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# Numerical Analysis of Gurney Flap Impact on NACA 4415 Airfoil Aerodynamics Performance

## Analisis Numerik Dampak Gurney Flap Terhadap Performa Aerodinamika Airfoil NACA 4415

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**Abstract**

Improving airfoil aerodynamic performance is an essential aspect of aerodynamic technology. The use of passive flow control is one way to enhance the aerodynamic performance of the airfoil. The influence of using gurney flaps as passive flow control was explored through the CFD approach employing the RANS control equations with the k-epsilon turbulence model. The airfoil model utilized in this investigation was the NACA 4415 operating at a Reynolds number of $1{\times}10^6$. This study explored three different variations of flap height, namely 0.5%, 1%, and 2% of chord length. The outcomes showed that adding gurney flaps showed quite positive results in increasing the lift and drag performance of NACA 4415. An airfoil with a 0.5%c height flap has an average percentage increase in Cl of 12%, followed by a height flap of 1%c, which is 23%, and a percentage $C_l$ of 37% for a height flap of 2%c. Meanwhile, each variation in height flap affected the increase in $C_d$. A height flap of 0.5%c increased $C_d$ with an average percentage of 2%, while a height flap of 1%c increased the percentage of Cd by 4% and 6% for a height flap of 2%c. Moreover, visualization of fluid flow with pressure and velocity contours given at AoA 12° to determine the effect on the increase in $C_l$ and $C_d$ in NACA 4415.

***Keywords:*** airfoil, computation, gurney flap, flap size, aerodynamics performance.

***SDGs*:**

**Abstrak**

Meningkatkan kinerja aerodinamis *airfoil* merupakan aspek penting dari teknologi aerodinamis. Penggunaan *passive flow control* merupakan salah satu cara untuk meningkatkan performa aerodinamis airfoil. Pengaruh penggunaan *gurney flaps* sebagai kontrol aliran pasif dieksplorasi melalui pendekatan *CFD* menggunakan persamaan RANS dengan model turbulensi k-epsilon. Model airfoil yang digunakan dalam penyelidikan ini adalah *NACA 4415* yang beroperasi pada bilangan *Reynolds* $1{\times}10^6$. Penelitian ini mengeksplorasi tiga variasi tinggi flap yang berbeda, yaitu 0,5%, 1%, dan 2% dari panjang *chord*. Hasil penelitian menunjukkan bahwa penambahan gurney flap menunjukkan hasil yang cukup positif dalam meningkatkan kinerja *lift* dan *drag NACA 4415*. Sebuah airfoil dengan tinggi flap 0,5%c memiliki rata-rata persentase kenaikan Cl sebesar 12%, diikuti oleh tinggi flap 1%c yaitu sebesar 23%, dan persentase $C_l$ sebesar 37% untuk tinggi flap 2%c. Sedangkan setiap variasi tinggi flap mempengaruhi peningkatan $C_d$. *Height flap* 0,5%c meningkatkan $C_d$ dengan persentase rata-rata 2%, sedangkan height flap 1%c meningkatkan persentase $C_d$ sebesar 4% dan 6% untuk *height flap* 2%c. Selanjutnya dilakukan visualisasi aliran fluida dengan kontur tekanan dan kecepatan pada AoA 12° untuk mengetahui pengaruhnya terhadap peningkatan $C_l$ dan $C_d$ pada NACA 4415.

***Kata Kunci:*** *airfoil, computation, gurney flap, flap size, aerodynamics performance.*

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## 1. INTRODUCTION

In aviation and aerodynamic technology, improving airfoil performance is essential to achieve better performance in various applications (Çıtak, 2015; Aftab, Razak, *et al.*, 2016). Several studies and methods are still being developed to improve the aerodynamic efficiency of airfoils, which are mainly used in aircraft wings, wind turbine blades, and others (Abbas, de Vicente and Valero, 2013). Improving the airfoil aerodynamic performance can be achieved by utilizing a passive fluid flow control device (Collis *et al.*, 2004). A passive device can manipulate fluid flow without needing external energy by changing the surface of an object, in this case, the airfoil (Shan *et al.*, 2008).

Studies related to passive flow control devices are interesting to discuss because the impacts received by airfoils are quite varied. One of them is the modification of the NACA0010 airfoil with the addition of a self-actuated flap carried out by Rosti et al., which is done in Re 2x104. The results show that the flap can provide an average increase in lift of around 20% at AoA 20° (Rosti, Omidyeganeh and Pinelli, 2018). Then, another study examined the Bionic flap with varying angles on the HQ17 airfoil at Re = 106, the results showed that the bionic flap was quite effective in increasing the lift to the drag ratio at AoA is more than 7° (Hao *et al.*, 2021). Various types of passive flow control devices have been discussed with the addition or modification of flaps to improve aerodynamic performance; this is in line with what was carried out in this study to examine airfoils with the addition of gurney flaps on the trailing edge of the airfoil.

The Gurney flap is a passive flow control device in the form of a microtab mounted perpendicular to the airfoil on the trailing edge (Liebeck, 1978). In general, using gurney flaps on airfoils can provide significant lift forces on airfoils. Moreover, the gurney flap induces additional drag on the airfoil. However, the increase in lift is relatively greater and causes an increase in the lift-to-drag ratio, thereby enhancing the airfoil's performance (Giguere, Lemay and Dumas, 1995). Another advantage can be seen from the relatively simple structure of the gurney flap with its low weight so that the flap system can be applied easily. The Gurney flap is quite interesting for further research because it can be used in many aerodynamic applications (Zhang, Liu and Wang, 2009).

Several studies discuss the effect of installing gurney flaps on the trailing edge of airfoils and wings, explicitly focusing on their influence on aerodynamic efficiency. One of these studies discussed using a gurney flap on the NACA0012 with a Reynolds number of 8.5×103, which was then tested with a water tunnel. The results show that with the addition of flaps, there is an increase in lift of up to 40%, accompanied by a decrease in drag force (Neuhart and Pendergraft, 1988). Li et al. carried out experimentally on NACA0012 airfoil at Re of 2.1×106. The results show that Gurney flaps at various installation angles increase the lift coefficient, with a 45° flap achieving a maximum lift force increase of 12.3% (Li, Wang and Zhang, 2003). Yang et al. examined gurney flap on the DTU-LN221 airfoil, which was then tested with a wind tunnel. The results show that adding flaps with varying 1%c to 2%c flap heights effectively increases the lift-to-drag ratio from 2.74% to 14.35% (Yang *et al.*, 2020). Another study showed similar results regarding gurney flaps, carried out experimentally by Graham et al. with a low-speed wind-tunnel to determine the effect of the gurney flap's thickness and height on the airfoil's aerodynamic characteristics. The results show that lift increases with increasing flap height and an inverse relationship between lift and flap thickness (Graham, Muradian and Traub, 2018).

Another study was conducted using computational methods to optimize gurney flaps on NACA 2412 airfoils with a Reynolds number of 2.74×105. The flap height is set at 2% to 5% of the airfoil length. The conclusion obtained from this study is that optimization of the flap with 2% chord height gives a reasonably good performance compared to other variations in height. Gurney flaps cause a reduction in drag in the maximum lift area, thereby increasing the Cl/Cd before a stall occurs (Saha, Alam and Hasan, 2018).

Numerous investigations have been conducted, employing both experimental and computational methods, to explore the impact of the gurney flap on airfoil aerodynamics. The results show that using a passive gurney flap control device sometimes still affects the geometric configuration, location, and size. So, the outcome of this passive control device still needs to be expanded further to reach optimal efficiency. Therefore, this study focused on examining the aerodynamic characteristics inherent to the NACA 4415 airfoil and analyzed the influence of using a gurney flap. This airfoil type was chosen because of its wide application in various aerodynamic devices and its ability to produce excellent lift force even in unstable fluid flows (James Julian, Iskandar and Wahyuni, 2023). Subsequently, this study involved modifying the height flap to ascertain the optimal aerodynamic efficiency for the airfoil employing the Computational Fluid Dynamics (CFD) approach with the k-epsilon as a turbulence model.

## 2. METHODOLOGY

This study was carried out with several main stages in the research or simulation process using CFD on the NACA 4415 airfoil. Each stage of the research process is depicted in a flowchart, as seen in Figure 1. The initial stage of research begins by conducting a literature study to gain insight into the theory, methods, and results of previous research related to the NACA 4415 airfoil. After understanding the literature study, the next stage is the pre-processing stage, which includes creating a geometry mesh and determining boundary conditions. Then, the geometry carried out in the pre-processing stage is used in the solving stage using CFD tools. After obtaining the computational data, it will proceed to the post-processing stage to collect and distribute the data obtained in the computing stage. The results of the data that have been processed at the post-processing stage will then be validated to ensure that the data used is proven correct so that it can proceed to the data analysis stage. However, suppose the data obtained from the computational results is still invalid. In that case, the research will return to the pre-processing stage until the data is suitable and valid.

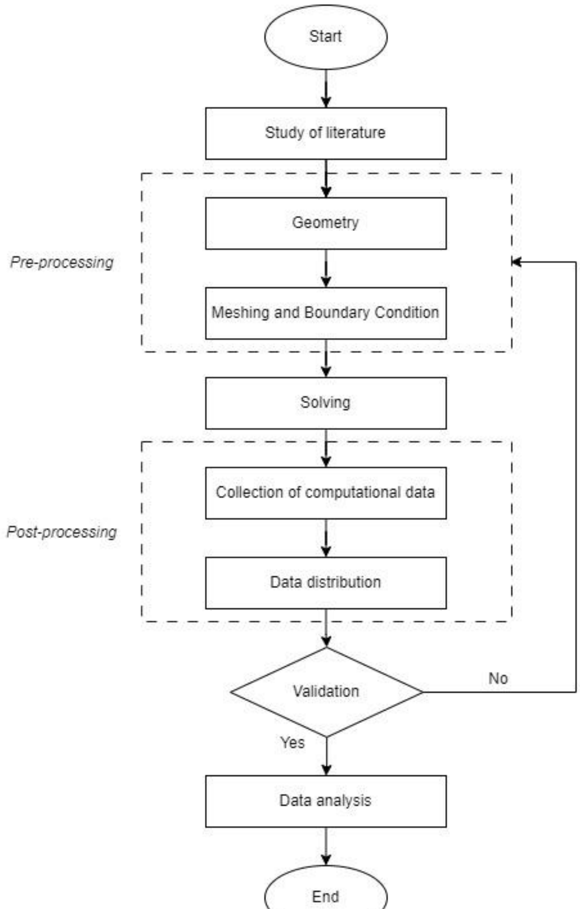


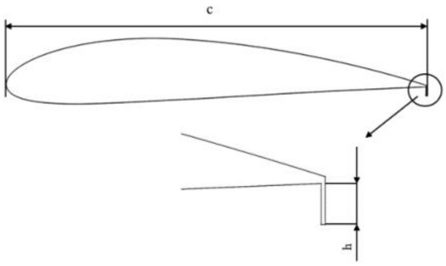

**Figure 1.** Flowchart.

### 2.1. NACA 4415

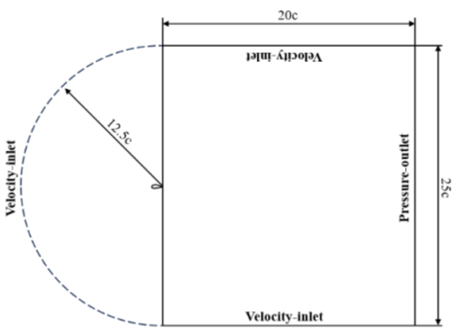
Initially, the National Advisory Council on Aeronautics (NACA) introduced a system of airfoil profiles designated by numerical codes that follow the 'NACA' label. The equations obtained from the components of the numerical code can be used to generate the airfoil cross-sections (Abbott, Von Doenhoff and Stivers, 1945). In general, the characteristics of NACA can be determined from the numbers. For instance, the NACA 4415 airfoil is characterized as an asymmetric 4-digit NACA airfoil, with the first digit indicating 4% camber, the second digit representing the maximum camber at 40%, and the last two digits signifying a 15% thickness along the chord length. On the other hand, the upper chamber of the symmetrical airfoil is identical to the lower chamber (Durrani *et al.*, 2011; Julian, Anggara and Wahyuni, 2023). This study's airfoil chord length (c) is 1 meter.

### 2.2. Geometry Configuration

In this study, two airfoil geometry models were made, namely the Airfoil without gurney flap and Airfoil with a Gurney flap. Then, there are four variations of height gurney flap will be investigated in this study. The initial variation involves no gurney flap, the second variation is with a 0.5%c height flap, then the third and fourth variations are 1%c and 2%c height gurney flap, respectively. These gurney flaps were positioned at the trailing edge, each having a width of 0.05%c. Then, the geometric models were placed within the fluid domain, which consisted of a combination of rectangular and semicircular shapes. The domain was chosen because this form makes it easier to create a structured mesh, this will certainly help the computational process to be more accurate and efficient. Overall, the geometry and domain details in this study are shown in Figure 2.




(a)

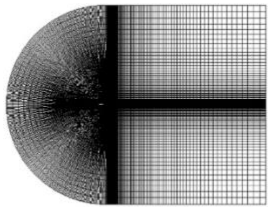



(b)

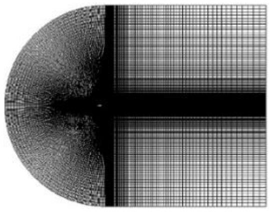
**Figure 2.** Detail geometry, Airfoil NACA 4415 with gurney flap (a), Fluid domain (b).

### 2.3. Mesh and Boundary Condition

After completing the geometry setting stage, the next stage is the meshing process. This stage is a computational process in which the domain geometry is split into more minor element for the calculation process to be carried out. Each piece of mesh is referred to as a mesh element. In this study, three different mesh configurations were employed.



(a)



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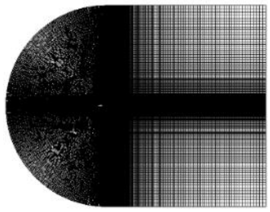
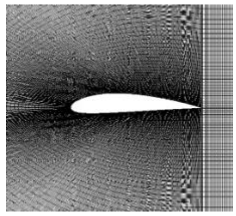


(c)



(d)

**Figure 3.** Mesh in this study, Coarse mesh (a), Medium (b), Fine (c), Around airfoil (d).

Figure 3 illustrates the variations in mesh configurations, the first consists of 25000 elements, categorized as the coarse mesh, as depicted in Figure 3(a). The second is the medium mesh, consisting of 50000 elements, illustrated in Figure 3(b) and the last configuration employs a fine mesh containing 100000 elements, as shown in Figure 3(c). The selection of mesh elements is based on a method generalized by Roache, namely the Richardson extrapolation method. Further, this method is explained in the mesh independence tests section (J. Julian, Iskandar and Wahyuni, 2023). Then, each mesh element is organized into a rectangular shape and strategically positioned closer to the airfoil's surface to capture a range of fluid flow phenomena near the airfoil, as shown in Figure 3(d).

### 2.4. Governing Equation

This study tackles fluid flow issues by employing the equation of Reynolds Average Navier-Stokes (RANS) as the primary governing equation. The analysis assumes a steady-state fluid flow, and the equation of RANS encompasses the continuity and momentum equations (Xiao *et al.*, 2016).

Equation (1) represents the fluid flow continuity equation, while equation (2) describes the fluid flow momentum equation. The analysis assumes that the flow occurs exclusively in the x-axis direction, and the equation is subsequently solved using a pressure-based coupled algorithm (Aftab, Rafie, *et al.*, 2016).

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (1)$$

$$\frac{\partial \rho}{\partial t}(\rho u_i u_j) + \frac{\partial}{\partial x_i}(\rho u_i) = \frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_i}\left(-\rho\overline{\acute{u}_i \acute{u}_j}\right) \quad (2)$$

This study uses the k-ε model selected as the turbulence model. This turbulence model is generally used using Computation Fluid Dynamics (CFD). The k-ε equation was chosen because it is reliable in predicting aerodynamic forces. Equations (3) and (4) contain the turbulence model equations (Lew†, Buscalgia and Carrica, 2001).

$$\frac{D}{Dt}(\rho k) = \frac{\partial \rho}{\partial x_j}\left[\left(\mu + \frac{u_i}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\varepsilon \quad (3)$$

$$\frac{D}{Dt}(\rho\varepsilon) = \frac{\partial \rho}{\partial x_j}\left[\left(\mu + \frac{u_i}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{el}\frac{\varepsilon}{k}G_k - \rho C_{\varepsilon 2}\frac{\varepsilon^2}{k} \quad (4)$$

### 2.5. Aerodynamics Forces

Aerodynamic forces are common in airfoils, this aims to find out how the airfoil moves through the fluid. The interaction between airfoils and fluid generates aerodynamic forces, specifically drag and lift. The drag force aligns with the airflow direction, whereas the lift force is perpendicular to the airflow direction (Julian *et al.*, 2016). Understanding these forces is essential for designing an effective flow control system like a gurney flap. Generally, these forces are typically quantified in dimensionless form, commonly referred to as the Cd and Cl. Each is given in equations (5) and (6) (Tamura and Miyagi, 1999; Alom, Borah and Saha, 2018).

$$C_d = \frac{2F_D}{\rho u^2 c} \quad (5)$$

$$C_l = \frac{2F_L}{\rho u^2 c} \quad (6)$$

## 3. RESULTS AND DISCUSSION

### 3.1. Mesh Independence Test

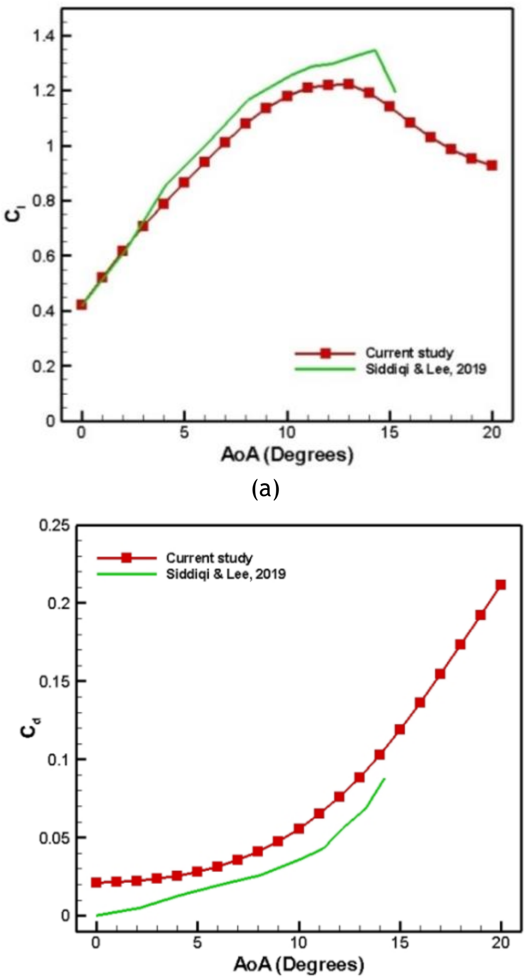
A mesh independence test aims to verify the mesh's accuracy and establish its optimal efficiency by ensuring a minimum error value. The data for the mesh test is obtained from the fluid flow velocity recorded at the coordinates x = 0.5 and y = 0.15 (Julian, Anggara and Wahyuni, 2023). Each stage of the mesh-independent test is executed in accordance with research conducted by Julian et al. (Julian, Iskandar and Wahyuni, 2022). The test results indicate that the variations of mesh fall within the convergence index range, as evidenced by the values approaching 1. The quantity of grids is established based on identifying the error value that is at its minimum. Thus, the entire computational process will be carried out using a fine mesh of 100000 elements. Overall, the mesh test data results can be seen in Table 1.

**Table 1.** Result of mesh independence test.

| Variation | Coarse | Medium | Fine |
|---|---|---|---|
| Velocity | 40.3069 | 40.4237 | 40.4496 |
| $f_{rh=0}$ | | 40.456979648 | |
| r | | 2 | |
| p | | 2.173016271 | |
| GCI *coarse* | | 0.1029% | |
| GCI *fine* | | 0.023% | |
| Results | | 1.000468 | |
| Error | 0.3710% | 0.0823% | 0.0182% |

### 3.2. Validation

Validation is an essential step to ensure the accuracy of all computational processes. It was conducted at a Reynolds number of 1×106, utilizing experimental data obtained from Siddiqi (Siddiqi and Lee, 2019). Comparisons were made to the results of the NACA 4415 airfoil data. The outcomes of the validation process are depicted in, showcasing the curves for the Coefficient of Lift (Cl), as depicted in Figure 4(a) and Coefficient of Drag (Cd), as shown in Figure 4(b). In general, the Cl and Cd data comparison reveals consistency in the curve trends, although a minor distinction is present in the Cl curve, which lies in a stall condition in computational calculations which shows the result is 1 degree faster, namely at AoA=13°, which is different when compared to experimental data at AoA=14°. Then there is a difference after the stall condition, this is because the airfoil data is difficult to predict after the stall condition. Meanwhile, the Cd curve shows no significant change between the two data. Both Cd increases with increasing AoA. Thus, the comparison of these datasets suggests the validity of the computational data used.

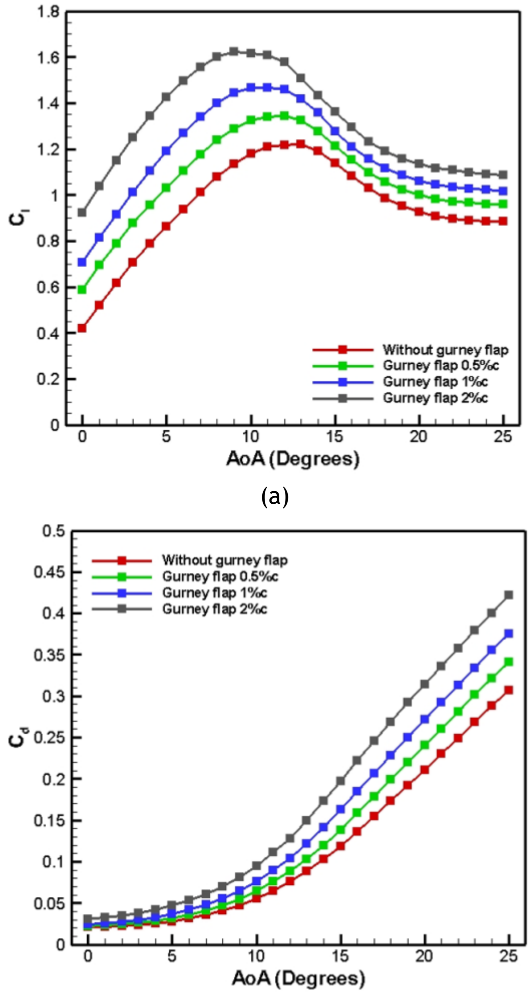



(b)

**Figure 4.** Aerodynamics validation, (a) Plot of Cl validation; (b) Plot of Cd validation.

### 3.3. Analysis

The gurney flap has the capability to additional lift force of the airfoil. This can be seen in Figure 5(a), which illustrates alterations in the Cl distribution with varying AOA, ranging from 0° to 25°on the airfoil without flap and airfoil with height flap variations. The enhancement in the lift coefficient is achieved by adjusting the flap's height, specifically at 0.5%c, 1%c, and 2%c length. At 0.5%c gurney flap, there was an increase in Cl with the condition of the maximum lift point at AoA 12°, which is different with the airfoil without flap. In addition, when the height flap is increased to 1%c, the maximum lift is obtained at AoA 11°. Meanwhile, the maximum lift value at AoA 9° is when the height flap is increased to 2%c. The impact of the gurney flap significantly enhances the maximum Cl. An average percentage of height flap of 0.5%c can increase Cl to 12%, while a height flap of 1%c increases Cl by 23%, and a height flap of 2%c can increase the value of Cl by 37%.




(b)

**Figure 5.** Aerodynamics forces of NACA 4415, (a) Plot of Cl NACA 4415; (b) Plot of Cd NACA 4415.

On the other hand, using gurney flaps tends to increase the drag coefficient as the flap size increases, especially at high angles of attack. An increase in Cd provides an advantage in aerodynamic applications, one of which is airplanes. Increasing Cd can be beneficial because it can delay the movement of the aircraft when it lands on a trajectory that is not too wide. However, it also helps maintain stability in certain situations (Çıtak, 2015). The influence of using gurney flap along with increasing flap size is depicted in Figure 5(b). The increase in Cd forms at the initial AoA, where the greater the AoA, the more significant the increase in Cd. The difference in Cd produced by the airfoil has increased which begins to be seen at AoA ≥10°. The average percentage increase in Cd based on the increase in flap height is obtained that when the flap height is 0.5%c, there is an increase in Cd by 2%, then when the flap height is increased again to 1%c, the percentage increase in Cd increases significantly to 4% and continues to increase the Cd value is up to 6% when compared to the airfoil without flap if the flap height is increased to 2%c.

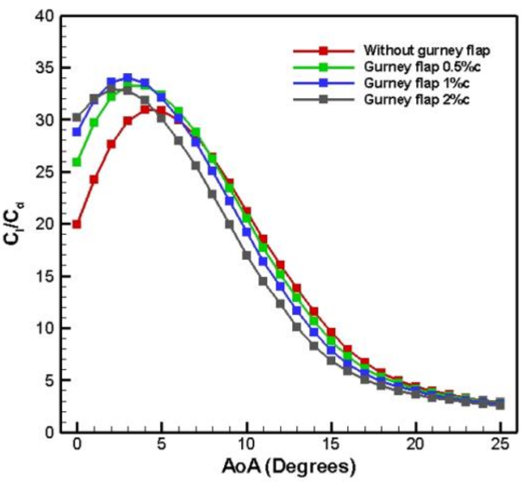



**Figure 6.** Lift to drag ratio.

Figure 6 is made to determine the optimum airfoil AoA. In the $C_l$ and $C_d$ ratio plot, the peak of the AoA curve corresponds to the optimal AoA. the optimum AoA is achieved at AoA=4° for the airfoil without flap. A gurney flap with a 0.5%c height flap can obtain the same optimal at AoA=4°, while a height flap with a 1%c can accelerate the optimal AoA to 3°. Also, if GF increases the height flap to 2%c, it will make the optimal AoA 2°. The peak of the curve on the GF with a 1%c height flap is the highest among the others. This is because the resulting increase in $C_l$ and $C_d$ is not significantly different. However, different things are shown when the height flap is 2%c where the initial trend of the curve shows positive results at the beginning but slowly decreases at AoA ≥5°. This decrease is influenced by the more dominant $C_d$ obtained in the height flap. Thus, based on the results of this analysis, using a gurney flap at a height flap of 1%c is more recommended when compared to other variations of the height flap.

Based on the velocity contour analysis in Figure 7, the gurney flap also changes the fluid flow velocity at the NACA 4415 upper and lower chamber. The upper chamber of the fluid flow has increased significantly. Even so, the increase is of course different for each variation in flap height. The greater the height flap given, the wider the high-speed area. Conversely, the gurney flap causes the fluid flow at lower chamber NACA 4415 to decrease. This decrease will be more significant as the size of the flap height on the NACA 4415 increases. Meanwhile, based on the streamlined contour of the trailing edge in Figure 8, a gurney flap does not significantly affect the fluid flow surrounding the NACA 4415 airfoil along with increasing the flap height. Therefore, the enhanced performance of the NACA 4415 using this fluid flow control device is fully influenced by the upper and lower chamber pressure difference.

Furthermore, pressure contour visualization also examined in this study as shown in Figure 9. Similar to the velocity contour, pressure contour samples were also taken at AoA = 12°. According to the pressure contour analysis, the gurney flap changes the pressure distribution in the upper and lower chamber NACA 4415. Upper airfoil fluid flow has decreased significantly. This decrease occurs for each variation in flap height. The larger the height flap size given, the wider the low-pressure area. Conversely, the height flap causes the lower airfoil fluid flow to increase because the Gurney flap influences it in the trailing edge. This increase will be more significant as the size of the flap height on the airfoil increases. Overall, this difference in upper and lower pressure causes the airfoil to experience an increase in Cl.

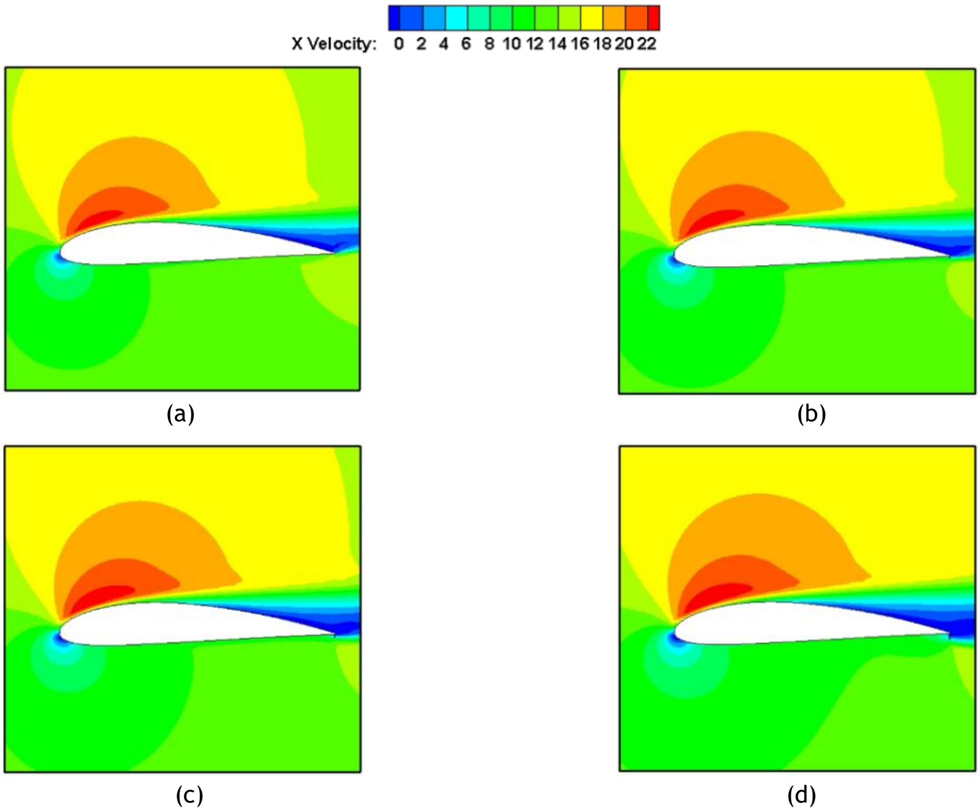



**Figure 7.** Velocity contour at AoA 12°, (a) Without gurney flap; (b) 0.5%c height flap; (c) 1%c height flap; (d) 2%c height flap.

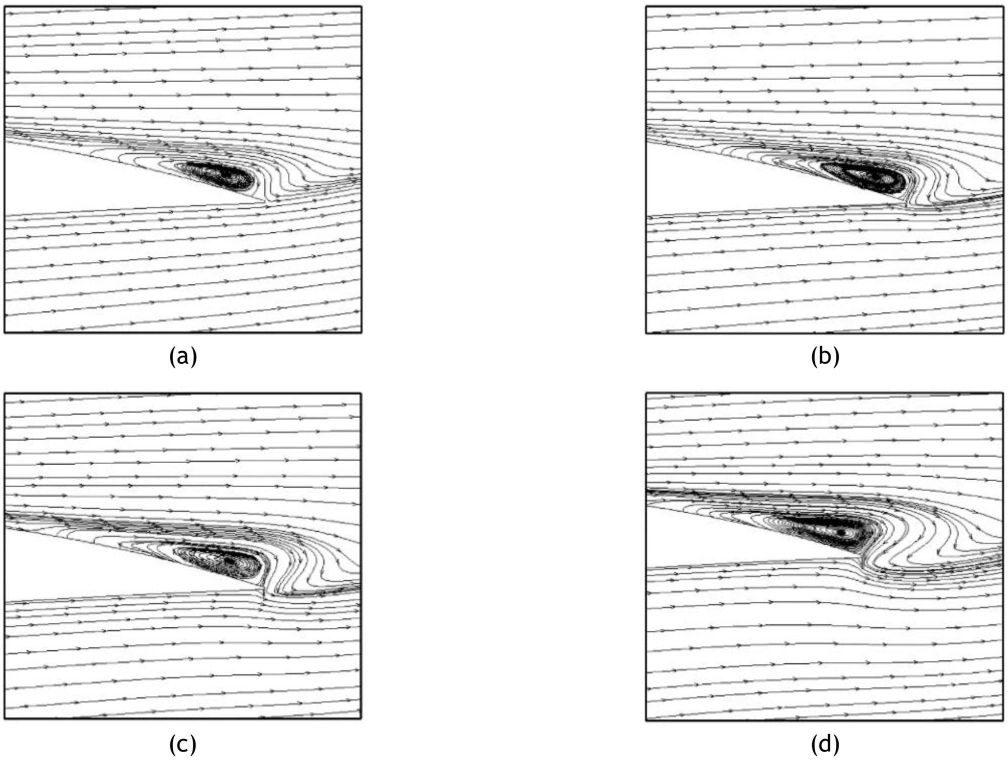



**Figure 8.** Streamline contour at AoA 12°, (a) Without gurney flap; (b) 0.5%c height flap; (c) 1%c height flap; (d) 2%c height flap.

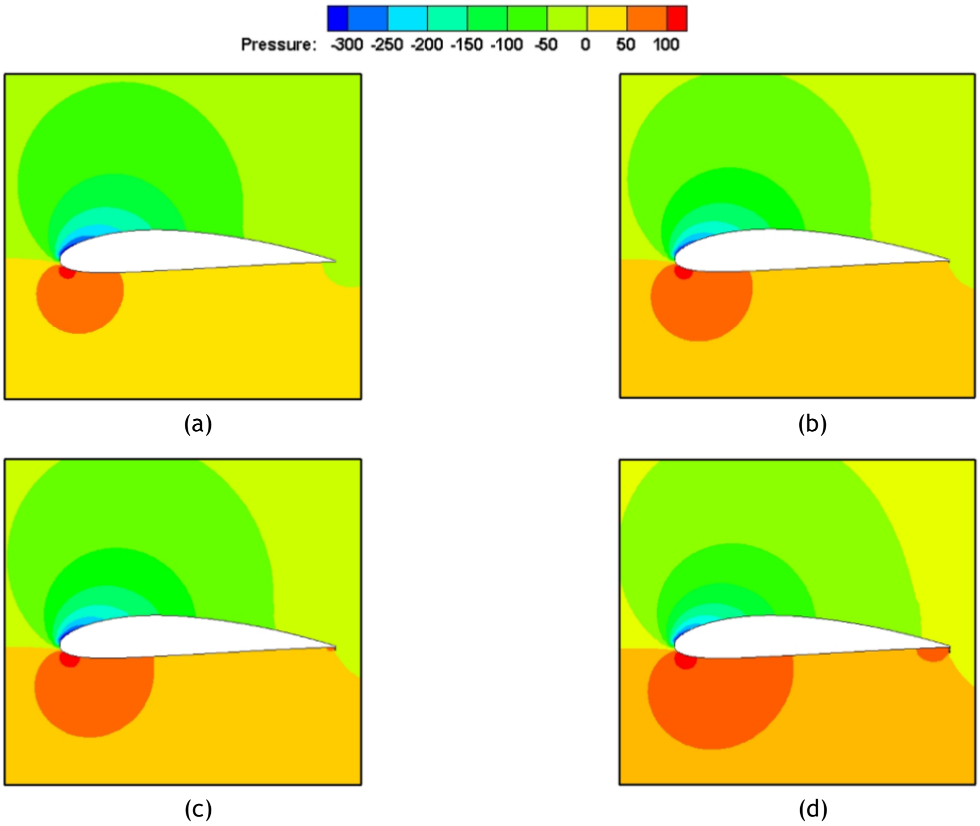



**Figure 9.** Pressure contour at AoA 12°, (a) Without gurney flap; (b) 0.5%c height flap; (c) 1%c height flap; (d) 2%c height flap.

In addition, adding gurney flaps to the airfoil changes the fluid flow pressure at the trailing edge of the NACA 4415. This causes an increase in pressure on the trailing edge, thus affecting the resulting Cd value as the flap height increases.

## 4. CONCLUSION

This research was conducted to determine how the gurney flap affects the performance of the NACA 4415 airfoil. The computational results showed that the height flap of the gurney flap had a significant impact. A 0.5%c height flap increased the lift ($C_l$) by 12%, peaking at an angle of attack (AoA) of 12°, while a 1%c height flap increased it by 23% at AoA 11°. At 2%c height, the highest flap increased $C_l$ by 37%, reaching the maximum at AoA 9°. However, as the flap size increases, the drag ($C_d$) increase can be delayed. The average increase in $C_d$ was 2% for a 0.5%c height flap, 4% for a 1%c height flap, and 6% for a 2%c height flap, starting at AoA≥10°. Visualizations showed that adding a gurney flap increased velocity in the upper chamber and increased fluid flow pressure in the lower chamber, which caused the NACA 4415 to increase $C_l$. Thus it can be concluded that adding gurney flaps to the NACA 4415 can effectively improve aerodynamic performance.

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