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Original Research Article

Computational analysis of porous structured cryo-regenerator with baffles for additive manufacturing

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ABSTRACT
Regenerators play an essential role in cryocoolers by enhancing heat transfer between the working fluid and porous matrix. This study examines the effects of incorporating baffles in a stainless steel (SS) regenerator, comparing its performance with a baffle-free SS regenerator. The design is optimized for additive manufacturing to ensure seamless integration into cryogenic systems at the Tata Institute of Fundamental Research, Mumbai. Computational Fluid Dynamics simulations in ANSYS 2024 R2 analyze temperature, pressure, and velocity variations, while Von Mises stress analysis evaluates structural integrity under operating conditions and REGEN3.3 Software cross-verifies thermal and flow results. The baffle-type regenerator is expected to outperform alternative models by achieving a greater temperature drop for improved heat absorption, a lower pressure drop, and a higher velocity reduction for more effective gas flow control.

1. Introduction

The regenerator is the heart of any cryocooler, and its performance decides the performance of the cryocooler system. Regenerator performance is dependent on parameters such as porosity, matrix material, and geometric design. The present study is on the regenerator used in the existing Stirling cycle-based liquid nitrogen plant at the Low Temperature Facility (LTF) of Tata Institute of Fundamental Research (TIFR), Mumbai, India.

The existing regenerator model is a woven wire mesh type, with many sets of mesh stacked up to form the desired height and size [1]. This study aims to develop an optimised, high-performance, cost-effective regenerator that can be fabricated with greater flexibility. Additive Manufacturing (AM) techniques offer potential advantages in regenerator fabrication, such as further control over geometry, porosity, and packing density. Previous studies have investigated lattice-structured regenerators fabricated via Direct Metal Laser Sintering (DMLS), but found that thermal losses through the axial flow segmentation walls prevented the model from achieving the necessary temperatures for nitrogen liquefaction [1, 2]. To address this, it has been proposed that incorporating multiple layers of radially oriented baffles in the lattice-structured regenerators could improve cooling efficiency by minimizing/eliminating axial heat leakage [3].

2. Objective and scope

This study aims to evaluate the performance of a baffle-integrated lattice-structured porous regenerator optimized for additive manufacturing and compare it to a baffle-free counterpart. REGEN3.3 simulation software is first used to calculate key parameters to use as inputs for further analysis in ANSYS 2024 R2. Computational Fluid Dynamics (CFD) simulations on ANSYS are used to assess temperature, pressure, and velocity variation across the regenerator, aiming to minimize the pressure drop, achieve lower gas temperatures for increased suitability in cryogenic applications, and maximize the velocity drop to facilitate more effective heat transfer and cooling. REGEN3.3 simulation software is then used to cross-verify the results from ANSYS and further compare key thermal and flow parameters between the baffle-type and SS regenerators, including heat capacity and conductive heat flux. The approach to the proposed study to analyze the regenerator is schematically explained in Figure 1.

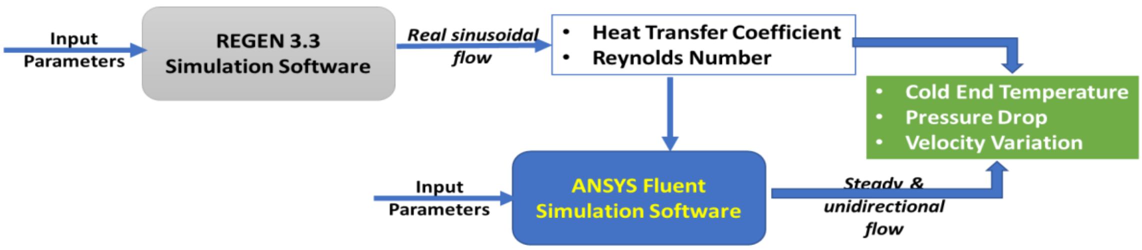

Figure 1: Approach of regenerator analysis.

The study also includes the structural analysis to identify maximum Von Mises stresses that develop under the operating pressure and temperature, aiming to ensure that stresses remain within the material's safe limit and assess the need for further optimization in the geometry and working pressure.

3. Methodology

The present study builds upon the prior development of regenerators designed for retrofit compatibility with the existing regenerator at the TIFR, Mumbai, whose dimensions are shown in Figure 2(a). The considered lattice structure of the porous regenerator, a body-centred cubic (BCC) unit cell with a length of 1.9 mm, a strut diameter of 0.55 mm, and a total porosity of 66.39%, selected based on the optimal porosity, surface area to volume ratio, and machinability for AM is shown in Figure 2(b). Based on the BCC structure, the 3D CAD model of the regenerator was developed for the required size and is shown in Figure 2(c).

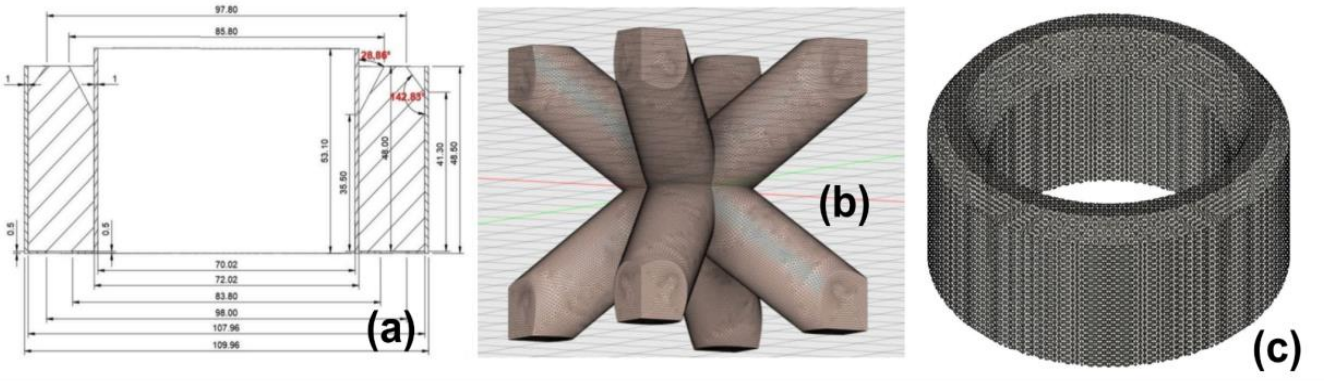

Figure 2: (a) Regenerator dimensions; (b) Lattice cell; (c) Mesh model of regenerator [4].

3.1 SS regenerator with Baffles

The current work analyses a model where trapezoidal baffles are integrated into the SS Porous structure to maximize the interaction time between the fluid and the regenerator matrix, enhancing the efficient heat exchange and allowing the regenerator to attain lower temperatures [3, 4]. The baffles were designed with key objectives to maximize interaction time between the working fluid (helium gas) and the matrix material (SS porous structure). There are 2500 pairs of baffles arranged in 10 rows with linear high-density packing at a 7-degree gap. The orientation of the baffles is integrated into the BCC lattice structure to improve gas flow and ensure minimal pressure drop. The technical details of the baffle are shown in Table 1, the baffle dimensions and orientation pattern are shown in Figure 3(a) and (b), and the complete CAD model of the regenerator with baffles in Figure 3(c).

Table 1: Technical details of the Baffles.

Baffle volume	Porosity	Number of baffles	Number of rows	Baffle Pattern
6,793.92 mm^3	63.41%	2500	10	Linear high density packing with a 7° gap, arranged in the same line with an irregular stack spacing.

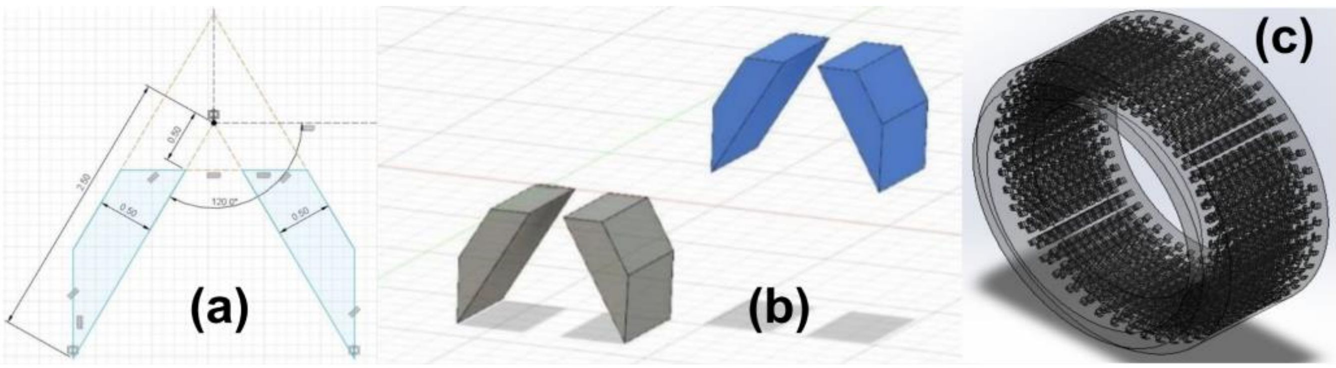

Figure 2: (a) Baffle dimensions; (b) Baffle 3D model; (c) CAD model of regenerator with Baffles.

3.2 Fluid flow parameters

Based on the CAD model, parameters such as porosity, wetted surface area and fluid flow area were obtained. Several other fluid flow parameters were calculated based on the input parameters from the CAD model and expected output parameters, which are used for the ANSYS and REGEN simulation set-up, tabulated in Table 2. REGEN 3.3 software was used to recalculate Reynolds number and heat transfer coefficient for the baffle-type regenerator, with values indicated by an asterisk in Table 2.

Table 2: Calculated fluid flow parameters [5].

Parameter Name	Symbol	Formula	Unit	SS Regenerator with Baffles	SS Porous Regenerator
Porosity	ε	Given		0.634146	0.6639
Volume of unit lattice cell	a	From CAD model	mm^3	2.3108	2.3108
Mean diameter for packed lattice bed	d	d = 2((3/4) π a^3)^1/3	M	0.006149	0.0061488
Strut diameter	dstrut	Given	mm	0.55	0.55
Relative Velocity Resistance	Rv	Rv=(150*(1-ε)^2)/(d^2*ε^3)	m^2	2082382	1531586.84
Inertial Resistance Coefficient	Ri	Ri=(3.5(1-ε))/(dε^3)	m^{-1}	816.6176	653.791433
Total volume of free flow	V	V = ε*Vo	mm^3	144522	151303
Total porous volume	Vo	From CAD model	mm^3	227900	227900
Wetted area	Aw	From CAD model	mm^2	521186.7	472000
Interfacial Area Density	Afs	Afs=Aw/Vm	m^{-1}	6.25E+03	6.16E+03
Reynolds number	Re	From REGEN3.3		411 *	10100.6475
Prandtl number	Pr	Pr= (Cp * μ)/k		1.02405938	1.02405938
Nusselt number	Nu	Nu=(Hl)/k		212.7481	212.748121
Heat Transfer Coefficient	h	From REGEN3.3	$W\ m^{-2}\ K^{-1}$	666.757 *	666.757
Viscosity (Helium)	μ	At 300K	$Kg\ m^{-1}\ s^{-1}$	0.0000199	0.0000199
Thermal Conductivity for Helium	k	At 300K	$W\ m^{-1}\ K^{-1}$	0.152	0.152
Thermal conductivity in a fluid medium	k'	k′=ε*k	$W\ m^{-1}\ K^{-1}$	0.09639	0.1009128
Specific heat of helium	Cp	At 300K	J / (kg K)	5193	5193
Hydraulic Diameter	Dp	Dp= (4*Aff *L)/Aw	M	1.89E-03	2.09E-03
Turbulent Intensity			%	5	5
Mass flow rate	m	Given	g/s	1.2	1.2
Fluid superficial velocity	v	v= (Re * μ)/(ρ*L)	ms^{-1}	27.50961	25.4257017
Characteristic length of regenerator	L	Given	Mm	48.5	48.5
Density (Helium)	ρ	At 300K	kg/m^3	0.163	0.163
Density (SS316)	ρ	At 300K	kg/m^3	7900	7900
Area of fluid flow	Aff	From CAD model	mm^2	5080.33	5080.33
Cross sectional free flow area	Afr	Afr = ε*Aff	mm^2	3221.671	3372.83108
Volume of regenerator	Vm	From CAD model	mm^3	83378.01	76454.0885

3.3 ANSYS computational fluid dynamics (CFD) analysis

CFD analysis was carried out on ANSYS Fluent 2024 R2 to evaluate the baffle-type regenerator's thermal and flow performance. The input parameters and fluid properties for the simulation set-up were adapted from the previous regenerator modelling literature [3, 4].The solver was configured for a steady, pressure-based solution with absolute velocity formulation. Based on the calculated Reynolds number from REGEN3.3, which was lower than 2000, the viscous laminar model was chosen for the analysis to model laminar flow conditions. The mesh model comprises 1124979 nodes and 633720 elements, achieving a mesh metric with an average element quality of 0.74. The working fluid was set as standard helium gas. Matrix material as, SS316L, was assigned temperature-dependent properties using a piecewise polynomial function for specific heat from 20-300 K and a piecewise linear function for thermal conductivity. Boundary conditions reflected the actual conditions of the TIFR liquid nitrogen plant. The inlet was set to 300 K, with a pressure of 30 bars. The outlet was set to a mass flow rate of 1.2 g/s, a temperature of 30 K and anaverage pressure of 24 bars. Gravity was enabled along the positive Z direction. All walls were treated with no-slip and stationary motion, and the external surface had a fixed temperature of 298 K. Under cell-zone conditions, the regenerator body was defined as a porous zone with viscous resistance (Rv) and inertial resistance (Ri) to reflect the existing regenerator material accurately.

Table 3: Simulation set-up and computational procedures for ANSYS CFD.

Element Quality of Mesh Model		Average Pressure	24 bar	Polynomial Profile	3rd Order
Mesh	Tetrahedral Element	Wall Heat Generation	0	Temp. Range	30 to 300K
Element Size	2.3 e-002 m	Wall Heat Flux	0	Material	Helium
Nodes	1124979	**Fluid Conditions**		**Adopted Solution Scheme**	
Elements	633720	Working Fluid	Helium gas	Model used	Viscous Laminar model
Mesh metric (Element quality)	Max: 0.98 / Min: 0.3 / Avg: 0.74	Material (solid)	SS316L	Solution Method	Pressure Velocity Coupling
Boundary Conditions		Time	Steady	Gradient	Least Square Cell-based
Inlet Temperature	300 K	Gravity Action	+ve Z direction	Pressure	2nd Order
Inlet Pressure	30 bar	Flow Model	Laminar	Momentum	2nd Order upwind
Mass Flow	1.2 g/s	Energy Model	ON	Energy	2nd Order upwind
Outlet Temperature	30 K	Heat Flux	Zero	Iterations	5000

Figure 3 shows the simulation results in terms of variation of pressure, temperature and velocity across the length of the SS Regenerator with Baffles. The pressure variation was found to be 12.5 Pascals. The temperature variation of the gas (TGAS) was 246.89 K. Finally, the velocity variation was 2.17 m/s. Figure 4 depicts the residual plots for the solution, which monitored convergence for continuity, momentum, energy, and turbulence parameters. After 5000 iterations, all variables except energy met their convergence criteria. This confirmed that most of the numerical solutions stabilized with acceptable error thresholds for accurate post-processing.

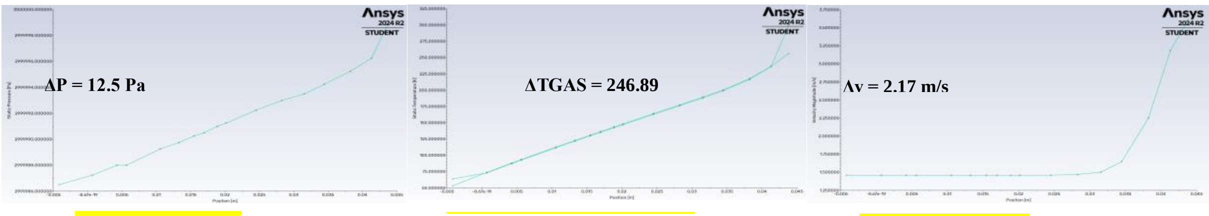

Figure 3: ANSYS CFD results for regenerator with Baffles.

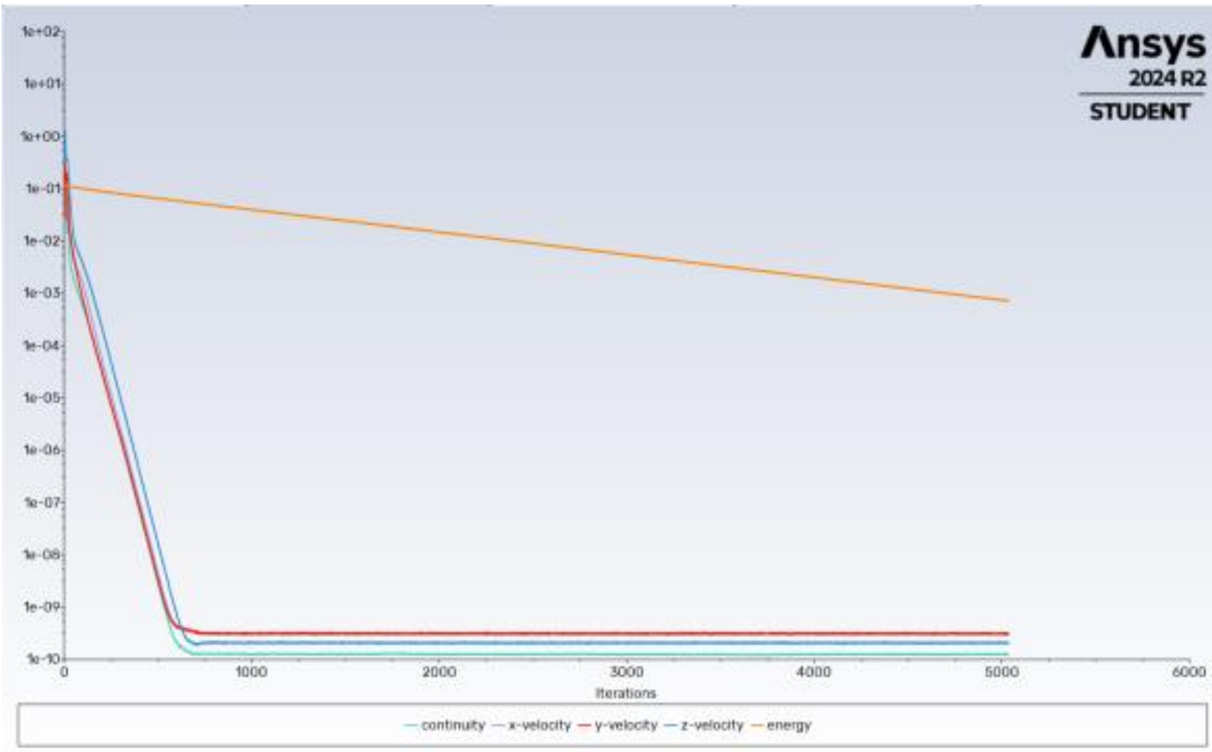

Figure 4: Scaled residuals showing convergence of results.

3.4 REGEN3.3 analysis and cross-verification of ANSYS results

REGEN3.3 was first used to cross-check the results obtained from ANSYS by comparing the temperature, pressure, and velocity variations across the baffle-type regenerator, as seen in Figure 5. The simulation was configured with a pressure ratio of 1.25, an average pressure of 27 bars, an inlet and outlet temperature of 30K and 300K, and a mass flux of 1.2 g/s, based on the working parameters in the TIFR plant. Hydraulic diameter, matrix porosity, and other inputs are seen in Table 2.Additionally, REGEN3.3 was used to compare and evaluate the heat capacity and conductive heat flux for both the SS and baffle-type regenerators, as shown in Figure 6. The conductive heat flux of the gas was evaluated at the exit of the regenerator (0.0485m), and the heat capacity was evaluated at 30 K.

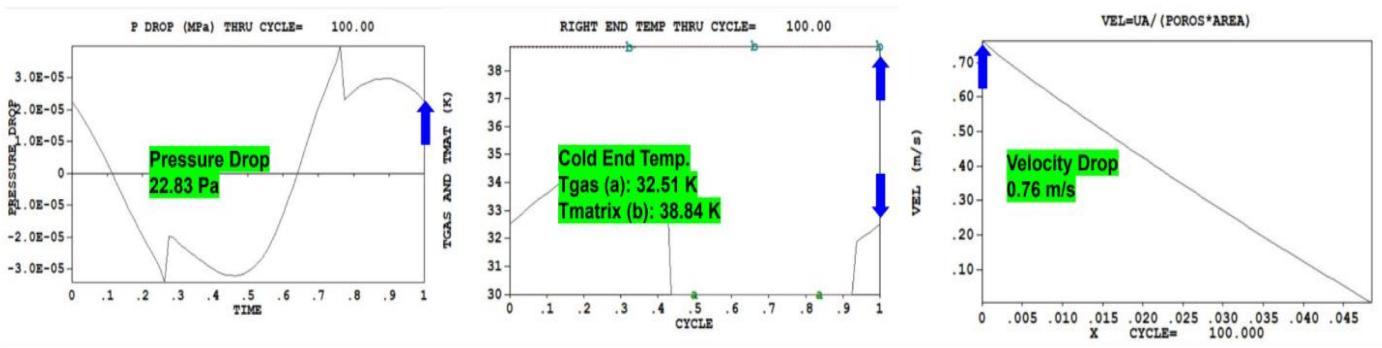

Figure 5: REGEN3.3 results for ANSYS cross-checking of pressure, temperature, velocity drop.

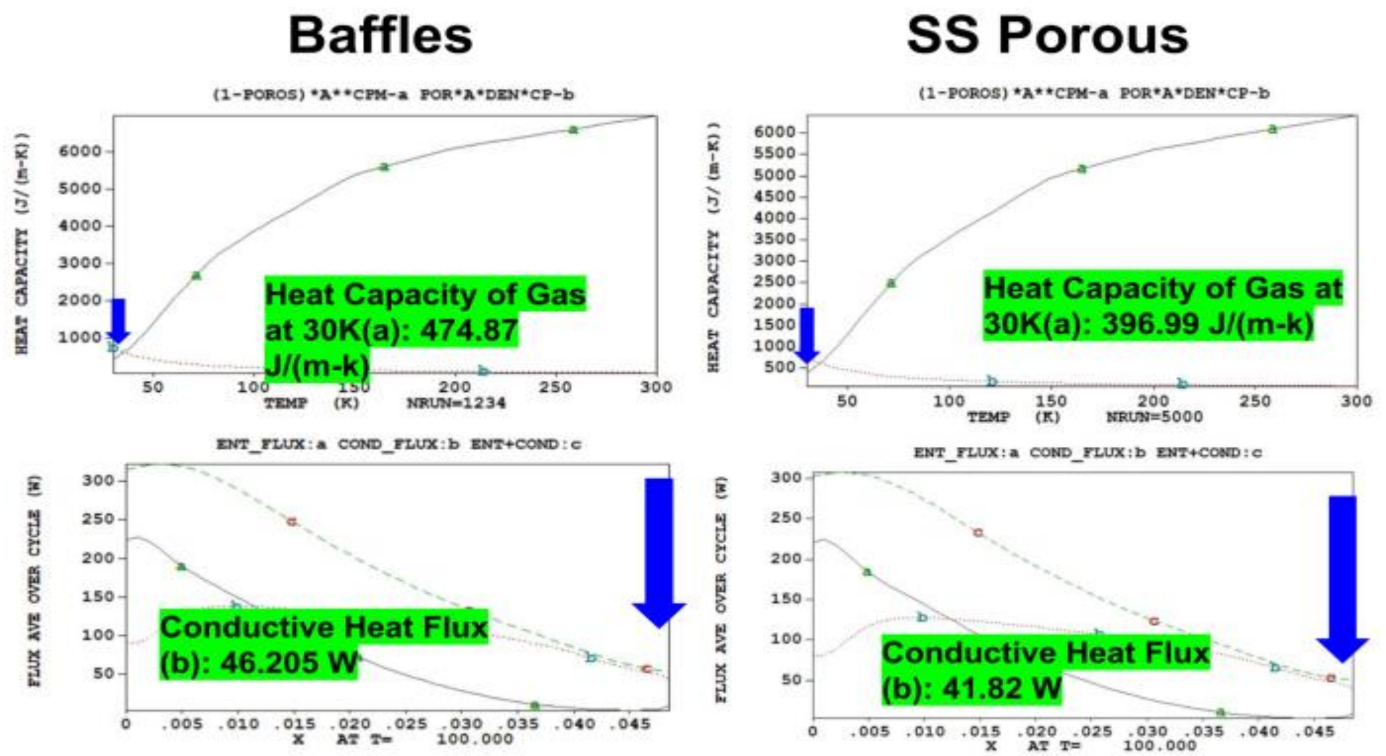

Figure 6: REGEN3.3 results for Baffle vs. SS porous regenerator.

3.5 Von Mises stress analysis

A Von Mises stress analysis was conducted using ANSYS Structural Analysis to assess the mechanical integrity of the baffle-type regenerator under operational conditions. The objective was to ensure the structure adheres to the material's elastic limit and does not yield, following a methodology adapted from previous work by Srinivasan et al. [3]. The BCC Unit Cell was first replicated using a linear pattern to represent a simplified regenerator section. The external walls were modelled as fixed supports to simulate constraint conditions. As shown in Fig. 7a, the internal surfaces of the lattice were subjected to a pressure load of 30 bars, equivalent to the operating pressure in the TIFR Liquid Nitrogen plant. By considering the yield stress of SS316L, 4.6 x 10^8 Pa, the maximum stress developed in the lattice structure is 3.65 x 10^6 Pa, as shown in Fig. 7b. The maximum stress is significantly below the yield stress, indicating the regenerator is within the permissible limit for safe operating pressure. The detailed comparison of the stress analysis with the previous work is tabulated as Table 4.

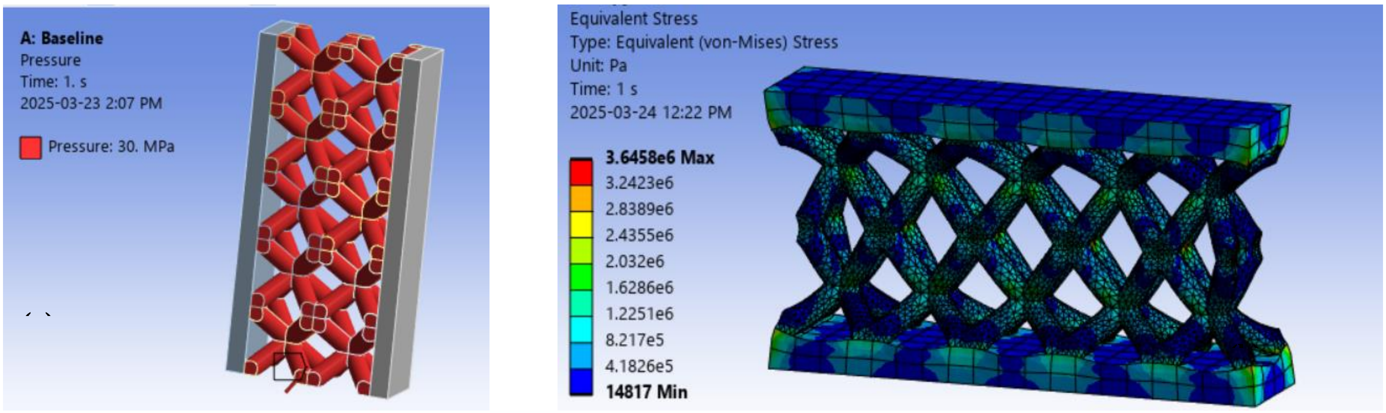

Figure 7: (a) Pressure variation across the lattice structure (@P = 30 bars; (b) Stress analysis of lattice structure.

Table 4: Von Mises stress analysis comparison with previous lattice structure.

Parameters	Current Lattice Structure	Previous Lattice Structure [4]
Strut Diameter	0.55 mm	0.38 mm
Working Pressure	30 Bars	20 Bars
Yield Stress (SS316L)	4.6×10^8 Pa	4.6×10^8 Pa
Max. Von Mises Stress	3.4571×10^6 Pa	1.77×10^5 Pa

4. Results and discussion

4.1 ANSYS CFD analysis and REGEN3.3 cross-validation

The flow and thermal performance of the baffle-type SS regenerator were compared against the SS porous regenerator from the previous work [4], which had been tested under identical conditions and material properties. The results are compared with the previous works and tabulated in Table 5. ANSYS results showed the SS Regenerator with Baffles had a significantly higher gas temperature drop than the SS Porous Regenerator, from 104.36 to 246.89 K (~150% more). The baffle-type regenerator also had a moderately higher drop in velocity based on ANSYS, 0.47 m/s higher than the velocity variation across the SS Porous regenerator. These improvements indicate more effective thermal exchange between the gas and matrix, with the baffles successfully increasing the residence time and surface contact between the helium and the regenerator matrix and improving the cooling performance. The pressure drop across the SS Regenerator with Baffles was minimally higher than the SS Regenerator, 12.5 Pa compared to 10.5 Pa. This increase is likely due to the slight gas flow resistance caused by the baffle geometry. However, the pressure drop is still well within the acceptable range for the system due to the optimised baffle design and does not significantly impact the efficiency of the cryocooler.REGEN3.3 results are used to cross-validate the ANSYS results for the baffle-type regenerator and ensure trends are acceptably close to those observed in real operating conditions. The REGEN results are not directly comparable to the previous work on the SS Porous model, which was also performed using ANSYS simulations.

Table 5: CFD results comparison with SS porous regenerator.

Parameter Name	Baffles		SS
	ANSYS	REGEN3.3	ANSYS [4]
Pressure Drop (Pa)	12.5	22.83	10.5
Temperature (TGAS Drop (K)	300 to 53.10987 (246.89 K)	300 to 32.51 K (267.49 K)	300 to 194.78 (104.36 K)
Velocity Drop (m/s)	2.17	0.76	1.7

4.2 REGEN3.3 heat results

The thermal and flow performance of the baffle-type SS regenerator was compared against the stainless steel regenerator based on the parameters obtained from the REGEN 3.3 simulations tabulated in Table 6. The heat capacity of the gas at 30K was 19.62% higher for the baffle-type regenerator, indicating a greater capacity for thermal energy storage. The conductive heat flux at the exit was 10.50% higher for the baffle-type regenerator. This suggests that the baffles enhance the heat transfer rate, contributing to overall higher thermal efficiency in the system.

Table 6: Comparison of thermal and flow parameters between SS and Baffle-type regenerators.

Parameter Name	SS	Baffles	Baffles vs. SS
Heat Capacity of Gas at 30K (J / (m-k))	396.996	474.87	19.62% higher than SS
Conductive Heat Flux at Exit (W)	41.816	46.205	10.50% higher than SS

4.3 Von Mises stress analysis results

The current lattice structure stress analysis is compared to the lattice structure previously tested by Srinivasan et al. [3]. The previous model incorporated thinner struts (0.38 mm) and was tested under a lower operating pressure of 20 bars. The present design, in contrast, incorporates slightly thicker struts to improve porosity and manufacturability via additive techniques, as mentioned previously. As shown in Fig.7, the maximum Von Mises stress in the current model was 3.46 MPa, compared to 0.177 MPa reported in the earlier configuration. While this reflects a significant increase, the observed stress remains well below the material yield strength of SS316L (460 MPa), indicating that the structure remains within the safe elastic limit. However, there may be a need to further optimize the lattice design and operating conditions, such as working pressure, in order to reduce localized stress concentrations and improve structural resilience.

4. Conclusions

This study presented an analysis and comparative evaluation of a stainless steel regenerator with trapezoidal baffles for additive manufacturing. The baffle-type design significantly improved thermal and flow performance compared to the baseline SS Porous model. Specifically, the temperature drop of the working fluid improved by over 100%, and the reduction in flow velocity improved by over 20%, with a minimal acceptable increase in pressure drop. These improvements indicate increased fluid interaction time and more efficient heat transfer. The results from REGEN 3.3 further confirmed these findings. The baffle-type design showed a significant increase in heat capacity and conductive heat flux compared to the SS regenerator, suggesting that the baffles contribute to better thermal energy storage and more effective heat transfer of the cryocooler system. Structural analysis of the porous lattice confirmed that the maximum Von Mises stress remained well below the material yield strength. However, the observed stress was higher than in previous, lower-pressure designs, indicating potential for further optimizing strut geometry and pressure conditions.

Limitations of the current study include constraints in mesh resolution due to the use of the ANSYS Student version. This may have contributed to the non-convergence of the energy residual, as energy balance may not have fully been captured in certain regions. Additionally, since inputs were fixed and no sinusoidal forcing was applied, the CFD simulation did not represent a Stirling cycle's true oscillatory flow characteristics. Future work will aim to obtain a commercial license to remove mesh size and node count limitations, allowing for more detailed geometry representation and solution accuracy.

Authors' contributions

The author read and approved the final manuscript.

Conflicts of interest

The author declares no conflict of interest.

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Data availability

No new data were created.

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