≪Research Paper≫ Applied Science and Convergence Technology Vol.24 No.5, September 2015, pp.136~141
http://dx.doi.org/10.5757/ASCT.2015.24.5.136

# Compact Anode Design with the Heat Capacity Performance in Rotating Anode X-ray Tube for Digital Radiography

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(Received September 21, 2015, Accepted September 30, 2015)

We studied the compact anode design to develop 100 kW rotating anode X-ray tube with large focal spot 1.2 mm, small focal spot 0.6 mm and tube voltage 150 kV for large hospital digital radiography using computer thermal simulation. The larger thermal radiation effect in a high vacuum can reduce the temperature of anode so the method to increase the surface area of anode is investigated. The anode has the multi-tier shape at the back side of TZM body of anode and also bigger diameter of anode. The number of multi-tiers was varied from 6 to 15 and the diameter of anode was also varied from Φ74 to Φ82. From ANSYS transient thermal simulation result, we could obtain 1056.4°C anode maximum temperature when applying 100 kW input power at 0.1 second on target focal track which is less than 1091°C of the conventional 75 kW X-ray tube with reduced anode weight by 15.5% than the conventional anode. The compact anode of reduced anode weight is able to improve the unwanted noise when the rotor is rotating at high-speed and also reduce the rotational torque which the cost effective stator-coil is possible. It is believed that the anode with 15 ea multi-tiers using Φ82 can satisfy with the specification of the anode heat capacity. From the results of this paper, it has been confirmed that the proposed compact anode can be used as the anode of 100 kW rotating anode X-ray tube for digital radiography.

Keywords : X-ray tube, Rotating anode, Heat capacity, Stator-coil, Thermal characteristics

## I. Introduction

X-ray tube for generating X-rays, one of the core components of Medical Digital Radiography (DR) used in the early diagnosis of the patient disease, is increasing in demand. Especially X-ray tube used in many large hospitals should endure to exposure continuously at a short interval due to many patients' usage so the replacement cycle time of the X-ray tube has to be shortened.

Medical X-ray tube for generating X-rays consists of the cathode filament to emit the bundle of thermal electrons, the anode to generate X-rays by accelerating electrons and the glass bulb to keep in high vacuum ($10^{-7}$ torr). The anode consists of body made of TZM alloy (Titanium 0.50% Zirconium 0.08% and Carbon 0.02% with the balance Molybdenum) and the umbrella shaped target made of the Tungsten containing the Rhenium 3～10%. The target focal track surface collided with the high accelerated electron beams is connected

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to the anode and rotor rotating up to 9,700 rpm in the high speed to prevent damage to the target surface due to the increase of up to 2,600°C [1-5].

In case of high frequency of use of the X-ray tube such as a large hospital, it requires the anode which has a high cooling rate. The common solution to get it is to increase the volume of the anode as shown in Table 1.

But the anode weight should be also increased so the load of the rotor in high-speed rotation is more added. Therefore, X-ray tube needs the stator-coil with higher rotational force (torque) and increased the unwanted noise as well.

In this paper, we propose the new anode design that has high heat contents by enhancing the cooling rate while minimizing the increase in weight of the anode for 100 kW X-ray tube. This can get designing the anode shape to improve the effect of thermal radiation by increasing the surface area while maintaining its volume by using ANSYS transient thermal analysis for one shot exposure in X-ray tube. From this simulation results, we propose the compact anode design with less-weight for the 100 kW rotating anode X-ray tube.

## II. Thermal Simulation of Rotating X-ray Tube

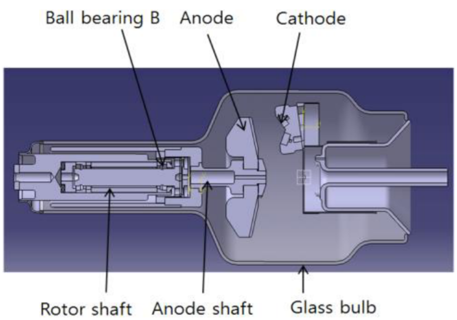
### 1. Simulation condition

Fig. 1(a) shows the 3D modeling schematic diagram of 75 kW rotating anode X-ray insert tube for simulating which has 1.2 mm large focal spot, 0.6 mm small focal spot and 150 kV maximum tube voltage. After improving the anode heat capacity in 75 kW X-ray insert tube, it will be applied to 100 kW rotating anode X-ray tube. Anode consists of the umbrella shaped target which the electron beams impact and body. The target is made of Tungsten (W) and Rhenium (Rh) of 1 mm thickness is boned TZM alloy body which has a 12 degree inclination angle by using diffused junction method. In order to increase thermal radiation of anode, back side of TZM is added the plasma black coating. Rotor has the ball bearing made of special steels. The width of focal track surface in Fig. 1(b) is defined 10 mm considering the filament length for large focal spot and ANSYS transient thermal analysis simulation was carried out using this focal track surface applied input power 75 kW in the rotating anode X-ray insert tube.

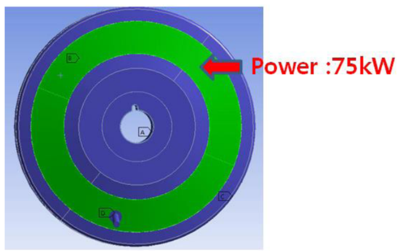
The material properties of each part such as thermal conductivity and radiation emissivity were defined. In case of anode, thermal conductivity of TZM and Tungsten was 130 W/mK and 174 W/mK, respectively.

Table 1. Anode specifications.

| Max. output [kW] | Anode heat capacity [kHU] | Anode weight [g] | Focal spot [mm] |
|---|---|---|---|
| 47 | 140 | 320 | 2.0/1.0 |
| 75 | 300 | 680 | 1.2/0.6 |
| 100 | 400 | 830 | 1.2/0.6 |




(a)




(b)

Figure 1. (a) Schematic diagram of rotating anode X-ray tube. (b) Focal track applied input power.

Radiation emissivity of TZM, Tungsten and the back side of TZM (black coating surface) was 0.15, 0.1 and 0.95, respectively. The simulation results when one-shot condition with 75 kW input power at 0.1 second in rotating X-ray tube are shown in Fig. 2.

The heat flux in focal track surface was radiated to glass bulb by radiation emissivity of the anode surface. A few heat fluxes were conducted to rotor along anode shaft (Molybdenum) connected back side of anode and also transmitted to glass bulb along KOVAR.

When temperature occurred between two different surfaces without any intermediate medium, heat transfer in the form of electromagnetic waves takes place by thermal radiation as shown in equation (1). Even though thermal conductivity of the components of X-ray tube in high vacuum condition was already defined when material of parts was determined, the temperatures of parts after treating the surface of parts could be decreased by increasing radiation emissivity of heat flow $Q_R$ in equation (1) [6].

$$Q_R = \sigma \varepsilon FA(T^4_{surface} - T^4_{ambient}) \tag{1}$$

Where σ is Stefan-Boltzman constant, ε is emissivity, A is area of radiating surface, T is temperature of object and F is form factor. A form factor F describes in equation (2) how well one object can see another object. The form factor may take on a value from zero to unity. ANSYS can support to calculate it using many methods [7].

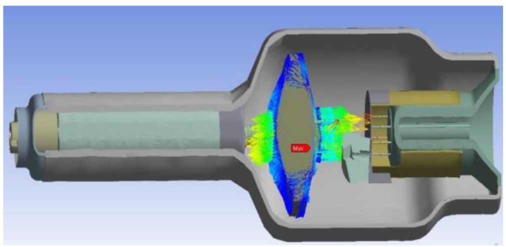


Figure 2. Heat flux distribution of X-ray insert tube by thermal simulation.

$$\mathrm{F}F_{12} = \frac{1}{A_1}\iint \frac{cos\theta_1 \cos\theta_2}{\pi r^2_{12}} dA_1 dA_2 \tag{2}$$

Where A is area of radiating surface, r is the length between two objects and $\theta$ is the angle from r vector to perpendicular vector of the object.

## 2. Rotating anode design

As can be seen from equation (1), heat flow by radiation is closely related to the area of radiating surface A and emissivity ε. If the plasma black coating on back side of TZM body in anode is applied, its emissivity can be increased from 0.15 to 0.95. So in this paper, TZM body structure is added multi- tiers and also increased the diameter to enlarge the surface area of plasma black coating as shown in Fig. 3.

The multi-tiers were applied to the back side of TZM excepting bonded area with Tungsten. The length, width and height of multi-tiers were 15 mm, 0.4 mm and 0.6 mm, respectively. Table 2 shows surface area change ratio and weight of anode according to the number of multi-tiers.

When multi-tiers were varied from 6 ea to 15 ea, the surface area of anode back side were increased 115~134.9% while anode weight was decreased to 2.4~3% compared to non-multi-tiers.

In order to obtain the more large areas to install the multi-tiers, the diameter of anode is also varied

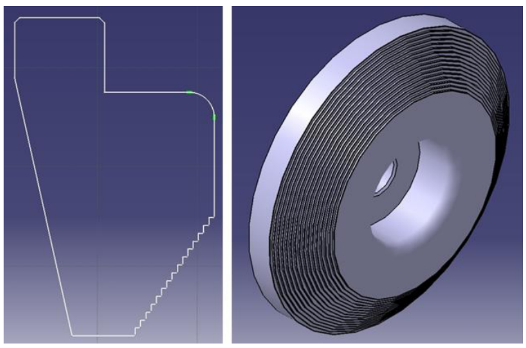


Figure 3. Anode design with multi-tiers at the back side of TZM body.

from Φ74 to Φ82 as Table 3.

## 3. Anode temperature according to multi-tiers and anode diameters

The ANSYS transient thermal simulation results when one-shot condition with 75 kW input power at 0.1 second for rotating anode X-ray tube using the anode design based on Table 2 and 3 are shown in Table 4, 5 and Fig. 4.

Table 4 shows that anode maximum temperature according to the number of multi-tires can decrease 6.2%~12.7% compared to that of non-multi-tiers. Table 5 shows that to Φ82 diameter of anode can also reduce 5.3% compared to that of Φ74.

These results could be obtained that the thermal radiation effect was improved due to increased surface area including multi-tiers having similar volume. As the results, if these anode design concepts apply to 100 kW rotating anode X-ray tube, it is possible to get the desired anode heat capacity while suppressing increase of anode.

Table 2. Surface area ratio of anode back side compared to on non-multi-tiers and anode weight.

| Number of multi-tires | Surface area ratio of anode back side [%] | Anode weight [g] |
|---|---|---|
| Non | 100 | 676 |
| 6 ea | 115.0 | 660 |
| 9 ea | 121.6 | 658 |
| 12 ea | 128.3 | 657 |
| 15 ea | 134.9 | 656 |

Table 3. Surface area ratio of anode back side according to the diameter of anode.

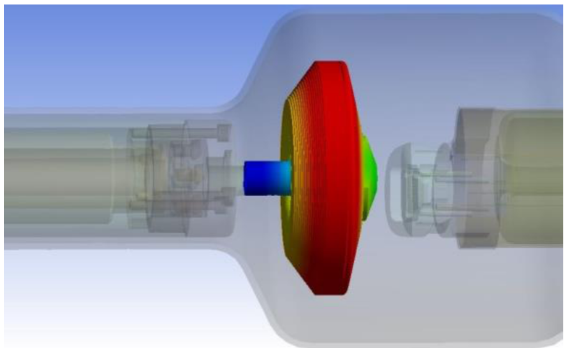
| Anode diameter (mm) | Surface area ratio of anode back side [%] | Anode weight [g] |
|---|---|---|
| Φ74 | 100 | 676 |
| Φ82 | 115.3 | 683 |

Table 4. Anode maximum temperature vs. number of multi-tiers of anode back side.

| Number of multi-tires | Anode max. temperature [°C] | Ratio of anode max. temperature [%] |
|---|---|---|
| Non | 1091 | 100 |
| 6 ea | 1023.9 | 93.8 |
| 9 ea | 1010.5 | 92.6 |
| 12 ea | 998.5 | 91.5 |
| 15 ea | 952 | 87.3 |

Table 5. Anode maximum temperature vs. diameter of anode.

| Anode diameter (mm) | Anode max. temperature [°C] | Ratio of anode max. temperature [%] |
|---|---|---|
| Φ74 | 1091 | 100 |
| Φ82 | 1033 | 94.7 |



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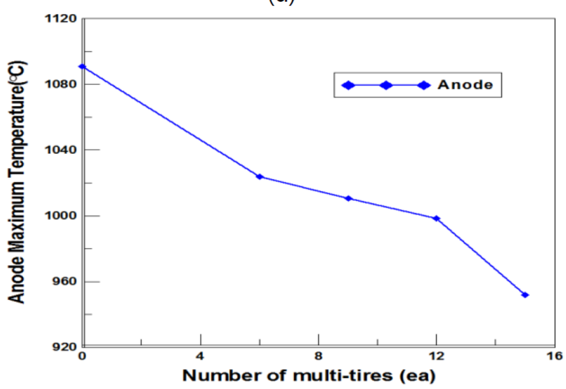


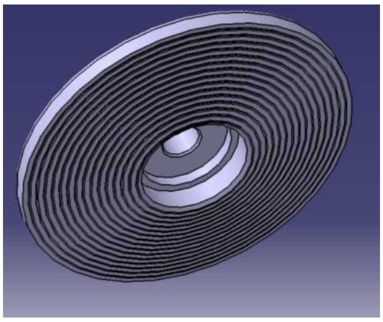

(b)

Figure 4. (a) Temperature distribution of anode in thermal simulation (b) Anode temperature according to the number of multi-tiers at anode back side for one shot exposure in X-ray tube.

## III. Results and Discussion

The anode of 100 kW X-ray tube was designed using concepts of multi-tiers of anode back side and bigger diameter of anode as shown in Fig. 5(a). The anode has 15 ea multi-tiers on its back side using Φ90 diameter of anode.

Fig. 5(b) shows that the anode maximum temperature at input power 100 kW 0.1 second for one shot exposure condition is about 1056.4°C which is a little less than 1091°C of the conventional 75 kW X-ray tube. Especially the anode weight could be reduced approximately 15.5% from 830 g to 702 g. This result can be improved the unwanted noise when the rotor is rotating at high speed by reduced anode weight for 100 kW rotating anode X-ray tube.



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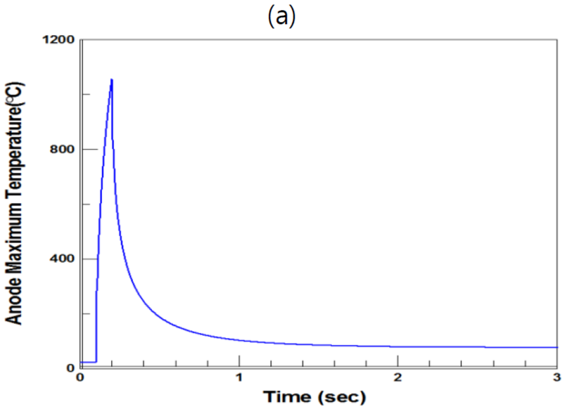


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Figure 5. (a) Anode design result (b) Anode maximum temperature at 100 kW X-ray tube.

## IV. Summary

In this paper, we studied the compact anode design to develop 100 kW rotating anode X-ray tube with large focal spot 1.2 mm, small focal spot 0.6 mm and tube voltage 150 kV for large hospital digital radiography. The larger thermal radiation effect in a high vacuum can reduced the temperature of parts. It could obtain by increasing the surface area of anode back side so the anode had the multi-tier shape at the back side of TZM body of anode and also bigger diameter of anode. The number of multi-tiers was varied from 6 to 15 and the diameter of anode was also varied from Φ74 to Φ82.

From ANSYS transient thermal simulation result, we obtained characteristic of anode heat capacity, the anode maximum temperature 1056.4°C, less than 1091°C of the previous 75 kW X-ray tube when applying 100 kW input power at 0.1 second on target focal track with reduced anode weight by 15.5% than the conventional model.

The compact anode of reduced anode weight is able to improve the unwanted noise when the rotor is rotating at high-speed and also reduce the rotational torque which the cost effective stator-coil is possible.

The simulation result could be utilized the development of the compact 100 kW rotating anode X-ray tube later.

## Acknowledgements

This research (2014105037) was supported by Business for Cooperative R&D between Industry, Academy, and Research Institute funded Korea Small and Medium Business Administration in 2014.

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