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Design, analysis and testing of x-ray tube for next generation x-ray machines

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Abstract. A conceptual design of x-ray metal tube frame assembly is done to establish the technical feasibility and characterize the performance of a base design of x-ray metal tube frame assembly to meet the experimental critical to qualities (CTQ's) of x-ray tube at 72 kW for 20 seconds. Experimental test configuration with linear variable differential transformers (LVDT's) & thermo-couples is set to study the thermal prediction of x-ray tube with model results. Graphs of temperature versus time and deflection versus time shows curve shape magnitudes within 5% and 1%. A thermal – structural analysis is considered in analyzing the thermal – structural behavior in x-ray metal tube by considering worst protocol as 3.2 kW in steady state condition and 14.4 kW in transient state condition for 30 seconds. This analysis is done by doing a conceptual design of x-ray metal tube frame assembly with major modifications in frame and electron collector based on thermal – structural results. 3D modelling of x-ray metal tube frame assembly is done in Creo parametric 2.0 CAD software and analysis is done in ANSYS 16.1 simulation software. FEA results of conceptual design are in good agreement with CTQ's results of x-ray tube at 72 kW for 20 seconds.

1. Introduction

X-ray machines are used in medical imaging field for visualizing the extent and location of disease on bone structures and other dense tissues. The two main fields are Radiography, which is used for fast and highly penetrating images of high bone content and Fluoroscopy, which is used to get real-time visualization of blood vessels of human body. Some of the applications of X-ray machines are Mammography, Renal studies, Extremity exams, Chest x-rays and Dental studies.

The X-ray technique is one of typical human body diagnostic techniques. It depends on the range of radiation given to the object intern X-ray radiation depends primarily upon the X-ray tube current, tube voltage, and exposure time. D. Tilak Raju and K. Shanthi finds on Analysis on "X-ray Tube Parameters of Exposure by Measuring X-ray Tube Voltage and Time of Exposure" helps to diagnose and has some hazardous health effects upon human exposure or the tissue which is being irradiated. [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 1.2mm, 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]

Mihye Shin, Prasheel Lillaney, Waldo Hinshaw and Rebecca Fahrig findings on "Design optimization of MR-compatible rotating anode x-ray tubes for stable operation" to analyze dynamic characteristics to identify possible modes of mechanical failure to check the stability and safety of the motor operation. [4]

Madhusudhana T. S, Carey S. R, Michael J. P. invention on "Jet Cooled X-ray tube window and Chilled beam x-ray tube window" to provide window cooling assembly for an x-ray tube. This cooling assembly contains electron collector body, x-ray tube window and first coolant circuit. Here coolant circuit includes an inlet and outlet for direct the coolant fluid as refrigerant at an x-ray tube window surface to cool the surface. [5 & 6]

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 also includes a window aperture is extending from the window region to internal bore. Plastic strain on the window and heat transferred to the window are reduced. [7]

Madhusudhana T. S, Michael S. H, Gregory A. S. invented on "Structure for collecting scattered electrons" includes two sided first, second plates, fluid inlet and outlet. This structure is capable to absorb scattered electrons and transfer thermal energy to the electrons. [8]

Carey S. R, Shawn, Rogers finds "Electron absorption apparatus for an X-ray device". It is a shield assembly for an x-ray tube which includes a radiation shielding layer and thermally conductive layer. It also consists of electron absorption layer which absorbs backscattered electrons. [9]

Madhusudhana T. S, Michael S. H, Gregory A. S. findings on "System and Method for collecting backscattered electrons in an X-ray tube" consists of first & second plates, an internal member, fluid inlet & outlet. Here internal member is placed between the first and second plates, includes an internal conduit for conveying a heat absorbing cooling fluid through it. [10]

D. L. Warburton, Jason W. D, Gregory C. A. invented on "X-ray tube cooling system" to obtain x-ray tube housing includes a tube frame, window. Tube housing defines an aperture through which first electron can pass from cathode to anode then generate x-ray can pass through window opening area. Here tube housing and window frame are designed such that a liquid can flow from the inlet to outlet port by either a first liquid path or a second liquid path. [11]

Gregory C. Andrews, findings on "Evacuated enclosure window cooling" for evacuated enclosure window which includes first and second axes. The first axis is relatively shorter than the second axis. Here x-ray tube consists of directing coolant flow system. This means for directing coolant across an exterior surface of the evacuated enclosure window in a direction parallel to the first axis to cool it. [12]

Many research papers were patented on X-ray tube. Some of them have investigated on X-ray tube parameters to radiation, Compact design and design optimization of rotating anode of x-ray tube; some are investigated on cooling of X-ray tube by findings on Jet cooled system, Electron collector systems & methods, and Evacuated enclosure cooling system. There are many challenges in designing the X-ray tube with increase in rate of cooling for its variety of applications. Therefore numerical technique like thermal – structural analysis is needed in analyzing the heat transfer behavior in x-ray tube.

In the present work, a conceptual design with positioning of the window away at the end of collector and tapered electron collector design is done to establish the technical feasibility and characterize the performance of a base design of x-ray metal tube frame assembly to meet the experimental CTQ's of X-ray tube at 72 kW for 20 seconds. A numerical technique like thermal – structural analysis is considered in analyzing the thermal - structural behavior in x-ray metal tube by considering worst protocol as 3.2 kW power in steady state condition and 14.4 kW average power in transient state condition for 30 seconds. This analysis is done by doing 4 sets of conceptual designs of x-ray metal tube frame assembly with major modifications in frame and electron collector based on thermal – structural results.

2. Materials and its properties

Materials are so important in development of material science, it allows to designing a new materials and providing a knowledge base for the materials engineering. Innovation in engineering materials require engineers to understand the concepts of material science & engineering, it enables the engineers to select a material for a given application based on cost effectiveness & performance, understand the limits of materials & change of their properties with use, create a new material that will have a desirable properties, and use of material for different applications.

2.1. Identified materials

Figure 1 shows x-ray metal tube envelope and identified materials for respective parts of tube envelope are Window-Beryllium, Electron collector-OFHC Copper, Frame – 304L Stainless steel and Back plate & Cathode side frame-304L Stainless steel.

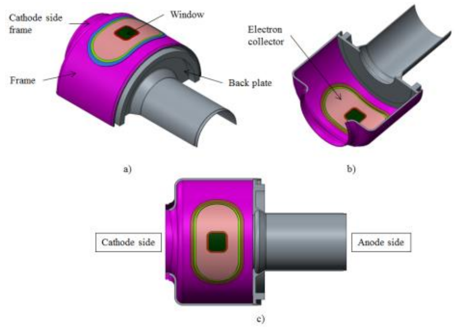

Figure 1. X-ray metal tube envelope (a) Isometric view-1, (b) Isometric view-2 and (c) Bottom view

2.2. Materials properties

Tables 1, 2 and 3 gives material properties namely Density, Isotropic elasticity (Young's modulus, Poisson's ratio, Bulk modulus and Shear modulus), Isotropic thermal conductivity and Specific heat values for different temperature values. These material properties are considered in engineering data of ANSYS 16.1 simulation software.

Table 1. Beryllium material properties

Tempe rature (°C)	Density (kg/m3)	Young's modulus (Pa)	Poisson's ratio	Bulk modulus (Pa)	Shear modulus (Pa)	Isotropic thermal conductivity (W/m°C)	Specific heat (J.kg°C)
0	-	2.9E+11	0.07	1.124E+11	1.3551E+11	-	-
25	-	-	-	-	-	200	1925
50	-	-	-	-	-	157	-
100	1860	-	-	-	-	-	-
200	-	2.9E+11	0.07	1.124E+11	1.3551E+11	134	-
204	-	-	-	-	-	-	2410
300	1860	-	-	-	-	-	-
400	-	2.9E+11	0.07	1.124E+11	1.3551E+11	111	-
427	-	-	-	-	-	-	2752
600	1860	2.9E+11	0.07	1.124E+11	1.3551E+11	92	-
649	-	-	-	-	-	-	3009
800	-	2.9E+11	0.07	1.124E+11	1.3551E+11	75	-

871	-	-	-	-	-	-	3237
1000	1806	2.9E+11	0.07	1.124E+11	1.3551E+11	63	-

Table 2. OFHC Copper material properties

Tempe rature (°C)	Density (kg/m3)	Young's modulus (Pa)	Poisson's ratio	Bulk modulus (Pa)	Shear modulus (Pa)	Isotropic thermal conductivity (W/m°C)	Specific heat (J.kg°C)
0	8950	-	-	-	-	-	388
25	8950	1.17E+11	0.34	1.2188E+11	4.3657E+10	391	-
41	8950	-	-	-	-	387	-
104	8950	-	-	-	-	-	404
200	8950	1.108E+11	0.34	1.1542E+11	4.1343E+10	-	-
202	8950	-	-	-	-	-	415
300	8950	1.074E+11	0.34	1.1188E+11	4.0075E+10	-	-
350	8950	-	-	-	-	366	-
400	8950	1.04E+11	0.34	1.0833E+11	3.8806E+10	-	431
540	8950	-	-	-	-	354	-
600	8950	-	-	-	-	-	456
785	8950	-	-	-	-	335	-
800	8950	-	-	-	-	-	477

Table 3. 304L Stainless steel material properties

Tempe rature (°C)	Density (kg/m3)	Young's modulus (Pa)	Poisson's ratio	Bulk modulus (Pa)	Shear modulus (Pa)	Isotropic thermal conductivity (W/m°C)	Specific heat (J.kg°C)
0	8030	-	-	-	-	14.17	460
23	8030	1.95E+11	0.24	1.25E+11	7.8629E+10	-	-
150	8030	1.87E+11	0.28	1.416E+11	7.3047E+10	-	-
200	8030	-	-	-	-	18.11	539
260	8030	1.8E+11	0.3	1.5E+11	6.9231E+10	-	-
370	8030	1.7E+11	0.32	1.5741E+11	6.4394E+10	-	-
400	8030	-	-	-	-	21.26	568
480	8030	1.6E+11	0.28	1.2121E+11	6.25E+10	-	-
595	8030	1.5E+11	0.29	1.1905E+11	5.814E+10	-	-
600	8030	-	-	-	-	24.02	594
705	8030	1.41E+11	0.28	1.0682E+11	5.5078E+10	-	-
800	8030	-	-	-	-	26.77	623
1000	8030	-	-	-	-	29.13	651

3. Geometrical modelling

Geometrical modelling is a creation of Computer aided design (CAD) model of physical geometry. Modelling of engineering applications requires higher in accuracy of geometric size and shape representation.

Below **Figures 2 and 3** shows an axisymmetric base design and concept design model for X-ray metal tube frame assembly. In concept design, a new design of Electron collector is done with added 2 mm thick fins near Window area and 3 mm thick fins on both sides in arc length. Tapered electron collector is considered to make the backscattered electrons heat load on the window lesser than the base design. Window is positioned away at the end of the tapered electron collector to further reduction possibilities of backscattered electrons directly reaching the window in comparison with the base design. And Frame thickness is increased from 3 mm of base design to 4 mm of metal tube frame assembly.

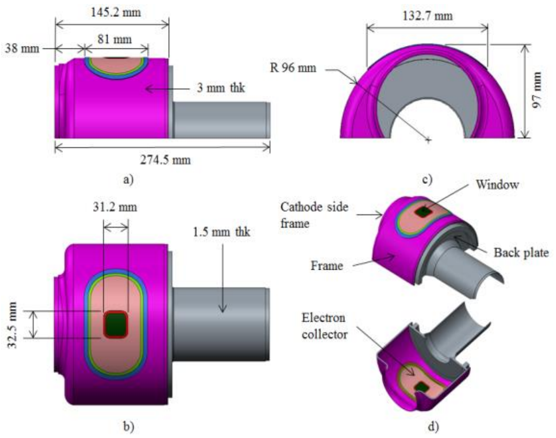

Figure 2. Geometric model of Base design (a) Front view, (b) Top view, (c) Side view and (d) Isometric views

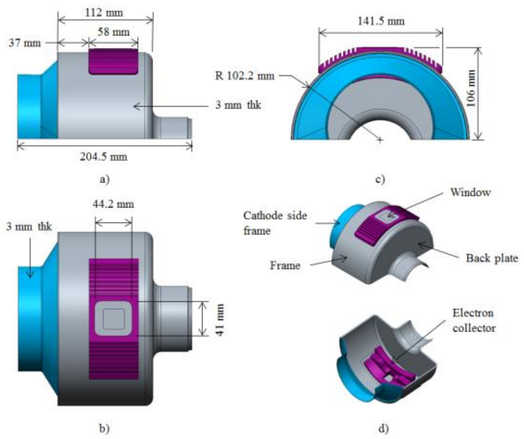

Figure 3. Geometric model of Concept design (a) Front view, (b) Top view, (c) Side view and (d) Isometric views

4. Finite element modelling

Figure 4a and b shows the meshed model of Base design and Concept design of x-ray metal tube frame assembly. There are four settings considered for mesh modelling of X-ray metal tube frame assembly as per below,

1) Element types : SOLID90, SOLID95, SOLID87, SOLID92, CONTA174 and TARGE170
2) Element size : a) 3 mm for Window and Electron collector
   b) 4 mm for Frame, Back plate, and Cathode side frame
3) Bode sizing : Relevance Center – Coarse
4) Advanced setting : Shape checking – Aggressive mechanical

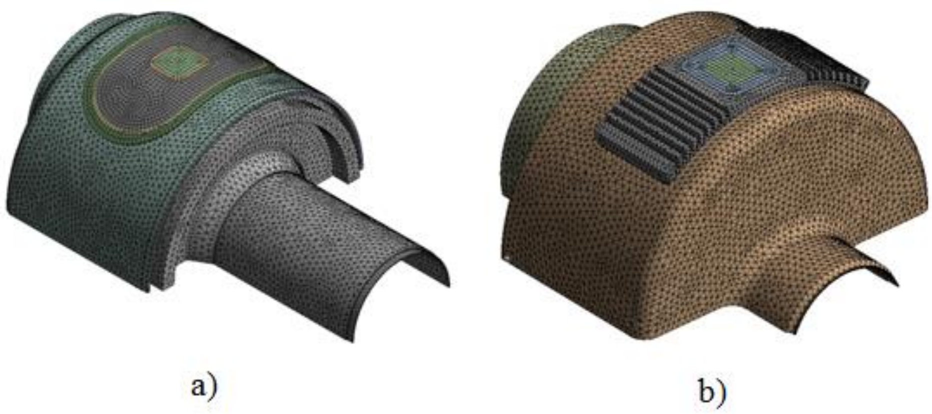

Figure 4. Mesh models (a) Base design and (b) Concept design

5. Numerical analysis

Numerical analysis is an approximation technique for finding the approximate solutions to boundary value problems of partial differential equations. The main objective of this analysis is to establish the technical feasibility and characterize the performance of Base design for sub parts of X-ray metal tube frame assembly namely Window, Electron collector, Frame, Back plate, and Cathode side frame. Based on number of analysis results of thermal – structural analysis of new conceptual design of x-ray metal tube frame assembly identified worst case field protocol as 3.2 kW steady state condition and 14.4 kW average power for 30 seconds. Below **Table 4** gives experimental CTQ's for thermal – structural analysis of x-ray metal tube frame assembly.

Table 4. Experimental CTQ's for thermal - structural analysis

Parameter	Specifications
Window |Be - temperature	< 275°C
Window Be – Anode to Cathode delta deflection	< 50 microns
Shear stress at Be-Cu-Braze joint	< 150 Mpa
Normal stress on Window (Contact pressure)	< 120 Mpa
Yield stress on Frame	< 200 Mpa

5.1. Thermal model and Boundary conditions

Figures 5 and 6 shows thermal model and boundary conditions and are given below,

1) Applied oil convection at outer surface of X-ray metal tube frame assembly with initial temperature = 50°C, heat transfer coefficient = 200 W/ m2K.
2) Applied mapped heat flux (Mono-polar) on vacuum side of X-ray metal tube frame assembly.
3) Considered thermal contact at Braze joints and Welded joints with heat transfer coefficient = 1, 00,000 W/ m2K.

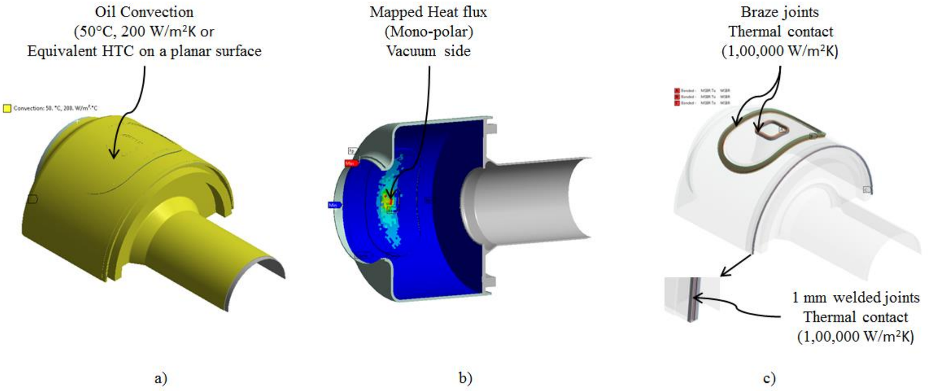

Figure 5. Thermal model and Boundary conditions of Base design (a) Oil convection, (b) Mapped heat flux and (c) Thermal contacts

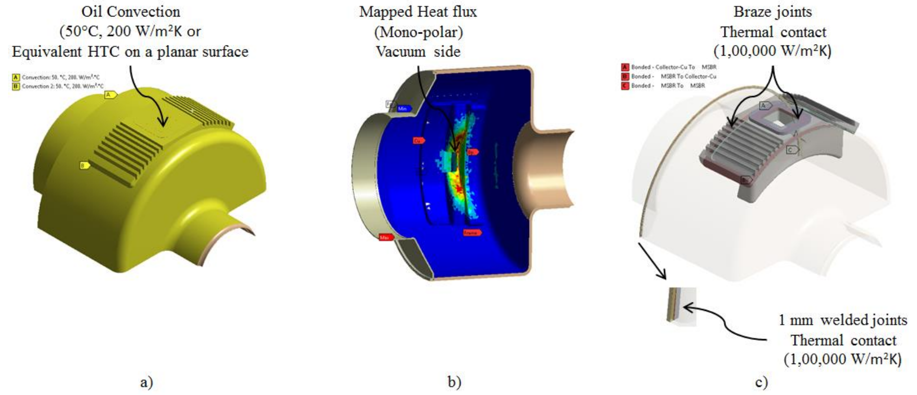

Figure 6. Thermal model and Boundary conditions of Concept design (a) Oil convection, (b) Mapped heat flux and (c) Thermal contacts

5.2. Structural model and Boundary conditions

Figures 7 and 8 shows structural model and boundary conditions and are given below,

1) Considered two symmetry regions on X-ray metal tube frame assembly because doing thermal - structural analysis of half model only.
2) Considered two displacement boundary conditions on X-ray metal tube frame assembly and these are Radial constraint (X = 0) – Cathode side frame is fit with tube housing and Axial (Z = 0) and Radial (X = 0) constraints – Back plate is sitting on rotor cover assembly.

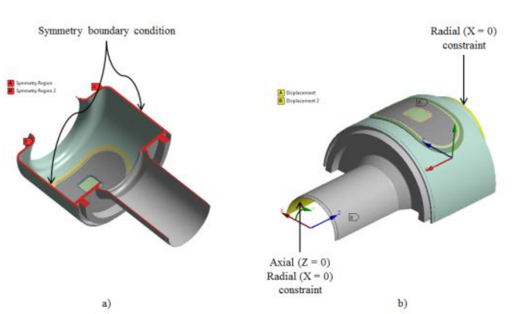

Figure 7. Structural model and Boundary conditions of Base design (a) Symmetry BCs and (b) Structural BCs

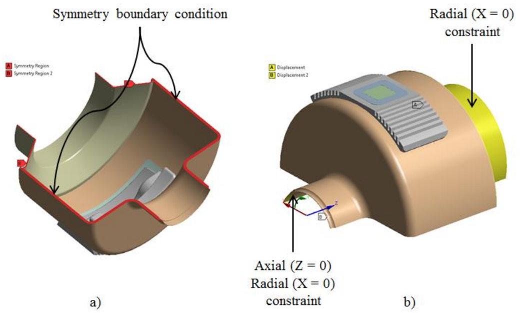

Figure 8. Structural model and Boundary conditions of Concept design (a) Symmetry BCs and (b) Structural BCs

5.3. Thermal and structural analysis results

Figures 9 and 10 shows temperature and deformation plot for 3.2 kW steady state + 14.4 kW average power for 30 seconds of X-ray metal tube frame assembly. And **Tables 5 and 6** shows individual thermal & structural analysis results.

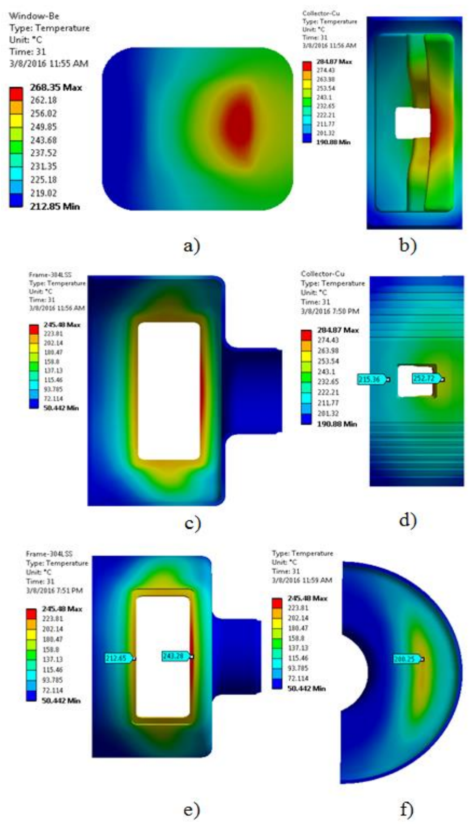

Figure 9. Thermal analysis results of Concept

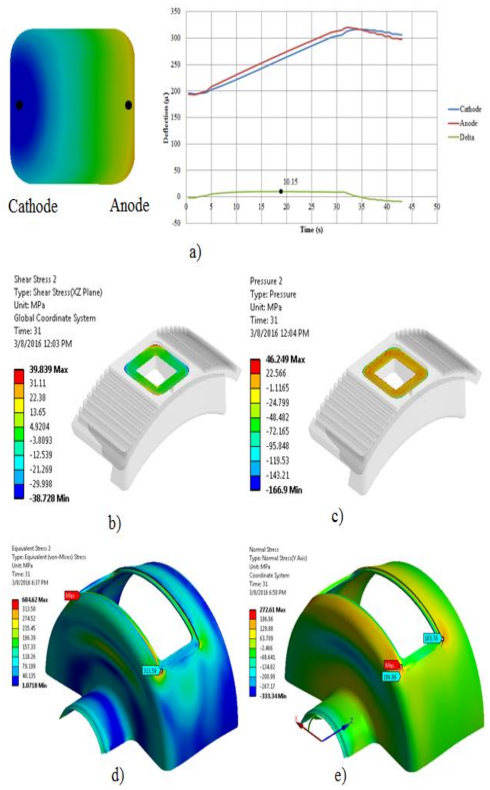

Figure 10. Structural analysis results of

design (a) Window, (b) Collector, (c) Frame, (d) dT Be-Cu, € dT Cu-SS and (f) Back plate

Concept design (a) Delta, (b) Shear stress, (c) Normal stress, (d) von-Mises stress and (e) Hoop stress

Table 5. Individual thermal analysis results

Design type	Be window (Tmax)	Collector (Tmax)	Frame (Tmax)	dT Be-Cu braze joint (°C)	dT Cu-SS braze joint (°C)	Back plate (Tmax)
Base design	1611.9	721.1	566.2	112.4	58.2	86.6
Concept design	268.3	284.9	245.5	37.4	30.4	200.2

Table 6. Individual structural analysis results

Design type	Differential delta deflection (<50μ)	Shear stress (<150 Mpa)	Normal stress (<120 Mpa)	Von-Mises stress (<200 Mpa)	Hoop stress (<200Mpa)
Base design	0.162	391.5	327.5	686.8	225.7
Concept design	10.1	39.8	46.2	313.6	196.6

Referring **Figures 9 and 10 & Tables 5 and 6** thermal – structural analysis summary shows that in conceptual design, window temperature is within the oil coaking/cracking temperature, collector temperature is more whereas it helps to attract backscattered electron hitting the back plate & frame otherwise can lead to hot spots, tapered electron collector with fins appear to be better from structural integrity compared with base design, von-Mises stress value is reduced that is in only particular small area of frame that too very thin in depth and hoop stress on frame shows within the acceptable historic limit.

6. Experimental test versus model correlations

In house x-ray tube, a new test configuration with LVDT's & Thermo-couples is set to study the thermal prediction of Perseus model with test results. Here testing is conducted with 72 kW for 20 seconds. In **Figure 11** all thermo-couple locations the graph of Temperature v/s Time shows match in shape and there magnitudes are within 5%. And also in **Figure 12** Deflection v/s Time shows almost same shape with magnitudes is within 1%. These test versus model correlations is obtained for consideration of thermal contact at Beryllium-Copper Braze joints and Welded joints with heat transfer coefficient = 1,00,000 W/m^{2}K. The above thermal contact conductance, thermal and structural analysis results are used further in temperature and deformation prediction of next generation X-ray tubes conceptual design.

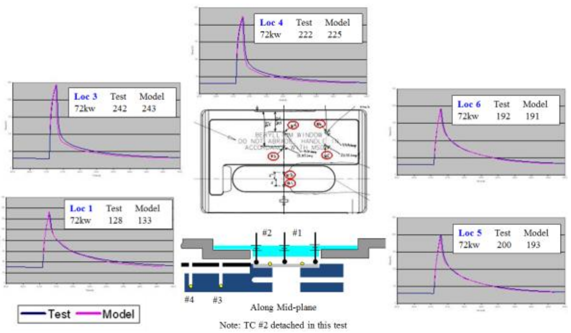

Figure 11. Temperature results of Perseus x-ray tube

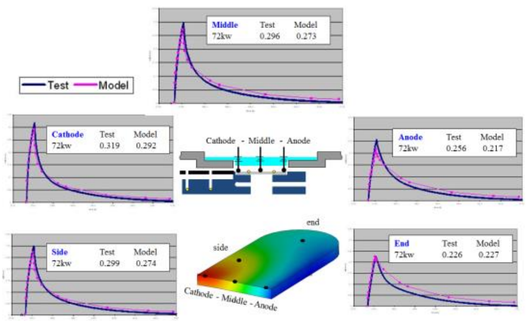

Figure 12. Deflection results of Perseus x-ray tube

7. Conclusion

The numerical investigations have shown that a conceptual design of x-ray metal tube frame assembly meets the requirements of experimental CTQ's of x-ray tube at 72 kW for 20 seconds.

In the present work a new conceptual design of X-ray metal insert with positioning of the window away at the end of collector and tapered electron collector design has been developed using thermal – structural analysis by considering worst case analysis as 3.2 kW power in steady state condition and 14.4 kW average power in transient state condition for 30 seconds. During thermal analysis, considered oil convection at outer surface of X-ray metal tube frame assembly with 50°C initial temperature & 200 W/m^2K heat transfer coefficient, heat flux EBS analysis on vacuum side of x-ray metal tube, and thermal contact at braze & welded joints with 1,00,000 W/m^2K heat transfer coefficient. While doing structural analysis, considered two symmetry regions for axisymmetric x-ray metal tube model and two displacement boundary conditions.

This job is done by doing conceptual design for x-ray metal tube frame assembly with major design modifications in frame and electron collector as per thermal – structural analysis results. As part of the project work, 3D modelling of x-ray metal tube frame assembly was carried out in Creo parametric 2.0 CAD software and thermal – structural analysis was carried out in ANSYS 16.1 simulation software to obtain temperature and deformation profiles. Thermal – structural analysis gives the following results,

1) In conceptual design, window temperature is within the CTQ's limit and it is safe.
2) In conceptual design, electron collector temperature is high which helps to attract more backscattered electrons otherwise can lead to hot spots on frame & back plate and it is acceptable.
3) In conceptual design, von-Mises stress value is more than CTQ's limit and that value is seen in only particular small area (very thin in depth) of frame and it is acceptable.
4) In conceptual design, hoop stress on frame shows within the CTQ's limit and it is safe.

8. Future work

Future work may include the following steps for further analysis of X-ray metal tube frame assembly,

1) Verification and validation of a concept design of x-ray metal tube by doing experimental test setup, conducting thermal tests.
2) Check manufacturing feasibilities based on experimental test results and redesign the concept design to solve design issues.

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