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“MRI Cooling System Analysis & Optimization: CFD, Temperature Control & Efficiency Enhancement”

Sunil Shinde[1*], Sunil Chougule[2], Vikas Sanap[3], Durgesh Sandhan[4], Aditya Saravade[5], Mukta Rasal[6], Kushal Shah[7], Ketaki shirbavikar[8]

[3,4,5,6,7,8]Department of Mechanical Engineering, Vishwakarma Institute of Technology. 666, Upper Indira Nagar, Bibwewadi, Pune- 411037, Email: - vikas.sanap22@vit.edu
[1*,2]Faculty of Mechanical Engineering, Vishwakarma Institute of Technology. 666, Upper Indira Nagar, Bibwewadi, Pune – 411037, Email: - sunil.shinde@vit.edu

Abstract— This paper presents a compressive analysis and optimization of a twisted heat tube exchanger for MRI cooling system. The objective of this study is to enhance the efficiency and temperature control of the system adhering to ASHRAE standards by altering the coolant inlet temperature from 18° C to 27°C & the hot inlet temperature from 75°C to 100°C. The research encompasses design modifications, thermal analysis of tubes with varying lengths (400mm,800mm,1200mm), CFD Analysis simulation to understand fluid behavior. By employing these analyses & optimizations, we aim to improve the overall performance & efficiency of the MRI cooling system. This work not only contributes to the field of heat exchangers & MRI Cooling but also provides valuable insights for HVAC world by replacement of refrigerant or conventional MRI cooling system.

Index Terms— MRI, CFD, Twisted Tube, ASHRAE

I. INTRODUCTION

MRI (Magnetic Resonance Imaging) is a non-invasive scanning technology that produces cross sectional images of the body. It is used in a range of medical field including
Musculosketal, Gastrointestinal, Oncology, Cardiovascular
Neuroimaging.

MRI scanning can differentiate soft tissue structures in any plane, making it an invaluable diagnostic tool. MRI scanners generates a strong magnetic field that is used in conjunction with radio-frequency currents to simulate specific molecules of the body. The behavior of the molecule can be used to generate a three-dimensional image of the body tissues.[2]

For MRI machines to work efficiently, there magnets inside have to stay cool at all times. Therefore, they required a reliable cooling source; the MRI chiller. The refrigeration unit cools MRI machines, radiation therapy cancer treatment machines, CT scans and other medical equipment’s and laboratory applications.[15] Air-cooled and water-cooled MRI chillers work well for MRI machines. They transfer heat to different areas. Air cooled chillers transfer heat to the surrounding ambient air.

These are ideal in facilities without a water source. On the other hand, water cooled chillers transfer heat to a water source, like a cooling tower or a plant chilled water system. Both air-cooled & water-cooled chillers are used to cool down the magnet coils by running cold water around the magnet. They can also be used to cool down the gradient cabinet.

The question arises is that why chiller system is needed for MRI machine, MRI chillers are important because they serve to cool down the gradient coil & Liquid helium compressor. The magnets temperature is controlled at -269°C to maintain the superconducting state of the coils by the whole refrigeration of the system. If the chiller fails, the entire refrigeration system will stop working. Furthermore, MRI chillers are vital to reduce economic losses to the hospital due to a loss of large amount of liquid helium. These can happen when the magnet has a great risk of a quenching & the liquid level is below 60%.[8]

If there is no constant cooling water or the water from the MRI chiller stop, the machines compressor will get very hot & eventually halts operating. As a result, you will start losing helium on the magnet.

Over the understanding the too much maintenance & cost value of helium of compressor we design twisted tube heat exchanger over helium compressor and refrigeration system. Up to this study we have done material analysis for tube and also made the design consideration like change in coolant and the pinch (pattern).[6]

This paper measuredly focuses on change in coolant and hot gas inlet temperature and their effect on design and calculation, along with this as standard of ASHRAE (American Society of Heating, Refrigerating & Air Conditioning Engineers).We made change in coolant temperature in between 18°C to 27°C. By using this and implementing changes in length of tubes through design optimization, we conducted thermal analysis for 400 mm, 800 mm, 1200 mm tube by giving boundary condition like internal heat generation and providing different coolant inlet temperature values. Our study focused on assessing the cooling system’s efficiency by adjusting coolant temperatures (18°C to 27°C) and optimizing tube lengths (400 mm, 800 mm, 1200 mm). Through detailed thermal analysis under various conditions, we observed thermal behavior, crucial for design optimization in line with ASHRAE standards. These modifications significantly enhanced the cooling unit’s performance , offering key insights into thermal management for SPECT/ MRI.[10]

II. METHODOLOGY

In methodology mainly we focus on Enhancing MRI system efficiency by introducing a twisted tube heat exchanger, optimizing coolant utilization, and conducting a comprehensive material design optimization analysis.

Design (Introduction to Twisted Tube Heat Exchanger Over Helium Compressor).
Rationale: Excessive maintenance costs and inefficiencies of the existing helium compressor system necessitated a redesign.
Approach: A twisted tube heat exchanger is integrated above the helium compressor to improve heat exchange efficiency and reduce maintenance frequency, leveraging advanced material properties to cost effectiveness.[16]

Change in coolant utilization.
Rationale: Advance in material science indicate Carbon Nanotube (CNT) and Aluminum Matrix Composites (AMCs) as superior to traditional materials, prompting a shift in coolant strategy.
Objective: Utilize liquids as coolants to exploit CNT and AMC's superior heat transfer capabilities, aiming for improved efficiency over liquid nitrogen.

Material Analysis (Comparative analysis of tube materials)
Findings: CNT & AMC materials outperform conventional stainless steel and copper in heat transfer efficiency, offering significant energy and maintenance savings.

Design Optimization
i)Alteration of inlet temperature for hot medium gas.
Analysis of the heat exchangers performance with hot medium gas between 75-100°C to optimize design parameters.
ii)Change in coolant temperature as ASHRAE standard & Tube lengths
Adhering to ASHRAE standards, the study evaluates coolant temperature (18-27°C) and tube lengths (400mm, 800mm,1200mm) to identify optimal thermal performance configurations.
iii)Introduction of star pattern(pinch) for tube design
Rationale: To address turbulence and corrosion, transitioning to a star pattern tube design aims at enhancing heat transfer efficiency and reducing maintenance.
Impact: This design innovation is anticipated to offer a reliable, durable, and efficient solution for MRI system cooling.

The methodology integrates design innovations, advanced materials, and optimization techniques to substantially upgrade the MRI cooling system. Initial phase has focused on material analysis, with subsequent efforts centered on thermal and CFD analysis, alongside comprehensive assessments of design optimizations, to ensure the helium compressors effectiveness in recycling helium for system cooling. Adjustments in coolant temperatures and tube dimension are calculated to meet ASHRAE standards, ensuring optimal cooling and system performance.

III. DESIGN CALCULATIONS & OPTIMIZATION

In a closed loop MRI system, superconducting magnets and coil generate heat, necessitating efficient cooling. Helium, used as a coolant to maintain these components low temperatures, warms up during the process. The project aims to develop a twisted tube heat exchanger to cool the helium for reuse, ensuring efficient operation of the MRI system.[1]
The cooling system involves a parallel flow heat exchanger where hot helium and cold-water flow at rates of 0.2 kg/s, respectively, with inlet temperatures of 75°C for helium and 20°C for water. To calculate the required heat exchanger area with given heat transfer coefficients of 650W/m^2 °C, we focus on optimizing the systems thermal performance. This optimization includes adjusting the systems thermal performance. This optimization includes adjusting coolant temperatures between 18°C to 27°C, as recommended by ASHRAE standards, and considering variations in tube length and surface area for effective helium cooling. This approach aims to enhance the cooling efficiency and maintain the MRI systems operational integrity.
Given,
$M_h = 0.2$ kg/s;
$M_c = 0.5$ kg/s;
$T_{h1} = 75°C$;
$T_{h2} = 9°C$;
$T_{c1} = 20°C$;

$h_{i} = h_0 = 650$ W/m^2 °C
$C_{ph\ (Helium)} = 5.193$ (J/g°C)
$C_{pc\ (Water)} = 4.187$ (J/g°C)

The heat transfer rate
$Q = M_h \times C_{ph} \times (T_{h1} - T_{h2})$ (1)
$= 68.55$

Heat lost by helium = Heat gained by cold water
$M_h \times C_{ph} \times (T_{h1} - T_{h2}) = M_c \times C_{pc} \times (T_{c2} - 20)$ (2)
$= 52.74$

Logarithmic Mean Temperature Difference (LMTD) is given by,

$$\theta_m = \frac{\theta_1 - \theta_2}{\ln \theta_1 - \theta_2} \quad (3)$$

$$\theta_m = \frac{(Th_1 - Tc_1) - (Th_2 - Tc_2)}{\ln (Th_1 - Tc_1) - (Th_2 - Tc_2)}$$

$$\theta m = \frac{(75° - 20°) - (9 - Tc_2)}{\ln (75° - 20°) - (9 - Tc_2)}$$

$\theta m = 21.51$

Overall Heat Transfer Coefficient (U) is calculated from the relation

$$\frac{1}{U} = \left(\frac{1}{h_i}\right) + \left(\frac{1}{h_o}\right) \quad (4)$$

$$\frac{1}{U} = \left(\frac{1}{325}\right) + \left(\frac{1}{325}\right)$$

$$\frac{1}{U} = \left(\frac{1}{325}\right)$$

U = 325

$Q = A \times U \times \theta_m$ (5)
$= 0.0009809$
$= 98{,}009.64$

Tube area,
Cross sectional shape – slot (rectangle + two semicircles)
Rectangle – Length- 15 mm & Breadth – 10 mm.
Two semicircles – each have radius of 10 mm.
By calculating the cross-sectional area of tube,

Total heat transfer area per tube = 464.16 mm^2

Total No. of tubes,

$$= \frac{Total\ heat\ transfer\ area}{Heat\ transfer\ area\ per\ tube} \quad (6)$$

$$= \frac{98009.64}{464.16}$$

Total no. of tubes = ≈ 212

Length of Tube,

$$\frac{Total\ heat\ transfer\ area}{Total\ no.of\ tubes} = \frac{98009.64}{212} = \approx 465 \text{ mm}$$

Due to fouling factor consideration & the change in coolant temperature as ASHRAE standard length of tube may be varied from 400 mm to 1,200 mm.

In this design phase, optimization calculations are performed for two different cases to examine changes in design parameters and overall efficiency. The paper primarily aims to calculate all parameter, thereby creating an optimized sheet, which will be useful for the datasheet in the manufacturing of twisted tube heat exchangers. Additionally, considerations for cooling by ASHRAE standards are taken into account.

For the consideration of the hot inlet temperature, it varies from 75°C to 100°C. The temperature range is varied from 75°C to 100°C, and the gas medium used is helium at a mass flow rate of 0.2 kg/s, with a heat transfer coefficient of 650 $W/m^2°C$.

Based on the calculation for the change in the temperature across these 25 grouped values, the overall heat transfer area changes from 98,009.64 mm^2. Additionally, the number of tube changes from approximately 211 to 226, and the length of the tubes varies from 408 mm to 1,200 mm. Based on these calculations, thermal analyses were conducted for tubes of lengths 400 mm, 800 mm,1,200mm, providing insights into the system’s thermal performance.

The goal is to cool tubes of various lengths 400 mm, 800 mm, and 1,200 mm. by adjusting the inlet temperature of the coolant liquid (water) according to ASHRAE standards. We performed steady- state thermal analyses on three tubes of the given lengths. For each tube, we conducted a coupled analysis ten times, as the convection value changed from 18°C to 27°C.

TABLE I CHANGE IN OUTLET TEMPERATURE OF COOLANT BY CHANGING INLET TEMPERATURE OF COOLANT.

CHANGE IN TEMPERATURE (T1)	RESULT IN THE CHANGE OF T2
18°C	50.74°C
19°C	51.74°C
20°C	52.74°C
21°C	53.74°C
22°C	54.74°C
23°C	55.74°C
24°C	56.74°C
25°C	57.74°C
26°C	58.74°C
27°C	59.74°C

Boundary condition to calculate temperature distribution and heat flux rate for tubes of lengths 400 mm, 800 mm, 1,200 mm.

Calculation for internal heat generation,

Internal heat generation is taken as ratio of power (watt) to volume (mm^3).

Given,
Helium,
Mass flow rate- 0.2 kg/s (200 g/s)
Specific Heat Capacity – 5.193 J/g °C
Temperature Mean- taking mean temperature in between 75°C – 100 °C.

I) Heat Flow (Q) = $m \times C_p \times \Delta T$ (7)
$= 200 \times 5.193 \times 87.5$
$= 90{,}877.5$ Watt.

II) Volume = Cross Sectional Area × Length (8)
Cross Sectional Area of Slot = 464.16 mm
Length = 400 mm, 800 mm, 1,200 mm.

III) Convection (Forced convection at stagnant water)
Temperature range- 18°C to 27°C.

TABLE II LENGTHWISE VOLUME OF TUBES & INTERNAL HEAT GENERATION.

Tube length	400 mm	800 mm	1,200 mm
Volume	1,85,664 mm^3	3,70,128 mm^3	5,55,192 mm^3
Internal heat generation (W/mm^3)	0.4896	0.2458	0.164

Material for tubes,

As the first phase of these work done on material analysis for twisted tube for a closed loop MRI machine, from that research 'Carbon nanotube composite' for tube, from that research we got better result over aluminum matrix composite for our chosen application.

TABLE III MATERIAL PROPERTIES OF CNT COMPOSITE.

Properties	Value
Density	2 g/cm3
Young's modulus	65000 MPa
Poisson's ratio	0.25
Tensile yield strength	500 MPa
Thermal conductivity	250 W/m-K
Specific heat at constant pressure	900 J/kg-K

The tool used for thermal analysis of tubes is ANSYS; the following details pertain to tube meshing.

TABLE IV MESHING DETAILS

Type	Patch confirming method. Element type -Tetrahedrane Geometry - tube
	Face meshing Element type - All quadrilateral Geometry - Inlet/ Outlet Slot.
Mesh size	0.5 mm

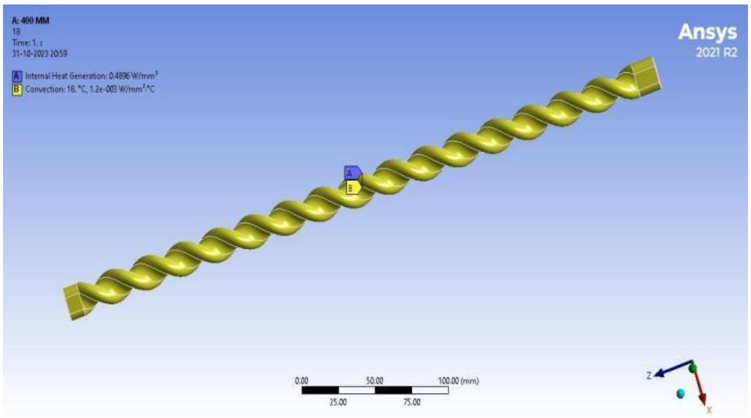

Figure 1 Boundary Conditions.

Boundary condition is given as internal heat generation and convection that changers from 18°C to 27°C.

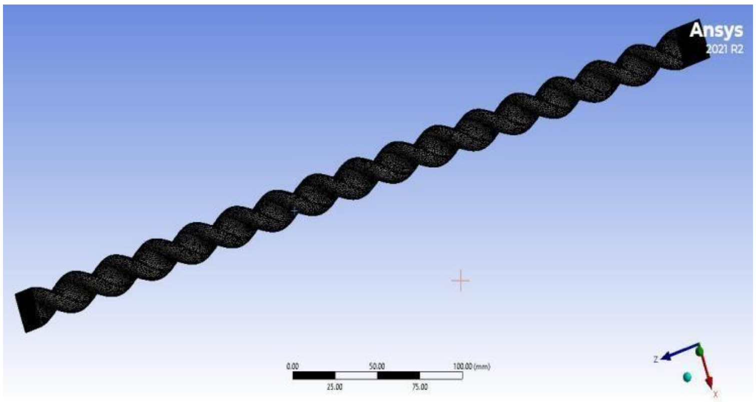

Figure 2 Meshing

Meshing is done by two methods; one is patch confirming and global meshing at the element size of 2 mm.

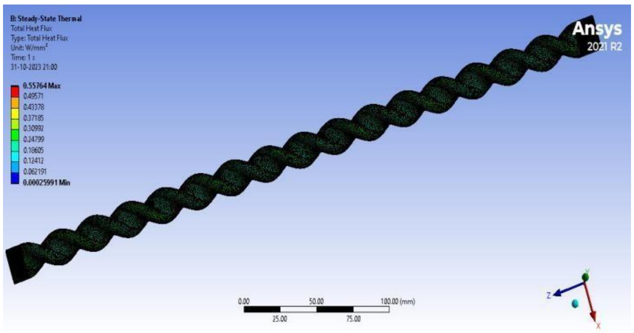

Figure 3 Temperature distribution over twisted tube.

Temperature distribution is changed according to length of tube, for 400 mm tube at 18°C stagnant water convection maximum temperature distribution from tube is 222.3°C,for 800 mm tube 105.49 °C & for 1200 mm tube it goes up to 76.25°C.

The maximum temperature distribution from the tube stagnant water at 18°C changes according to the length of the tube: for a 400 mm tube, it is 222.3°C, for an 800 mm tube , it decreases to 105.49°C; and for a 1200 mm tube, it further reduces to 76.25°C.

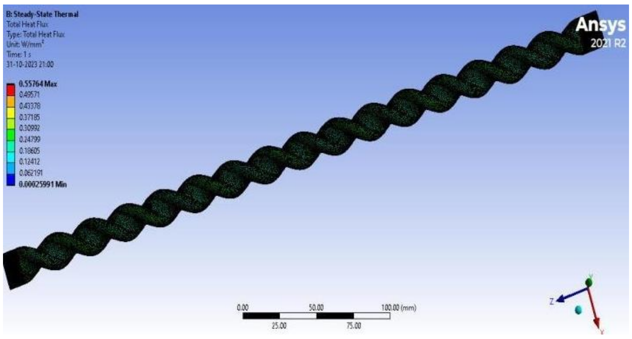

Figure 4 Heat Flux Distribution Over Twisted Tube.

The heat flux rate remains constant as convection alters the temperature distribution, but it varies with the length of the tube. For a 400 mm tube, the maximum heat flux value is 0.55 W/mm^2 at 18°C, and this value stays constant up to 27°C. For an 800 mm tube, the maximum heat flux at 18°C is 1.0002 W/mm^2, remaining constant up to 27°C.Similarly,for a 1200 mm tube, the maximum heat flux at 18°C is 0.715 W/mm^2, which also stays up to 27°C.
By doing steady state thermal analysis of tube of length 400 mm, 800 mm, 1200 mm. we are able to understand the removal of temperature range and heat transfer rate for forced convection at stagnant water condition temperature range 18°C to 27°C.

CFD Analysis of Twisted Tube Heat Exchanger

The objective is to conduct a CFD analysis of tubes to primarily understand the behavior of turbulence kinetic energy, velocity and pressure. The boundary conditions are defined by temperature and velocity: an inlet temperature of 75°C for the hot gas at one face of the enclosure, designated as the inlet, and 20°C at another face for the coolant inlet , and 20°C at another face for the coolant inlet, establishing the temperature conditions. Additionally, the mass flow rate is set 0.2 kg/s for the hot helium gas 0.5 kg/s
at the coolant liquid inlet.

RESULTS:

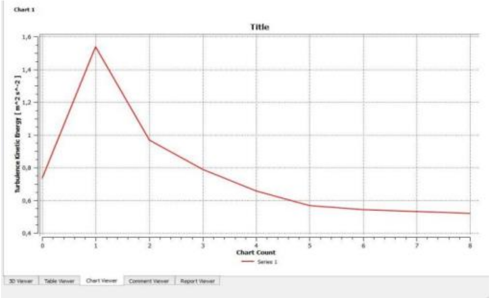

Figure 5 Turbulence Kinetic Energy

Turbulence kinetic energy quantified intensity and shows distribution of turbulence, aiding in understanding flow patterns.

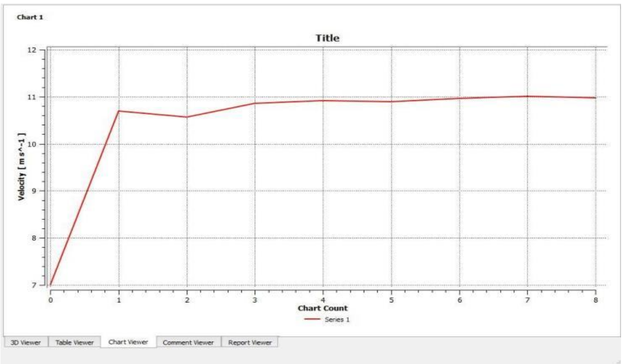

Figure 6 Velocity Result

Velocity profiles shows detailed flow patterns and velocities, crucial for enhancing heat transfer efficiency within the heat exchanger.

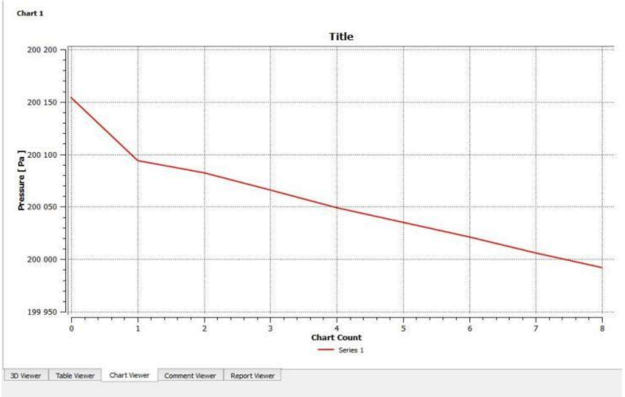

Figure 7 Pressure gradient

Pressure gradient is required to understand pressure drop, which help to optimize design for efficient operation.

Research successfully demonstrated advancements in heat exchanger system, focusing on design optimization and material analysis. Key findings include,

Efficiency confirmation: twisted tube heat exchanger outperforms traditional systems in MRI machine cooling, proving higher efficiency and effectiveness.

Coolant utilization enhancement: using AMC and CNT composites, we eliminated the need for liquid nitrogen coolant, improving system performance.

Material analysis impact: AMC and CNT materials enhanced corrosion resistance and heat transfer, promising longer system durability and efficiency.

Design optimization: thermal analysis under varied inlet conditions revealed insights into performance improvements for different tube lengths.

Optimized geometry: a star patterned design improved turbulence and corrosion resistance, optimizing the heat exchanger's geometry.

CONCLUSION

In conclusion, this study represents a significant leap forward in the field of thermal engineering, particularly in the optimization and enhancement of heat exchanger systems. Through design optimization and advanced material analysis, we have demonstrated the superior performance of twisted tube heat exchanger over conventional MRI machine cooling systems, highlighting their increased efficiency and effectiveness in application such as MRI machine cooling.[4] By integrating aluminum matrix composite (AMC) and carbon nanotube (CNT) composites, we successfully shifted away from traditional coolant systems, eliminating the need for liquid nitrogen and thereby making a milestone in coolant utilization. Furthermore, the adoption of AMC and CNT materials not only improved the system's corrosion resistance and heat transfer capabilities but also promised an extension in the durability and overall efficiency of heat exchanger system. The detailed ANSYS thermal analysis under varied inlet conditions provided vital insights into the system's performance, guiding the optimization of tube lengths for enhanced heat exchange. Lastly, the introduction of a star patterned design within the heat exchanger has been proven to significantly augment turbulence and corrosion resistance, thereby refining the system's geometry for optimal performance. This comprehensive exploration underscores the potential of innovative design and material composition in transforming heat exchanger systems, setting a new benchmark for future developments in the domain of thermal management and energy efficiency. This research underscores the critical role of computational fluid dynamics (CFD) and thermal simulation in pushing the boundaries of what is achievable in heat exchanger technology. Ultimately, the research mainly helps in advancement in HVAC by changing the refrigeration system into an energy saving heat exchanger.

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