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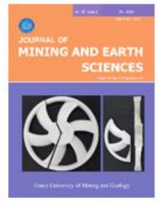

Investigating the effect of axial fan shrinkage obtained by centrifugal casting technology on aerodynamic characteristics

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ABSTRACT

Centrifugal casting technology was developed for the application of manufacturing axial fans. In the literature, these fans were usually manufactured by injection molding, mechanical processing or heat pressing. The main characteristic of this molding technology allows the creation of thick and hollow blades. This characteristic of the blades gives useful advantages of the fan that cannot be achieved by conventional methods. The centrifugal casting technology has been applied to fabricate axial fans in recent research. However, the issue of quality control and especially the shrinkage of the resulting fan compared to the molding has not yet been considered. Therefore, more in-depth studies and approaches are required. In this study, 3D scanning method is used to evaluate the shrinkage of the blades. The used 3D scanner is the Comet L3D 5M type based on structured light (blue LED) with a 5-megapixel sensor. This device achieves high accuracy and reliability (resolution 18 μm). The theoretical basis for determining fan shrinkage compared to CAD molds is based on the following main parameters: Chord line L (mm), relative thickness E_{max} (%), and stagger angle γ (degrees). In addition, the aerodynamic characteristics of the proposed fan are compared to those of a fan made of aluminum (blades are identical, but different in fabricating technology). Characteristics of this aluminum rigid-fan are assumed as reference. The results showed that the difference was not large between the blades. Besides, the results of aerodynamic testing on the test bench of the two fans are almost similar. This indicates the good adaptability of the axial fan received by the centrifugal casting technology.

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1. Introduction

Centrifugal casting technology was developed in the early years of the 20th century. This is a casting method that is completely different from other methods. The feature of this method is the creation of a hollow casting element due to the action of centrifugal force. The working principle is introduced in Figure 1, a motor - transmits motion that rotates two rollers 1, and rollers 5 against the outer wall of the casting mold 4 (opposite of the motion of the drive motor). When molten metal 6 is poured into the mold, under the action of centrifugal force, this metal layer adheres to the inner wall of the mold. After cooling the molding mold, the final product 3 is removed from the mold. The characteristic phenomenon in casting methods in general and centrifugal casting, in particular, is the shrinkage of cast products. The degree of shrinkage depends on the material, temperature, and pressure in the mold. The cause of this phenomenon is a significant decrease in volume during the crystallization of the material (liquid phase - solid phase). Concerning this issue, there have been studies to reduce product shrinkage, to increase the productivity and efficiency of this molding method. Crawford et al. (2004), presented a centrifugal casting method using gravity and high pressure. When the shrinkage of the material layer in contact with the mold decreases, the smoothness of the casting surface increases. Besides increasing casting productivity and allowing to design multiple casting molds on the same machine, this method can save time and improve casting efficiency (Nugent, 2006). However, the main disadvantage of the method is that it can not mold complex parts and/or parts with many angles or small spaces inside the mold.

Currently, in the world, centrifugal molding technology is an attractive field, especially in the plastic industry with an annual growth rate of approximately 10÷20% (Crawford, 2012). The axial fan mentioned in this study was fabricated by centrifugal casting technology, which is different from the traditional centrifugal casting method. The process of filling the powder into the mold consists of 4 main steps (Figure 2): 1 - filling the powder into the mold; 2 - rotating mold and heating in the oven; 3 - rotating mold and cooling mold; 4 - final products. The mold is placed on two perpendicular spindles, and the rotation speed of the two axes is independent and customized. This allows flexibility when fabricating complex-shaped molded parts or products that require high quality (Crawford, 2012). Normally, the rotational speed is kept constant during the heating and cooling processes.

The main advantage of this molding technology is allow to creat thick and hollow blades. This characteristic of the blades gives the fan's useful advantages that cannot be achieved by conventional methods (Figure 3).

The axial fan mentioned in this study is applied in automotive cooling systems (Figure 4). This is a relatively active industrial market today. The productivity, noise reduction, and production costs are required to be improved and new

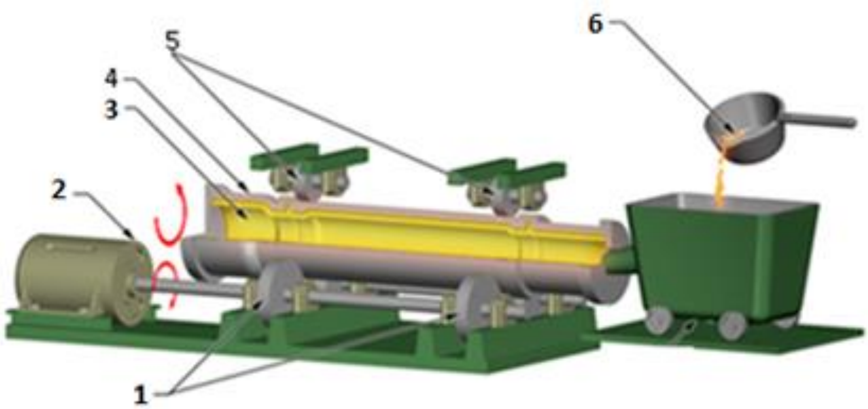

Figure 1. Casting in a metal mold. 1- active roller; 2- driving motor; 3-cast products; 4-mold; 5-roller against above the mold; 6-molten material (https://sumitech.vn, accessed 26th March 2024).

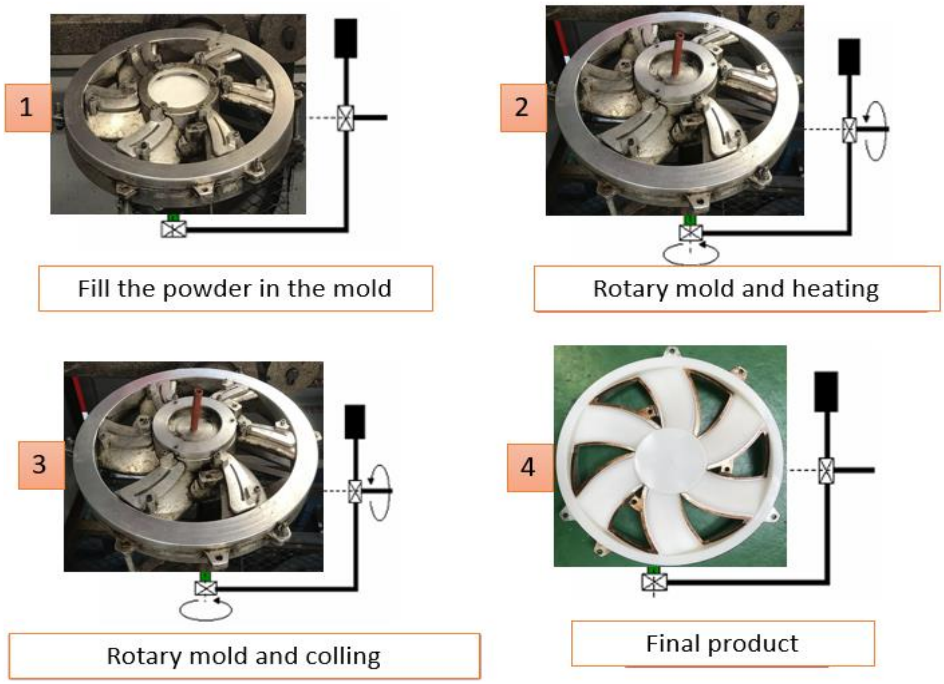

Figure 2. Main steps of the fan casting process.

Figure 3. Cross-section of the obtained fan.

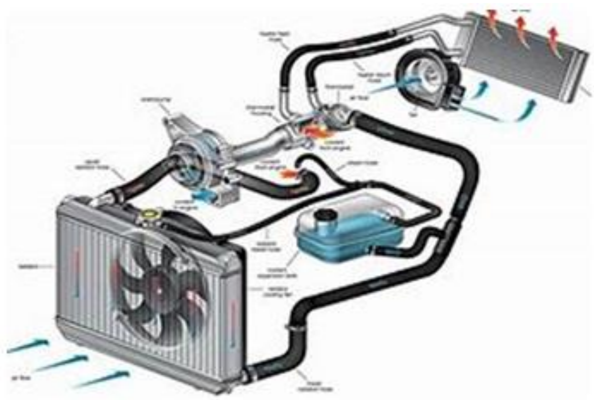

Figure 4. Axial fan installation position and automobile cooling system (https://sellhimvs.life, accessed 26th March 2024).

product solutions should be applied. To seize this new market opportunity, it is therefore necessary to optimally study the fabrication parameters and geometric dimensions of the fan fabricated by centrifugal casting technology.

The material used in the fan manufacturing process is polyethylene (PE). In the casting process, the material goes through the process: Solid (powder) - melted - crystallized - solid (product).

The application of centrifugal casting technology to fabricate axial fans has also certain limitations, e.g., the control of blade shrinkage during casting. Therefore, more in-depth studies and approaches are needed. Two main factors affecting the shrinkage of the fan are:

- Cooling method (blower-cooled, water-cooled, or a combination of both).

- Cooling time has an effect on the crystallinity of the material. If cooled for too long, it will lead to a long fabrication cycle of a fan. If cooling time is too short, blade warping due to uneven shrinkage can be occured.

However, the method of determining the shrinkage of fabricated fans have not mentioned in detail by recent studies in the field of axial fan fabrication (Tarik, 2018; Pereira et al., 2021). The shrinkage of the external fan affects the shape and geometrical dimensions, and it's also related to the profile of the blades. This change directly affects the nature of the flow through the blades, and the flow on the surface of the blades. This can change the dynamic characteristics of the fan. Sarraf et al. (2011) studied the effect of the thickness of metal blades of 4 mm and 8 mm types on the pressure and performance of the blades. The results indicated that the efficiency decreased by 3% for a fan with a thickness of 8 mm compared to a fan with a thickness of 4 mm. So, the centrifugal casting technology may lead to the shrinkage phenomenon of the fan, which causes undesirable disadvantages of this method such as:

+ Performance of fan.
+ Noise (by deformation of the blades).
+ Stability (vibration, shake).

Therefore, if this phenomenon is actively controlled, it is possible to optimize the centrifugal casting technology process to fabricate a fan.

From this point of view, this study refers to the method and procedure for testing the blade geometric dimension parameter (blade shrinkage) achieved by centrifugal casting technology. The study presented a method of 3D scanning (laser scanning) to control the shape, geometric dimensions of the blades. The obtained results are compared with the CAD dimensions of the casting mold to evaluate the degree of shrinkage of the rotor obtained by centrifugal casting technology. In addition, the polymer fan (PE) is compared to an identical fan fabricated of aluminum. These two fans differ only in the manufacturing process. The aluminum fan used in the study is considered as reference one. The main parameters of the reference fan are introduced in Table 1. The blade of the fan is designed according to NACA 65(xx)yy: xx - relative camber and relative thickness yy. The ratio between the center hub radius and blade tip radius R_{min}/R_{max} = 0.365. The blade thickness of the propellers is 10 mm. The reference fan is designed with specifications Δp = 270 Pa, flow rate Q_v = 0.8 m^3/s, n = 2500 rpm.

Table 1. Main characteristics of the reference fan.

Layer	Radius (mm)	Chord (mm)	Stagger angle (°)	Profil NACA 65
Hub	65,4	66.6	53	NA CA 65 (07)15
Mide	122.2	74.0	66	NA CA 65 (10)13.5
Tip	179.0	81.3	70	NA CA 65 (11)12

2. A theoretical basis for determining the geometrical parameters of the fan

The geometry of the blades plays an important role in the overall performance of the fan. In particular, the structure and shape of the blades have a great influence on the flow and the effects they create. Important geometric parameters of the fan considered in this study are:

- Chord line L (mm).
- Relative thickness E_{max}(%).
- Stagger angle γ(°).

2.1. Chord line L (mm)

Chord line length is determined by two points on the leading edge A and trailing edge B of the blade profile. Two points A and B have coordinates $A(x_A,y_A,z_A)$ and $B(x_B,y_B,z_B)$ respectively. Each cross-section corresponding to a radius r (mm) is cut by a cylinder. To determine the length of the chord line L (mm), the length of AB on the cylinder must be determined (Figure 5).

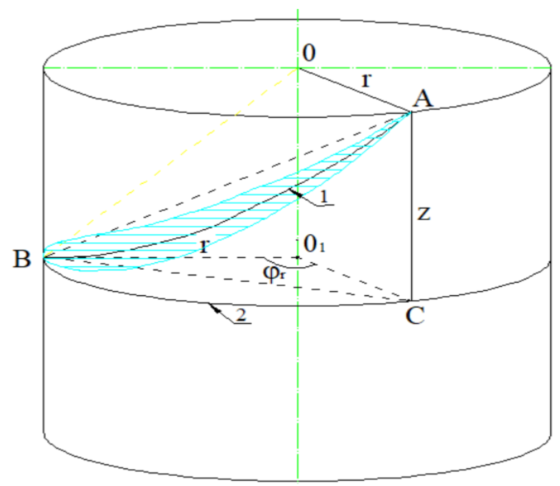

Figure 5. Section profile cut by cylinder. (1 - length of the arc (AB)͡ on cylinder; 2 - length of the arc (BC)͡ on cylinder).

In the triangle ΔACB, set: AC = "Z" - is the segment projection coordinate AC and is defined:

$$Z = Z_A - Z_B \tag{1}$$

Another side:

$$AB = \sqrt{(x_A - x_B)^2 + (y_A - y_B)^2 + (z_A - z_B)^2} \tag{2}$$

Angle φ_r determined in triangle ΔBO_1C:

$$BC^2 = 2r^2 - 2r^2.cos(\varphi_r)$$
$$\varphi_r = acos(\frac{2r^2 - BC^2}{2r^2}) \tag{3}$$

Therefore, arc $\widehat{BC}$ is defined as follows:

$$\widehat{\mathrm{BC}} = \frac{\pi.\mathrm{r}.\varphi_\mathrm{r}}{180} \tag{4}$$

Then the length of the chord line L(mm) is determined by the formula:

$$L = \sqrt{Z^2 + (\frac{\pi.r.\varphi_r}{180})^2} \tag{5}$$

NACA airfoil design consists of specifying an airfoil camber line followed by calculating the body of an airfoil. An airfoil consists of two parabolic curves. The distance between a tangent and a leading edge is equal to L*. We need to know the geometric characteristics of a profile that was calculated when designing a wing to draw a camber line shape. We can move on to calculating the camber line of the NACA profile:

- It is necessary to select the coordinates from the first edge of the profile with x = 0 to the end edge of the profile with x = 1 (Figure 6).
- After determining the points required with x-coordinates, we can start by evaluating the y-coordinates of a camber line.

The camber line equation is determined:

$$y_s = \frac{\frac{m}{l}}{(\frac{L}{l})^2}\left[2.\frac{L}{l}.x - x^2\right] \; where \; 0 \leq x \leq L$$
$$y_s = \frac{\frac{m}{l}}{(1-\frac{L^*}{l})^2}\left[1 - 2\frac{L^*}{l} + 2\frac{L^*}{l}x - x^2\right] \; where \; L^* \leq x \leq 1 \tag{6}$$

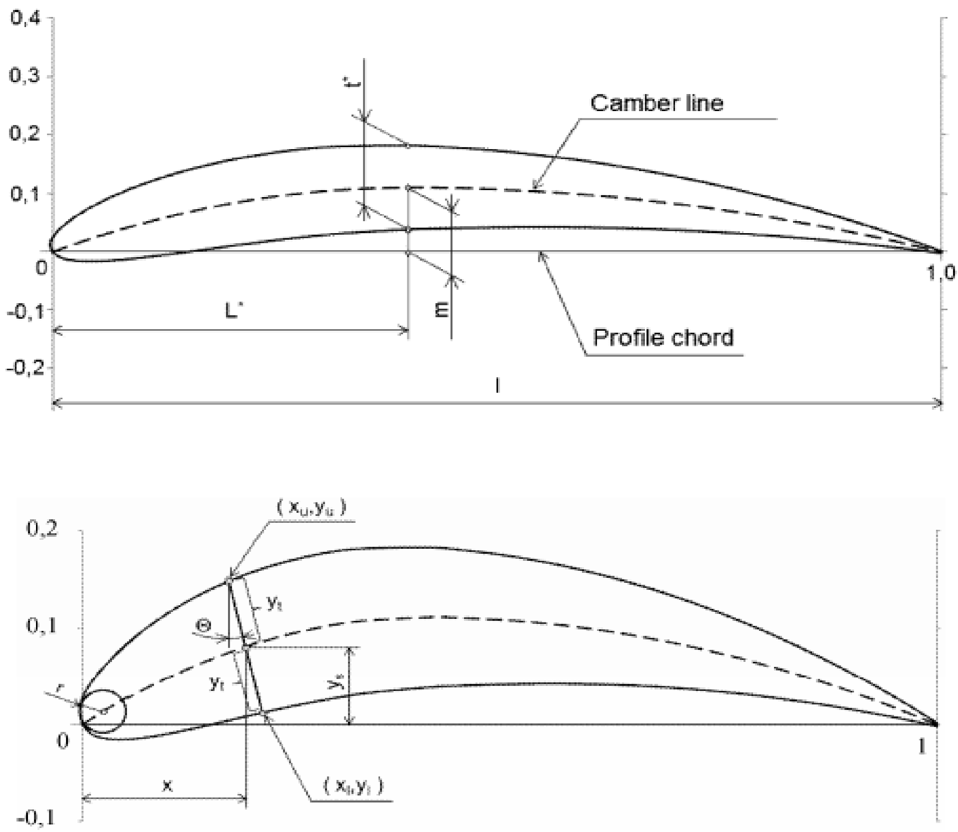

Figure 6. Identifying NACA profile characteristics.

Half the thickness of the y_t profile corresponds to a specific point of the camber line (x_t, y_t) determined by the equation (Varchola et al., 2013):

$$y_t = \frac{\frac{t^*}{l}}{0.2}(0.2969.\sqrt{x} - 0.126x + 0.3516x^2 + 0.2483x^3 - 0.1015x^4) \quad (7)$$

2.2. The relative thickness of the blade

The thickness of the blade E_{max} (%) is determined according to the following formula:

$$E_{max} = 2.y_t \quad (8)$$

Therefore, the relative thickness of the blade E (%):

$$E(\%) = \frac{E_{max}}{L} \quad (9)$$

To simplify the geometric parameters of the blades, the profile of the blade is determined by rolling this profile on a plane. Then a 2D profile of the fan (or blades) is obtained (Figure 7). This profile consists of two curved faces (convex face "extrados" and concave face "intrados") or a profile at any cross-section of the blade.

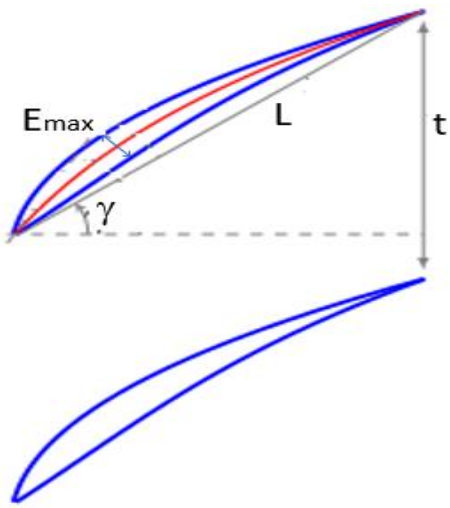

Figure 7. The relationship of the geometry parameters on the blade profile.

2.3. Stagger angle γ

The stagger angle is determined as follows:

$$\gamma = acos\left(\frac{Z}{L}\right) \quad (10)$$

2.4. Introduction to the 3D scanning method

To determine the profile of the fan, the 3D scanning method was used in this study. The used 3D scanner is the Comet L3D 5M type (the dimensions of the measured object are 45 mm x 38 mm x 30 mm) based on structured light (blue LED) with a 5 megapixel sensor. This device achieves high accuracy and reliability (resolution 18 μm). During blades scanning, data are obtained in the form of cloud coordinates (3-dimensional space x, y, z) over the entire geometric dimension of the fan (Figure 8).

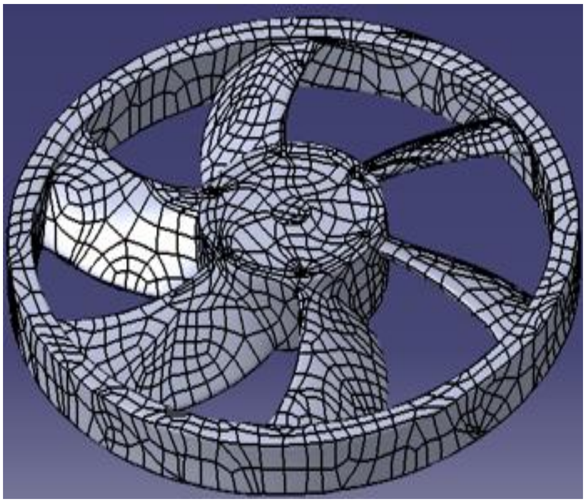

Figure 8. Fan profile obtained by 3D scanner data.

The process of determining the geometrical dimensions of the fan is shown in Figure 9.

On the basis of the fan's 3D scanner database, we process it on Paraview software. Each blade is divided into 11 sections (from r_1 to r_{11}) (Figure 10).

The cross-section at each section is defined by a cylinder with a radius from r_1 to r_{11}, respectively (Figure 11). Each profile at a section is defined by 4000 points (each point is defined corresponding to x, y, z coordinates). Figure 12 shows the profiles obtained for the entire fan.

3. Aerodynamic characteristics test bench

To determine the performance of the fan, an aerodynamic characteristics test bench has been

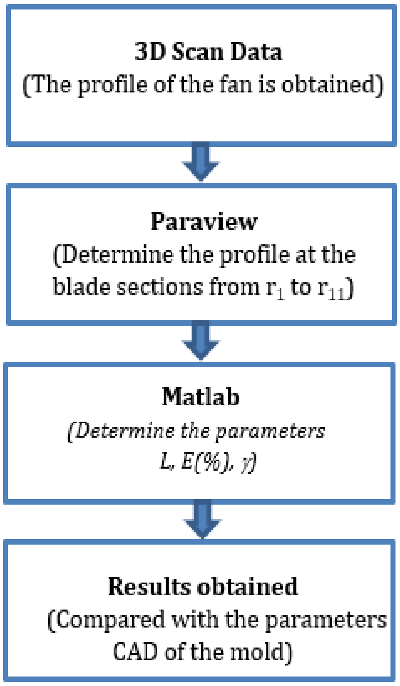

Figure 9. The procedure for determining the geometrical parameters of the fan.

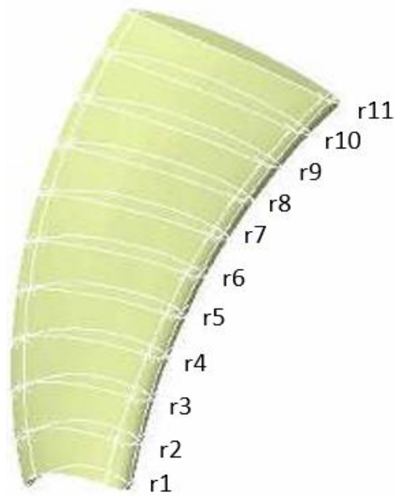

Figure 10. The blade is divided into 11 sections from r_1 to r_{11}.

designed according to ISO 5801 standard. The test bench standard has dimensions of 1.3 m x 1.3 m x 1.8 m as shown in Figure 13. The air flowrate is determined according to ISO 5167, by modifying the inlet diameter. The average static pressure generated in the box is measured with an absolute accuracy of ± 0.1 Pa. The mass flow rate Q_v is determined as follows:

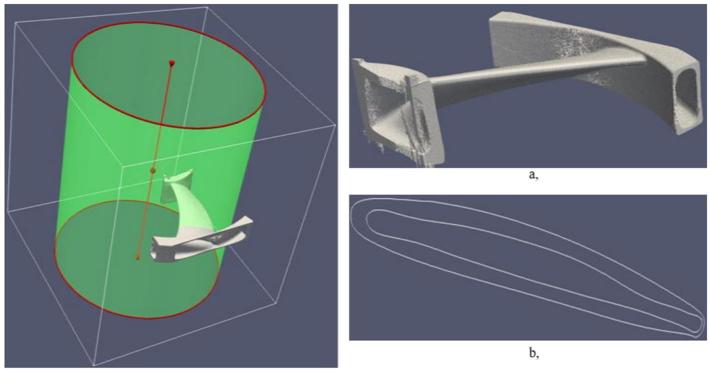

Figure 11. The profile at each section of blade is defined by a cylinder with radius from r_1 to r_{11}.

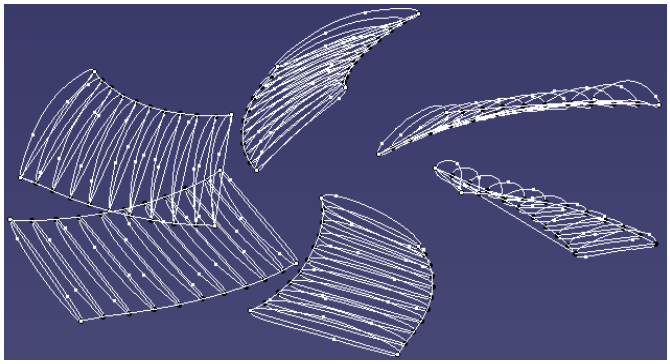

Figure 12. The obtained profile of 06 corresponding blades at 11 cross-sections from r_1 to r_{11}.

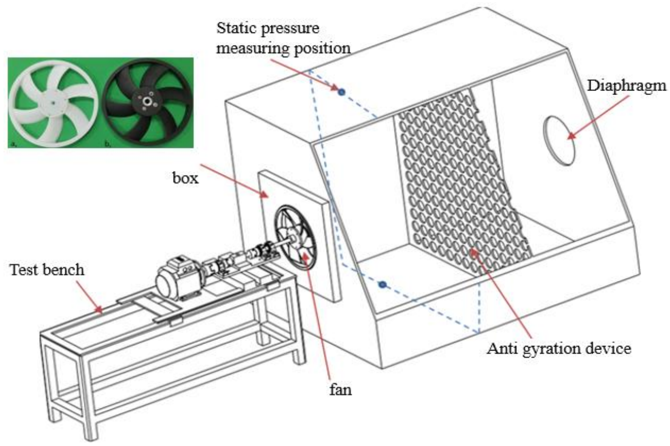

Figure 13. The fan test bench.

$$Q_v = \frac{\alpha.\varepsilon.\pi.d^2}{4}\sqrt{\frac{2\Delta p}{\rho}} \qquad (11)$$

Where: α and ε are the constants, d - inlet diameter (mm), Δp - static pressure (Pa), ρ - the air density (kg/s).

The torque (C) of the fan is determined by the HBM T20WN torque measuring device 5 (N.m).

The allowable error of the measuring device is 0.1% for the measured maximum torque. The angular speed (ω) of the fan is measured by a device with a relative accuracy of ± 0.2% (for the range ± 500 Pa). Static efficiency is determined using equation (5) within about ± 0.5% of accuracy.

$$\eta_s = \frac{\Delta p . Q_v}{C . \omega} \qquad (12)$$

The flow coefficient (ϕ) and the static pressure coefficient (ψ) were determined with uncertainty ± 0.5 and ± 0.3%.

$$\phi = \frac{Q_v}{\pi . \omega . R_{max}^3} \qquad (13)$$

$$\psi = \frac{2 . \Delta p}{\rho . \omega^2 . R_{max}^2} \qquad (14)$$

4. Results and discussion

In the fabrication process, when the PE powder melts, the material creates a transition between the phases: the liquid phase during the heating of the mold and the solid phase during the cooling of the mold. During fabrication, the fan can appear in various phenomena such as shrinkage or oxidation of materials, this is explained by Crawford, (2012). Therefore, the quality or external shape of the fan may differ from the molding. This can lead to significant changes in the aerodynamic characteristics of the fan. The geometrical dimensions of the fan are determined by the 3D scanner method, and the result is compared with the CAD design of the mold. The analysis results show that at the contact surface between the material and the mold, there is shrinkage. This phenomenon appears during the cooling of the mold. In Figure 14, the results show that the curves obtained with six rotors, corresponding to the chord line L (mm), relative thickness E (%), stagger angle γ (degrees) tend to be the same. The greatest shrinkage of the fan occurs in between the blade and gradually decreases to the sides. This can be explained by the alignment of the central section (r_1) and the tip section of the blade (r_{11}). The largest difference in thickness between the blades is 0.47 mm (about 5.2%), this difference is not too large. The results show that the general shape of the fan obtained

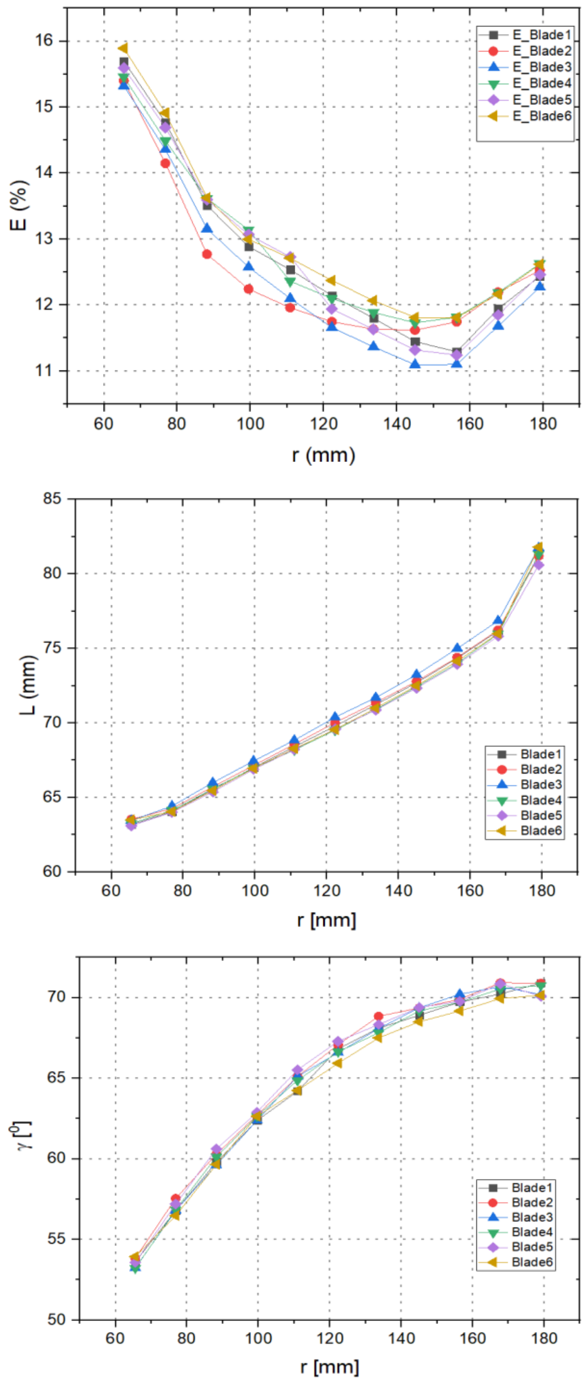

Figure 14. Relative thickness E(%), chord line L(mm), stagger angle γ (°) as a function of radius r(mm).

from centrifugal casting is relatively homogeneous and shows the adaptation of the material distribution in the mold.

To get a clearer view of shrinkage, the results are compared with the CAD model of the mold. The average values of six blades are used for

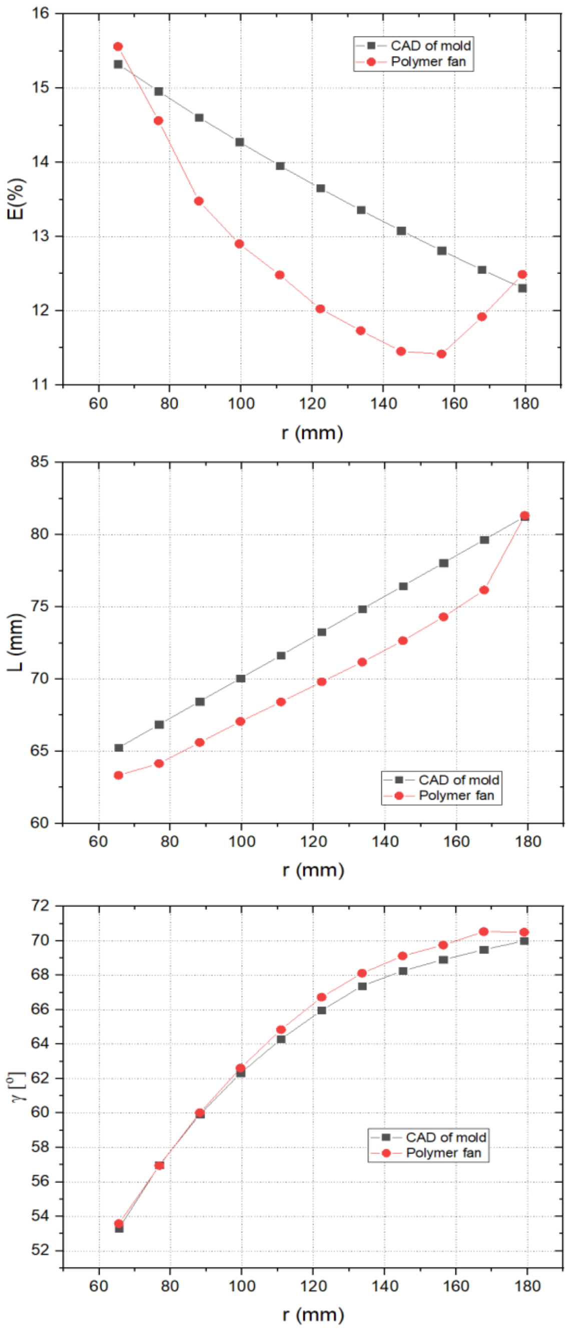

Figure 15. The average values of six blades: relative thickness E(%), chord line L(mm) and stagger angle γ(°) are compared with the CAD of the mold.

comparison. It can be noticed that the general shape of the fan is fabricated in accordance with the molded CAD shape. However, both the relative thickness E (%) and the chord line L (mm) are smaller than the CAD size of the mold. The greatest difference in the thickness of the blade from the casting mold observed (at the r_8 = 142.23 mm position) is 1.3 mm, corresponding to about 13%. In addition, shrinkage affects the length of the chord line L (mm). The maximum shrinkage observed at position r_8 is 3.58 mm and decreases relative to positions near the center radius r_1 and blade tip radius r_{11}.

- Dynamic characteristics: as already mentioned, in order to compare the general aerodynamic characteristics of the fan fabricated of aluminum with those fabricated by centrifugal casting technology (Figure 16), a test study on the test bench was conducted. These two fans have the same dimensions geometry, except that the molded fan has hollow blades.

Figure 16. Aluminum reference fan and fan fabricated by centrifugal casting technology (a-reference fan; b-polymer fan).

The results of the comparison of the two fans show that the trend of the obtained dynamic characteristics of the two fans is quite similar (Figure 17). Besides, the difference in efficiency obtained on the test bench (with a rotation speed of 2000 rpm) between two fans is about 1.5% (Table 2). This difference is significant within the uncertainty limit of the measuring device. This indicates a good adaptation of the fan obtained by the rotational molding process. This difference can be explained by the following factors: Due to the effect of blade shrinkage, there is a decrease in the relative thickness E (%) of the blade and a decrease in the length of the chord line L (mm). Besides, there is a difference of about 4.5% in the value of mechanical power (P = C.ω) between the aluminum fan and the fan fabricated by centrifugal casting technology.

Table 2. Dynamic characteristics comparison of two fans.

Name	Ψ	Φ	η_{max} (%)
Reference	0.171±0.003	0.138±0.005	42.35±0.5
Polymer fan (PE)	0.173±0.003	0.137±0.005	43.84±0.5

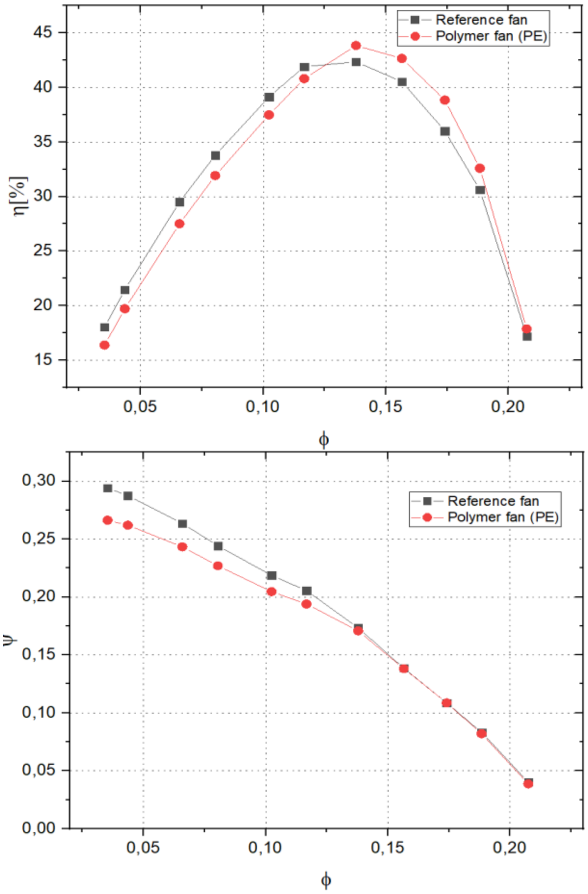

Figure 17. Efficiency η(%) and the pressure coefficient Ψ as a function of the flow coefficient ϕ between the reference fan and the casting fan (at the rotation speed of 2000 rpm).

5. Conclusions

From the above studies, following observations can be drawn:

- The basis and process for determining the shrinkage of fan fabricated by centrifugal casting technology was conducted.

- Shrinkage of the fan is controlled through the parameters of chord line L (mm), relative thickness E (%), and stagger angle γ (degrees). The results of the study showed that the difference was not large between the blades, which indicates the good adaptability of the axial fan received by the molding process. In addition, the results on the test stand show similarities in the performance curve, flow coefficient ϕ and pressure coefficient Ψ of the two fans. The difference in efficiency is about 1.5% (at the rotational speed of 2000 rpm) between the fan fabricated by centrifugal casting technology and the reference fan.

- The research results are the basis for the design of the molding casting into account the shrinkage of the fan

- Further research direction can be expanded with different molding conditions such as: the temperature, the heating time in the oven, the mass of powder, or the noise, and the stability of the fan compared to the reference fan. These problems will be addressed in the upcoming studies.

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Contribution of authors

Dinh Vu Dang - generated major ideas, and analyzed the data and finalized the checking of the manuscript; Hong Thang Thi Le - reviewed and edited the manuscript; Linh Viet Tran and Binh Kim Doan - collected and analyzed the data.

References

Crawford, R. J., Spence, A. G., Cramez, M. C., & Oliveira, M. J. (2004). Mould pressure control in rotational moulding. Proceedings of the Institution of Mechanical Engineers, Part B: *Journal of Engineering Manufacture*, 218(12),

Crawford, R. J. (2012*). Practical guide to rotational moulding*. Smithers Rapra.1683-1693.

Nugent, P. (2006). Rotational molding. *Handbook of Plastic Processes*, 387-453.

Pereira, M., Ravelet, F., Azzouz, K., Azzam, T., Oualli, H., Kouidri, S., & Bakir, F. (2021). Improved aerodynamics of a hollow-blade axial flow fan by controlling the leakage flow rate by air injection at the rotating shroud. Entropy, 23(7), 877.

Sarraf, C., Nouri, H., Ravelet, F., & Bakir, F. (2011). Experimental study of blade thickness effects on the overall and local performances of a controlled vortex designed axial-flow fan.

Experimental Thermal and Fluid Science, 35(4), 684-693.

Tarik, A. (2018). Aerodynamic and tip clearance flow control of an axial fan obtained with rotational molding. PhD thesis - HESAM University, Paris.

Varchola, M., Bielik, T., & Hlbocan, P. (2013). Methodology of 3D hydraulic design of a impeller of axial turbo machine. *Engineering Mechanics*, 20(2), 107-118.

https://sumitech.vn/gia-cong/gia-cong-co-khi-duc.html. (accessed 26th March 2024).

https://sellhimvs.life/product_details/37473367.html. (accessed 26th March 2024).