Numerical Investigation of Drag Reduction on Flat Plates using Dents

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Abstract- **Drag force in vehicles – auto motives, aircrafts, ships and submersibles – result in increased fuel consumption. Various researches had been conducted to minimize the drag forces in terms of passive methods as well as active methods. This research focused on studying the influence of dents on flat plates over the drag coefficient. The dents were defined by three parameters – depth of the dent, main radius of the dent, diameter of the dent. A total of seven dent configuration was studied for flow conditions of 5 m/s to 40 m/s. The study was conducted with the help of computational fluid dynamics (CFD) simulations in ANSYS FLUENT. Pre-processing activities such as meshing was performed in ANSYS Work Bench. Necessary mesh refinement near the plate wall was provided to predict the skin friction components. Reynolds Averaged Navier-Stokes (RANS) formulation was employed in the simulation with the two equation SST k-omega turbulence model. With the increase in flow velocity, the drag coefficient was observed to increase. The results obtained indicate the drag reduction of nearly 30% by providing dents on the flat plate. This was observed for the flow condition of 10 m/s to 40 m/s for the dent plate -1. However, the drag reduction from the remaining configurations was minimal. The results were compared against the existing experimental data for the validation.**

Index Terms- **Drag Reduction, Dents, RANS, CFD, Skin friction**

I. INTRODUCTION

When a solid object moves through a fluid, an equal and opposite force was exerted on the solid object' surfaces. A component of this force, in the direction of solid object motion, offers resistance to the motion and is known as drag force. Normally, the drag force is characterized in the form of drag coefficient, C_D. The drag coefficient is defined as $C_D = \frac{1}{2}\,\rho\, V_\infty^2\, A$. The automobiles are designed to keep C_D to an acceptable range.

There have been multiple methods for reducing the drag and these are broadly classified under two categories

- Passive methods
- Active methods

Passive drag reduction mechanism introduces additional components such as dimples, protrusions etc. in the solid body. The presence of these components alter the flow profile and tend to reduce the skin friction drag. Active drag reduction methods would infuse energy in to the system.

II. LITERATURE REVIEW

PritanshuRanjan[2] had studied the influence of square grooves on the flat plate surfaces over the drag coefficient. With the help of CFD simulations using ANSYS FLUENT, they had studied three variants - Single grooved plate, groves at a distance of 100 mm and grooves at a distance of 200 mm. Based on their results, the authors concluded that the distance between the grooves had a strong influence over the drag coefficient. L.L.M. Veldhuis[3]had conducted Large Eddy Simulations (LES) for studying the impact of dents on the flat plates for four dent depths – 0.5 mm, 1.5 mm, 2.5 mm and 3.5 mm for the flow conditions of 5 m/s to 50 m/s. In their research, the authors noted that the shallow dent's drag reduces because of the reduction in wall shear stress whereas in case of deeper dents, the pressure forces near the dents become severe. This was due to the separation that was observed in the deeper dents. This resulted in high drag in case of deep dents. C. M. Tray [4] had studied the effect of shallow circular dimples on a channel over the influence on drag. The dimple depth to the channel diameter ratio of 5% was studied experimentally by the author for the flow conditions corresponding to Re = 5,000 to 40,000. Coverage ratio was varied for 40% and 90%. The author noted that with the increased coverage area, the drag reduction potential also increases. G. Ghassabi[5] had applied Taguchi method for investigating the effect of the rectangular cylinder placed near the flat plate on the skin friction coefficient. The authors had performed the experimental studies with reduced configuration that resulted from the Taguchi optimization method. The flow speed for their study was 13 m/s. Another passive drag reduction method was investigated by Thomas Ryan Rehmeier[6] with the help of 2-dimensional computational fluid dynamics (CFD) simulations. In this research work, drag reduction for the supersonic flow over the flat was achieved by minimizing the skin friction drag with the help of the micro cavities. The flow conditions for the research work corresponding to Mach number 1.2, 2.0 and 3.0. For the flow condition of Mach 2.0, the author was able to reduce the drag coefficient up to 18-20%. The addition of heat in the wall and subsequently to the turbulent boundary would reduce the skin friction drag. This was studied by Brian R Kramer [7] for the aircraft surfaces. The flight test was conducted for the speeds of Mach no 0.7, 0.75 and 0.8 at the altitudes of 25,000, 30,000 and 35,000 feet. Based on their findings, they had suggested that the effectiveness of the boundary layer heating over the skin friction drag reduction was significant for the lower Reynolds number flow conditions.The active drag reduction methods for the automobiles was analyzed by Torbjorn Gustavsson[8] with the focus on reducing the rear end drag. The authors had collected information on controlled boundary layer methods wherein high energy fluid will be injected to prevent the flow separation.

Chen Yu [9] had studied the effect of corrugation for reducing the drag from the flat plates. The author had employed experimental and Numerical simulations (CFD). The Direct Numerical Simulation (DNS) and Detached Eddy Simulation (DES) were used by the author for estimating the drag coefficient. Based on the results, the author concluded that the corrugated surfaces would help to reduce the drag in comparison to other passive methods such as riblets etc.

Jeffrey Michael Mode [10] had simulated the passive drag reduction for the flat plate with dimples. The author had used Fractional Step Method and the Immersed Boundary Method for the numerical simulations. Flow conditions corresponding to Re = 3000 and Re = 4000 were studied in this research work. It was noted that the flow was accelerated across the dimple because of the pressure field. This resulted in favorable pressure gradient along the flow direction which prevents any flow separation. So, the skin friction drag was reduced in this approach. A theoretical study for drag reduction on flat plate polymer additives was developed by Shu-Qing Yang [11]. With the help of order of magnitude analysis, the authors had obtained the governing equations in ordinary differential equation format. By solving these equations, the wall shear stress and subsequently the velocity profiles and the friction factor were estimated. With this approach, the velocity profile in the boundary layer was predicted with and without the polymer additives by having one additional parameter that defines the polymer species, its concentration and Reynolds Number. The results predicted from this theoretical approach were compared with the available experimental data and the authors found that the results were acceptable.Super-hydrophobic surfaces contain high nanometer sized high contact angle features. These prevent the water to move in to the space between the surface peaks, resulting less wetting area. Because of this, the skin friction drag will be reduced. This was studied by Robert J Daniello[12] for the ships.

III. PROBLEM DESCRIPTIONS

The present work focused on identifying the influence of the dimples on the flat plate over the drag for various operating conditions ranging from 5m/s flow velocity to 40 m/s. Seven different dent configuration was studied. The details of the dents are provided below.

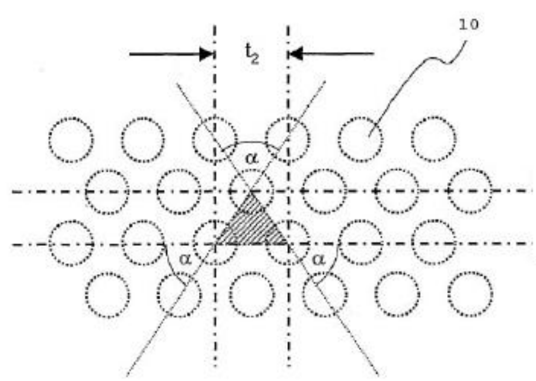

Fig 1 Distribution of Dents [1]

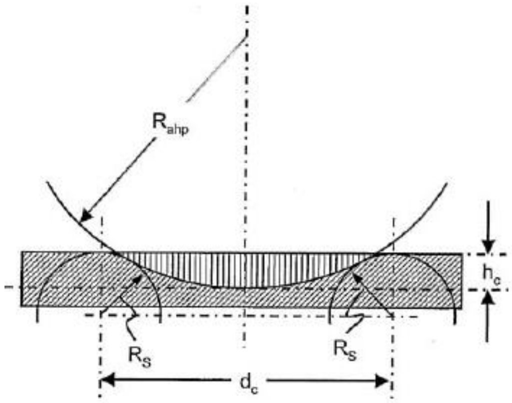

Fig 2 Dent definition parameters [1]

This work was based on the research carried out by E.Vervoort[1]. The parameters as provided by the authors are t1 = 28.6 mm, t2 = 33.0 mm and dc = 20.0 mm. In this study, CFD based simulations will be conducted to estimate the drag coefficient for these dented plates.

The seven dents were based on hc, Rahp and Rs. The following table lists the seven configurations based on these parameters.

Table 1 Details of the Dent

Name	Variables, mm		
	hc	Rahp	Rs
Flat plate	-	-	-
Dented Plate-1	0.343	136.3	10.0
Dented Plate-2	0.686	68.2	5.0
Dented Plate-3	1.843	25.0	3.1
Dented Plate-4	1.988	22.8	3.3
Dented Plate-5	2.133	21.0	3.6
Dented Plate-6	2.422	17.9	4.0
Dented Plate-7	3.000	13.2	5.0

The geometry was built in ANSYS Design Modeler V16.0 and the snapshots of the geometry were provided in figures 3 – 5.

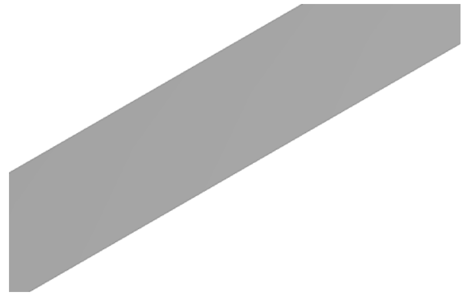

Fig 3 Geometry of the Flat plate

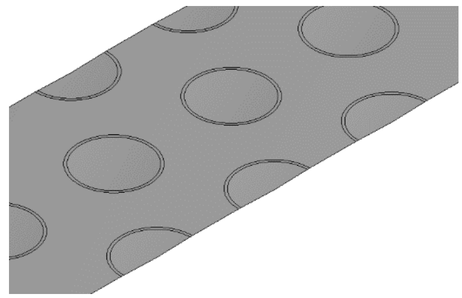

Fig 4 Geometry of the dented plate -1

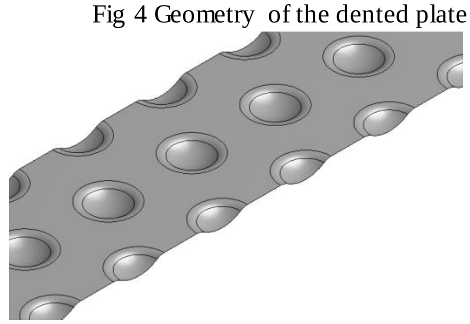

Fig 5 Geometry of the dented plate -7

The drag coefficient for these configurations will be compared against the flat plate and the influence of the dent configuration will be studied from these results.

IV. CFD METHODOLOGY

The simulation was carried out with the help of periodicity assumptions on either side of the computational volume. In this approach, only a part of the plate was simulated. The computational volume had been shown below. The meshing for the project was carried out in ANSYS WorkBench Mesher 16.0. In these simulations, the flow gradients were expected to be stronger nearer to the plate surfaces. And, it's critical to resolve these flow gradients accurately in order to obtain the precise wall shear stress on the plate surfaces. This was achieved by providing the necessary grid refinements near the plate surfaces with the help of 'inflation layers / prism layers'. Similar meshing strategy had been applied for the remaining configurations as well. Figure 6 highlights the boundary conditions that were applied for the simulations.

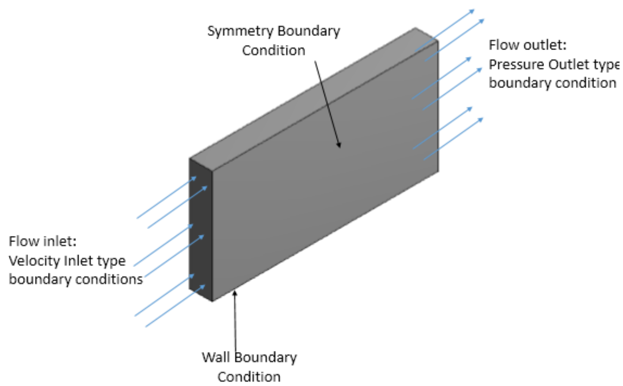

Fig 6 Boundary conditions

V. RESULTS AND DISCUSSIONS

Drag coefficient for each dented plate was plotted against the flat plate in the following figure.

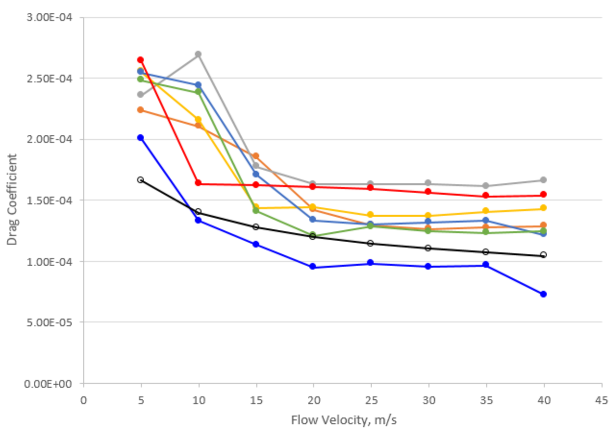

Fig 7 Drag coefficient comparison

As can be observed, the drag coefficient for all the dented plate were higher than the flat plate for the flow speed of 5 m/s. However, when the flow speed was increased, the dented plate 1 which was having least depth provided almost 30% reduced drag (Table 2).

Table 2 Drag Reduction for Dented plate 1

Velocity (m/Sec)	Flat Plate	Dented Plate 1	% difference
5	1.66E-04	2.01E-04	21%
10	1.40E-04	1.33E-04	-5%
15	1.27E-04	1.13E-04	-11%
20	1.20E-04	9.48E-05	-21%
25	1.14E-04	9.79E-05	-14%
30	1.10E-04	9.53E-05	-14%
35	1.07E-04	9.63E-05	-10%
40	1.05E-04	7.25E-05	-31%

Drag coefficient for the flat plate was reducing for the increased flow speed in an almost linear patter (Fig 8). However, for the dented plate 1, a sharp reduction (~33%) drag was observed when the flow velocity changes from 35 m/s to 40 m/s.

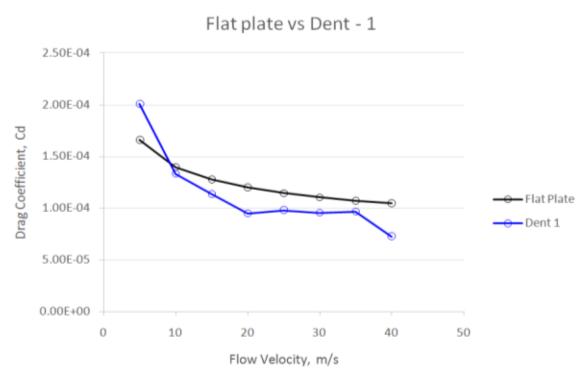

Fig 8 Drag coefficient for Flat plate and dent plate 1

From the velocity contours (Fig 9), the flow profile for the shallow dent (dented plate 1) didn't had flow separation as compared to deep dents (dented plate 7).

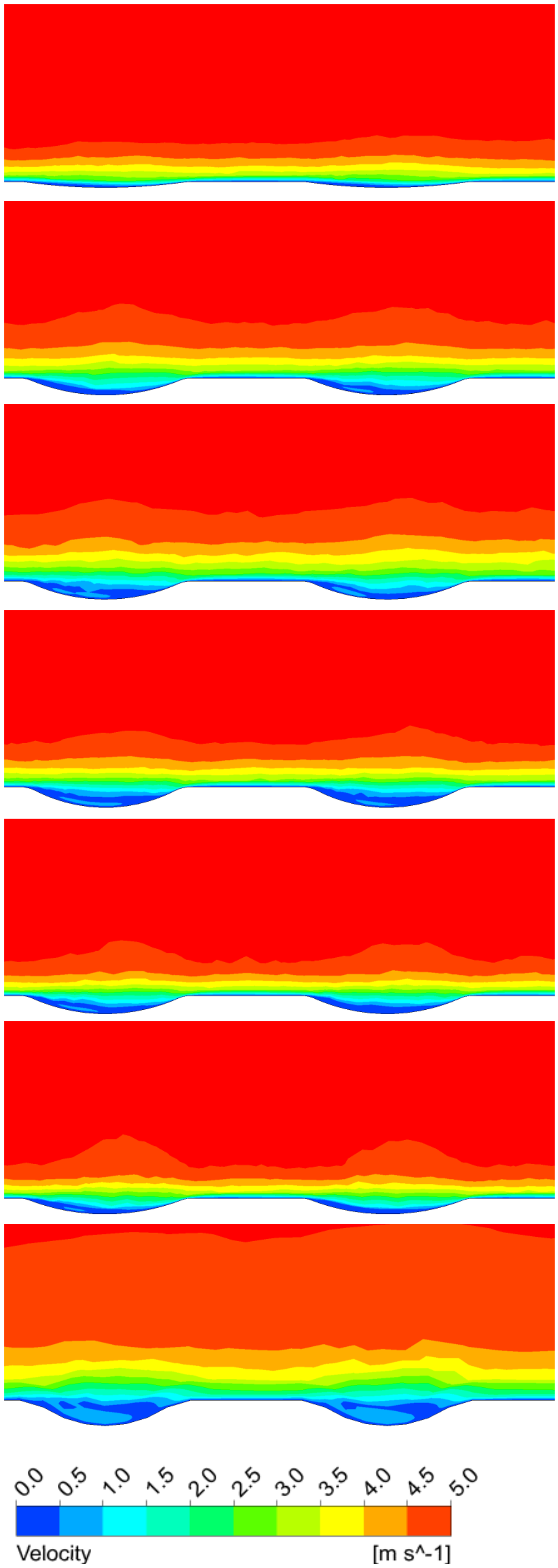

Fig 9 Velocity contour for Dented Plate 1-7

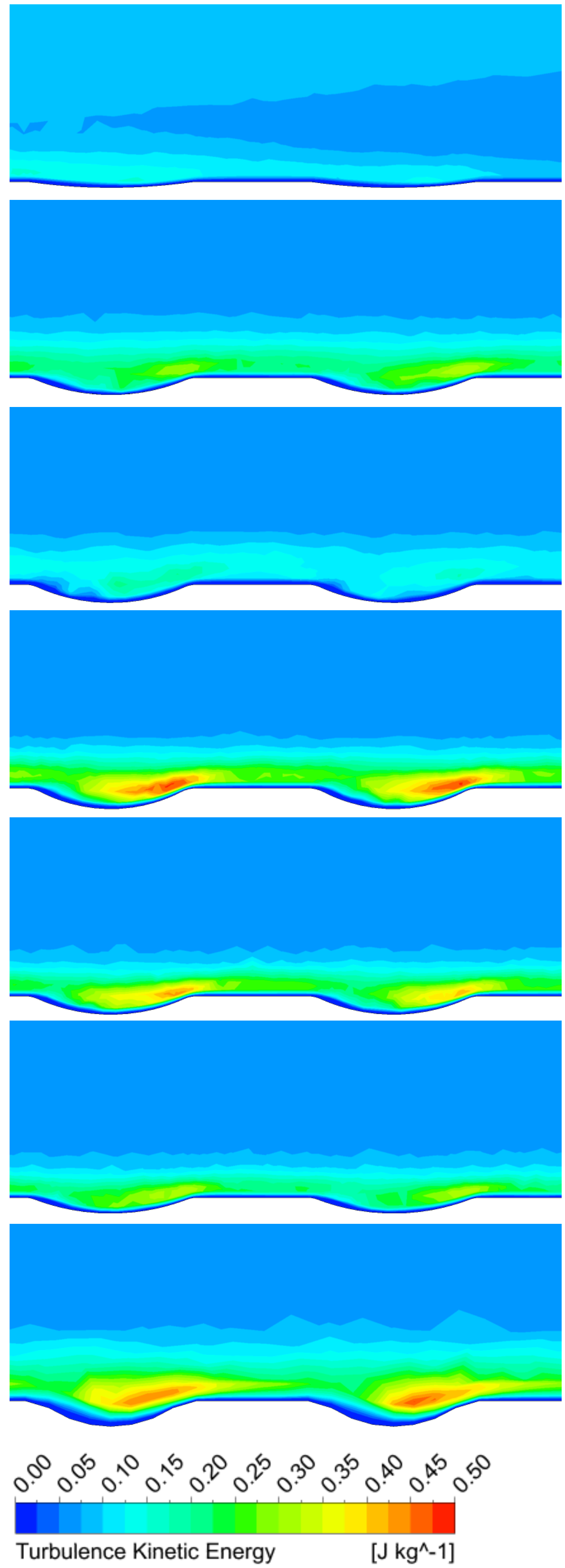

Fig 10 Turbulent kinetic energy contour for Dented Plate 1-7

The contour plots were obtained for the flow speed of 5 m/s and the remaining plots were not produced here to avoid repetitive representation.
The drag was attributed to the sum of skin friction effects and the pressure forces. In cases of dents with mild depths (dented plate 1) the flow still remain attached which resulted in lesser skin friction forces. However, the deep dents produced strong flow separation. The flow separation would result in high local pressure forces as well as the skin friction forces (wall shear stress). Because of this, the drag reduction for the dented plate 1 was observed.

VI. CONCLUSIONS

CFD simulations for investigating the passive drag reduction mechanism with the help of dents on flat plate was performed.
From the comparisons of the Cd for all the dented plates, it was observed that the dented plate-1 had least drag coefficient for these flow conditions among all the dented plate configurations.
The Cd for dented plate-1 reduces as the flow velocity increases. Also, there's sharp reduction in Cd from flow velocity 35 m/s 40 m/s, an indication that there's further potential to reduce the drag further.
For the Dented plate-7, Cd value reduces sharply from 5 m/s to 10 m/s and then remain almost constant for the remaining flow conditions
Among all configurations, dented plate-1, was observed to have lesser drag coefficient than the flat plate. This trend was observed for the flow conditions of 10 m/s to 40 m/s, however, dented plate-1 was having high drag coefficient than the flat plate for the flow velocity of 5 m/s.

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