Optimizing Flow Uniformity through Regenerators of Large Cryocoolers Using CFD

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ABSTRACT

The regenerator is the key component of any cryocooler from small to large scale. A desirable regenerator should have a low friction factor in the flow direction, high thermal capacity, and low conduction from the hot to the cold end. To achieve these conditions, an advanced regenerator is under development by West Coast Solutions (WCS) and Georgia Tech for a co-axial single stage pulse tube cryocooler with 150 W at 90 K cooling power. The flow uniformity through the regenerator at both cold and warm ends is critical for high efficiency performance of the regenerator and reducing losses. Any flow non-uniformity deteriorates the regenerator performance in comparison with an ideal one-dimensional operation. This study focuses on optimizing the flow through a large regenerator by designing specific flow distribution components composed of perforated blocks with open and screen mesh-filled plena. All analyses and optimizations are performed using Computational Fluid Dynamics (CFD). The depth of open plenum, mesh screen type, and the number of mesh screens in the mesh screen-filled plenum are among the parameters in the sensitivity and optimization study.

INTRODUCTION

Efficient, lightweight and large capacity cryocoolers, with cooling capacities of up to hundreds of watts, are needed for future human space activities, including in-situ resource utilization (ISRU) and long-term storage of cryogenic propellants. Georgia Institute of Technology (Georgia Tech) and West Coast Solutions are designing a large two stage cryocooler that is optimized to have a heat lift of 150 W at 90 K (LOX temperature) and 20 W at 20 K (LH_2 temperature). The first stage, whose simplified schematic is shown in Figure 1, is a co-axial pulse tube cryocooler that is comprised of an innovative and efficient regenerator.

The design and optimization process comprises two iterative steps. Initially, a system-level optimization is performed using Sage [1], which is the 1D software widely used for design and optimization of any cryocooler. Using the predictions of Sage as boundary conditions, separate components are then investigated and optimized in detail using CFD simulations. System-level optimizations are then repeated should detailed component-level analysis lead to significant modifications.

The first stage of the aforementioned cryocooler uses an annular regenerator with a microstructure which only allows flow in the axial direction with virtually no cross-flow. The thermal-fluid aspects of the regenerator microstructure have been characterized computationally at the pore level based on the technique used by the same research team in the past [2-5]. The lack of cross-flow inside the regenerator renders the regenerator's performance sensitive to flow non-uniformity, however as a result, the in-flows at the two ends of the regenerator need to be uniform.

Cryocoolers 22, edited by R.G. Ross, Jr., J.R. Raab and S.D. Miller

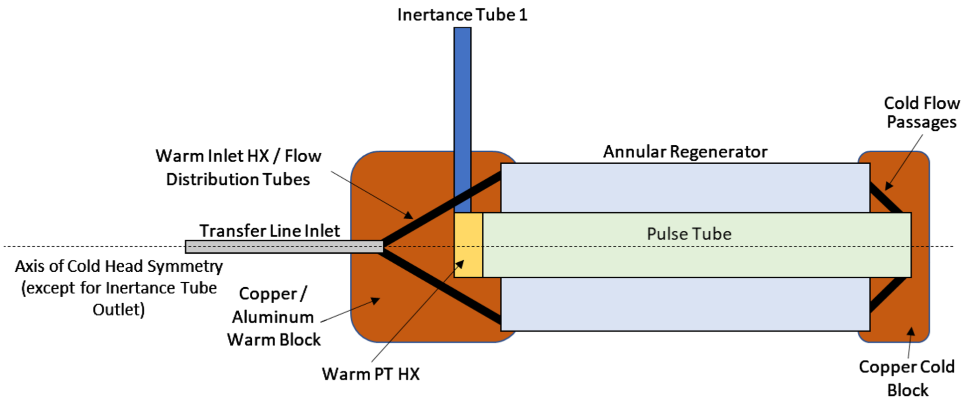


Figure 1. Rough schematic of the expander components of the theoretically optimized 200 W, and 90 K pulse tube cryocooler.

In this paper we discuss the development and optimization of two flow distribution components, which are shown to render the in-flows for the annular regenerator to be nearly uniform.

GEOMETRIC CONFIGURATION AND MODEL ASSUMPTIONS

Figure 2 shows the complete fluid region of the computational domain. The full computational domain consists of a transfer line, flow distribution channels at the warm end of the expander, a plenum and flow straightener (mesh screens) at the warm side of regenerator, another plenum and flow straightener (mesh screens) at the cold side of the regenerator, and flow distribution channels at the cold end of expander. The computational domain is divided into two parts, the warm and cold sides of the regenerator, as shown in Figure 3. Each one of these two halves is investigated and optimized separately first. The regenerator and its adjacent components in their entirety are then simulated to ensure that flow uniformity is maintained. In this paper we investigate the effect of plenum thickness, mesh straightener (mesh screen-filled plenum) thickness, and mesh screen type on flow uniformity in the regenerator.

Figure 3 (a) shows CAD representations of the way the warm end flow distribution component is connected to the annular regenerator. The working gas coming from the compressor and warm heat exchanger enters a large number of parallel holes (shown as parallel tubes in the figure), and from there it is led into a shallow open plenum. Beyond this plenum is another shallow layer of stacked screen meshes that lead to the regenerator itself. At the warm end of the regenerator, total number of 324 straight distribution channels with a diameter of 2 mm are located. The cross section of the regenerator is divided into 9 equally spaced radial segments in such a way that the number of distribution channels in each segment is proportional to the cross-sectional area in of that segment. For the boundary condition the oscillating mass flow rate with amplitude of 6.943E-2 kg/s and phase of 75.6 degree (with respect to compressor phase), which are borrowed from system-level Sage simulations, are applied at the inlet of transfer line. An oscillating pressure of 4.112 bars with phase equal to 35 degree, also based on Sage simulations, is applied at the outlet of the regenerator. The simulation is isothermal at 300 K and a mean pressure is set to 6 MPa. The working gas is helium with constant properties.

Figure 3 (b) shows CAD representations of the way the cold end flow distribution component is connected to the cold end of the annular regenerator. The flow distribution passages form a complicated system. This complexity is primarily because the working fluid needs to undergo a 180º change in direction while it moves between the pulse tube and the annular regenerator. At the cold end of regenerator, a total number of 72 inclined distribution channels with diameter of 2 mm are distributed in three equally spaced radial locations. The number of tubes on each radial location is proportional to the cross-sectional area of each section. An oscillating mass flow rate of 6.801E-2 kg/s amplitude with 10.19 degrees phase angle is applied at the inlet of the regenerator

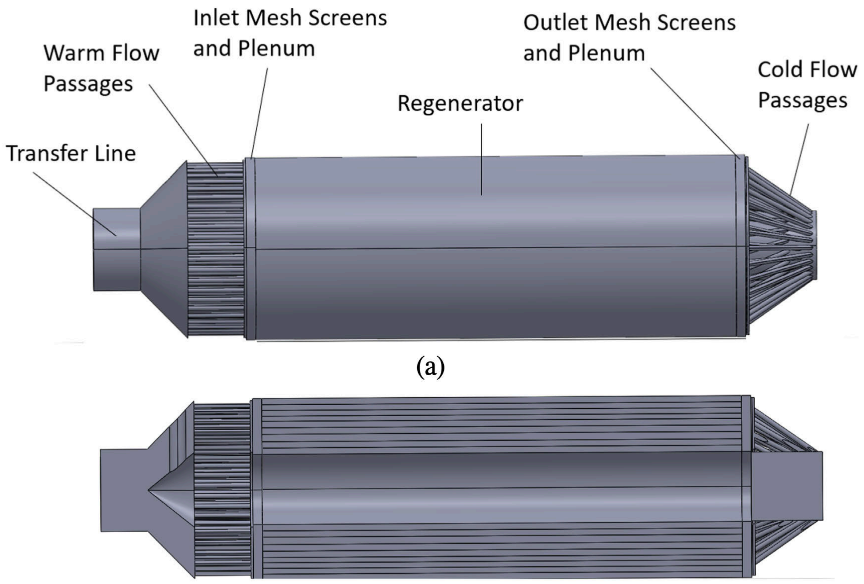


Figure 2. CAD representation of the 90 K cryocooler expander (only the fluid region). (a) 3D model, (b) cross section view.

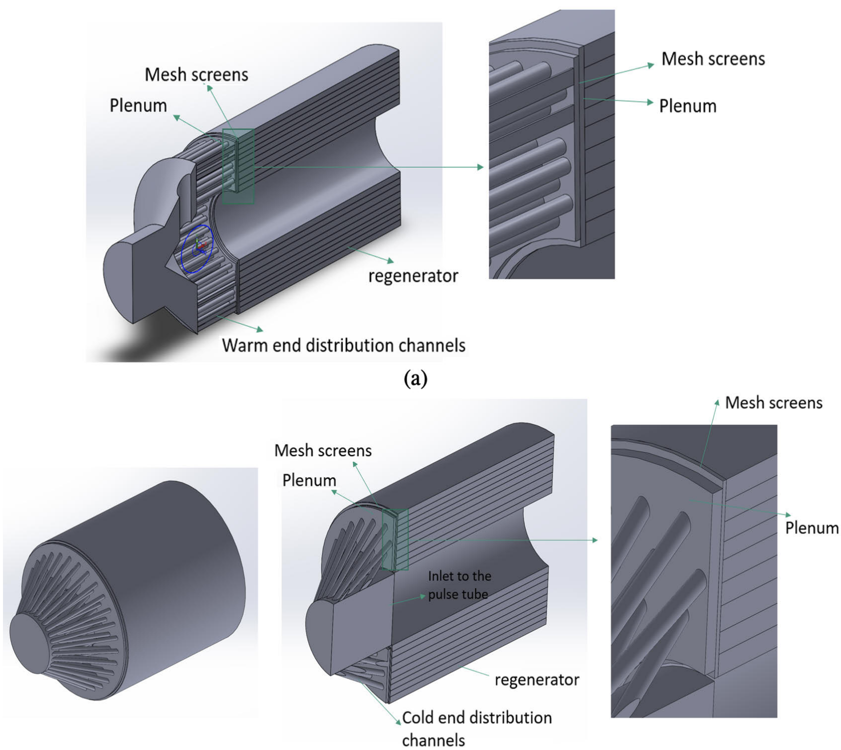


Figure 3. Fluid computational domain, (a) the warm-side flow distribution component of the 90 K cryocooler regenerator, (b) the cold-side flow distribution component of the 90 K cryocooler regenerator.

and an oscillating pressure of 4.081E5 Pa at 35 degrees phase angle is also applied at the outlet of the cold end flow distribution channels (the inlet of the pulse tube). The isothermal temperature here is 90 K with a mean pressure of 6 MPa. The flow oscillation frequency for both warm and cold end flow distribution components is set at 30 Hz.

The effect of open plenum thickness and mesh screen-filed plenum thickness, as well as mesh screen type on regenerator flow uniformity is investigated at both cold and warm end. All dimensions are normalized, to avoid IP issues. The regenerator dimensions including inner diameter, outer diameter, and the length are normalized by the regenerator outer diameter. The open plenum and mesh screens-screen field thicknesses are normalized by $(D_o - D_i)/2$, where D_o and D_i represent the regenerator outer and inner diameters, respectively and reported as a percentage of that. All model parameters and dimensions are summarized in Table 1.

THEORY AND METHOD OF SOLUTION

By assuming incompressible and Newtonian fluid, the continuity and momentum equations which are numerically solved are as follows:

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} u_j u_i = -\frac{1}{\rho}\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \nu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{2}$$

where ν and ρ are kinematic viscosity and density of the fluid, respectively. Regenerator and mesh screens are modeled as porous medium. The volume-averaged hydrodynamic resistance of the porous medium is represented by ANSYS Fluent using a momentum source term composed of viscous and inertial components. The continuity and momentum conservation equation that ANSYS Fluent [6] numerically solves for flow in an isotropic porous medium can be represented as:

Table 1. Model parameters.

Model parameter	Value
Working gas	Helium
Frequency (f)	30 Hz
Isothermal temperature at cold end (T_{cold})	90 K
Isothermal temperature at warm end (T_{warm})	300 K
Mean pressure (P_{mean})	6 MPa
Normalized pulse tube diameter (D_{PT})	0.37
Normalized regenerator inner diameter (ID_{Regen})	0.38
Normalized regenerator outer diameter (OD_{Regen})	1
Normalized regenerator Length (L_{Regen})	2.63
Transfer line diameter (D_{TL})	0.45
Normalized plenum inner diameter (ID_{plenum})	0.38
Normalized plenum outer diameter (OD_{plenum})	1
Normalized mesh screen inner diameter (ID_{ms})	0.41
Normalized mesh screen outer diameter (OD_{ms})	0.97
Normalized plenum thickness (t_{plenum})	4.2 – 16.7 %
Normalized mesh screen thickness (t_{ms})	2.1 – 16.7 %
Mesh screen type	#325 SS, #635 PhBrz

$$\frac{\partial(\varepsilon\rho)}{\partial t} + \nabla.(\varepsilon\rho\vec{u}) = 0 \tag{3}$$

$$\frac{\partial(\varepsilon\rho\vec{u})}{\partial t} + \nabla.(\varepsilon\rho\vec{u}\vec{u}) = -\varepsilon\nabla P + \nabla.(\varepsilon\bar{\bar{\tau}}) + \varepsilon\vec{B}_f - \left(R_v\varepsilon^2\mu\vec{u} + \frac{\varepsilon^3 R_i}{2}\rho|\vec{u}|\vec{u}\right) \tag{4}$$

where ε, R_v and R_i are porosity, viscous resistance and inertial resistance coefficients, respectively. For the regenerator, the radial resistance coefficients are set to infinity to avoid any radial flow (cross-flow) in the regenerator, which is consistent with the geometric configuration of the regenerator filler. For modeling the mesh screens, #325 Phosphor Bronze (#325 PhBrz) and #635 stainless steel (#635 SS) are considered. The properties of these two types of mesh screens as well as the regenerator are summarized in Table 2 [7].

At the regenerator ends, radial flow non-uniformity is calculated at 9 evenly spaced radial sections. A flow non-uniformity parameter, ξ, is defined, where the mass flow rate ideally is expected to be proportional to the cross-sectional area:

$$\xi = \left(\frac{mfr\ of\ each\ region / total\ regenerator\ mfr}{area\ of\ each\ region / total\ cross\ sectional\ area} - 1\right) \times 100 \tag{5}$$

By this definition, the flow at each region is more uniform the closer value of ξ is to 0. Any deviation from 0 would imply flow non-uniformity. Values higher than 0 mean higher than ideal flow through that region and values lower than 0 imply lower than ideal flow through that region. The flow non-uniformity parameter values correspond to the peak flow rate during the periodic flow.

NUMERICAL SOLUTION PROCEDURE

ANSYS Fluent [6] is used for performing this sensitivity analysis and solving equations 1-4. The oscillating mass flow rate and static pressure boundary conditions are applied in the computational domain by the aid of a user define function (UDF) in Fluent. The UDF code is developed in C++.

The analysis is three-dimensional. Pressure based solver with SIMPLE algorithm is used to solve pressure-velocity coupling. For discretization of governing equations, the standard second order method for pressure, second order upwind scheme for momentum and energy equations, and least squares method for gradients is implemented by finite volume technique. For convergence criteria, the residual is set to 10^{-6} for continuity and momentum equations, and 10^{-13} for energy equation. The analysis is transient and the time step is set to . This time step is equivalent to 100 time steps for each cycle since the frequency is set to 30 Hz. The periodic steady state solution, where the cyclic variation of all parameters is repeated identically, was achieved after 10 cycles for all simulation cases. Post processing of results was performed by Tecplot [8].

RESULTS AND DISCUSSION

Figure 4 summarizes the results corresponding to the effects of mesh screen-filled plenum thickness, open plenum thickness, and mesh screen type on the flow non-uniformity at the warm end of regenerator.

Figure 4 (a) shows the effect of mesh screen-filled plenum thickness on flow uniformity. This figure indicates that the innermost and outermost regions (close to inner and outer diameters of the regenerators carry less flow than the remainder of the regions. This is primarily caused by the fact

Table 2. Regenerator and mesh screens parameters for modelling the porous medium region.

Mesh type	ε	$R_{i,axial}$ $(1/m)$	$R_{v,axial}$ $(1/m^2)$	$R_{i,radial}$ $(1/m)$	$R_{v,radial}$ $(1/m^2)$
#325 PhBrz	0.67	50000	1.7E+10	60000	2.9E+10
#635 SS	0.63	40000	9.5E+10	120000	1.11E+11
Regenerator	0.60	2309	4.81E+10	infinity	infinity

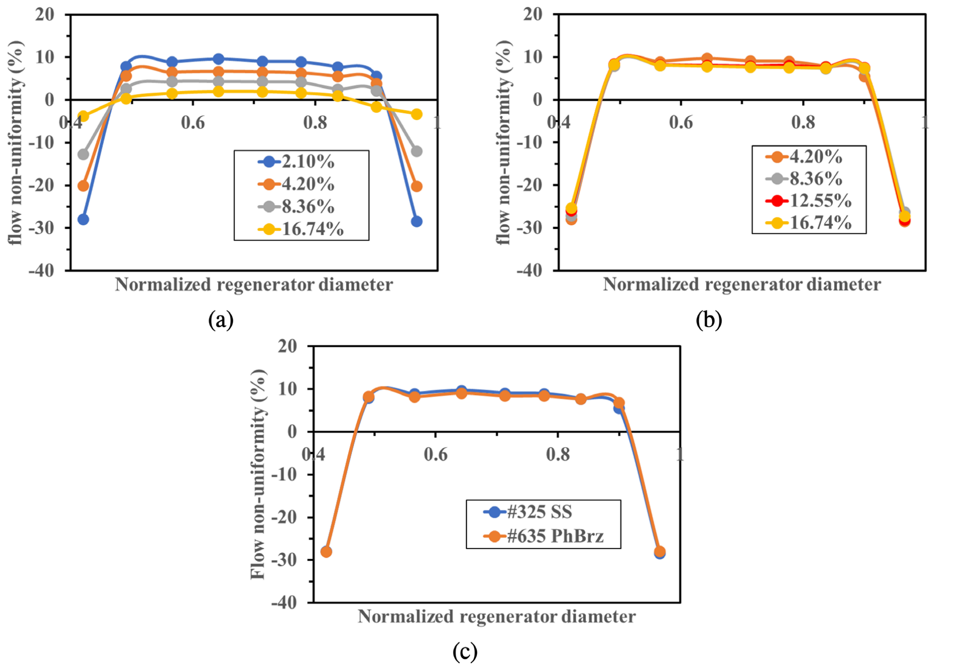


Figure 4. Flow non-uniformity at the warm end of regenerator, (a) effect of mesh screen thickness at 4.2% plenum thickness and with #325 SS flow straightener, (b) effect of plenum thickness at 2.1% mesh screen thickness and with #325 SS flow straightener, (c) effect of mesh screen (flow straightener) type at 4.2% plenum thickness and 2.1% mesh screen thickness.

that the inner diameter of the open shallow plenum is slightly larger than the inner diameter of the regenerator, and similarly the outer diameter of the open plenum is slightly smaller than the outer diameter of the regenerator. Theses geometric features can be seen in Figure 3, and are needed for making the assembly of the system possible. The presence of a shallow porous plenum at the warm end of the regenerator mitigates the flow non-uniformity caused by these geometric features. However, increasing the thickness of the scree-filled plenum clearly improves the flow uniformity in all regions, lowering the excess of flow at the middle of the regenerator and increasing the flow near the inner and outer diameter of regenerator. Having 5% flow non-uniformity as a maximum

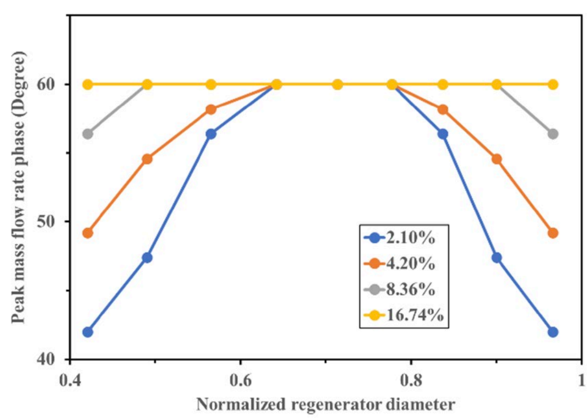


Figure 5. Phase angle of peak mass flow rate at the regenerator inlet with changing the mesh screen (#325 SS) thickness at 4.2% plenum thickness.

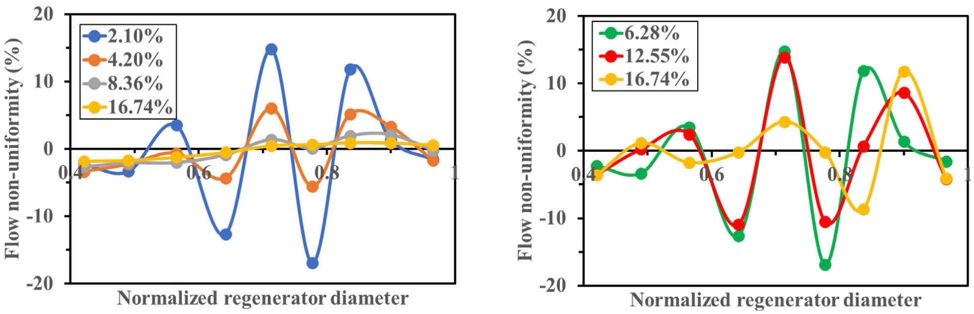


Figure 6. Flow non-uniformity at the cold end of regenerator, (a) effect of mesh screen thickness at 6.28% plenum thickness and with #325 SS flow straightener, (b) effect of plenum thickness at 2.1% mesh screen thickness and with #325 SS flow straightener.

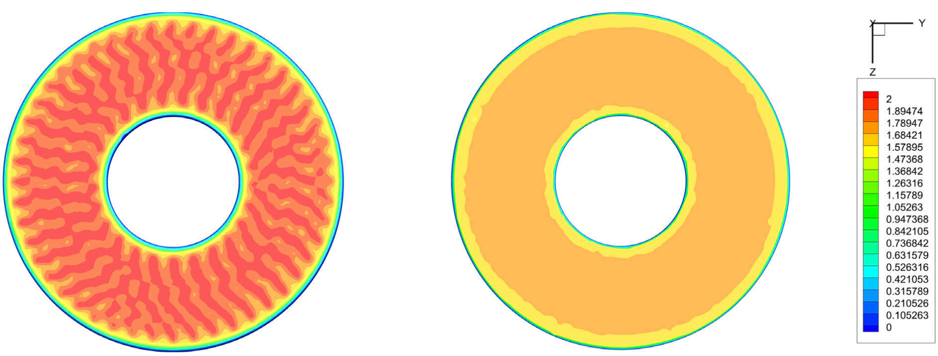
allowable value, which leads to a regenerator effectiveness above 95%, requires the dimensionless mesh screen thickness of 16.74% at the regenerator warm end.

As can be seen in Figure 4 (b), increasing the open plenum thickness does not have a significant effect on radial flow non-uniformity. However, it slightly improves the flow uniformity in the core of regenerator.

As can be seen in Figure 4 (c), the flow uniformity is almost unchanged by changing the mesh screen type, and both #325 SS and #634 PhBrz perform the same as flow straighteners.

Figure 5 shows the dependence of the phase angle of peak mass flow rate at the warm end of the regenerator on the mesh screen-filled plenum thickness. The occurrence of non-uniform mass flow rate phase angles over the cross section of the regenerator is another problem that originates from flow non-uniformity. Having different phase angles at the same cross section increases exergy destruction. The flow next to the inner and outer walls of the regenerator is lagging behind the flow in the core of the regenerator. Increasing the mesh screen-filled plenum thickness mitigates this problem where at 16.74% dimensionless thickness of mesh screen-filled plenum the entire cross section of the regenerator has same mass flow rate phase angle.

The cold end of the regenerator is now discussed. Figure 6 shows the effect of open and mesh screen-filled plenum thicknesses on radial flow uniformity at the regenerator cold end. Having 5% maximum allowable flow non-uniformity at all regions, leads to a minimum required thickness of 8.36% for the mesh screen-filled plenum to perform as an effective flow straightener. This is lower



(a) (b)

Figure 7. Velocity magnitude contour plots at the warm end of regenerator at time step 80 (maximum mass flow rate), (a) at 4.2% plenum thickness and 2.1% mesh screen thickness, (b) at 4.2% plenum thickness and 16.74% mesh screen thickness.

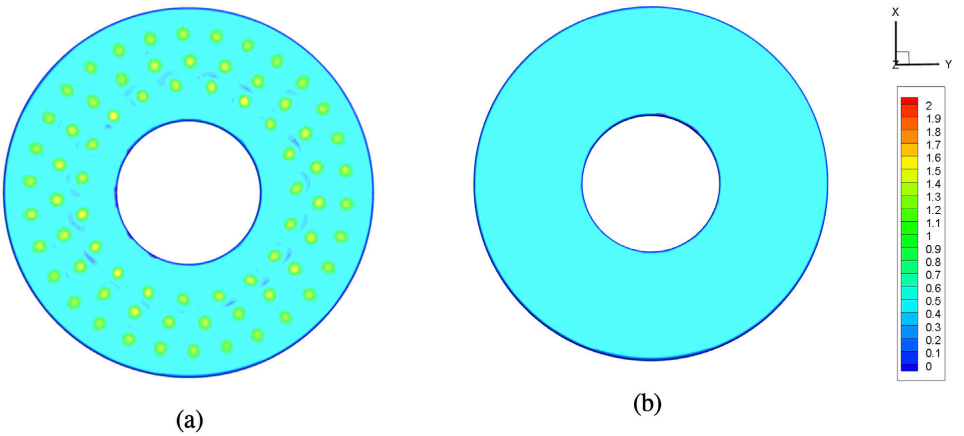


Figure 8. Velocity magnitude contour plots at the cold end of regenerator at time step 48 (maximum mass flow rate), (a) at 6.28% plenum thickness and 2.1% mesh screen thickness, (b) at 6.28% plenum thickness and 16.74% mesh screen thickness.

than the required 16.74% at the warm end, mainly because the mass flow rate is lower at the cold end. Furthermore, we considered a thicker open plenum at the cold end, 6.26% at the cold end versus 4.20% at the warm end.

Figure 7 and Figure 8 show the velocity magnitude contour plots at the warm and cold ends of the regenerator, respectively, for cases with different mesh screen-filled plenum thicknesses. These two figures clearly show the flow straightening effect of mesh screens, especially at the locations where the regenerator meets the outlet of flow distribution channels. The velocity magnitude is depicted for an open plenum thickness of 4.2% at the warm end and 6.28% at the cold end at maximum mass flow rate.

CONCLUSION

A practical approach for mitigating mass flow non-uniformity through a large regenerator has been developed by the aid of CFD simulations. CFD simulations were performed on a large regenerator and flow distribution components connected to its warm and cold ends. The flow distribution components comprise of large numbers of miniature flow passage that are connected to a shallow open plenum, and a flow straightener in the form of a shallow mesh screen-filled plenum. By parametric simulations it was shown that mesh screen-filled plenum thickness is the most important and sensitive parameter for making the flow uniform through the regenerator. Increasing the open plenum thickness slightly improves the flow uniformity at the middle of the regenerator. The flow uniformity is insensitive to the mesh screen type.

ACKNOWLEDGMENTS

This project is supported by NASA Early Stage Innovation (ESI) Grant Number 80NSSC21K0218.

REFERENCES

1. Gedeon, D., *Sage User's Guide*, Sage v11 Edition, 259 (2016).
2. Ghavami, A., Kirkconnell, C., Ghiaasiaan, S.M., Chen, W., Zagarola, M., "Analysis of a Novel Micro-Structured Regenerator Filler," *Cryocoolers 20*, ICC Press, Boulder, CO (2018), pp. 235-244.
3. Ghavami, A., Fang, T., Ghiaasiaan, S.M., "March. Entropy generation in the woven mesh regenerator filler of cryocoolers," *IOP Conference Series: Materials Science and Engineering,* Vol. 755, No. 1, (2020), p. 012064.

4. Fang, T., Ghavami, A. Ghiaasiaan, S.M., "A Second Law Study of the Regenerators in Cryocoolers based on Pore-level Analysis of Entropy Generation," *IOP Conference Series: Materials Science and Engineering,* Vol. 755, No. 1, (2020), p. 012049.

5. Ghavami, A., Kirkconnell, C., Ghiaasiaan, S.M., "Development of a 2D/3D Computational Fluid Dynamic Code for Pore-Level Analysis of Cryocooler Regenerators," *Cryocoolers 21*, ICC Press, Boulder, CO (2021), pp. 325-335.

6. *ANSYS FLUENT User's Guide*, ANSYS, No. Release 14.5, Canonsburg, PA 15317: Southpointe, (2012).

7. Landrum, E.C., Conrad, T.J., Ghiaasiaan, S.M., Kirkconnell, C.S., "Hydrodynamic parameters of mesh fillers relevant to miniature regenerative cryocoolers," *Cryogenics*, 50(6-7), (2010), pp.373-380.

8. *Tecplot 360 User's Manual,* Tecplot, I.N.C., Release 1, (2013).