Thermal analysis on x-ray tube for exhaust process

Rakesh Kumar¹, Srinivas Rao Ratnala², Veeresh Kumar G B³ and P S Shivakumar Gouda⁴

¹Department of Mechanical Engineering, SDMCET, Dharwad, Visvesvaraya Technological University, Belagavi, India.
²Department of X-Ray Tube Engineering, GE BE Private Limited, Bangalore, India.
³Department of Mechanical Engineering, Amrita School of Engineering, Amrita Vishwa Vidhyapeetam, Amrita University, Bangalore Campus, India.

E-mail: rakhi0216@gmail.com

Abstract. It is great importance in the use of X-rays for medical purposes that the dose given to both the patient and the operator is carefully controlled. There are many types of the X-ray tubes used for different applications based on their capacity and power supplied. In present thesis max1 ray 165 tube is analysed for thermal exhaust processes with ±5% accuracy. Exhaust process is usually done to remove all the air particles and to degasify the insert under high vacuum at 2e-05Torr. The tube glass is made up of Pyrex material, 95% Tungsten and 5% rhenium is used as target material for which the melting point temperature is 3350⁰C. Various materials are used for various parts; during the operation of X-ray tube these waste gases are released due to high temperature which in turn disturbs the flow of electrons. Thus, before using the X-ray tube for practical applications it has to undergo exhaust processes. Initially we build MX 165 model to carry out thermal analysis, and then we simulate the bearing temperature profiles with FE model to match with test results with ±5% accuracy. At last implement the critical protocols required for manufacturing processes like MF Heating, E-beam, Seasoning and FT.

1. Introduction

X-ray machines are utilized as a part of therapeutic imaging field for envisioning the degree and area of sickness on bone structures and other thick tissues. The two fundamental fields are Radiography, which is utilized for quick and exceptionally entering pictures of high bone substance and Fluoroscopy, which is utilized to get genuine time perception of veins of human body. A portion of the uses of X-ray machines are Mammography, Renal reviews, Extremity exams, Chest x-rays and Dental reviews. By R. C. Robinson and C.N. Moore on the ‘Manufacture of the Coolidge x-ray tube said that, The Coolidge x-ray tube is presently made in the two distinct sorts, Universal and Radiator. (For a portrayal of these and their method of operation the reader is refereed to different publications which have been issued during recent years. The procedure of manufacturing of this tube might be isolated into the following steps:
1. Preparation of the Metal Parts.
2. Assembly of the X-ray Tube.
3. Exhaust of the assembled tube.
4. Testing X-ray Tubes.

The primary operation in the exhaust comprises of heating the tube to around 400°C. for seventy five percent of 60 minutes. This heating evacuates water-vapor, carbon dioxide and different gasses from the glass and metal parts. Subsequent to cooling the tube is associated with a x-ray machine and worked as a x-ray tube. For the early phases of the gasses, a machine is utilized which is arranged to the point that it works consequently, passing simply enough current through the tube to drive out the
gasses at a rate at which it can be expelled by the exhaust framework.[1] Seok Moon Lee findings on “Thermal Characteristics and Compact Anode Design with the Heat Capacity Performance in Rotating Anode X-ray Tube with Emissivity in Aging Process for Digital Radiography” to get a long life of anode target as well as x-ray tube and to develop 100 kW rotating anode x-ray tube with different focal spot sizes of 1.2 mm, 0.6 mm and tube voltage of 150 kV for large hospital digital radiography. Based on the larger thermal radiation effect in a high vacuum can reduce the temperature of anode, the method to increase the surface area of anode is investigated. He also investigated the relationship between the diameter of the anode shaft and the temperature of the anode and rotor assembly. And it has been confirmed that the smaller anode shaft could be good for the rotor thermal characteristics. [2 &3] Deficient cooling of an X-ray tube can make it flip in two ways. The first is sublimation of the anode target material. In changing over the anode target material Straight forwardly from a strong to a gas (sublimation), the subsequent vapor quickly corrupts the inside high vacuum vital for legitimate operation on the X-ray tube. The loss of high vacuum brings about a disappointment of the X-ray tube to withstand the high voltage current between the cathode electron source (helical tungsten fiber) and the target anode. The second failure mode brought about by improper heat scattering is the liberation of harming ions. If the X-ray tube anode is permitted to surpass the vapor pressure point of the target material, ions will be liberated. These ions are pulled in back toward the helical tungsten filament and start to erode the filament through an ion scrubbing process. This can cause filament to break, making an open circuit [4] Liqin W, Michael S. H, Mark D, R. K. Hockersmith findings on “Electron collector system” for an x-ray tube of both anode and cathode internal bore for receiving x-rays from anode target. It additionally incorporates a window opening is reaching out from the window locale to interior exhaust. Plastic strain on the window and warmth exchanged to the window are lessened. [5] Many research papers were protected on X-ray tube. Some of them have researched on X-ray tube parameters to radiation, Conservative plan and outline enhancement of turning anode of x-ray tube a few are examined on cooling of X-ray tube by discoveries on Fly cooled framework, Electron authority frameworks and strategies, and in area cooling framework. There are many difficulties in outlining the X-ray tube with increment in rate of cooling for its assortment of utilizations. Consequently, numerical strategy like heat – auxiliary examination is required in investigating the heated conduction in x-ray tube. So before assembly of the tube, there are various steps in exhaust process which have been carried out on the X-ray tubes to remove all air particles, moisture content and waste gases under high vacuum. So here in the present work, we analyze the thermal characteristics of the target and rotor assembly according to their emissivity by using ANSYS transient thermal simulation, and then compare with the measured data i.e., the protocols given for various exhaust process like MF Heating, E-beam, Seasoning and FT are matched with the simulation results under transient conditions using Ansys workbench with ±5% accuracy.
2. Materials and its Thermal Properties

| Materials          | Density Kg/m³ | Specific heat J-Kg-k | Thermal conductivity W/m-k | Emissivity |
|--------------------|---------------|----------------------|---------------------------|------------|
| Kovar              | 8370          | 440-649              | 16-25                     | 0.33       |
| Pyrex              | 2230          | 753.5-0.1            | 0.88-0.1                  | -          |
| OFHC               | 8950          | 388-477              | 391-335                   | 0.8        |
| 1010Steel          | 7920          | 427-1181             | 57.6-36.7                 | 0.3        |
| Glidcop Al60       | 8810          | 388-477              | 322-270                   | 0.2        |
| T5 Tool steel      | 8170          | 411-677              | 24.3-27.7                 | 0.5        |
| 410 Stainless steel| 7750          | 460-897              | 25-28                     | 0.3        |
| Molybdenum         | 10200         | 262-394              | 140-104                   | 0.18       |
| Inco718            | 8200          | 429-559              | 11-20                     | 0.2        |
| Haste alloy        | 9230          | 361-605              | 11-27                     | 0.2        |
| TZM                | 10300         | 361-605              | 125-67                    | 0.18       |
| Graphite           | 1850          | 707-2067             | 126-11(orthotropic)        | 0.85       |
| W-5Re              | 19400         | 134-171              | 77-89                     | 0.1        |

3. Analytical Model Geometry

MX 165 insert thermal FE model validation is done by building the model of mx 165 to carry out thermal analysis then simulating the bearing temperature profiles with model to match with test results (±5% accuracy) and at last perform the critical protocols required for manufacturing process (Exhaust Process) like E-beam/MF heating process, seasoning Process and FT process.

![Figure 1. Mx165 insert thermal 2D model with parts](image)
Table 2 gives the component temperatures specified are maximum allowable operating values that ensure acceptable insert operation and maximum tube life. The critical temperatures are provided as guidelines that should not be exceeded during insert processing in exhaust conditioning, and functional test.

4. FE element modelling

Figure 2 shows the meshed model of x-ray anode tube There are four settings considered for mesh modelling of X-ray anode tube assembly as per below,
1) Element mid-side nodes: Dropped
2) Size function: Proximity and curvature
3) Body sizing: Relevance centre- Fine
4) Advanced setting: Shape checking- Aggressive mechanical

5. Heat load Boundary conditions for MF, E-Beam, and Seasoning Process

Figure3. MF production
Figure4. E-beam/ seasoning production
Figure 3 gives the clear view of the heating of the target above using induction coil. In practice MF heating is done from temperature 900\(^\circ\)c to 1150\(^\circ\)c ± 25\(^\circ\)c. Given Protocols are applied on the target according to heating time and cooling time in seconds. E-beam and seasoning process is done on the track in order to remove the amount of moisture content and to degasify the track from unwanted gases under high vacuum.

Figure 4 gives the amount of heat load applied on the track, we can predict from figure 90% of the heat is applied on the track and remaining 10% is distributed above and below the target. Because this is the major portion where electrons strike the target.

5.1 Analytical Model Convection and Radiation

Figure 5. HTC and Emissivity values on the different parts of the tube

Figure 5 gives the estimation of heat transfer co-efficient changes for the distinctive portions; this is because of rate of the heat produced by x-rays during the operation.

| Parts       | Particulars         | HTC Value( W/m\(^2\)\(^\circ\)C) |
|-------------|---------------------|----------------------------------|
| A           | Stem- Kovar         | 50                               |
| B           | Rotor region        | 50                               |
| C           | Slant region        | 260                              |
| D           | Centre region       | 250                              |

Table 3 gives the different HTC values on the different regions. Region C is glass target there the convection is given more and area D is glass center which is additionally nearer to target, so when x rays are radiated, those rays strike to these two regions more than the region A and B.

| Parts | Particulars       | HTC Value( W/m\(^2\)\(^\circ\)C) |
|-------|-------------------|----------------------------------|
| A,C,D | Over frame        | 300                              |
| B     | Rotor/stator gap  | 200                              |

Table 4 shows the list of HTC values for seasoning and FT process. From comparing the table 3.0 the values of HTC are more this is because seasoning and FT process is done at high temperature.
6. Results and Discussion

6.1 Thermal Results for MF Heating

Figure 6 gives the simulation temperature profile for MF Heating process. From the simulation we can perceive how the heat is circulated over the model. High temperature is at above target and least temperature is close anode sleeve.

Figure 7 describes the direct correlation between the tested and simulation results on target, front bearing and rear bearing for peak temperature.

Table 5. Comparison of tested v/s simulation results for MF

| Cycle     | FBIR Test | FBIR Simulation | %Error | RBIR Test | RBIR Simulation | %Error | Target Test | Target Simulation | %Error |
|-----------|-----------|-----------------|--------|-----------|-----------------|--------|-------------|-------------------|--------|
| 900°C ±25°C | 271       | 281             | 3.69   | 151       | 158             | 4.63   | 904         | 901               | 0.33   |
| 1000°C ±25°C | 318       | 312             | -1.88  | 180       | 179             | -0.55  | 1004        | 995               | 0.89   |
| 1100°C ±25°C | 378       | 364             | -3.79  | 224       | 213             | -4.91  | 1150        | 1153              | -0.26  |
Table 5 gives the error estimation of temperature between tested and simulation results on target, front bearing and rear bearing for different heat inputs.

6.2 Thermal Results for E-beam

Figure 8 gives the simulation temperature profile for E-beam process. From the simulation we can perceive how the heat is circulated over the model. High temperature is at target and least temperature is close anode sleeve.

Figure 9 gives the direct relationship between the tested and simulation for E-beam process.

Table 6. Verification data match with test results

| Cycle   | Target test | Target Simulation | %Error |
|---------|-------------|-------------------|--------|
| 1150°C  | 1139        | 1151              | 1.05   |
| 1200°C  | 1173        | 1191              | 1.54   |

Table 6 gives the error estimation of temperature amongst tested and simulation comes about on target for various heat inputs. Following list gives temperature predictions at critical regions of bearing during E-beam.
• Maximum bearing temperature=344°C(<480°C)
• Maximum focal spot temperature=1561°C(<2540°C)
• Maximum track temperature=1358°C(<1800°C)
• Maximum target braze joint=1268°C(1495°C)
• Maximum stud/Hub braze joint=817°C(850°C)

6.3 Thermal Results for Seasoning

Figure 10 gives the simulation temperature profile for seasoning process. From the simulation we can perceive how the heat is circulated over the model. High temperature is at target and least temperature is close anode sleeve.

Figure 11 gives the simulation results on Track, Focal spot and Target for peak temperature for seasoning protocols specified. Below list gives the temperature predictions at critical regions of bearing during seasoning. Here we can see almost the simulated temperatures are nearer to the maximum operated temperatures this is because seasoning is done at very high temperatures to remove all the unwanted gases.
• Maximum bearing temperature= 377°C(<480°C)
• Maximum focal spot temperature=2454°C(<2550°C)
• Maximum track temperature=1720°C(<1800°C)
- Maximum target braze joint=1486°C(<1495°C)
- Maximum stud/Hub braze joint=908°C(<850°C)

6.4 Thermal Results for FT (Functional test)

**Figure 12.** Simulated temperature profile at maximum target for FT

*Figure 12* gives the simulation temperature profile for FT process. From the simulation we can perceive how the heat is circulated over the model. High temperature is at target and least temperature is close anode sleeve.

**Figure 13.** Simulated temperature variations on critical regions for FT

*Figure 13* gives the simulation results on RBIR, FBIR, target and track for peak temperature for FT protocols.

Following list gives the temperature predictions at critical regions during Functional test.
- Maximum bearing temperature=203°C(<480°C)
- Maximum focal spot temperature=2335°C(<2540°C)
- Maximum track temperature=1298°C(<1800°C)
- Maximum target braze joint=1056°C(<1495°C)
- Maximum stud/Hub braze joint=545°C(<850°C)
Conclusion

Following are the conclusions drawn from the above work
✓ MX-165 Thermal Model is validated with ±5% accuracy
✓ Critical component temperatures are within the design criteria as defined by the TST
✓ E-beam and seasoning protocol temperatures are predicted using validated thermal model and all the critical temperatures are within the acceptable limits.
✓ Comparison of focal spot temperatures for min., nominal, maximum target speeds.

Scope for further work

By considering the above work we can predict the amount of temperature developed in major parts like Target, focal spot, front bearing and rear bearing etc. In the present work we used ball bearing, for further improvement we can replace ball bearing with liquid metal bearing so that the temperature distribution near bearing may decrease and also we can reduce the noise level.

Acknowledgements

I take this opportunity to thank our Principal, HOD Mechanical SDMCET, and Deputy Dean CIII Dharwad for allowing me to work in GE BEL Private Limited, Bengaluru.
I would like to express my sincere special thanks to associated employees of GE BE Private limited, Bengaluru for constant support & encouragement to this thesis.

References

[1] “Manufacture of the Coolidge X-Ray Tube” By R. C. Robinson and C.N. Moore

[2] S M Lee, Thermal characteristics of rotating anode x-ray tube with emissivity in aging process for digital radiography Applied Science and Convergence Technology, Volume 24, No.5, Pages 125-131, September 2015.

[3] S M Lee, Compact anode design with the heat capacity performance in rotating anode x-ray tube for digital radiography Applied Science and Convergence Technology, Volume 24, No.5, Pages 136-141, September 2015

[4] Heat,https://www.oxford-instruments.com/OxfordInstruments/media/x-ray-technology/application-notes/Managing-the-Heat-Produced-by-X-ray-Tubes.pdf

[5] Liqin W, Michael S H, Mark D and R K Hockersmith, Electron collector system United States Patent. Patent No: US 6,980,628 B2, December 2005.