Optimization of the aerodynamic characteristics of a NACA air intake based on DoE and numerical methods

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Abstract-The Design of Experiment (DoE) method combined with numerical simulations is employed to optimize the aerodynamic characteristics of a National Advisory Committee for Aeronautics (NACA) air intake. The drag force, total pressure recovery coefficient, mass flow rate at the outlet, and Mach number at the outlet are used to evaluate the performance of the air intake based on computational fluid dynamics (CFD) numerical methods. Three critical geometric parameters, namely the ramp angle $\alpha$, ramp divergence angle $\theta$, and turning corner radius $R$, are considered as variables in the DoE design. Results under the baseline conditions indicated that axial vortexes are formed near the side edge close to the ramp wall. DoE analysis indicated that above four performance parameters are largely influenced by the ramp angle $\alpha$, while the ramp divergence angle $\theta$ has negligible effects. A small radius of the turning corner is beneficial to enhance the pressure recovery coefficient and the mass flow rate. The Mach number at the outlet declines and the velocity uniformity on a certain section increases with decreasing value of ramp angle $\alpha$. Meanwhile, larger total pressure recovery coefficient, mass flow rate, and vortex tube length are acquired under a smaller value of $\alpha$. Thus, the aerodynamic performance of this air intake can be improved by a set of optimized geometric parameters.

1. Introduction
The fuel tank of a civil aviation aircraft needs to be connected to the outside atmosphere to ensure the safety of the fuel tank structure. At the same time, the inerting system and environmental control system of an aircraft also need external cooling air to meet system operation requirements. For civil aircrafts, there are currently two main types of air intakes, scoop-type air intakes and submerged air intakes. Compared with scoop-type air intakes, submerged air intakes have no external protrusions, which reduces the aerodynamic drag. In addition, submerged air intakes do not require supporting structures and are therefore lighter in weight. National Advisory Committee for Aeronautics (NACA) submerged air intakes are the main type of submerged air intakes, which have been widely used in several aircrafts such as Boeing, Airbus and the Commercial Aircraft Corporation of China (COMAC).

The NACA submerged air intake generates a pair of axial vortexes on the side, which entrains the airflow on the wall surface into the air intake channel [1]. However, given that intakes are usually...
located in a thick boundary layer, they draw low-energy airflow from the boundary layer, thereby resulting in decreased flow rates and a high degree of unevenness of the outlet airflow [2]. In addition, because aircrafts fly at high Mach numbers, shock waves are easily generated at the throat of NACA air intakes, which increases aerodynamic drag and deteriorates aerodynamic performance.

Therefore, it is necessary to optimize the aerodynamic design of NACA air intakes. You et al. from the China Aviation Industry General Aircraft theoretically deduced the size of air intake required by an aircraft under the harshest descending conditions based on the two-dimensional boundary layer theory, and determined the specific size of air intake through the geometric relationship provided by NACA [3]. Xue et al. from the Shanghai Aircraft Design and Research Institute (SADRI) obtained the proportional relationship between the total pressure recovery coefficient of air intake and the captured flow rate of section and confirmed the design operating points of an aircraft cruising in extremely hot weather based on experimental data [4]. The authors then determined the final size of air intake through the geometric relationship recommended by NACA [4]. SADRI proposed to design air intake based on full airflow rate with the compensatory loss of fuel being used as a comprehensive evaluation index [5]. Foreign researchers selected the appropriate shape of air intake based on the NACA report series, and then determined the specific size of basic section based on the semi-empirical formula provided by EDUS [6].

For air intakes composed of non-parallel surfaces, the air flow at the bottom of the ramp diverges, and the outer airflow is not parallel to the ramp wall, which will cause the formation of vortex. The direct use of formulas based on the boundary layer theory oversimplifies the calculation of air intake parameters, which will result in insufficient calculation accuracy. In addition, because the key geometric size ratios adopt the early recommended values of NACA, the specific effect and mechanism of action of each geometric parameter cannot be resolved. Therefore, the existing air intake design methods cannot fully satisfy the intelligent and digitalized design of high-performance commercial large aircraft.

In this paper, we employed the computational fluid dynamics (CFD) method to establish a numerical model for analysing the aerodynamic characteristics of the NACA air intake. Four performance indicators, namely the drag force, total pressure recovery coefficient, mass flow rate at the outlet and Mach number at the outlet, were adopted to optimize the geometric parameters. Firstly, several key air intake geometric parameters were determined through theoretical analysis. Then these parameters were optimized through the Design of Experiment (DoE) method, and the optimal geometric parameter combination was identified through statistical regression. The analysis of variance (ANOVA), which was first proposed by British statistician R.A. Fisher to interpret experimental data [7], was performed on the DoE results to analyse the respective and mutual influences of each geometric parameter. Finally, based on the CFD calculation results, we studied in detail the influencing mechanism of each geometric parameter on the aerodynamic characteristics of velocity, pressure distribution, vortex intensity and streamline pattern of the air intake, so as to obtain the geometric structural parameter with the best aerodynamic characteristics.

2. Numerical method

2.1. Geometric and boundary conditions

As shown in Figure 1 (a), the NACA air intake used in this study is composed of an inlet, a ramp, a turning corner, and an outlet. Baseline conditions: outlet size 68×24 mm; ramp height 30 mm; turning corner outer radius 30 mm, turning corner inner radius 10 mm; and outlet height 232 mm. The overall computational domain is shown in Figure 1(b). The origin of the coordinates is located at the sharp front tip of the inlet. The computational domain starts at 1 m from the front tip, extends 0.5 m on each side of the air intake and 0.7 m downward, and ends 1 m behind the outlet. After the airflow passes through the NACA air intake, it turns upward at an angle of 90° and reaches the flame suppressor. This study adopts a straight inlet with a straight passage of a certain length. The surface near the inlet is the wall surface, the pressure-far-field boundary conditions are adopted for the side and the bottom
surfaces of the main flow calculation domain, and the pressure outlet boundary conditions are adopted for the outlet. The main flow parameters are shown in Table 1.

![Figure 1. Geometric structure (a) and computational domain (b)](image)

Table 1. Main flow parameters

| Items                               | Values   |
|-------------------------------------|----------|
| Static pressure of incoming airflow | 23.8 (kPa) |
| Mach number of incoming airflow     | 0.78     |
| Static temperature of incoming airflow | 217 (K) |
| Angle of attack of incoming airflow | 3°       |

2.2. Grid and grid independence

Both the main flow wall surface and the NACA air intake wall surface adopt three layers of prismatic grids. Because the K-omega SST turbulence model is employed, the heights of the first layer of grids are 0.025 mm and 0.02 mm, respectively, for main flow wall surface and the NACA air intake wall surface to ensure \( y^+ \approx 1 \) for the wall surface [8]. Since this paper only studies the influence of geometric structure and only selects the cruise design point as the single boundary condition, the same set of grid resolution is used for different calculation conditions. Partition the entire computational domain and use different grids to fill different parts: For the NACA air intake and the area 10 mm downward of the intake, a structured polyhedral grid with a spatial resolution of 1.25 mm is adopted; for a certain area around the air intake, a structured polyhedral grid with a resolution of 4 mm is used; for other areas, structured polyhedral grids with a resolution of 15 mm are used. The interface between structured grid and boundary layer grid is filled with unstructured grid. Since the airflow entering the NACA air intake comes from the boundary layer, unstructured filling will reduce the numerical dissipation problem. The overall distribution and local details of the grids are shown in Figure 2.

![Figure 2. The overall and local distribution of the grids (Left: surface; Right: z=0 section)](image)
the main flow area, the area near the intake, and inner part of the intake (including the turning corner) increase and decrease by 20%. Thus, three sets of grids with 1.1 million, 1.97 million and 2.97 million nodes are generated respectively.

Figures 3, 4, and 5 respectively show the velocity distributions of two axial vortex development sections ($x=0.08$ m and 0.14 m) in the $x$, $y$, and $z$ directions under different grid numbers. At $x = 0.08$ m, the boundary layer begins to develop toward the inside of the intake. At $x = 0.14$ m, the two axial vortexes have developed. Increasing the number of grids from 1.97 million to 2.97 million does not significantly change the value of the velocity component along the span wise direction. Therefore, the following parts of this paper will adopt the strategy of 2.97 million grids.

![Figure 3](image1.png)

Figure 3. Comparison of the x-direction velocity components of the two axial vortex development sections under different grid numbers.

![Figure 4](image2.png)

Figure 4. Comparison of the y-direction velocity components of the two axial vortex development sections under different grid numbers.

![Figure 5](image3.png)

Figure 5. Comparison of the z-direction velocity components of the two axial vortex development sections under different grid numbers.

2.3. Numerical methods
The steady-state RANS is calculated using the k-omega SST turbulence model and is solved by a density-based solver. The density adopts the ideal gas law, the specific heat capacity adopts a piecewise polynomial, and the dynamic viscosity adopts the Sutherland model. The turbulent flow
energy and turbulent dissipation rate are discretized with the help of second order upwind discretization, and the operating pressure is selected as zero. All the wall surfaces are adiabatic.

3. DoE method

According to the delta-wing [9] and tetrahedral vortex generator [10] theories, intake ramp plays an important role in the generation of axial vortices. However, the literature has not yet given a conclusion on whether the axial vortices need to be strengthened or weakened for the NACA air intake. The side of the existing NACA air intake is designed according to reference [11]. In the original NACA literature, this shape is obtained by reducing the spanwise angle of the inlet based on a triangle. Whether the design affects the aerodynamic performance of the air intake has not yet been analysed in detail.

3.1. Geometrical parameters

As shown in Figure 6, the shape of NACA air intake ramp can be simplified into two triangles connected by smooth curves [12]. According to the analysis of surface curve in reference [13], can be kept unchanged to reduce the number of parameters. In addition, the Mach number of a cruising civil aviation aircraft is always lower than 1, and the design of air intake lip is not covered in this article.

Therefore, this paper mainly studies three key geometric parameters. As shown in Figure 6, they are α, θ and turning corner radius . After the geometric size of the intake and its downstream geometric domain are fixed, the DoE is performed under the premise that the main flow domain and the griding strategy remain unchanged. We first perform a three-factor-three-level design to determine whether the geometric parameters have a nonlinear effect on the performance of the air intake. Based on the analysis in the first step, eight examples are selected, and the three-parameter-two-level DoE results are subjected to analysis of variance (ANOVA) to obtain the main influencing parameter(s).

Value analysis of the three parameters is as follows:

1. Angle α is the ramp angle. Under the premise that the turning angle remains unchanged, increasing α will cause the air intake to be shortened. According to delta-wing and tetrahedral vortex generator theories, the value of α directly affects the shape of axial vortex. The incoming main airflow has an angle of attack of 3°, while the diffusion angle of a general flat-plate boundary layer is 11°. Therefore, three values of 11°, 13°, and 15° are selected for α in this paper. Correspondingly, the aerodynamic angles of attack of the main airflow to the ramp are 8°, 10°, and 12°, respectively.

2. Angle θ determines the position of inflection points of the ramp. When the value of θ is small, the inflection points are close to the front tip. There is no description of this angle in the NACA report series. Instead, smoothing splines are used to connect the outlet and the front triangle. This paper uses θ to quantitively describe the position of inflection points. The values of θ are 36°, 40° and 44°.

3. Turning corner radius . Under the premise that the position of outlet remains unchanged, the value of will affect the drag force and cause changes in the surface area of turning corner, which will in turn result in changes in Mach number of the airflow in the channel. The values of are 32 mm, 40 mm, and 44 mm.

Table 2 is the three-factor-three-level experimental design table. The examples selected for three-factor-two-level ANOVA are marked with “V” in the rightmost column. Note that only the boundary values of the three-factor-three-level design are selected for the three-factor-two-level ANOVA.
Table 2. DoE design

| No. | $\alpha$ (°) | $\theta$ (°) | $R$ (mm) | Three factor-two level |
|-----|--------------|--------------|----------|-----------------------|
| 1   | 11           | 40           | 40       | V                     |
| 2   | 15           | 36           | 36       | V                     |
| 3   | 15           | 40           | 32       | V                     |
| 4   | 11           | 44           | 40       | V                     |
| 5   | 13           | 44           | 32       | V                     |
| 6   | 15           | 44           | 40       | V                     |
| 7   | 11           | 36           | 32       | V                     |
| 8   | 13           | 36           | 32       | V                     |
| 9   | 13           | 44           | 36       | V                     |
| 10  | 15           | 36           | 32       | V                     |
| 11  | 11           | 36           | 40       | V                     |
| 12  | 13           | 40           | 36       | V                     |
| 13  | 11           | 44           | 36       | V                     |
| 14  | 13           | 44           | 40       | V                     |
| 15  | 13           | 40           | 40       | V                     |
| 16  | 13           | 40           | 32       | V                     |
| 17  | 13           | 36           | 36       | V                     |
| 18  | 15           | 44           | 32       | V                     |
| 19  | 15           | 44           | 36       | V                     |
| 20  | 11           | 40           | 32       | V                     |
| 21  | 11           | 40           | 36       | V                     |
| 22  | 15           | 36           | 40       | V                     |
| 23  | 15           | 40           | 36       | V                     |
| 24  | 11           | 44           | 32       | V                     |
| 25  | 15           | 40           | 40       | V                     |
| 26  | 13           | 36           | 40       | V                     |
| 27  | 11           | 36           | 36       | V                     |

3.2. Performance parameters

The following four performance parameters are selected as the dependent variables of the experiment:

1. Drag force ($D$). The drag force is the sum of friction and pressure acting on the NACA air intake ramp, the side of the ramp, and all turning corner surfaces. An absolute value is adopted for $D$.

2. Total pressure recovery coefficient, which is defined as follows [11]:

![Figure 6. Key geometric parameters](image)
\[
\eta = \frac{p^* - p_m}{p_{m}^* - p_m}
\]  

(1)

Where \( p^* \) represents the mass averaged total pressure on the section in front of the turning corner; \( p_{m}^* \) is the total far-field pressure; \( p_m \) is the static far-field pressure.

3. Mass flow rate (\( m \)) at the section in front of the turning corner.

4. Average Mach number (\( Ma \)) at the section in front of the turning corner.

4. Results and analyses

4.1. Baseline conditions

Figure 7 shows the limiting streamline and static pressure distribution on the air intake surface under the baseline conditions. It can be seen that there is a low-pressure area on the side of the 1/2 axial position, and the static pressure is restored near the turning corner.

The surface limiting streamlines at the bottom of the ramp exhibit a scattered trend along the flow direction. Therefore, there is no separation of the streamlines at the ramp bottom. The bottom streamlines gather at the side edge near the bottom of the intake, while the side streamlines gather on the side surface close to the main flow. Therefore, it can be inferred that the main flow induces an axial vortex on the side, which develops downstream. This axial vortex is not close to the ramp bottom, otherwise there will be streamlines converging at the ramp bottom.

In order to analyse the axial vortex more intuitively, an iso-surface with a vorticity of \( 1.03 \times 10^8 \) s\(^{-1} \) is selected and analysed by static pressure visualization, as shown in Figure 8. The axial vortexes are formed from the front part of the NACA air intake. The vortexes are always close to the side edge where the ramp side intersects the main flow, but not to the ramp bottom. Therefore, it is inferred that the pressure difference between the main flow on the side and the channel and the speed discontinuity surface brought by the side are the key to the generation of axial vortexed. If the axial vortexes are to be enhanced, it is necessary to increase the pressure difference and intensify the discontinuity surface, that is, increase the ramp angle and minimize the side chamfer. The side chamfer is restricted by the manufacturing process, but the ramp angle \( \alpha \) can be designed. The static pressure of the two axial vortexes is low near the inlet, while the static pressure on the vortex tube increases sharply at the inflection point of the ramp side. The axial vortexes formed on the side continue to develop downstream and extend to the outlet through the 90° turning corner. In addition, the two vortex tubes gradually move closer to each other as they develop downstream. The speed direction changes near the turning corner, which can be captured by the Q-criterion and has a relatively low static pressure.

Figure 7. Limiting streamline and static pressure distribution on surface under baseline condition

Figure 8. Vortex core region static pressure visualization
4.2. DoE results

The calculated performance parameters of the 27 DoE examples are shown in Table 3. It can be seen that in all combinations where the value of ramp angle $\alpha$ is 15°, the Mach number at the outlet exceeds 1; in all combinations where $\alpha$ is 11°, the Mach number at the outlet is lower than 1; while in all combinations where $\alpha$ is 13°, some Mach numbers at the outlet exceed 1, while others are lower than 1. When the Mach number exceeds 1, the total pressure loss caused by crossing the shock wave surface increases, the speed decreases, and the static pressure increases. This is unfavourable in terms of aerodynamic loss, but this is also a way to quickly reduce the speed of incoming airflow within a short distance. The 2nd ($\alpha = 15^\circ$) and 27th ($\alpha = 11^\circ$) conditions in the table is taken as an example. When other parameters remain unchanged, compared with Condition 27, which has a smaller $\alpha$ angle value, the total pressure recovery coefficient of the combination with a larger $\alpha$ angle value (Condition 2) is 11.12% smaller, and the drag force is also reduced by 9.62%. However, compared with the Condition 2, the air low rate increase by 14.57% under Condition 27.

| No. | $D$ (N) | $\rho_0$ | $m$ (kg/s) | $Ma$ |
|-----|---------|----------|------------|------|
| 1   | 39.51   | 0.9286   | 0.1067     | 0.9053 |
| 2   | 39.17   | 0.8266   | 0.0938     | 1.2023 |
| 3   | 39.57   | 0.8107   | 0.0906     | 1.1384 |
| 4   | 41.58   | 0.9119   | 0.1050     | 0.8843 |
| 5   | 43.61   | 0.8877   | 0.1057     | 0.9444 |
| 6   | 38.25   | 0.8315   | 0.0893     | 1.1646 |
| 7   | 44.44   | 0.9197   | 0.1122     | 0.8903 |
| 8   | 40.86   | 0.9351   | 0.1082     | 1.0685 |
| 9   | 41.73   | 0.8854   | 0.1034     | 0.9410 |
| 10  | 40.99   | 0.8135   | 0.0920     | 1.1985 |
| 11  | 41.81   | 0.9171   | 0.1062     | 0.8856 |
| 12  | 41.76   | 0.8924   | 0.1044     | 0.9721 |
| 13  | 42.99   | 0.9127   | 0.1078     | 0.8852 |
| 14  | 40.03   | 0.8622   | 0.0963     | 0.9373 |
| 15  | 37.83   | 0.8918   | 0.0980     | 0.9780 |
| 16  | 42.84   | 0.8915   | 0.1072     | 0.9796 |
| 17  | 41.64   | 0.8958   | 0.1039     | 1.0356 |
| 18  | 39.71   | 0.8235   | 0.0903     | 1.0907 |
| 19  | 39.13   | 0.8314   | 0.0920     | 1.1149 |
| 20  | 44.13   | 0.9198   | 0.1108     | 0.8881 |
| 21  | 43.23   | 0.9132   | 0.1084     | 0.8868 |
| 22  | 38.45   | 0.8123   | 0.0899     | 1.2020 |
| 23  | 39.04   | 0.8215   | 0.0923     | 1.1472 |
| 24  | 43.94   | 0.9143   | 0.1103     | 0.8875 |
| 25  | 38.25   | 0.8144   | 0.0891     | 1.1848 |
| 26  | 40.53   | 0.8853   | 0.0974     | 1.0123 |
| 27  | 43.34   | 0.9190   | 0.1098     | 0.8866 |

The data in Table 3 are subjected to three-factor-three-level ANOVA. The main effects and interaction effects of each geometric factor on the performance parameters are shown in Figure 9 and Figure 10, respectively. It can be seen from Figure 9 that $\theta$ has a nonlinear effect on the drag force. Since the overall effect is relatively small, and the upper and lower limits change less than 2% relative to the average value, this nonlinear effect is negligible. Angle $\alpha$ has greater influences on the four
dependent variables than the other two geometric parameters. As the angle of $\alpha$ increases, except for the average Mach number at the outlet section, the values of other parameters all decrease. Therefore, reducing the angle of $\alpha$ is beneficial to the improvement of aerodynamic performance of the air intake. The influences of $\theta$ angle on the four dependent variables are the smallest among the three geometric parameters. Except for drag force, other parameters decrease with increase in $\theta$. Turning corner radius $R$ has large impacts on the average drag force and the average mass flow rate—both values decrease as the value of $R$ increases.

It can be seen from the interaction effects shown in Figure 10, for the average drag force and the average mass flow rate, both $\alpha$ and $\theta$ have strong interaction effects on $R$; for the total pressure recovery coefficient, the interaction effects between the factors are weak; for the average Mach number at the outlet section, there is an interaction effect between $\alpha$ and $\theta$. According to the above analysis of the main effects, the smaller the angle $\alpha$, the larger the total pressure recovery coefficient and the mass flow rate, and the better the performance of the air intake. According to the interaction effects, when the angle of $\alpha$ is kept constant, smaller values of $R$ and $\theta$ are beneficial to the total pressure recovery coefficient and the mass flow rate. In Table 3, Conditions 7 and 27 are two conditions with extreme parameters. It can be seen that Condition 27 has better performance.

![Figure 9. Main effects of the three geometric factors on the four performance parameters (from top to bottom: average drag force, total pressure recovery coefficient, average mass flow rate, and average Mach number)](image-url)
4.3. Comparison between the results of Condition 2 and Condition 27

It can be seen from Fig. 9 that angle $\alpha$ has a great influence on the aerodynamic characteristics of the air intake, and the performance of the intake is better when the values of $\alpha$, $\theta$, and $R$ are small. By further comparing the performance parameters under Conditions 7 and 27, it can be concluded that the comprehensive performance of the air intake is better under Condition 27 ($\alpha=11^\circ$, $\theta=11^\circ$, and $R=36$ mm). Therefore, the mechanism of effect of $\alpha$ on air intake performance is further analysed by comparing Condition 27 ($\alpha=11^\circ$) and Condition 2 ($\alpha=15^\circ$), with the other two geometric parameters being remained the same.

Figure 11 shows the Mach number distribution in the vortex core region of the air intake. The smaller the $\alpha$ angle, the larger the inlet, the weaker the squeezing effect of airflow at the front tip, and the smaller the Mach number at the front tip. Figure 12 shows the static pressure distribution in the vortex core region. The smaller the $\alpha$ angle, the greater the static pressure at the front tip, which is beneficial to reducing pressure loss. The smaller the $\alpha$ angle, the longer the vortex tube at the ramp, the more conducive it is to entrain the airflow, and the longer the vortex tube extends downstream. This is conducive to enhancing the mixing of downstream airflow, which in turn facilitates the improvement of the uniformity of outlet airflow.

Figure 13 shows the Mach number distribution on different ramp sections. It can be seen that the smaller the $\alpha$ angle, the more uniform the Mach number distribution on the sections, and the smaller the values. Figure 14 shows the streamlines entering the air intake and velocity distribution on different ramp sections. It can be seen that the smaller the $\alpha$ angle, the more uniform the velocity distribution on the same section. A more uniform velocity distribution is beneficial to reduce outlet distortion and improve air intake quality. From the perspective of the streamlines, the smaller the $\alpha$ angle, the weaker the wall separation effect, which is beneficial to reduce pressure loss and increase the uniformity of outlet airflow.
Figure 11. Vortex core region Mach number distribution

Figure 12. Vortex core region static pressure distribution

Figure 13. Mach number distribution on different ramp sections
5. Conclusions
(1) There is a low-pressure area on the axial side of the air intake. A pair of axial vortexes are formed near the side edge close to the ramp wall. These two vortex tubes gradually move closer to each other as they develop downstream.

(2) Angle $\alpha$ has great influences on the four performance parameters. When the angle of $\alpha$ increases, except for the average Mach number at the outlet section, values of other parameters all decrease. Angle $\theta$ has minimal impacts on the performance parameters. Turning corner radius $R$ has large impacts on the average drag force and the average mass flow rate—both values decrease as the value of $R$ increases.

(3) According to the interaction effects, for the drag force and the average mass flow rate, both $\alpha$ and $\theta$ have strong interaction effects on $R$. The smaller the $\alpha$ angle, the larger the total pressure recovery coefficient and the flow rate. According to the interaction effects, the smaller the values of $R$ and $\theta$, the better the performance of the air intake.

(4) The smaller the $\alpha$ angle, the smaller the Mach number at the front tip, the greater the static pressure, the longer the vortex tube extends downstream, the more uniform the Mach number and velocity distribution on the same section, and the weaker the wall separation effect. These are beneficial to reduce pressure loss, entrain the airflow, reduce outlet distortion, and improve air intake quality.

(5) In summary, the performance of the intake is better when the values of $\alpha$, $\theta$, and $R$ are small. By further comparing the performance parameters under Conditions 7 and 27, it can be concluded that the comprehensive performance is better under Condition 27 ($\alpha=11^\circ$, $\theta=11^\circ$, and $R=36$ mm).

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