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# Geometric Optimization of Hydraulic Rotation Device for Neutron Transmutation Doping

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## 1. Introduction

Neutron Transmutation Doping (NTD) has become one of the key functions of a research reactor. The Korea Atomic Energy Research Institute (KAERI) is developing a Hydraulic Rotation Device (HRD) for NTD facilities (NTDHRD) as a part of the Kijang Research Reactor (KJRR) project [1]. This concept has many advantages when compared to the motor driven method, which is currently used in the HANARO research reactor located at KAERI [2]. The OPAL research reactor located at ANSTO has already applied this method [3]. To achieve a constant rotation speed, which is substantial for uniform doping, with a minimal amount of fluid flow, certain geometric requirements should be satisfied. This paper describes the approach we used while determining the number of impulse jet nozzles used to rotate the NTDHRD at a set number of blades as well as the angle of the nozzles of the NTDHRD.

## 2. Geometric optimization methods

### *2.1. Number of impulse jet nozzles*

The NTDHRD should be durable enough to keep the NTD Hydraulic Rotation System (NTDHRS) in operation without maintenance. It should be strong against radiation damage and should not produce any fragments that may harm other facilities inside the reactor and the NTDHRD itself. In addition, it should be easy to manufacture to reduce costs. For these reasons, the shape of the blades should not follow the typical shape of a turbine blade, which is thin and occasionally curved for better efficiency, and instead should be sufficiently thick and simply shaped. However, the problem of this kind of design is that the blades periodically obscure the nozzles owing to their thickness. Since it is difficult to predict or set the initial angular position of the device, it may not rotate initially owing to a lack of fluid flow when a part of the nozzles is blocked by the blades. Thus, it is necessary to evaluate the degree of this blockage effect by calculating *the area blockage ratio*, which is defined as the blocked area of nozzles divided by its total area, to optimize the number of nozzles for a set number of blades and examine the required amount of fluid flow under this condition.

#### 2.1.1. Area blockage ratio calculation

There are three cases to consider while calculating the area blockage ratio of a nozzle: a blade is positioned within the range of a nozzle, where the nozzle will be fully blocked if the blade width is larger than the cross sectional area of the nozzle at the inner cylinder wall (hereinafter referred to as $A_n$); the blade intersects the boundary of the nozzle, where a part of the nozzle will be blocked; and the blade is located outside the range of the nozzle, i.e., no blockage effect. The following correlations describe each case where $\theta_r$, $\theta_n$, and $\theta_b$ stand respectively for the rotated angle of a blade from the line where the centerlines of the blade and the nozzle meet, e.g., from Blade to Blade* in Fig. 1; the angle formed by $A_n$; and the angle formed by the width of the blade, as described in Fig. 1. It is recommended to set the range of the rotated angle, $\theta_r$, from $-(\theta_b+\theta_n)/2$ to $360°/m - (\theta_b+\theta_n)/2$, where $m$ is the number of blades. Each value of $\theta_n$ and $\theta_b$ can be calculated using trigonometric functions with predefined dimensions of the NTDHRD blades and nozzles, i.e., the radius of the rotor and the nozzle, the blade width, and the tilt angle of the nozzle, $\theta_t$, in Fig. 1, which will be further discussed in this paper. Note that Fig. 1 is drawn for an easy understanding and the actual design of the nozzles and blades should be much smaller.

- Case 1 : $|\theta_r| < |\theta_b - \theta_n|/2$
- Case 2 : $|\theta_b - \theta_n|/2 \leq |\theta_r| \leq (\theta_b + \theta_n)/2$
- Case 3 : $|\theta_r| > (\theta_b + \theta_n)/2$

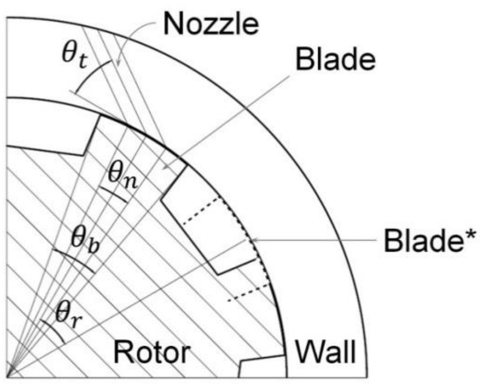


Fig. 1. Description of the angles that are used in the area blockage ratio calculation (the dashed part represents the blade after the rotation to describe $\theta_r$)

Case 2 requires some calculations to evaluate the area blockage ratio of a nozzle, whereas case 1 and case 3 are easy to determine, i.e., 1 and 0 when the nozzle is small. Since the shape of $A_n$ is an ellipse, the area blockage ratio can be calculated using Eq. 1, which is derived from the integral that calculates a segment of an ellipse divided by the whole area. The gap between the rotor and the wall was ignored and the curvature of the inner wall in the range of the nozzle was assumed to be flat.

$$\text{Area blockage ratio} = \left(\frac{2}{\pi a}\right)\int_{x_1}^{x_2}\left[1-\left(\frac{x}{a}\right)^2\right]^{1/2} \qquad (1)$$

The semi-minor axis, $b$, will be equivalent to the radius of the nozzle ($r$) and the semi-major axis, $a$, will be:

$$a = r[cos(\pi/2-\theta_t)]^{-1} \qquad (2)$$

when the nozzle is parallel to the ground. The upper and lower limit of the integral, $x_1$ and $x_2$, are:

$$x_2 = \left(\frac{2a}{\theta_n}\right)\left|\frac{\theta_b+\theta_n}{2}+\theta_r\right| - a \qquad (x_2 \le a) \qquad (3)$$

$$x_1 = x_2 - w \qquad (x_1 \ge -a) \qquad (4)$$

where $w$ is the blade width. To keep the interval within the range of the nozzle, the upper limit in Eq. 1 should be $a$ when $x_2$ is larger than $a$ and the lower limit should be $-a$ when $x_1$ is smaller than $-a$. Eq. 1 can also be applied to Case 1 when $A_n$ is larger than $w$.

2.1.2. Expansion of the method to all nozzles

To evaluate the overall area blockage ratio of the nozzles, the method introduced should be extended to every nozzle and each adjacent blade at the same time. The cylindrical wall that contains the rotor can be divided into $n$ parts where $n$ is the number of nozzles. Each part will be fan shaped with an inner angle of $360°/n$. Similarly, the inner angle formed by two neighboring blades will be $360°/m$ as defined previously. Thus, the difference between the rotated angles from each nozzle and each blade, which is facing the nozzle, will be the remainder of $(360°/n)/(360°/m)$. Here, the term, $360°$, should not be canceled since the remainder will change. Additionally, because one nozzle directly influences only the adjacent blade, at the same time, we should keep subtracting the angle with $(360°/m)$ until it becomes smaller than $(360°/m)$. For example, when $n=5$ and $m=24$, the remainder of $(360°/n)/(360°/m)$ is $12°$ and thus the angle between each nozzle and the blade facing each nozzle will be $0°$, $12°$, $9°$, $6°$ and $3°$ when the rotated angle of the first blade (the base blade) is $0°$. Note that $9°$ is derived from $(24°-15°)$, $6°$ from $(36°-30°)$ and $3°$ from $(48°-45°)$. Based on this rule and the previously introduced method, the area blockage ratio of nozzles for each rotated angle of the base blade can be calculated. The plots in Figs. 2 through 4 show several calculated results when $n=24$ and $m=5,6,7$ in Fig. 2, and when $n=32$ and $m=5,6,7,8$ in Figs. 3 and 4. The range of the rotated angle of the base blade ($\theta_r$ in Fig. 1) is set from $-(\theta_b+\theta_n)/2$ to $360°/m - (\theta_b+\theta_n)/2$ as discussed earlier. The radius of the rotor and the summation of the blade thicknesses, i.e., $m$ times $w$, were fixed in every calculation.

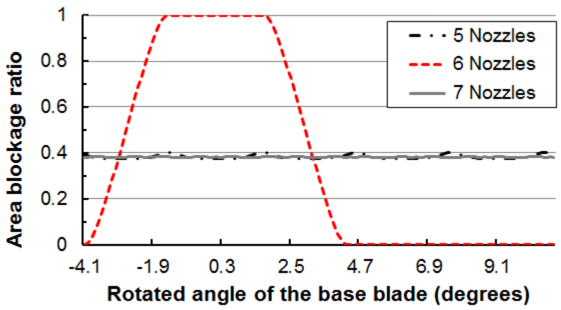


Fig. 2. Area blockage ratio of nozzles when the number of blades is 24 ($A_n$ is smaller than the blade thickness)

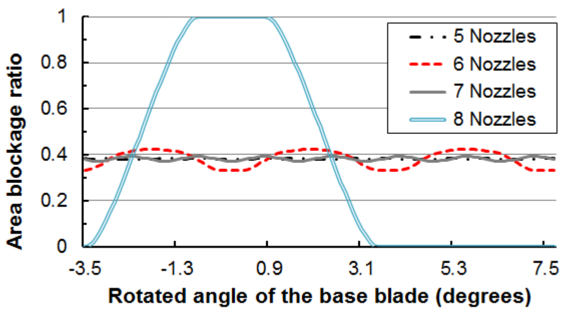


Fig. 3. Area blockage ratio of nozzles when the number of blades is 32 ($A_n$ is smaller than the blade thickness)

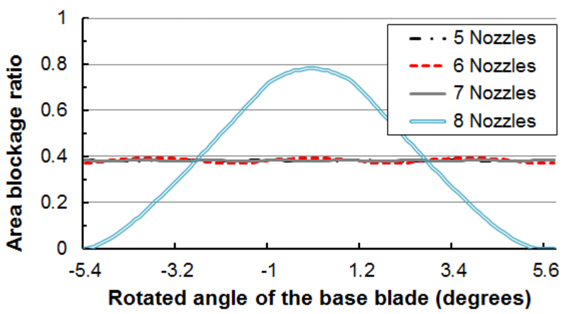


Fig. 4. Area blockage ratio of nozzles when the number of blades is 32 ($A_n$ is larger than the blade thickness)

The results show that one should avoid setting the number of nozzles to a divisor of the number of blades, i.e., $m$ should not be $6$ when $n$ is $24$ in Fig. 2 and $m$ should not be $8$ when $n$ is $32$ in Figs. 3 and 4. Otherwise, the area blockage ratio can reach a significant level. The nozzles can also be fully blocked when $A_n$ is smaller than the blade, and as a result, the NTDHRD will not be able to rotate at all. This is because the remainder of $(360°/n)/(360°/m)$ is zero in this case, and thus the relative positioning of each nozzle and each influenced blade becomes the same. Conversely, when $m$ is not a divisor of $n$, the plots of each area blockage ratio become quite uniform, which allows one to predict the required amount of fluid flow, e.g., all three cases will require about *40%* more fluid flow than the original value, which is calculated without considering the blockage effect. In addition, although the shape of the plots in the three figures were different when $m$ was a divisor of $n$, the area blockage ratio were almost the same regardless of the difference in the number of nozzles, the size of $A_n$ and the number of blades in other cases. This allows us to flexibly choose the number of nozzles and setting it to a divisor of *360˚* will be more desirable, i.e., $n=5$ will be better than $n=7$ in Fig. 2, when considering the manufacturing aspects.

### *2.2. Tilt angle of impulse jet nozzles*

The tilt angle of impulse jet nozzles ($\theta_t$ in Fig. 1) determines the torque, induced by the rotor, in addition to the amount of inlet fluid flow. It is clear that the direction of the inlet flow should be perpendicular to the blade in order to achieve the best efficiency. However, since the width of a groove is usually larger than that of a nozzle because a narrow groove will increase the pressure drop and thus the groove should be wide enough to take in all the incoming fluid, this moment should happen at the end of a cycle, i.e., when the edge of the next blade starts to intersect the nozzle. Otherwise, a portion of fluid will head toward the outside direction after hitting the blade and leak through the gap between the rotor and the inner cylinder wall. However, although these requirements are conceptually acceptable, a CFD analysis should be performed for verification.

## 3. Conclusions

The approach that our group has used to geometrically optimize the design of a NTDHRD was described. The adaptation of this approach allows one to predict the required amount of inlet fluid flow and to determine the number of nozzles based on the rule that it should avoid being a divisor of the number of blades, and provides a reference while determining the tile angle of the nozzles. A CFD analysis will be performed as a future study.

## ACKNOWLEDGEMENT

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