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Numerical Investigations of Air Flow Around a Model Freight Truck with a Rear Active Flow Control

Hamir Rahai, PhD
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California State University Transportation Consortium

CALIFORNIA STATE UNIVERSITY LONG BEACH

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NUMERICAL INVESTIGATIONS OF AIR FLOW AROUND A MODEL FREIGHT TRUCK WITH A REAR ACTIVE FLOW CONTROL

Hamid Rahai, PhD
Samuel Lopez
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16. Abstract

We performed numerical and experimental investigations of aerodynamic characteristics of a modified Ahmed body with two trailing vertical rotating cylinders. The freestream mean velocity was 24.5 m/sec. (55 MPH) for the numerical investigations and 16.67 m/sec. (37.4 MPH) for the experiments. For the numerical investigations, two 5 cm-diameter vertical cylinders were placed on the back side of the model, protruding 1/8 diameter into the freestream and 1/8 diameter from the back. The cylinders extend the height of the model and rotating in the opposite direction, injecting momentum into the back of the Ahmed body. The simulations were performed at three different rotation rates, with velocity ratios (λ) of 0.5, 1, and 2, where the velocity ratio λ is defined as the ratio of axial tangential mean velocity at the cylinder's surface to the freestream mean velocity. Simulations of Reynolds-Averaged Navier-Stokes Equations (RANS) were performed with the K-ω Shear-stress transport turbulence model. Approximately 15 million unstructured polyhedral cells were used for each simulation. The numerical results indicate that at a velocity ratio of 0.5, with rotating cylinders, the overall drag is reduced by nearly 4%. However at the velocity ratios of 1 and 2, the drag coefficient was increased. Reviewing flow details indicates that at high velocity ratios, the freestream flow overshoots the rotating cylinders, creating reduced back pressure and thus increased the overall drag.

The experimental verifications of the numerical results were performed in the CSULB/Boeing low-speed wind tunnel with velocity ratios of 0.3, and 0.6 (higher velocity ratios were not investigated due to difficulty of maintaining a high rotation rate). Results indicate more than 5% drag reduction at the velocity ratio of 0.3, and nearly 8% reduction at the velocity ratio of 0.6. The reduction in the drag force corresponds to increase in the average back pressure.

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EXECUTIVE SUMMARY

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I. INTRODUCTION

The Global Warming Solutions Act of 2006, or Assembly Bill 32 (AB 32), requires reduction of California's Green House Gases (GHG) emissions to 1990 levels by 2020. It directs the California state agencies to adapt regulations and implement investment strategies to achieve maximum GHG reductions with cost effective technologies. Governor Brown's Executive Order B-30-15 has established a new interim statewide greenhouse gas emission reduction target to reduce greenhouse gas emissions to 40% below 1990 levels by 2030, to ensure California meets its target of reducing greenhouse gas emissions to 80% below 1990 levels by 2050.

Road vehicles such as trucks and tractor-trailers are major means of transporting goods across the globe, and their aerodynamic drag is a major contributor to their fuel consumption. These vehicles are also major sources of pollutants. Reducing their aerodynamic drag results in reduction in their fuel consumption as well as the amount of pollutants introduced into the atmosphere. Figure 1 shows simulation models of air flow around tractor-trailers. A tractor-trailer's flow structure includes multiple stagnation points, gap flow, underbody flow, and a large wake region. All of these contribute to the aerodynamic drag of the vehicle.

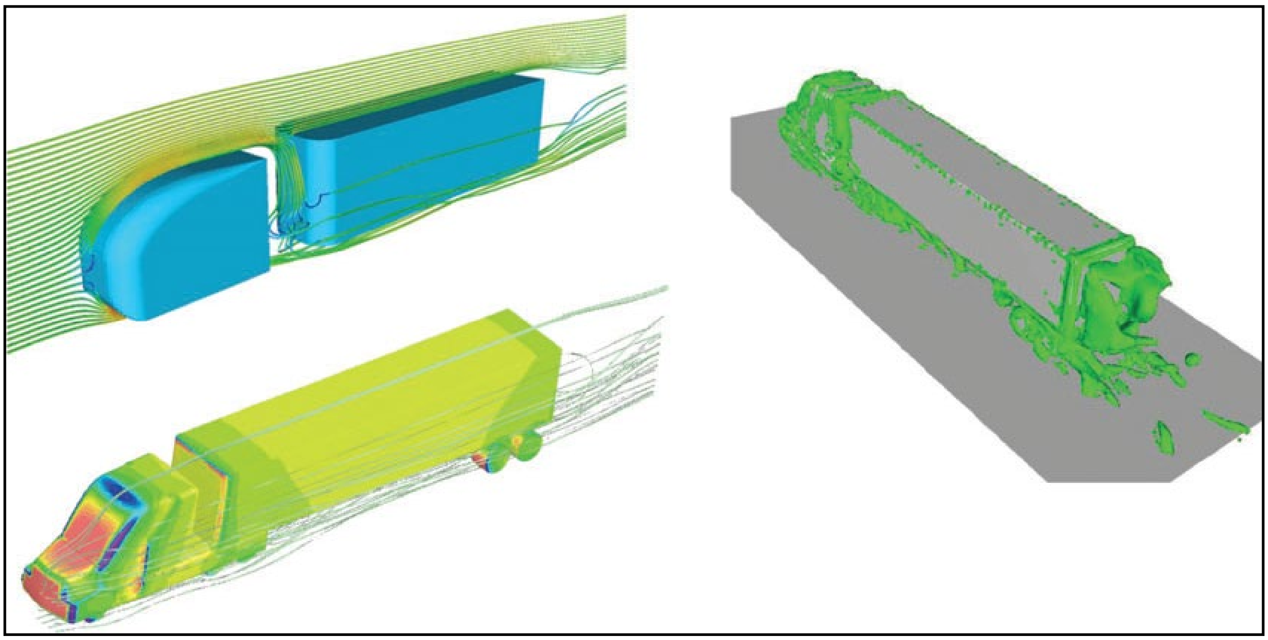


Figure 1. Air Flow Around a Tractor-Trailer (McCallen et al, 2004)

There is a significant pressure drop in the wake region, where separated shear layers form recirculation regions. When crosswind is present, there is additional drag due to increased separation, as well as increased side force on the vehicle.

There have been extensive studies on different methods of reducing drag of modified box-shaped ground vehicles such as vans, trucks, trailers and motor homes, some of which will be reviewed presently. These studies have resulted in aerodynamic shaped driver-passenger cabins, cab side extenders, and trailer side skirts. These modifications are mainly applied to the front and sides of the vehicles, reducing pressure and secondary flow at these locations, resulting in a reduced overall pressure differential and a net reduction in drag force.

Montoya and Steers (1974) and Steers and Saltzman (1977) have shown that with certain add-on devices added to the front of a conventional cab over engine tractor-trailer, substantial decreases in drag coefficient and fuel consumption are obtained in the zero-crosswind condition.[1] However, when the crosswind is present, these reductions were significantly less.

The base pressure of a tractor-trailer or of any box-shaped vehicle can be increased by making the tail of the vehicle more aerodynamic, resulting in elimination of the flow separation region and, consequently, in a substantial increase in the base pressure. One such device for making the tail more aerodynamic is a boat-tail attachment. Studies by Peterson (1981), Saltzman (1982), and Lanser et al (1996) have shown that attaching a boat-tail or other aerodynamic device to the rear of a truck can reduce the drag of the vehicle by as much as 10%.[2] Figure 2 shows some of these devices and methods. However, for rear add on devices, due to the length they add to the trailer, and their interference with loading and unloading through the trailer's back doors, they have not been widely adopted by truck manufacturers.

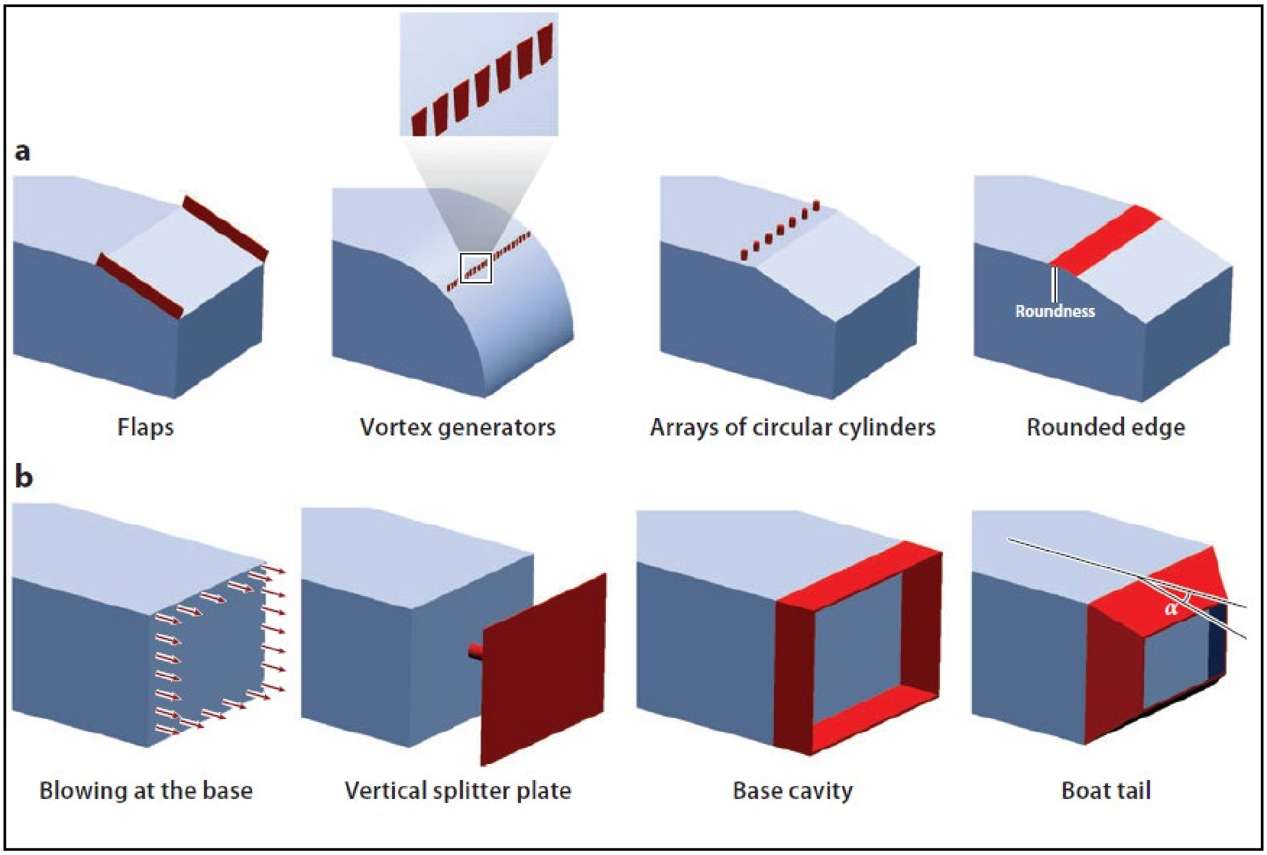


Figure 2. Devices for Base Drag Reduction (Choi et al, 2014)

Modi et al (1990) conducted experimental investigations on reducing drag of tractor-trailer trucks through momentum injection.[3] They used rolling surfaces comprised of motor-driven moving cylinders at the rear edge of the top surface, for injecting momentum into the wake and reducing the area of flow separation. Their results showed substantial increase in the base pressure, resulting in a significant reduction in the overall drag of the vehicle. Modi et al (1991a, 1991b, 1992) further investigated the wake of bluff and streamlined objects, by placing rotating controlled cylinders near the stationary objects, and found significant reductions in the objects' wake's unsteadiness and drag coefficients.[4]

Mitel (2001) studied the wake of a stationary cylinder with two control rotating cylinders placed at either 0.01*D* or 0.075*D* spacing above and below the cylinder, where *D* is the diameter of the stationary cylinder.[5] His results indicate that when the velocity ratio, the ratio of the tangential mean velocity of the surface of the rotating cylinders to the freestream mean velocity, is 5, significant reductions were obtained in the overall drag coefficient and in the unsteady aerodynamic forces acting on the stationary cylinder. The larger gap between the stationary cylinder and the rotating control cylinders, resulted in higher drag reduction.

II. PROCEDURE AND TECHNIQUES

Numerical Method:

Figure 2 shows top and side views of a modified Ahmed body with control cylinders. The Ahmed body was 104.4 cm in length, 28.8 cm in height and 32.7 cm in width. The standard Ahmed body has a rear that sloped downwards from top toward bottom. However, for the current investigation, the rear surface has been made vertical, to simulate the rear of a tractor-trailer, without changing the overall length. Two control cylinders 5 cm in diameter (*D*) were added behind the trailer, one on each side. The cylinders were placed with a gap of 1/8*D* from the rear of the trailer, and protruding from by 1/8*D* into the side freestream airflow. The freestream mean velocity was 24.5 m/sec (55 MPH), which corresponds to an approximate unit Reynolds number of 1.6×10^6. The control cylinders were rotating at the same RPM, but in opposite directions, injecting momentum into the back of the trailer. The study was performed at velocity ratios of 0.5, 1.0, and 2.0. The freestream mean flow momentum is $(\rho U_{\infty})U_{\infty}$ and the momentum injected by the rotating cylinders into the back of the modified Ahmed body is $(\rho U_{\infty})U_{t}$. The momentum ratio is the ratio of the later to the former and after simplification, it becomes equivalent to the velocity ratio defined as:

$$\lambda = \frac{U_t}{U_\infty} \qquad (1)$$

Here, U_∞ is the freestream mean velocity, and U_t the tangential velocity of the rotating cylinder is calculated as:

$$U_t = \frac{2\pi r \Omega}{60} \qquad (2)$$

where *Ω* is revolutions per minute and *r* is the radius of the cylinder. Thus, at the three velocity ratios chosen, the cylinders' tangential velocity moved at half the speed of the air, at the speed of the air, and at twice the speed of the air, respectively.

The simulations were carried out using Siemens STAR-CCM+ CFD software, on a UNIX-based high performance computer with 32 cores. A three-dimensional, constant-density incompressible fluid flow with implicit time-steps was modeled, and used to solve the Reynolds-Averaged Navier-Stokes (RANS) equations. The segregated flow solver algorithm was considered to solve the x, y, and z momentum equations, along with continuity equation using predictor-corrector approach. The Shear-stress transport turbulence model (the Wilcox K-ω turbulence model) was used.

After performing grid sensitivity tests, for increased numbers of polyhedral cells comprising the Ahmed body, until variation in the drag coefficient was reduced to a maximum of 1%, we chose to use approximately 8.75 million polyhedral cells for the simulations without rotating cylinders in place. However, when the rotating cylinders were added, approximately 15 million cells were required to obtain results with this level of precision.

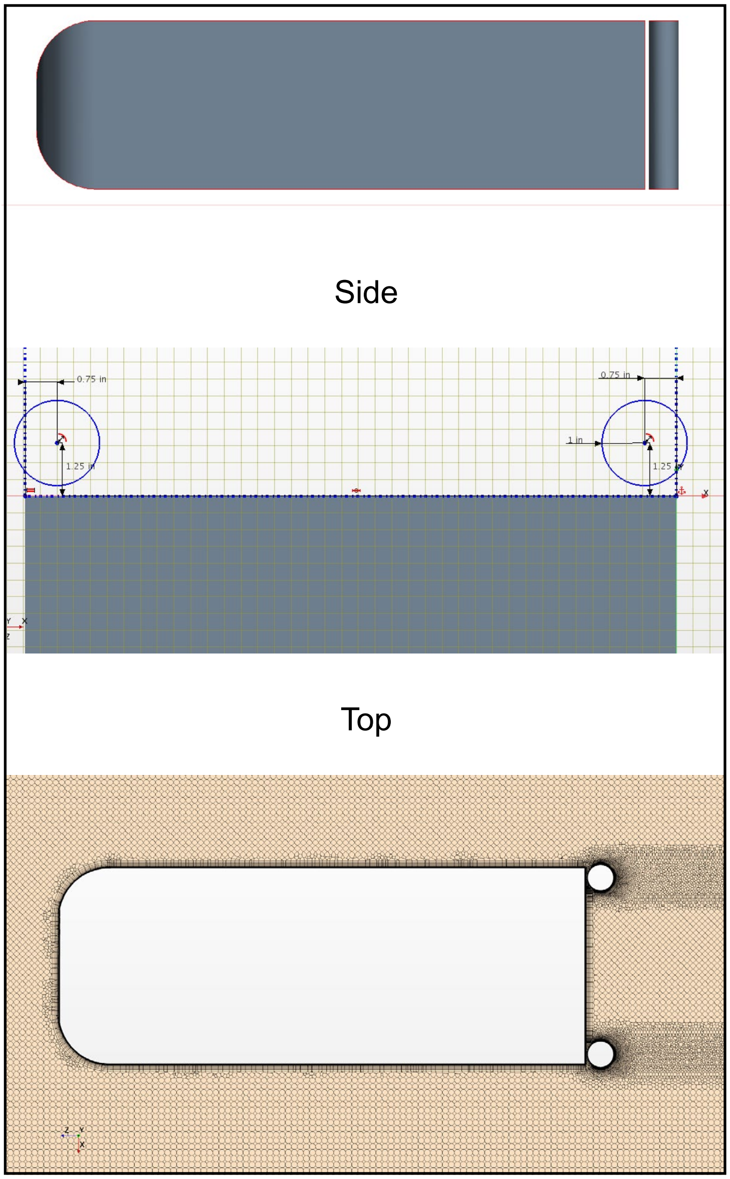


Figure 3. Modified Ahmed Body with Control Cylinders

Experimental Method:

Figure 6 shows the experimental model. The model was built using the same dimensions as the numerical model. Pressure taps were placed on the windward face, along the mid-section plane through the body and at the back face of the model. The experiments were performed in the CSULB/Boeing low-speed wind tunnel with a cross-sectional expanded working area of 2.4 m x 2.4 m, over a length of 3 m. The cross-sectional effective flow area with uniform flow condition was 1.2 m x 0.9 m, over a length of 3 m. Variations in the axial mean velocity and freestream turbulence intensity were less than 0.5% and 2% respectively. A one-component balance composed of an axial linear bearing connected to a 111.2 N load cell from Transducer Techniques, Inc. was used for drag measurements. A 16 channel Scanivalve, in connection with two transducers, were used for pressure measurements. One pressure transducer was used for measuring reference pressure while the other recorded the scanned pressure of the Ahmed body. The freestream mean velocity was 16.67 m/sec. and the two vertical cylinders RPMs were adjusted to correspond to velocity ratios of 0.3 and 0.6. Due to difficulty in maintaining high RPM, higher velocity ratios were not investigated.

III. RESULTS AND DISCUSSIONS

Numerical Investigations:

Figure 3 shows the contours of mean pressure, mean velocity, vorticity, and velocity vector for the modified Ahmed body without the rotating cylinders. Examining the Ahmed body from front to back, we see that the windward face of the Ahmed body experiences high mean pressure (stagnation pressure), followed by a significant drop in pressure due to flow acceleration around the round edges, a moderate increase in pressure on the body, and finally negative pressure in the near wake, due to flow separation. There is increase in vorticity on the body due to variation in velocity and flow acceleration, and there is flow separation in the wake. At the mid-section plane, flow is symmetric with separating vortices moving toward the back. The overall drag coefficient is calculated to be 0.249.

Figure 4 shows the corresponding contours for the modified Ahmed body with cylinders rotating at a velocity ratio of 0.5. The rotating cylinders inject momentum into the back, resulting in pressure recovery and thus in a reduced drag coefficient. The overall drag coefficient has been reduced by nearly 4%. There is an increase in pressure at the face of the cylinders where there is a flow impingement. However, due to rotation, pressure is reduced with flow acceleration. There is an increase in vorticity due to rotation.

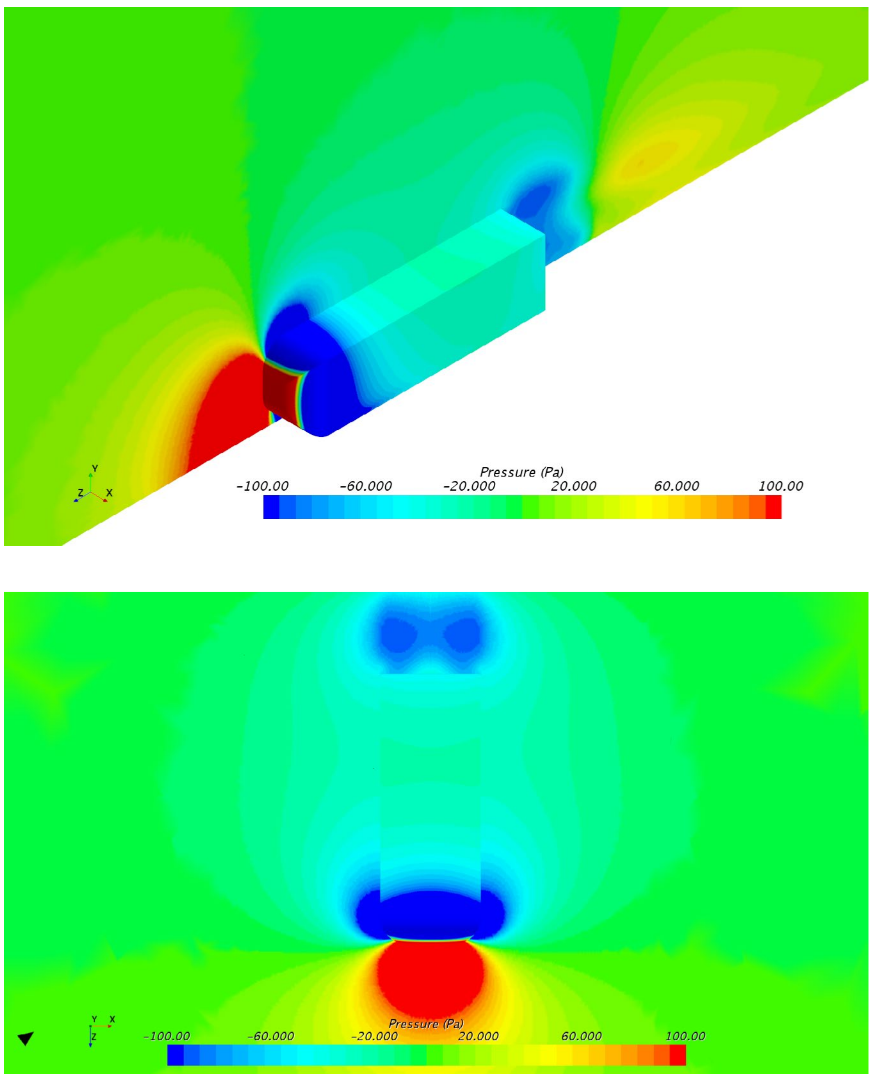
Figure 5 shows the contours of pressure on the back surface for the modified Ahmed body without cylinders, for the modified Ahmed body with non-rotating cylinders, and for the modified Ahmed body with cylinders rotating at a velocity ratio of 0.5. For the modified Ahmed body without cylinders, there is negative pressure around the circumferential of the back surface, with a positive pressure in the middle region due to recirculating vortices. The pressure shows vertical symmetry (left-right); however, it does not show horizontal symmetry (top-bottom), because of the ground effect.

With the addition of the cylinders without rotation, there is a significant reduction in the circumferential pressure and vertical symmetry is no longer observed. When the cylinders rotate, the surface pressure adjacent to the cylinders increases, and there are increases in pressure on the back surface, resulting in pressure recovery and drag reduction.

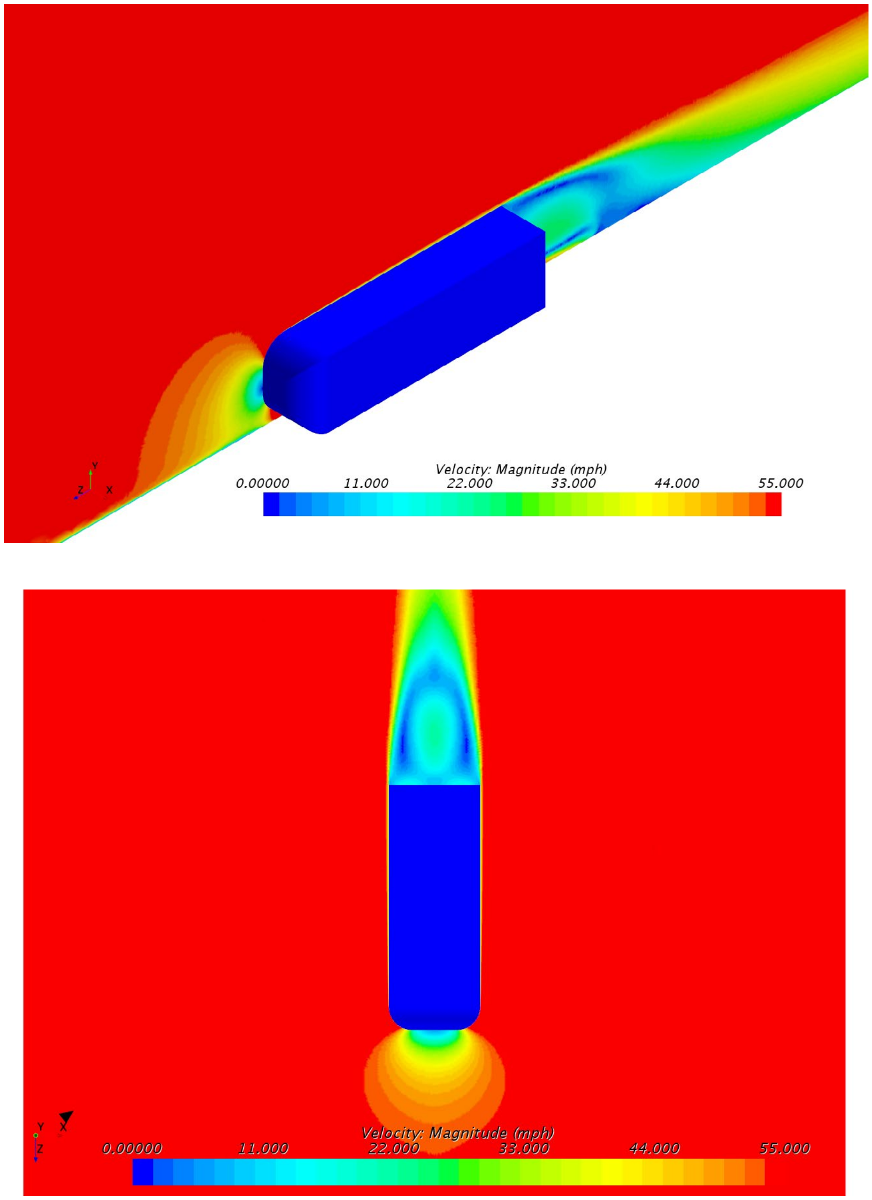
We have completed similar simulations for the modified Ahmed body with the rotating cylinders at velocity ratios of 1 and 2; results indicate that drag coefficients are increased, when compared to the baseline model (the modified Ahmed body without cylinders), by 13% and 66% respectively. Please note that the addition of the side cylinders without rotation results in increased drag coefficient by more than 5%. However, at the velocity ratio of 0.5, the results indicate a nearly 4% reduction in the drag coefficient; this suggests that for some ranges of velocity ratio lower than one, the rotating cylinders can overcome the additional drag imposed by the protruded cylinders and lower the overall drag coefficient.

Experimental Investigations:

Table 1 shows the experimental results of average change in back pressure and drag force normalized against the corresponding results without cylinders' rotation. For the velocity ratio λ=0.3, a 5% reduction in drag coefficient was obtained, with a 2.6% increase in average back pressure. However, at the velocity ratio λ =0.6, the drag reduction is nearly 8% with an 11% increase in the average back pressure. Because the effects of momentum injection into the back of the model could be non-uniform across the surface, we used the averaged back pressure, instead of a single back pressure, for assessing the effects of rotating cylinders on the overall drag force. The experimental results for the overall drag reduction at velocity ratio of 0.3 are qualitatively similar to the corresponding numerical results at velocity ratio of 0.5. These results seems to indicate that for some range of velocity ratios less than one, especially near 0.5, there is potential for reducing the overall drag with the addition of rotating cylinders.



(a)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11.000
22.000
33.000
44.000
55.000
Velocity: Magnitude (mph)
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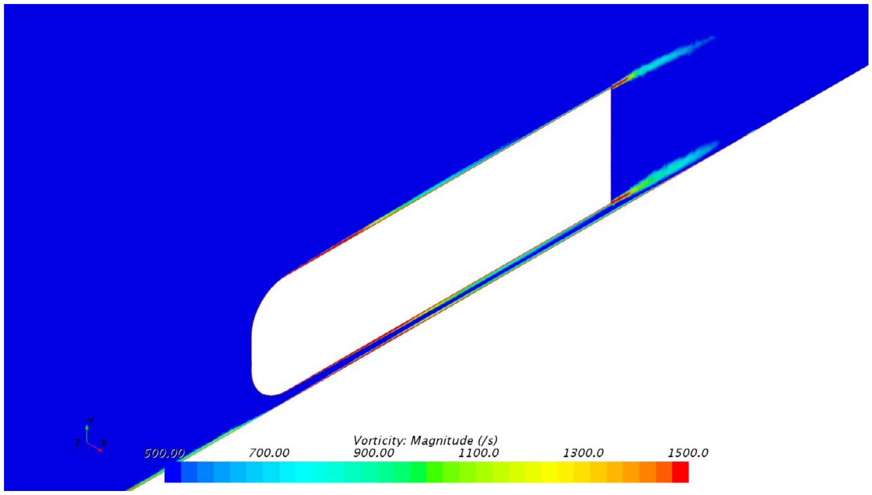
22.000
33.000
44.000
55.000

(b)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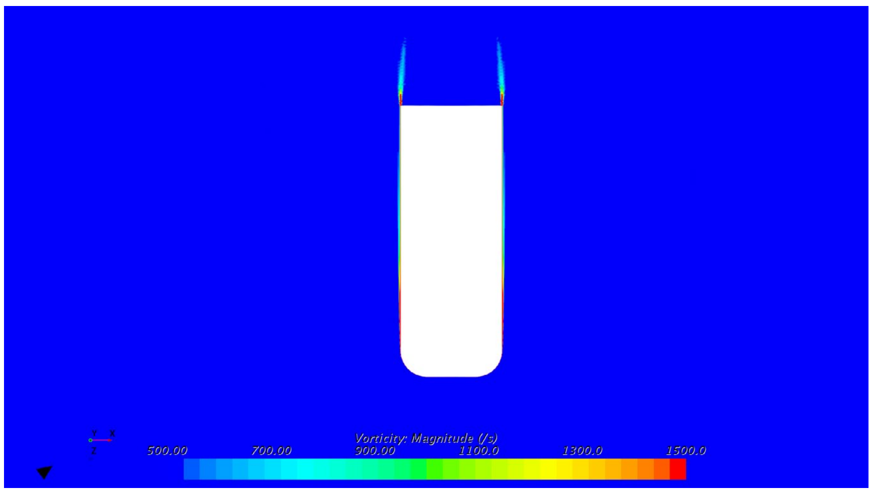
900.00
1100.0
1300.0
1500.0


Vorticity: Magnitude (/s)
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1100.0
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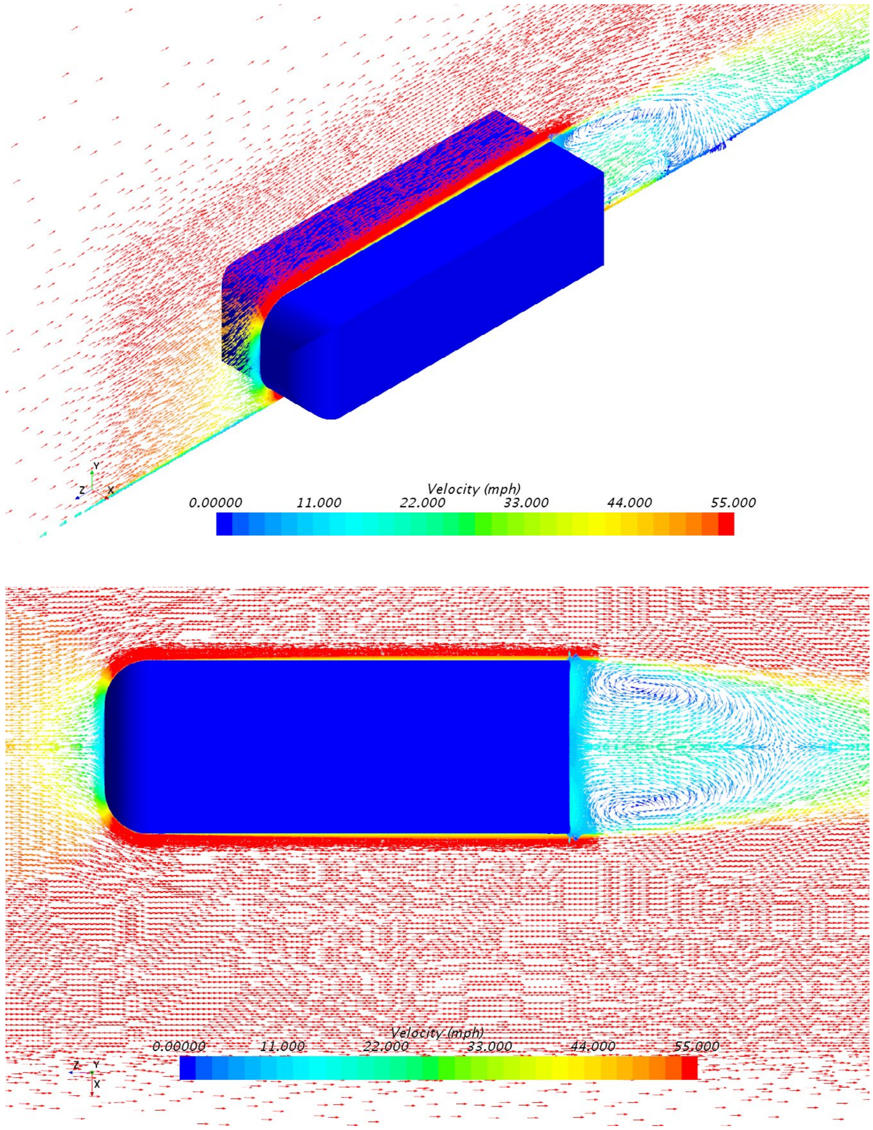
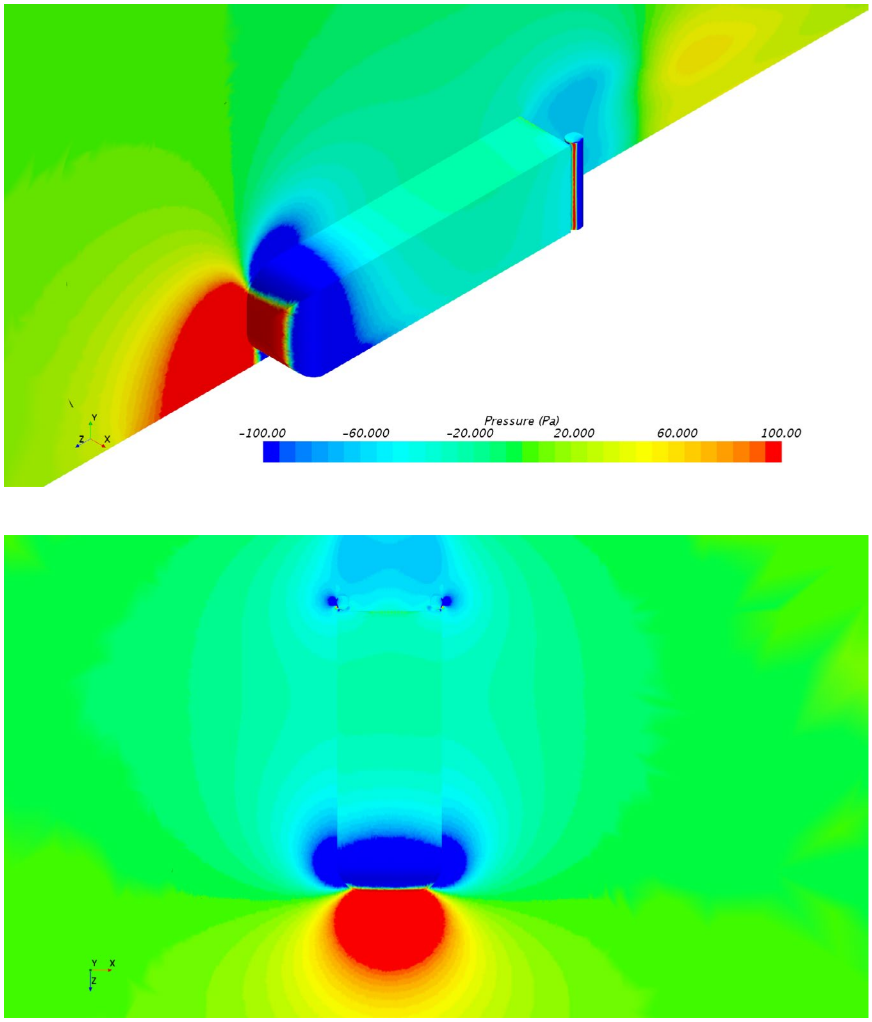
1500.0

(c)

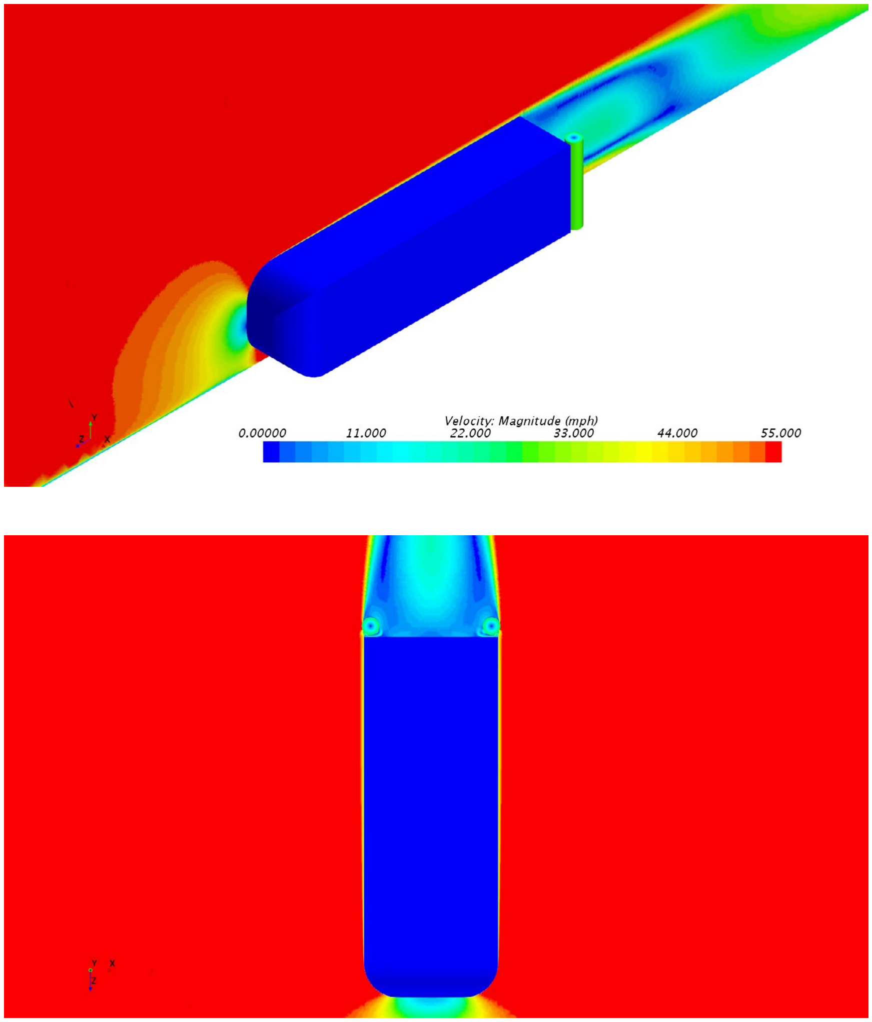


(d)

Figure 4. Flow Characteristics Around the Modified Ahmed Body: (a) Mean Pressure, (b) Mean Velocity, (c) Vorticity, and (d) Velocity Vector



(a)


Velocity: Magnitude (mph)
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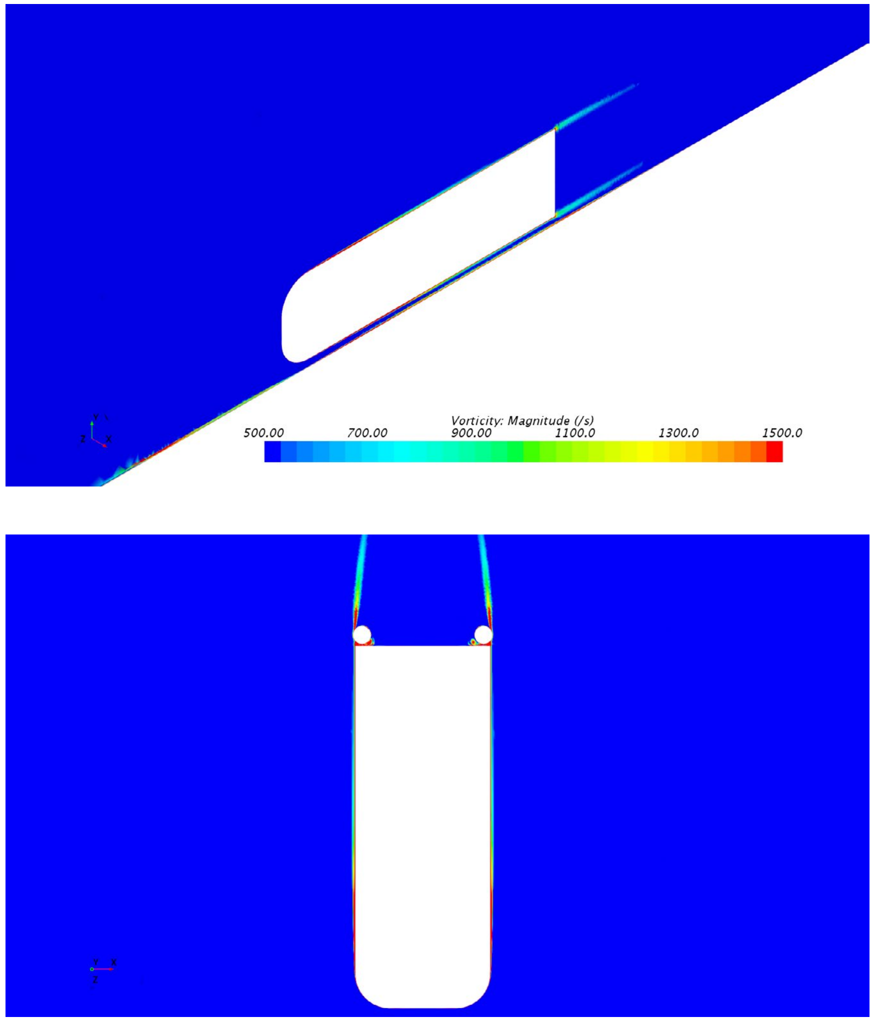
22.000
33.000
44.000
55.000

(b)



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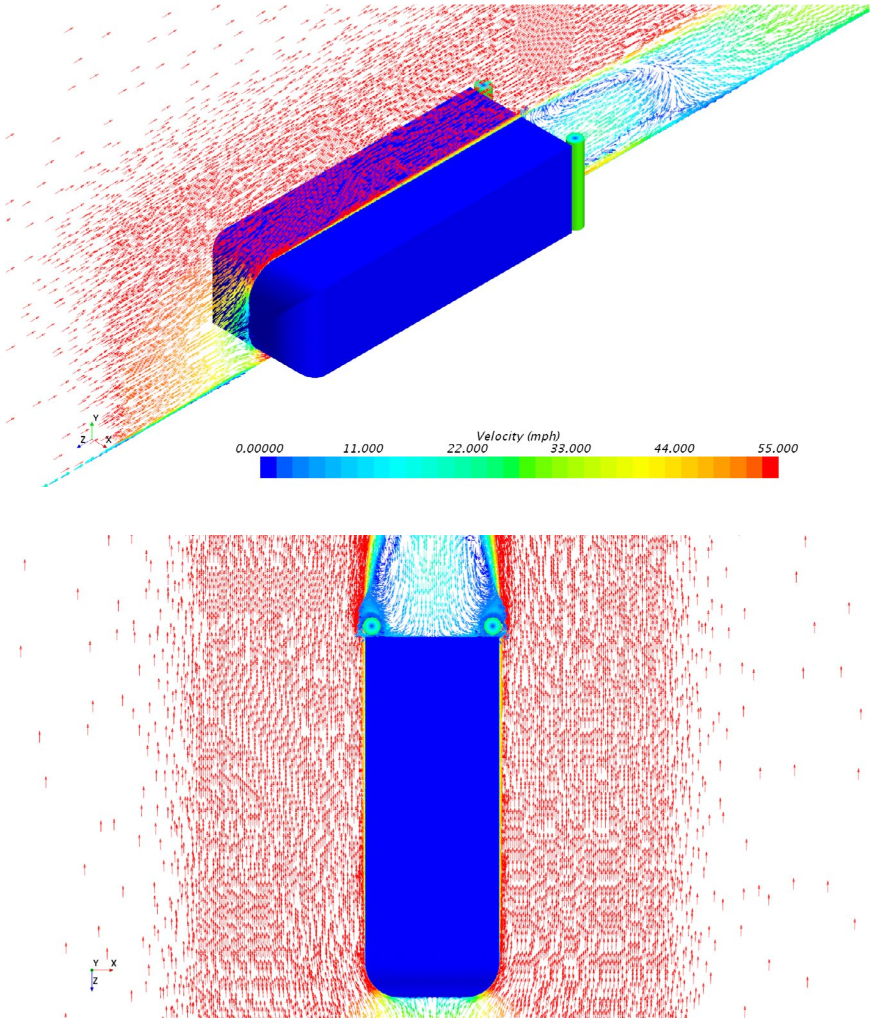
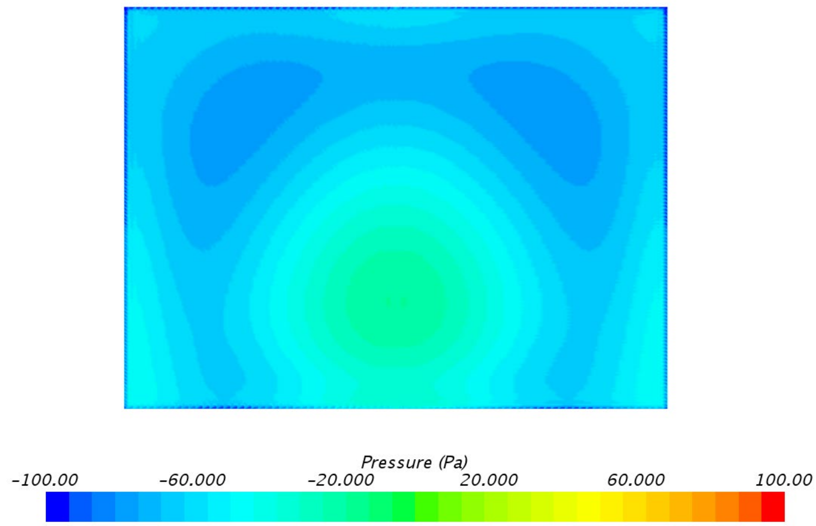


(d)

Figure 5. Flow Characteristics Around the Modified Ahmed Body with Rotating Cylinders At Λ=0.5: (a) Mean Pressure, (b) Mean Velocity, (c) Vorticity, and (d) Velocity Vector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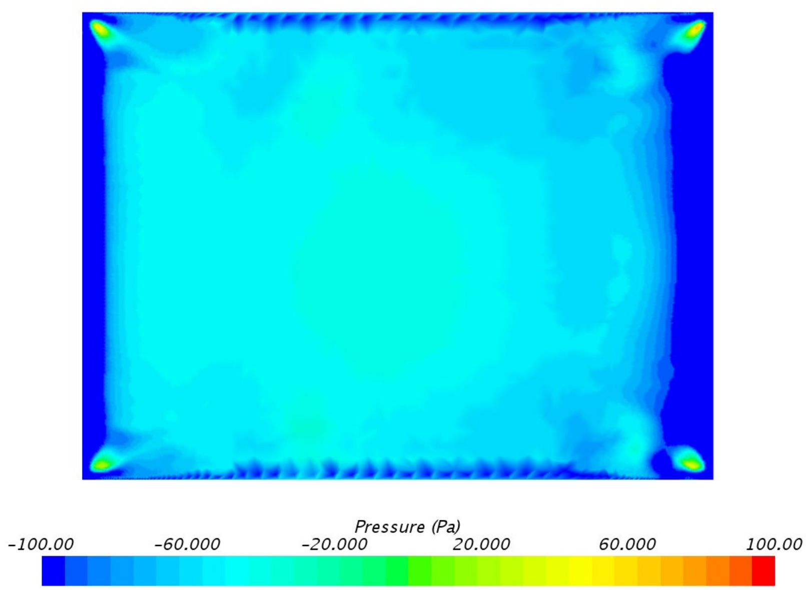
-60.000
-20.000
20.000
60.000
100.00

(a)


Pressure (Pa)
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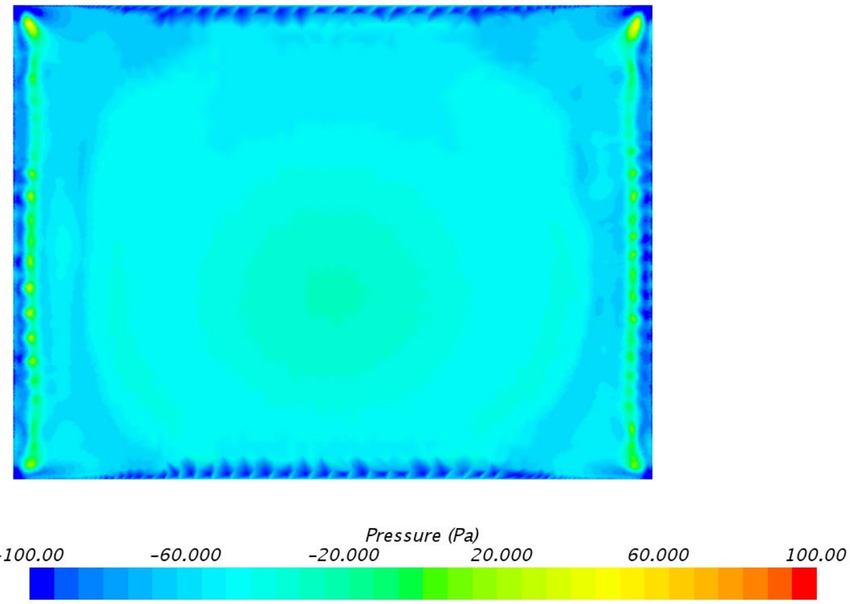
-60.000
-20.000
20.000
60.000
100.00

(b)



(c)

Figure 6. Contours of Mean Pressure on the Back Surface: (a) Modified Ahmed Body, (b) Modified Ahmed Body With Stationary Cylinders, (c) Modified Ahmed Body With Rotating Cylinders at Λ=0.5

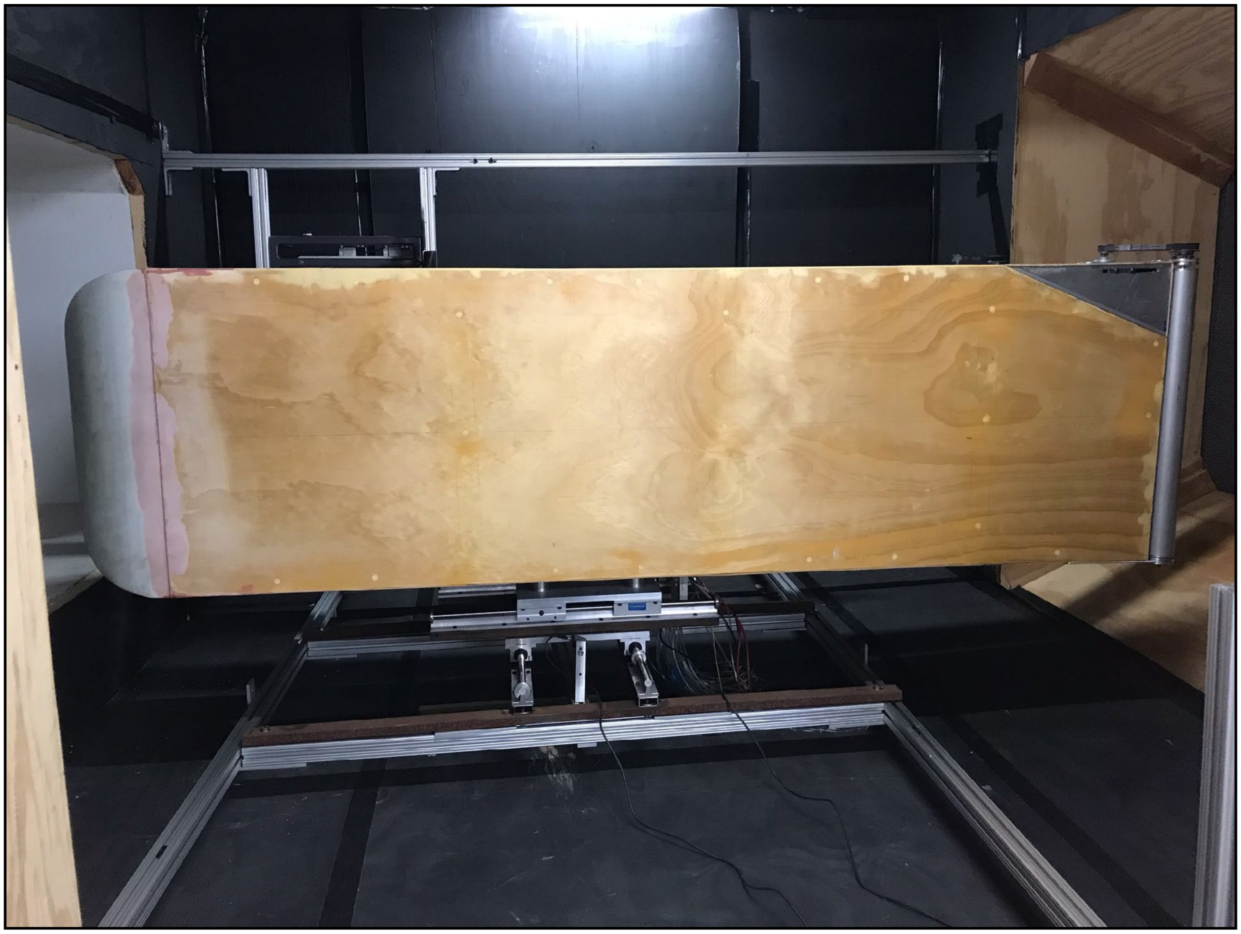


Figure 7. The Experimental Model

λ	0.3	0.6
$\Delta P_{back}/\Delta P_{b0}$	4%	11%
D/D_0	0.95	0.92

Table 1. Comparisons of Average Back Pressure and Drag Force for Different Velocity Ratios

IV. CONCLUSIONS

Numerical simulations of airflow past an Ahmed body with and without rear rotating control cylinders have been performed. The freestream mean velocity was at 24.5 m/sec. (55 MPH), and the unit Reynolds number was $1.6x10^6$. Two rotating cylinders of 5 cm in diameter were placed at the rear on each side edge at 1/8*D* from the back surface, protruding 1/8*D* into the freestream. Cylinders rotated in opposite directions of each other toward the back surface, injecting momentum into the back of the Ahmed body. Numerical simulation results were calculated for velocity ratios, defined as the ratio of the tangential mean velocity of the cylinders' surface to the freestream mean velocity, of 0.5, 1.0, and 2.0. Cylinder rotation with a velocity ratio of 0.5 resulted in a nearly 4% reduction in the overall drag coefficient as compared with the corresponding results for the modified Ahmed body without the cylinders rotating. However, when the velocity ratios are increased to 1 and 2, significant increases in the drag coefficient were obtained. Evaluation of the latter results indicate that at high velocity ratio, the cylinders' surface is moving faster than the freestream velocity and is too high to be able to extract momentum from the free-stream flow and inject it into the back of the Ahmed body. Experimental results at velocity ratios of 0.3 and 0.6 are in qualitative accord with the numerical results, suggesting that for velocity ratios near 0.5, there is potential for overall drag reduction in large vehicles by means of a rotating cylinder system.

ENDNOTES

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ABBREVIATIONS AND ACRONYMS

D	Drag force, Newton
r	Cylinder's radius, m
P	Pressure, Pascal
U_t	Tangential mean velocity, m/sec.
U_0	Freestream mean velocity, m/sec.
Ω	Cylinder's rotation, RPM
ρ	density, Kg/m^3
λ	Velocity ratio = U_t/U_0

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