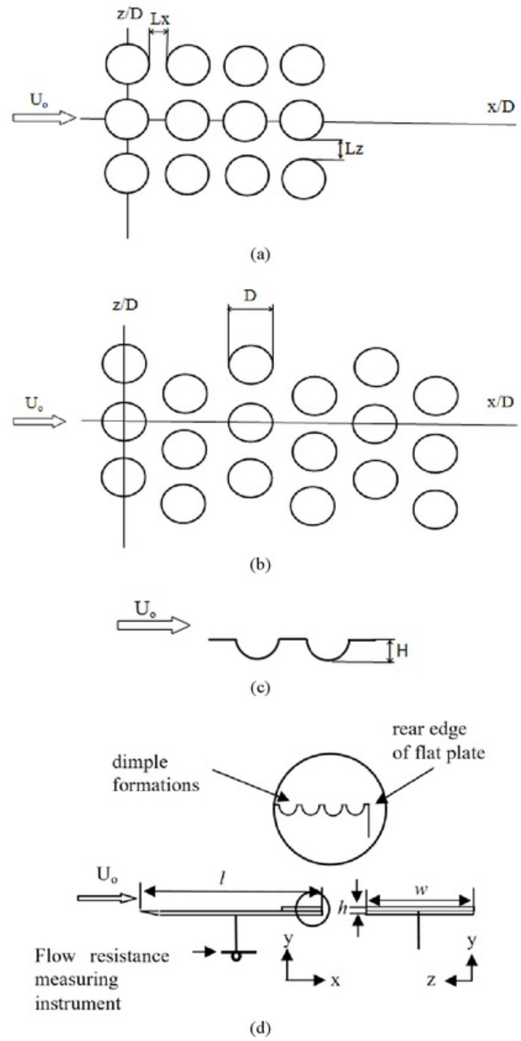
Fig. 1(a) shows the parallel dimple configuration, where the horizontal axis z is designed perpendicular to the flow direction and the x-axis is in the axial flow direction. The distances between dimples on the x axis and z-axis are denoted as L_x and L_z respectively. Fig. 1(b) depicts the zigzag dimple configuration where the hemispheric-dimple depth (H) is shown in Fig. 1(c), while the positioning of the flow resistance force measurement instrument is in Fig. 1(d). For flow velocity measurements, a manometer is used which is a calibrated wind tunnel device package, allowing the scale to be read directly in m/s [18]. The experiment has been carried out using international standard testing equipment in the form of wind tunnel in the Laboratory of Fluid Mechanics, Department of Mechanical Engineering, Faculty of Engineering, Hasanuddin University.

The wind tunnel used in this experiment has been made by Plint & Partners LTD Engineers, where the maximum airflow velocity through the test section with size of 300 mm × 300 mm is 20 m/s [13]. In order to analyze the experimental data from the observation of resistance force as well as to determine the flow characteristics of C_d, $F_{d_{th}}$ and Re due to the addition of the number of lines in each configuration, the following equations are used. Equation (1) is used to determine the coefficient of resistance C_d where the actual or measured resistance force $F_{d_{act}}$ and the theoretical resistance force or air flow $F_{d_{th}}$ have been obtained from Equation (2), whereas ρ and A are the air density and sectional area of plate. Determining the Reynolds number is conducted using Equation (3) where U_0 is the flow velocity across the test specimen, l is the length of the plate and υ is kinematic air viscosity [19]:

$$C_d = \frac{F_{d_{act}}}{F_{d_{th}}} \quad (1)$$

$$F_{d_{th}} = \frac{1}{2}\rho {U_0}^2 A \quad (2)$$

$$Re_L = \frac{U_0 l}{\upsilon} \quad (3)$$



Figs. 1. (a) parallel dimple configuration, (b) zigzag dimple configuration, (c) depth of dimples and (d) positions of equipment and measuring instrument

The study has taken place in the laminar flow region where Reynolds numbers calculated based on the length of the plate are Re_L=1.29×10^5 to 3.23×10^5.

III. Results And Discussion

III.1. Parallel Dimple Configuration

From the experimental results of the airflow across the hemispheric-dimpled plate in parallel configuration, the actual resistance value ($F_{d_{act}}$) of the airflow has been obtained on the use of dimples with the number of rows (N), i.e. 1 to 8 rows and without dimpled, 7 equal airflow velocity levels (U_0) from 8 m/s up to 20 m/s or at the number of Re_L=1.29×10^5 to 3.23×10^5. Furthermore, this value is compared to the one of the theoretical resistance force ($F_{d_{th}}$), then the one of resistance coefficient (C_d) as shown in Table I.

TABLE I
RESISTANCE COEFFICIENT (C_d)
FOR PARALLEL CONFIGURATION

Re (10^5)	Resistance Coefficient (C_d)						
	Without	Number of Rows (N)					
	Dimpled	1	2	3	5	6	8
1,29	0,0560	0,0467	0,0467	0,0513	0,0560	0,0560	0,0560
1,61	0,0538	0,0478	0,0448	0,0508	0,0538	0,0538	0,0538
1,94	0,0539	0,0498	0,0477	0,0519	0,0539	0,0539	0,0539
2,26	0,0518	0,0488	0,0472	0,0488	0,0533	0,0533	0,0533
2,58	0,0513	0,0478	0,0467	0,0490	0,0513	0,0537	0,0537
2,91	0,0516	0,0507	0,0498	0,0507	0,0516	0,0526	0,0535
3,23	0,0523	0,0500	0,0493	0,0508	0,0515	0,0530	0,0530

Table I indicates that the smallest drag coefficient at all levels of Reynolds number is on the use of 2 dimpled lines. In order to examine the characteristic pattern of each level of Reynolds number, a graph of the relationship between the resistance coefficient (C_d) and the number of rows (N) in the constant Reynolds (Re_L) number is developed, as shown in Fig. 2. The characteristic pattern in Fig. 2 also indicates that the alteration of the Reynolds number has no significant influence to the characteristic pattern of C_d to N, in this condition, when N is enlarged the C_d value shows no increase. However, the dimpled plate with 2 rows has a turning point, where for all the levels of Re, the smallest value of C_d is obtained on N=2 lines.

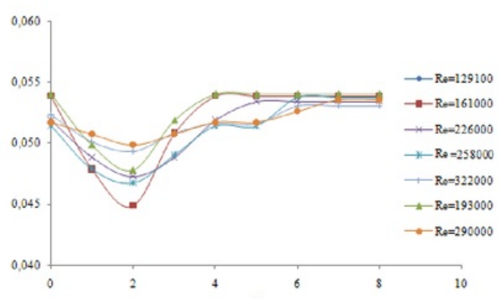


Fig. 2. Relationship between resistance coefficients with the number of lines of parallel dimple configuration for 7 equal levels of Reynolds number

This also indicates that at N=2 lines, the flow wake at the back of the plate is at smallest magnitude, resulting in the smallest flow separation. An interesting fact is that on the number of lines dimple of 4 the C_d, values tend to be constant for each Reynolds number level. This phenomenon shows that a large number of dimple lines is not able to delay the flow separation, so the value of $C_d$is just slightly larger when compared to the one without dimples.

The characteristic pattern of this alteration of resistance coefficient follows the pattern of objects disturbed in the tandem composed in rectangular cylinders where the exact interference position will decrease the flow resistance coefficient on tandem bodies[20].

III.2. Zigzag Dimple Configuration

Similar treatments are applied on hemispherical dimpled plates in zigzag configuration. The actual drag force ($F_{d_{act}}$) of the airflow is obtained from the application of dimples with the number of rows (N) of 1 to 8 with 7 equal levels of airflow velocity (U_0) varied from 8 m/s up to 20 m/s or on the Reynolds numbers of Re_L = 1.29×10^5 to 3.23×10^5. Similar number of airflow velocity is also applied to plate without dimples. Furthermore, the values are compared to the one of the theoretical resistance force ($F_{d_{th}}$). The value of the resistance coefficient (C_d) is shown in Table II.

TABLE II
RESISTANCE COEFFICIENT (C_d) FOR ZIGZAG CONFIGURATION

Re (10^5)	Resistance coefficient (C_d)						
	Without	Number of Rows (N)					
	Dimpled	1	2	3	5	6	8
1,29	0,0560	0,0467	0,0513	0,0560	0,0560	0,0560	0,0560
1,61	0,0538	0,0478	0,0508	0,0508	0,0538	0,0538	0,0538
1,94	0,0538	0,0497	0,0518	0,0518	0,0518	0,0538	0,0538
2,26	0,0517	0,0487	0,0517	0,0502	0,0517	0,0517	0,0532
2,58	0,0512	0,0477	0,0512	0,0501	0,0512	0,0512	0,0524
2,91	0,0515	0,0506	0,0515	0,0515	0,0515	0,0525	0,0534
3,23	0,0522	0,0499	0,0507	0,0507	0,0514	0,0522	0,0529

Table II shows that the smallest drag coefficient of all levels of Reynolds numbers is obtained by the use of 1 dimple line. Based on these results, it is shown that zigzag dimpled configuration does not significantly detract the coefficient of resistance, because on 1 dimple line, the configuration is not really zigzag. In order to examine the characteristic pattern of each level of Reynolds number, a graph of the relationship between the resistance coefficient (C_d) and the number of rows (N) in the constant Reynolds number (Re_L) is developed, as shown in Fig. 3. The characteristic pattern in Fig. 3 shows that Reynolds number change does not affect the characteristic pattern of C_d to N, i.e. when N is enlarged, the C_d value is smaller. However, dimpled plate with 1 row has a turning point, so for all levels of Re, the smallest value of C_d is obtained on N=1 line. This shows that at N=1 line, the flow wake at the back of the plate is smallest, resulting in the smallest flow separation. Another interesting finding is that on the number of lines dimpled by 4, the C_d value tends to be constant for each Reynolds number level.

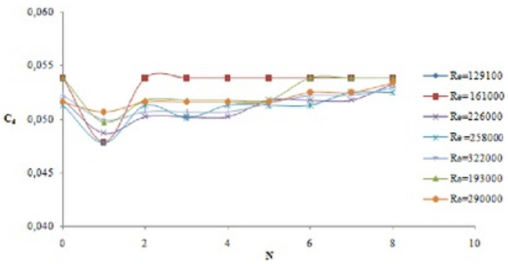


Fig. 3. Relationship between resistance coefficients with number of dimple lines in zigzag configuration for 7 equal levels of Reynolds number

This phenomenon shows that when the number of dimpled lines is added and then a zigzag configuration is formed, the delay the flow separation could not be achieved, so the value of C_d tends to be the same compared to that without dimples. The characteristic pattern of this resistance coefficient change follows the pattern on parallel configuration pattern, but the flow separation has occurred earlier in zigzag configuration.

III.3. Comparison of Parallel and Zigzag Dimple configurations

In order to compare the characteristic pattern of parallel configuration and zigzag configuration, experiments have been conducted at 3 equal levels of Reynolds numbers, as shown in Fig. 4, where the characteristic pattern shown indicates that Reynolds number change does not affect the characteristic pattern of C_d to N, i.e., when the number of N increases, the C_d value is smaller. However,1-row zigzag configuration has a turning point. The parallel dimple configuration with 2 rows also has a turning point. For all Re levels, the smallest C_d value has been obtained on N=1 row on the dimpled plate in zigzag configuration, whereas the smallest C_d value is on N=2 rows on dimpled plate in parallel configuration.

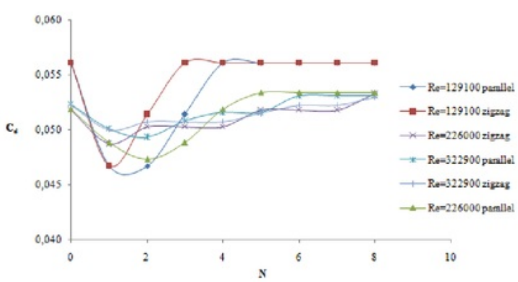


Fig. 4. Relationship between resistance coefficients with the number of lines dimpled parallel configuration and Zigzag at 3 levels of the same Reynolds number

This shows that, the wake of flow in the back of the dimpled plate in parallel configuration is smaller than the one of dimpled plate in zigzag configuration because the flow separation is more delayed. This phenomenon shows that on dimpled plate in 1 line zigzag configuration, resistance coefficient is equal to the one on dimpled plate in 2 lines parallel configuration. At $Re_L=2.26\times10^5$ the smallest C_d value for dimpled plates in 1-row zigzag configuration is 0.048723, while for dimpled plate in 2 rows parallel configuration is 0.047292. For 1-row parallel configuration, C_d is 0.048817. When the result is compared to plates without dimples (C_d=0.051768), the smallest resistance coefficient percentage for dimpled plate in zigzag configuration is 5.88%, while for dimpled plate in parallel configuration, the resistance coefficient is 8.65%.

This result shows that the application of parallel configuration is better than the application of zigzag configuration. This result also shows that it is not necessary to install large numbers of rows of hemispherical dimples on the plate where 1 or 2 rows are sufficient. Because in general the use of flat plates with dimple in zigzag or parallel configurations can be projected on a variety of objects, such as on the aircraft wings, vehicle bodies and blades on fluid machineries, based on the results of the research, the projection will also decrease the drag resistance, which is the main contribution of this research. None of the results of previous research as mentioned in the literature review in the introduction, has applied dimple by giving effect of the number of lines to parallel and zigzag configuration, and none has compared the effect of both configurations which is the novelty of this research. Based on the overall results, the hypotheses that parallel dimple configuration could reduce energy loss on fluid flow more optimally when compared to zigzag configuration is verified. It is also verified that two lines of dimples on plate surface produces the optimum reduction of energy loss.

IV. Conclusion

From the analysis of fluid flow resistance through the hemispherical-dimpled plates in parallel and zigzag configuration, on the number of dimpled rows (N) from 1 to 8 and without dimpled, with the wind tunnel inflows or outer sample flow (U_0) from 8 m/s to with 20 m/s or laminar flow which are on Reynolds number (Re_L) from 1.29×10^5 to 3.23×10^5, it can be concluded:

a. The larger the number of lines dimpled on the parallel configuration is, the smaller the resistance coefficient is, but at $N = 2$ it has a turning point or when $N > 2$ the resistance coefficient is larger. The smallest resistance coefficient value is C_d = 0.047292 on the Reynolds number $Re_L = 2.26\times10^5$.
b. The larger the number of dimple lines in the zigzag configuration is, the smaller the resistance coefficient is, but at $N = 1$ it has a turning point or when $N > 1$ then the coefficient of resistance is larger. The smallest resistance coefficient value is C_d = 0.048723at Reynolds number $Re_L = 2.26\times10^5$.
c. The resistance coefficient pattern tends to be similar for any alteration in flow velocity or Reynolds number and the number of dimple rows. This phenomenon shows that the use of dimples is better than without

using them.

d. The addition of the number of dimple lines on the plate will reduce the resistance coefficient i.e.5.88%for dimpled plate in zigzag configuration, while for dimpled plate in parallel configuration the reduction is about 8.65%.

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