CFD analysis of a round shaped air cushion vehicle with inclined skirt segments

M S Pavăl1*, A Popescu1 and D Zahariea2

1Mechanical Engineering and Road Automotive Engineering Department, “Gheorghe Asachi” Technical University of Iasi, Iasi, Romania
2Fluid Mechanics, Fluid Machinery and Fluid Power Systems Department, “Gheorghe Asachi” Technical University of Iasi, Iasi, Romania

*E-mail: mihai-silviu.pavala@tuiasi.ro

Abstract. This article presents various two-dimensional CFD analyses specific to the area of the flexible skirt segments for a round-shaped air cushion vehicle. This study aims to analyse the flexible skirt segments and the influence of their inclination angle on the lift force values. The simulations, as well as the geometries of the flow domain, were carried out with ANSYS Fluent software, in which three parameters varied: tilt angle, segment height and air clearance height. The choice of segments height was based on a previous study by the authors and the values for air clearance height imposed in the present study were 10, 20, 30, 40 and 50 mm. Regarding the values of the inclination angles, three values were imposed: 45°, 60° and 75°. Using ANSYS CFD-Post application, the resulting pressure / velocity contours and streamlines are interpreted and with Curve Fitting Toolbox application within the MATLAB program, the curves describing lift forces obtained from the simulation are approximated.

1. Introduction

This article presents a more complex continuation of the previous study on fluid flow in the flexible skirt segment area for an air cushion vehicle. This area was labelled zone 3 due to the fluid flow mode inside the vehicle cavity and is shown in figure 1.

Figure 1. The area of interest for this study.

Unlike the previous study in which the flexible skirt segments were arranged at 90°, this study highlights the influence of the flexible skirt segments on lift force values. Three angles of inclination were used in these analyses, resulting in the studied cases presented in table 1, where: \( \gamma \) – the angle of inclination of the segments, \( h_s \) – the height of the flexible skirt segments and \( a_{ch} \) – air clearance height.
Table 1. Description of the studied cases.

| Name of the case | $\gamma$ [$^\circ$] | $h_s$ [mm] | $a_{ch}$ [mm] |
|------------------|-----------------|-----------|-------------|
| Case A-45°       | 45              | 50        | 10/20/30/40/50 |
| Case B-45°       | 60              | 50        | 10/20/30/40/50 |
| Case C-45°       | 150             | 200       |             |
| Case D-45°       | 200             |           |             |
| Case A-60°       | 60              | 50        | 10/20/30/40/50 |
| Case B-60°       | 100             | 10/20/30/40/50 |
| Case C-60°       | 150             |            |             |
| Case D-60°       | 200             |            |             |
| Case A-75°       | 75              | 50        | 10/20/30/40/50 |
| Case B-75°       | 100             | 10/20/30/40/50 |
| Case C-75°       | 150             |            |             |
| Case D-75°       | 200             |            |             |

2. Main parameters that describe the chosen fluid domains
The shape of the fluid domains chosen for these simulations is rectangular, being practically a cross section of a flexible skirt segment. Figure 2 presents the main notations for describing these areas and table 2 presents the values of these parameters that have fixed values, where: $D_{efd}$ – the outer diameter of the fluid domain, $D_{es}$ – the outer diameter of the segments, $D_{is}$ – the inner diameter of the segments, $D_{efh}$ – the outer diameter of the feed orifice and $D_{ih}$ – inner diameter of the feed orifice. Regarding $H_{gfss}$, this is a resultant parameter consisting of the sum of the height of the flexible skirt segment and air clearance height.

3. Main steps of the simulations performed in the ANSYS Fluent program
The main steps in carrying out these simulations are:
- creating the geometries of the flow domains and imposing boundaries: the fluid domains were created using Design Modeler application within the ANSYS program and the defined boundaries are shown in figure 3.

![Image](image-url)

**Figure 2.** The main components and notations used in the description of the chosen fluid domains.

Table 2. The invariable parameters of the fluid domains.

| $D_{efd}$ [mm] | $D_{es}$ [mm] | $D_{is}$ [mm] | $D_{efh}$ [mm] | $D_{ih}$ [mm] |
|----------------|---------------|---------------|----------------|---------------|
| 6000           | 1000          | 996           | 946            | 846           |
Figure 3. The imposed boundaries that describe the fluid domains created.

- mesh generation: in contrast to the previous study, where structured meshes were obtained, here this can no longer be achieved due to the inclination angle. In order to obtain good quality parameters, it was also necessary to perform radii connection in the area of the flexible skirt segments. Mesh refinement used Edge Sizing and Inflation methods as well, and hence proper designs were obtained to perform proposed simulations. Using this procedure, a large number of meshes were generated. Figure 4 presents only three graphical designs and table 3 presents numerical values of quality parameters for the entire range of final meshes. Using both the mesh metric spectrum of the Skewness parameter and Orthogonal Quality parameter, it turns out that all the meshes generated fall into the good category, [1].

- parameters characteristics of the SETUP application: the main settings chosen to perform the simulations and which are specific to this application are shown in figure 5. The same calculation methodology is used as in the previous study to determine the turbulent intensity at the outlet1 and outlet2 boundaries. In the present cases, the areas shown in figure 6 were used and after performing several simulations, lift forces were considered.

Figure 4. Final meshes in the area of flexible skirt segments for different inclination angles:
(a) – case A-45° (h_s = 50 mm and a_ch = 10 mm);
(b) – case B-60° (h_s = 100 mm and a_ch = 10 mm);
(c) – case C-75° (h_s = 150 mm and a_ch = 10 mm).
Table 3. Quality parameters that define the final meshes for three mentioned cases.

| Case | h_a [mm] | a_{ch} [mm] | Nodes   | Elements | Aspect Ratio | Skewness | Orthogonal Quality |
|------|----------|-------------|---------|----------|-------------|----------|--------------------|
|      |          |             | Min     | Max      | Min         | Max      | Min                | Max                |
| A-45° | 50       |             | 10      | 138841   | 3.4148      | 0.7732   | 0.43674            |
|       |          |             | 20      | 144391   | 3.3100      | 0.75374  |                    |
|       |          |             | 30      | 149716   | 3.4318      | 0.75771  | 0.43092            |
|       |          |             | 40      | 150297   | 3.4318      | 0.79573  | 0.40959            |
|       |          |             | 50      | 157785   | 3.4318      | 0.74664  | 0.44564            |
| B-60° | 100      |             | 10      | 162029   | 3.3100      | 0.72939  | 0.51402            |
|       |          |             | 20      | 171510   | 3.4513      | 0.72746  | 0.55528            |
|       |          |             | 30      | 170704   | 3.3100      | 0.73738  | 0.53435            |
|       |          |             | 40      | 175758   | 3.3100      | 0.73578  | 0.58344            |
|       |          |             | 50      | 180491   | 3.3100      | 0.75421  | 0.55574            |
| C-75° | 150      |             | 10      | 182428   | 3.3100      | 0.71687  | 0.54174            |
|       |          |             | 20      | 183386   | 3.3706      | 0.77017  | 0.5659             |
|       |          |             | 30      | 189395   | 3.3100      | 0.79331  | 0.56311            |
|       |          |             | 40      | 192477   | 3.3194      | 0.77728  | 0.52615            |
|       |          |             | 50      | 198346   | 3.3100      | 0.79806  | 0.59832            |

2D Space: Axisymmetric  
Viscous Model: k-\(\alpha\) (2 eqn) SST  
Required working fluid: air  
Boundary conditions: Turbulence specification method → Intensity and Hydraulic Diameter  
INLET → Velocity magnitude = 15 m/s  
OUTLET1 → Gauge pressure = 0 Pa  
OUTLET2 → Gauge pressure = 0 Pa  
Pressure-Velocity Coupling Scheme: COUPLED  
Absolute criteria of convergence imposed: \(10^{-6}\)

Figure 5. Main settings in the SETUP application.

Figure 6. Main areas taken into account in the calculation of intensity and hydraulic diameter.

4. Simulation data analysis
After performing the simulations, it was found that for the following cases, the absolute convergence criteria could not be met:

- cases A-45° and A-60°, where \(h_a = 50\) mm and \(a_{ch} = 10/20/30/40\) mm
- case A-75° where \(h_a = 50\) mm and \(a_{ch} = 10/20/30\) mm
Figure 7. Lift forces values for all $\gamma$ angles analyses: (a) $\gamma = 45^\circ$; (b) $\gamma = 60^\circ$; (c) $\gamma = 75^\circ$.

Specific to these cases mentioned above, several iterations were performed and then final values of the lift forces were considered. For all the cases presented in this study, the numerical values of the obtained lift forces are shown in figure 7.

In order to correlate data from this study with the previous one, synthesis diagrams were performed in MATLAB, in which the surfaces describing the lift forces values, $L_f$, for $\gamma = 45^\circ$, $60^\circ$, $75^\circ$ and for $\gamma = 90^\circ$ are represented, figure 8.

From this diagram it can be observed that the surface described by angle $\gamma = 75^\circ$ is not found in the area of the maximum values, hence it can be deduced that the cases A-75°, B-75°, C-75° and D-75° cannot offer a high lift force compared to the other cases studied. Given that the largest range of maximum lift forces is shown by the configurations in which $\gamma = 45^\circ$, in figure 9 this surface is compared with the surfaces described by the angles $\gamma = 60^\circ$ and $\gamma = 90^\circ$.

Regarding the numerical values presented in figure 7, using Curve Fitting Toolbox application from MATLAB software it was possible to approximate all the curves obtained. Therefore, in table 4 are presented the equations as well as the coefficients that describe these power functions with two terms.

After the interpretation of the numerical data with MATLAB software, using CFD-Post application within the ANSYS program, the velocity contours, pressure contours and streamlines were analysed. Figures 10, 11 and 12 present the above-mentioned features for the cases:
- A-45° ($h_s = 50$ mm and $\alpha_{th} = 10$ mm),
- B-60° ($h_s = 100$ mm and $\alpha_{th} = 10$ mm),
- C-75° ($h_s = 150$ mm and $\alpha_{th} = 10$ mm).
Figure 8. Synthesis diagram regarding the lift forces values for all 4 angles studied: (a) – isometric view; (b) – maximum values; (c) – minimum values.

Figure 9. Synthesis diagrams for comparing the maximum values of lift forces: (a) – between $\gamma = 45^\circ$ and $\gamma = 60^\circ$; (b) – between $\gamma = 45^\circ$ and $\gamma = 90^\circ$. 
Table 4. The general form of the equations and the values of their coefficients.

| γ  | h_s [mm] | a_ch [mm] | General form of the equations | Coefficients of the equations |
|----|----------|-----------|-------------------------------|-------------------------------|
| 45°| 50       | 10/20/30/40/50 | f(x) = a x^b + c           | a = 3.105, b = -1.566, c = 61.23 |
|    | 100      | 10/20/30/40/50 |                               | a = 3.970, b = -1.506, c = 41.08 |
|    | 150      | 10/20/30/40/50 |                               | a = 3.044, b = -1.534, c = 28.72 |
|    | 200      | 10/20/30/40/50 |                               | a = 2.121, b = -1.558, c = 12.48 |
| 60°| 50       | 10/20/30/40/50 |                               | a = 1.251, b = -1.738, c = 36.47 |
|    | 100      | 10/20/30/40/50 |                               | a = 2.325, b = -1.620, c = 47.19 |
|    | 150      | 10/20/30/40/50 |                               | a = 1.654, b = -1.685, c = 70.56 |
|    | 200      | 10/20/30/40/50 |                               | a = 2.043, b = -1.619, c = 34.30 |
| 75°| 50       | 10/20/30/40/50 |                               | a = 0.708, b = -1.850, c = -22.96 |
|    | 100      | 10/20/30/40/50 |                               | a = 1.130, b = -1.762, c = 37.93 |
|    | 150      | 10/20/30/40/50 |                               | a = 1.209, b = -1.747, c = 49.34 |
|    | 200      | 10/20/30/40/50 |                               | a = 1.085, b = -1.770, c = 51.73 |

Performing a visual analysis on all the velocity contours, pressure contours and streamlines for the studied cases: γ = 45°, 60° and 75°, with the increase of the value of a_ch:

- the maximum velocity of the air jet decreases and the vortex / main vortices located on both sides of the air jet increase in intensity
- decreases the maximum pressure value inside the vehicle cavity.

Conclusion

As can be seen, with the help of specialized program in CFD analysis, a variety of simulations can be performed and the optimization of a desired product can be achieved. According to simulation data, highest lift forces were obtained for cases: A-45° where h_s = 50 mm; a_ch = 10 mm, for B-60° where h_s = 100 mm; a_ch = 10 mm and C-75° where h_s = 150 mm; a_ch=10 mm.

Figure 10. Graphic representations for the case A-45° in which h_s = 50 mm and a_ch = 10 mm: (a) – velocity contour; (b) – pressure contour; (c) – streamlines.
Figure 11. Graphic representations for the case B-60° in which \( h_s = 100 \text{ mm} \) and \( a_{ch} = 10 \text{ mm} \):
(a) – velocity contour; (b) – pressure contour; (c) – streamlines.

Figure 12. Graphic representations for the case C-75° in which \( h_s = 150 \text{ mm} \) and \( a_{ch} = 10 \text{ mm} \):
(a) – velocity contour; (b) – pressure contour; (c) – streamlines.

From the analysis of the variations of lift forces depending on the angle \( \gamma \) for each \( a_{ch} \) separately – \( L_f(\gamma, a_{ch}) \), the following aspects could be inferred:

• for configurations in which \( a_{ch} = 10 \text{ mm} \) and \( h_s = 50/100/150/200 \text{ mm} \), the highest lift values are obtained at the angle \( \gamma = 90° \)

• for configurations in which \( a_{ch} = 20/30/40/50 \text{ mm} \) and \( h_s = 100 \text{ mm} \), the highest lift forces meet at the angle \( \gamma = 45° \)
• for the configuration in which $a_{ch} = 20 \text{ mm}$ and $h_s = 150 \text{ mm}$, the highest lift force value is found at $\gamma = 60^\circ$ while at $a_{ch} = 30/40/50 \text{ mm}$, the highest lift force value is met at $\gamma = 45^\circ$

• for all configurations in which $a_{ch} = 20/30/40/50 \text{ mm}$ and $h_s = 200 \text{ mm}$, the highest lift forces are met at the angle $\gamma = 60^\circ$

From the analysis of lift forces variation as function of angle $\gamma$ for each $h_s$ separately – $L_f(\gamma, h_s)$ could be inferred one of the most important aspects regarding these simulations: with the increase of the value of $h_s$, the trend is that the maximum lift force values be obtained at $\gamma = 90^\circ$. Therefore, for values of $h_s$ greater than 200 mm, the case that offers the vehicle a higher lift force is the one with angle $\gamma = 90^\circ$.

Regarding the synthesis diagrams shown in figure 9, it can be observed that the surface described by the angle $\gamma = 45^\circ$ is the dominant one compared to the other two surfaces described by $\gamma = 60^\circ$ and $\gamma = 90^\circ$.

Another important aspect is the fact that from the analysis of all lift force values, with the increase of the inclination angle of the flexible skirt segments, the maximum value is obtained for $a_{ch} = 10 \text{ mm}$ (invariable parameter) but the $h_s$ parameter increases with this angle. Even though the highest lift force value shows the configuration $\gamma = 90^\circ$, $h_s = 200 \text{ mm}$ and $a_{ch} = 10 \text{ mm}$, it is clear from the synthesis diagrams that the best constructive option for a vehicle of this form should have the following parameters: $\gamma = 45^\circ$, $h_s = 100 \text{ mm}$ and $a_{ch} = 20 \div 50 \text{ mm}$ due to the highest values range.

5. References
[1] Pavâl M S, Popescu A and Zahariea D 2020 CFD analysis of a round shaped air cushion vehicle with flexible skirt segments at 90° and different air clearance height IOP Conf. Ser.: Mater. Sci. Eng. (in print).

Acknowledgments
The authors would like to acknowledge the technical resources offered by the Laboratory of Computer-Aided Fluid Engineering, from the Department of Fluid Mechanics, Fluid Machinery and Fluid Power Systems, The “Gheorghe Asachi” Technical University of Iasi, Romania. The Laboratory of Computer-Aided Fluid Engineering has been equipped with technical resources with the financial support of the grant ENERED, POSCCE-A2-O2.2.1-2009-4, ID 911.