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Design and Analysis of Cooling System for Linear Accelerator (LINAC)

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Abstract

A LINAC is an electron accelerating structure that uses radio frequency power to accelerate electrons. It has many scientific applications, and industrial applications such as microwave sterilization, pasteurization, and preservation of foods, and also in medical applications such as radiotherapy and medical sterilization. For thermally stable operation of the LINAC, it is required to prevent it from temperature-induced frequency shifts. LINAC operation at a high duty cycle dissipates average power of several kW in the structure. The main objective is to minimize the temperature rise to maximize the energy gained by the electron, reduction in thermal deformation of the cavities due to temperature rise and also to operate the LINAC within the efficient bandwidth of the RF source. An optimal thermal design with a web cooling channel system is developed for the efficient functioning of LINAC by using FEA. A water-cooled system (web cooling) for the room temperature 5 MeV traveling wave LINAC has been developed. It has been observed that the rise in temperature, thermal deformation, and energy loss are less in the developed design as compared to the pre-existing one. With the lower rise in temperature, the thermal detuning observed in LINAC will also be less. This makes the LINAC more efficient.

Keywords: *Cooling System, FEA, LINAC, Thermal Deformation*

1.0 Introduction

In the mining industry, Linear Accelerators (LINACs) are crucial for mineral analysis, material characterization, and non-destructive testing. They are used for ore grade analysis through techniques like X-ray fluorescence, providing essential data for identifying valuable ore deposits. LINACs also facilitate radiographic imaging for geological assessments, ensuring safe mine planning[1]. Additionally, they aid in environmental monitoring by analysing soil and water for pollutants, and in non-destructive testing of mining equipment, detecting internal flaws without damage. Furthermore, LINACs assist in measuring material density and thickness, optimizing extraction processes. It is also found that they are extensively used in radiographic imaging for geotechnical assessment where in LINACs can produce high-energy X-rays used for radiographic imaging of rock and soil samples. This technique helps in assessing the structural integrity and composition of geological formations, which is vital for safe and effective mine planning and operation. Elemental analysis of environmental monitoring in mining operations, environmental monitoring is essential to manage the impact on surrounding ecosystems. LINACs can aid in analysing soil and water samples for trace elements and

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pollutants, providing data necessary for environmental compliance and remediation strategies. In the case NDT process LINACs are used in the non-destructive testing of critical mining equipment components, such as pipelines, machinery parts, and structural elements. High-energy X-rays or gamma rays generated by a LINAC can penetrate these materials, revealing internal flaws or weaknesses without causing damage.

In the present work, an optimized cooling system for 5 MeV electron Linear Accelerator (LINAC) has been designed and simulated using finite element analysis. LINAC operation at a high duty cycle and dissipates average power of several kW in the structure, hence the thermal design and cooling layout have to be optimized. An attempt is made to optimised cooling system that minimizes the thermal detuning of LINAC during specific operation.

1.1 Description of Linear Accelerator

A traveling wave LINAC consists of an input RF coupler, buncher cavities, regular cavities, and output RF coupler. RF power is fed through the input coupler which sets up an electromagnetic field in the cavities that is used to accelerate electrons. The leftover RF power is taken out through the output RF coupler at the end of the accelerating structure. Some RF power is dissipated on the internal surfaces of RF cavities due to ohmic losses. This heat is to be removed effectively to avoid thermal detuning and unstable operation of LINAC. The accelerating structure is fabricated by vacuum brazing of these components. Different types of cooling schemes are reported in the literature[2-7] viz. cooling tubes brazed externally on the structure in a longitudinal or helical pattern, cooling channels built within the cavities in the longitudinal direction, cooling jacket on accelerating structure and cooling channels along with web cooling system[8,9].

1.2 Design Objectives

LINAC operation at a high duty cycle dissipates average power of several kW in the structure. A thermally stable operation of the LINAC is required to prevent temperature induced frequency shifts and phase advance errors which are converted into reduced energy gain and increased energy spread of the electron beam[3]. Hence the thermal design and cooling layout for the LINAC must be optimized. This work aims to design and analyse an optimised web cooling system for a 5MeV electron LINAC to meet above objectives by circulating demineralised water closest to heat generation areas for effective cooling. Temperature raises and thermal deformations in cavities are to be minimised for stable operation of LINAC within bandwidth of RF source.

2.0 Analysis Methodology

The thermal design is analysed using finite element software ANSYS[10]. Symmetric boundary condition is used to reduce the problem size and one fourth cavity is analysed. Second order tetrahedral elements are used to model the accelerating structure. The flow is a fully developed turbulent flow when it enters the LINAC cavities.

Dittus-Boelter correlation and Gnielinski correlation[11] are used for calculating average heat transfer coefficient in the cooling jacket.

$h = 0.023\ (k/d)\ (Re)^{0.8}\ (Pr)^{0.4}$

where, k is the thermal conductivity of water, d is hydraulic diameter, Re is Reynolds number and

Pr is Prandtl number. All the fluid properties are evaluated at bulk temperature of water. Reference temperature has been taken as 27°C (300 K).

Following material properties are used for OFE copper.

Table 1. Material properties used for OFE copper

Thermal Conductivity	390 W/m.K
Coefficient of thermal expansion	17.6×10^{-6} per K
Young's Modulus	115 GPa
Poisson ratio	0.3
0.2% proof stress	70 MPa

Coupled thermal- structural analysis is carried out. The design heat flux and convection are applied as loads and boundary conditions in thermal analysis. Temperature obtained from thermal analysis is applied as thermal loads in structural analysis. Appropriate boundary conditions are applied, and deformations are obtained.

2.1 Proposed Cavity Design

The proposed cooling design is illustrated in a solid model shown in Figure 1 and schematic shown in Figure 2. The Disc is machined to create a cooling channel in the disc thickness. Radial holes drilled on the cavity outer diameter provide a path to enter into and exit from the cooling channel in the disc. The idea of the proposed cavity cooling is based on a web cooling system. Thus, coolant flows through web channels (radial direction) as well as through already existing longitudinal cooling channels in the cavities. The rectangular cross section

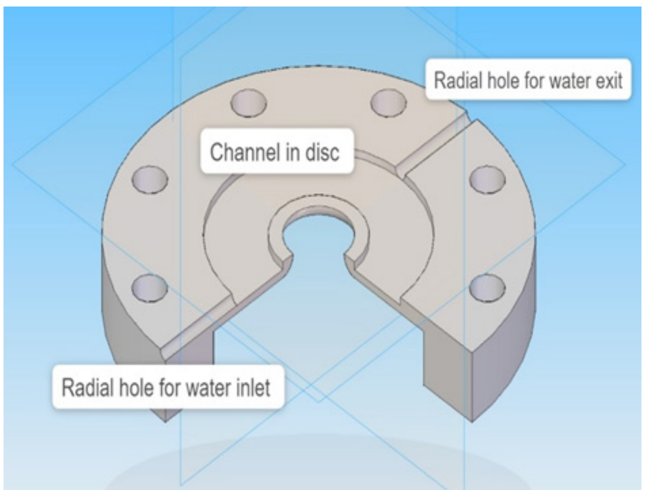


Figure 1. Isometric sectional view of proposed cavity cooling scheme.

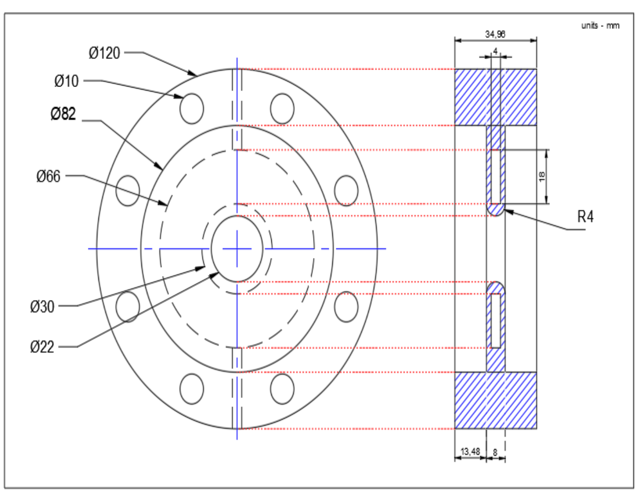


Figure 2. 2D drawing of proposed cavity.

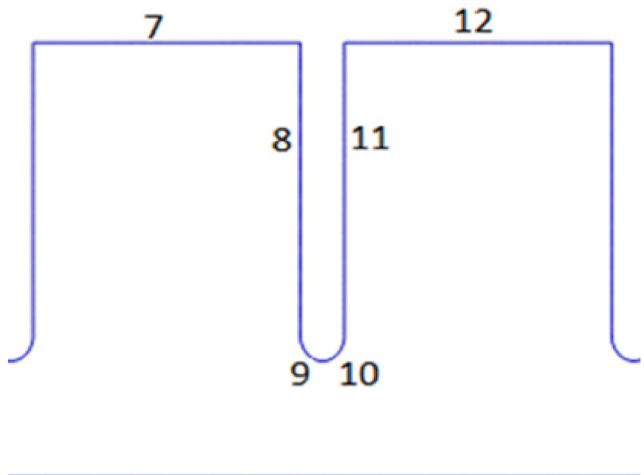


Figure 3. Surface designations for power loss.

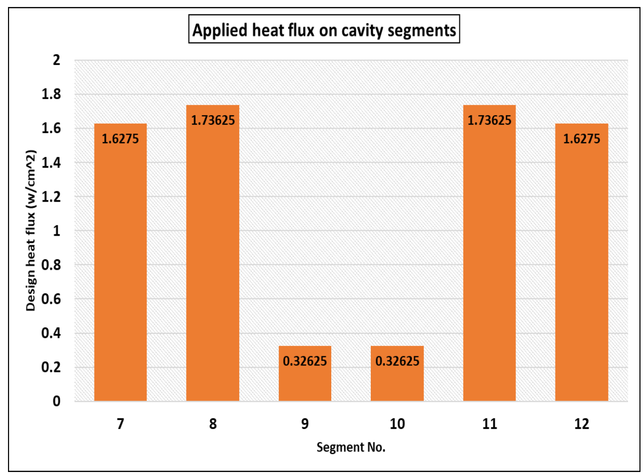


Figure 4. Amount of Heat flux applied at the specified region.

channel in the cavity starts from a radial distance of 4 mm from the iris.

A convection coefficient of 10000 W/m^2K is applied on cooling channel surfaces in contact with water. Heat flux applied on the cavity internal surfaces is mentioned in Figure 3 and Figure 4.

3.0 Results and Discussion

3.1 Thermal Analysis Results

Thermal analysis results, the temperature rise of the LINAC cavity is shown in Figure 5.

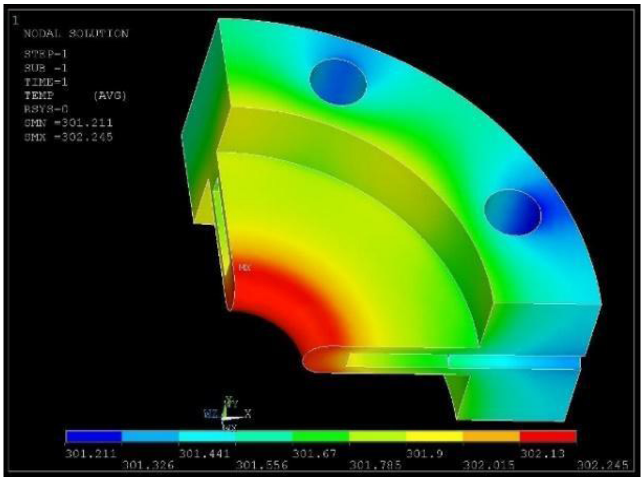


Figure 5. Temperature plot of cavity.

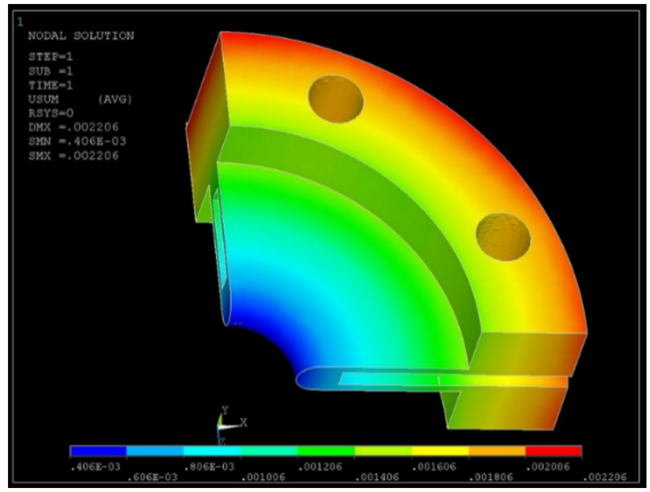


Figure 6. Thermal deformation in cavity.

A minimum temperature of 301.2 K is obtained, and a maximum temperature of 302.2 K is obtained with the proposed cooling system. The maximum temperature obtained at the equator region of the cavity is 301.9 K and minimum temperature is obtained in the cooling channel which has web cooling nearest to it because cooling fluid is flowing through cooling channels and the disc region. Maximum temperature is obtained at the iris of the cavity as heat is removed from the iris region to the disk header by conduction heat transfer.

3.2 Structural Analysis Results

Structural analysis results, the thermal deformation in the LINAC cavity for the proposed cooling scheme is shown in Figure 6.

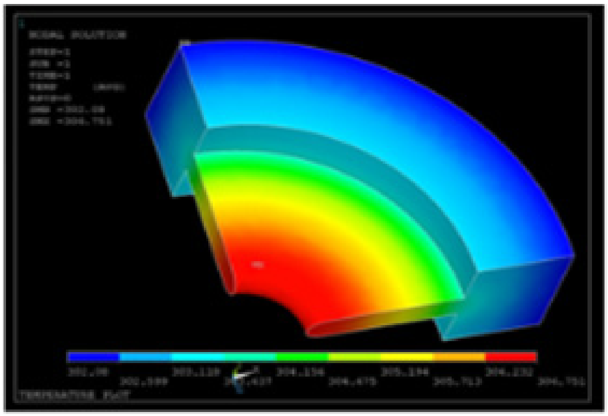
A minimum deformation of 0.000406 mm is obtained, and a maximum deformation of 0.002206 mm is obtained. The maximum deformation obtained at the equator region of the cavity is 0.00149 mm. Minimum deformation is obtained at the iris because of its smaller diameter. Maximum region is obtained at the outer surface of the cavity which is farthest from web cooling.

3.3 Temperature Comparison between Cooling Systems

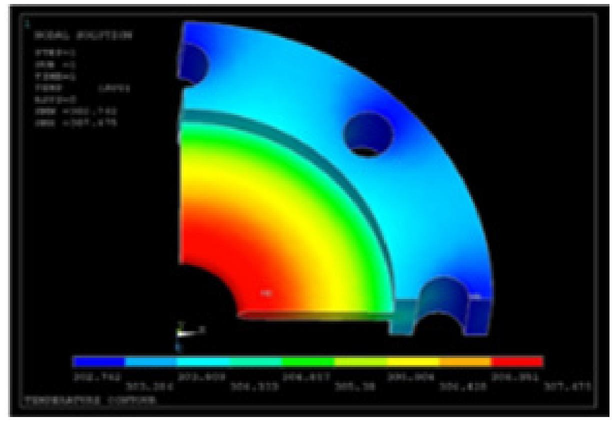
The maximum, minimum, and equator temperature for different cooling systems is shown in Figure 7. Figure 8 compares the temperature rise in various cooling schemes; it is observed that the maximum temperatures are found in the built-in longitudinal cooling channel scheme and minimum temperature rise is found in the proposed cooling scheme. It is also noted that the proposed design is able to minimize the temperature rise much more effectively as compared to the other cooling schemes.

Table 2. Temperature values for different cooling schemes

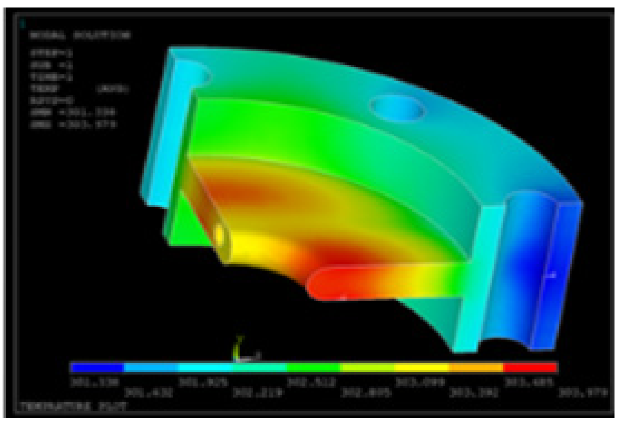
Sl. No.	Type of Cavity	Jacketed Cooling	Cooling Channels	Web and Cooling Channel	Proposed Cavity Design
1	MIN. TEMP. (K)	302.08	302.762	301.388	301.211
2	MAX. TEMP. (K)	306.757	307.481	303.978	302.245
3	EQUATOR TEMP. (K)	303.65	304.44	302.96	301.97



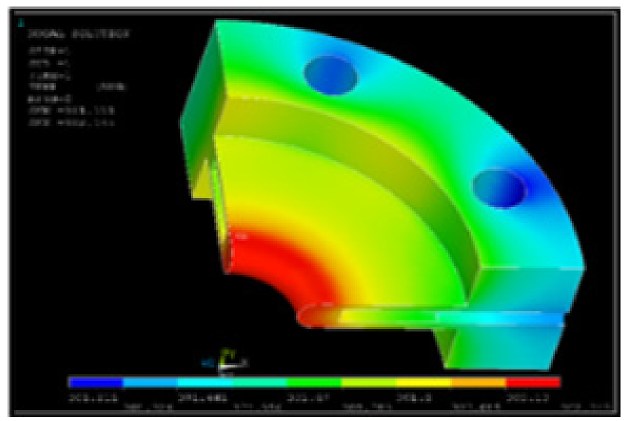
(a) Jacketed Cooling



(b) Cooling Channel



(c) Web and cooling channel



(d) Proposed Cavity Design

Figure 7. Temperature plots of different cooling schemes applied to the cavity.

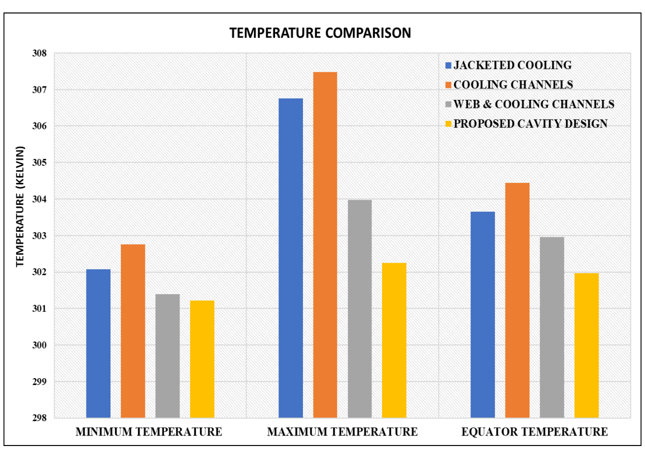


Figure 8. Temperature comparison between different cooling schemes.

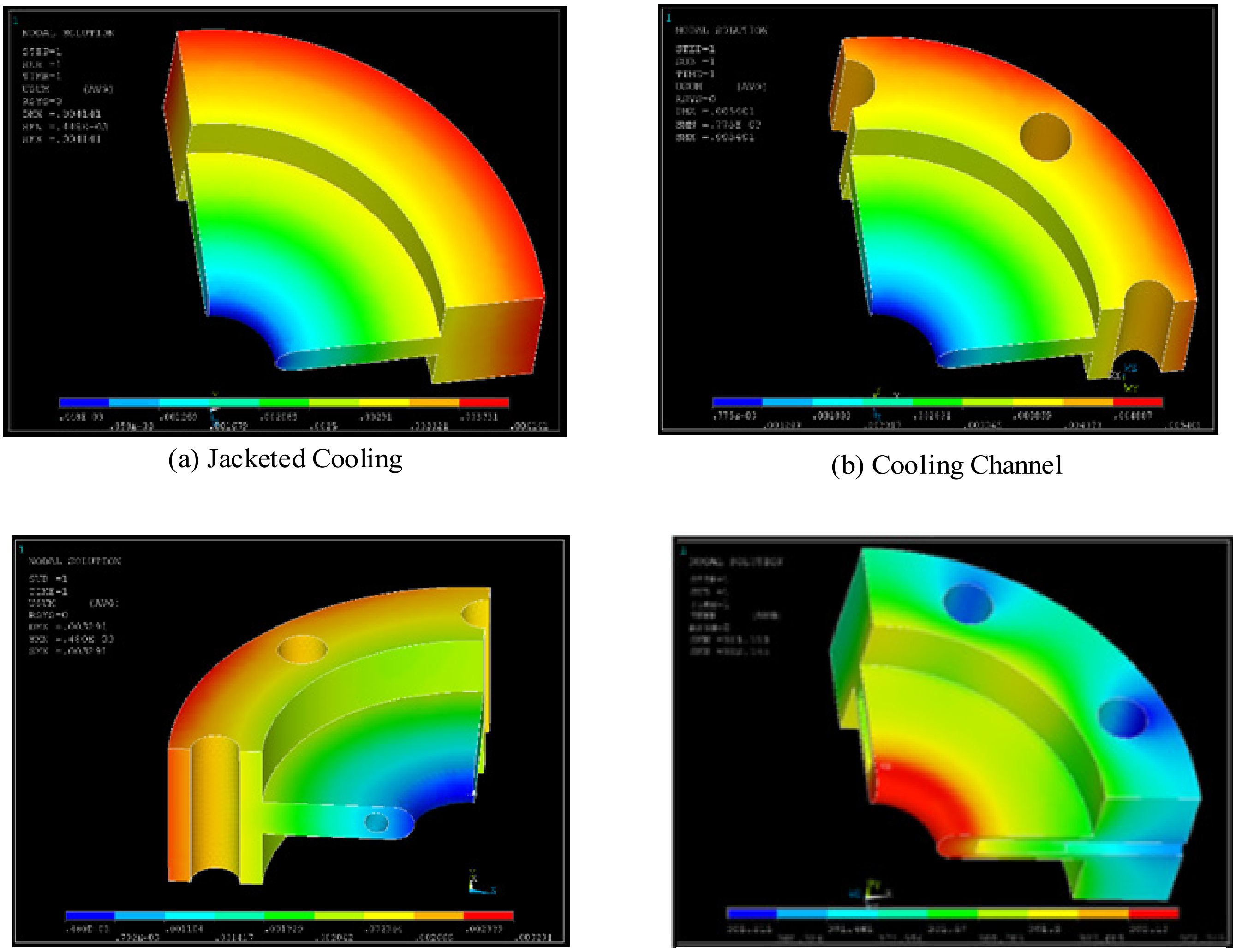
3.4 Thermal Deformation Comparison

Thermal deformations contour of cavity in various cooling schemes is shown in Figure 9 and also thermal deformation comparison between cooling schemes is shown in Figure 10.

Minimum equatorial thermal deformation is found in the proposed cooling scheme, which results in a minimum thermal detuning and minimum phase advance errors.

4.0 Conclusion

The innovative cooling system designed for a 5 MeV electron Linear Accelerator (LINAC) demonstrates



(a) Jacketed Cooling

(b) Cooling Channel

(c) Web and cooling channel

(d) Proposed Cavity Design

Figure 9. Thermal deformation in various cooling schemes.

Table 3. Thermal deformation values for different cooling schemes

Sl. No	Type of Cavity	Max. Deformation at Equator (Mm)	Min. Deformation in the Cavity (Mm)
1	Jacketed cooling	0.0031921	0.000448
2	Cooling channels	0.0040504	0.000775
3	Web and cooling channels	0.002323	0.00048
4	Proposed cavity design	0.0014915	0.000406

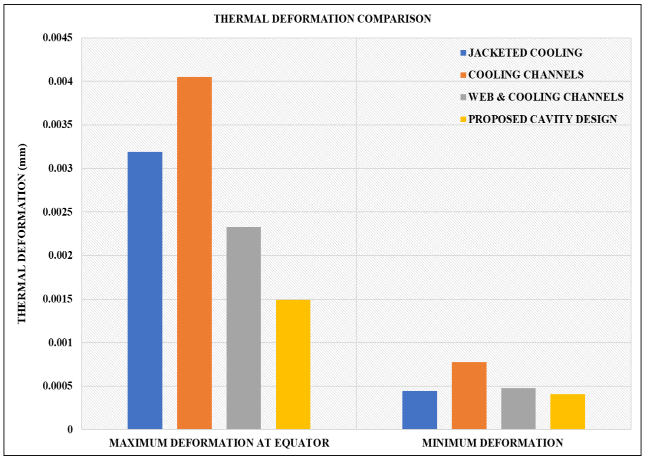


Figure 10. Thermal deformation comparison between cooling schemes.

significant advancements in managing thermal detuning, crucial for applications in the mining industry. Through Finite Element Analysis (FEA), this optimized web cooling system has proven to be more efficient than previous designs, successfully minimizing temperature rise, thermal deformation, and energy loss under high-duty cycle operations. This results in a more stable and efficient LINAC, which is particularly beneficial in mining industry applications like mineral analysis, material characterization, and non-destructive testing. The reduced thermal detuning and phase advance errors enhance the LINAC's performance in critical tasks such as ore grade analysis, radiographic imaging for geotechnical assessment, and environmental monitoring. This development not only optimizes LINAC operations within the mining sector but also sets a new standard in thermal management for high-power electron accelerators.

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