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Performance improvement of the high-frequency regenerator for miniature pulse tube cryocooler

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Abstract

A Miniature pulse tube cryocooler (MPTC) is the first choice for electronic cooling in space technology. A Regenerator is one of the main elements in the miniature pulse tube cryocoolers and its performance directly affects the overall system performance. MPTC working at a very high frequency of 100 Hz has been studied with two different regenerator materials. The regenerator is optimized by using REGEN 3.3 software for a miniature pulse tube cryocooler operating with a hot end and cold end temperature of 300 K and 80 K respectively. The MPTC system produces a maximum coefficient of performance (COP) for a given heat load capacity at the optimized regenerator. The dimensions of the regenerator (diameter and length) were fixed for the cooling load of 1 W @ 80K. The result shows that the regenerator model with brass matrix material provides better COP than the regenerator model having stainless steel matrix material.

Keywords: Miniature pulse tube cryocooler, REGEN 3.3, Regenerator, High Frequency, COP

1. Introduction

Cryocoolers are used for thermal management of infrared sensors in space & military applications and commercial applications such as infrared detectors, night vision cameras, transportation cooling of superconducting circuits and magnets, electronic IR sensors, earth observation, etc. These applications require regenerative cryocoolers to function below 120 K temperatures with a cooling load of few to few watts. Cryocoolers such as Gifford-McMahon Cryocooler, Stirling cryocooler, and Pulse tube Cryocooler (PTC) are the types of regenerative cryocoolers. A PTC cryocooler is one of the regenerative type cryocoolers which eliminates the moving component at the cold end of the system and thus capable to achieve the desired cooling of an electronic device with minimal vibration. In the PTC cryocooler, cooling is achieved by a pressure wave that shifts the working helium gas between the hot and cold end of the cryocooler. The PTC is further classified in terms of phase shift mechanism viz. orifice and inertance and various geometric arrangements such as u-tube, inline and co-axial. The Stirling type pulse tube cryocooler (STPTC) is pertained to be one of the miniature pulse tube cryocoolers and thus considered as one of the most promising cryocooler technology for the applications in space viz. cooling of IR focal planes, IR sensors, etc. for producing 80 K cryogenic temperature at small payload from few milliwatts up to 1 Watt. Besides the merit of miniaturization, it provides rapid cool down, high reliability, smaller volume, and low cost. The Miniature STPTC cryocooler uses helium as a working gas which oscillates periodically through a regenerator. The STPTC is typically composed of a linear compressor, hot and cold heat exchangers, a regenerator, a pulse tube, one or more orifice valves, or an inertance tube and a surge volume. The regenerator is considered the most complicated and crucial component of cryocoolers. The effective approach to reducing the overall dimension of the PTC is to increase the working frequency, high charge pressure, finer regenerator filler material, and thinner regenerator wall (O'Gallagher, 2006).

Vanapalli et.al (S. Vanapalli, 2007) designed, optimized, and performed experimentation for a 120 Hz PTC that achieved 50 K and produces 3.4 W at 80 K. They have achieved a fast cool downtime of fewer than 10 minutes to attain 50 K by using SS 635 # wire mesh screen as a regenerator matrix material with a working pressure of 3.5 MPa. They concluded that the pressure oscillator was not optimized for the system and thus higher electrical power was needed. Garaway et al. (I. Garaway, 2009) studied a prototype of an MPTC cryocooler operating at 150 Hz and reaches 97.5 K at a high cool downtime with a regenerator length of 27 mm and SS 635 # as matrix material. They reported the losses associated with the miniature devices. Xiaotao Wang et al. (Xiaotao Wang, 2012) also investigated a miniature coaxial PTC working at a very high frequency of 100 Hz and 260 Hz and reported that the regenerator losses are the most prominent affecting parameter in the system performance. J.R. Olson et al. (J. R. Olson, 2014) developed and examined a prototype PTC cryocooler with a new micro compressor operating at an input power of 25 W for cooling of tactical & space applications. They carried out experiments at four different cold end tip temperatures and heat lifts. They reported that with the electrical input power higher than the optimized design, the regenerator is undersized and less efficient. Conrad et al.(T.J. Conrad, 2009) numerically studied the effects of the geometric and working parameters on small-scale pulse tube cryocoolers using SS 635 # wire mesh screens. Consequently, the losses associated with the regenerator for MPTC are larger when operated at a very high frequency. The regenerator performance is affected by the various parameters viz. mass flux, operating frequency, porosity, hydraulic diameter, pressure ratio, operating charge pressure phase angle at the cold end, and a filler matrix material. A regenerator operating at a very high frequency causes thermal and pressure losses due to the regenerator matrix material, structure, geometry, heat condition in the axial direction, less contact time between gas and matrix material, etc. Therefore, a systematic analysis is required to realize the effect of a very high frequency on the performance of the regenerator of MPTC. The objective of the present work is to design and optimize the MPTC cryocooler operating at a very high frequency with different matrix materials using REGEN 3.3 open-source modeling software developed by the National Institute of Standards and Technology (NIST).

2. Regenerator

A regenerator is a pivotal component in the design of the STPTC cryocooler. The regenerator acts as a heat storage device that consists of a material having high thermal capacity with a high heat transfer surface area. In a regenerator, the heat is exchanged periodically between oscillating helium gas and porous matrix material. Different matrix geometry viz. wire mesh screen of different wire diameter, weave methodology, sphere, and materials are used regenerator for cryocooler. The warm gas exchanges the energy with porous filler matrix material during the hot blow period (compression stroke) and the energy is stored in the regenerator matrix material. During the cold blow period (expansion stroke) the flow reserves and the stored energy during the expansion stroke are absorbed back from the matrix material. The essential function of the regenerator is to transfer the acoustic power of the pressure wave generator to the cold end with minimal loss. The ideal requirements of a cryocooler regenerator are small axial heat conduction with minimum enthalpy flow, high volumetric heat capacity to reduce the axial losses, largest radial heat conduction to reduce thermal saturation of matrix material, minimum pressure drop, and perfect heat exchange between the filler matrix material and helium gas. Thus, the parametric study of the regenerator is required for the improvement of the system performance.

3. Numerical Methodology

The REGEN 3.3 [(Gary J, 2008)] is 1-D numerical analysis software developed at the NIST for the design and optimization of regenerator using Helium-3 and Helium-4 gas. The REGEN 3.3 model solves mass, momentum, and energy conservation equations with friction as an additional term in the momentum equation and heat transfer factor in the energy equation to take into account the effect of a porous medium in the mathematical model. It solves non-linear equations for mass, pressure, and temperature at the mesh nodes simultaneously by Newton iterative method. REGEN 3.3 allows for temperature-dependent thermal properties as well as very broad matrix materials and geometries for regenerators. REGEN 3.3 presumes sinusoidal mass flux at the hot and cold end of the regenerator. The regenerator numerical model is shown in figure 1. The regenerator loss for a given acoustic flow rate is significantly affected by the phase angle between mass flow and pressure amplitude. This loss is expected to be minimum at the mid-point of the regenerator and it is governed by the motion of the gas piston. For a fixed value of cold end PV work, the cold end mass flow rate (s) and the phase angle at the cold end (θ_c) are computed. Input parameters required in REGEN are temperatures of working fluid at the hot end and cold end, frequency, charge pressure, flow amplitude, pressure ratio, porosity, and phase angle at the cold end. To initiate a numerical simulation, guess values of all the above state parameters are used as the input. It provides regenerator performance in terms of output viz. net and gross cooling power, coefficient of performance, losses related to compressor work at warm and cold ends, and various hydrodynamic and thermal parameters. Thus, a regenerator is optimized for the desired heat lift at the cold end of the cryocooler.

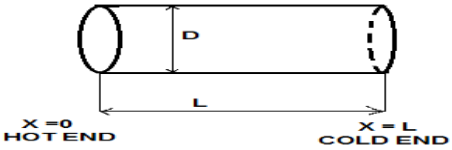


Figure 1. Regenerator Model defined in software REGEN 3.3

The following are the conservation equations for fluid flow solved in the REGEN 3.3 model.

Mass Conservation Equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho \upsilon)}{\partial x}=0$$

(1)

Momentum Equation

$$\frac{\partial \rho \upsilon}{\partial t}+\frac{\partial\left(\rho \upsilon^2+p\right)}{\partial x}-f\left(\rho, T, \upsilon\right)=0$$

(2)

Where $f\left(\rho, T, \upsilon\right)$ is the friction term

$$\frac{\partial D}{\partial t}+\phi A q(p, T, T_{m,} \upsilon)-\frac{\left(1-\phi\right) A k_m \frac{\partial T_m}{\partial x}}{\partial x}=0$$

(3)

Matrix thermal term D(x, T) is defined as

$$D\left(x, T\right)=\int_{T \min}^{T}\left(1-\phi\right) A c_m(x, T) d T$$

(4)

The form of heat transfer term is as follows

$$q\left(p, T, T_m, v\right)=4 H(p, T, v)(T_m-T) / D_h$$

(5)

Where $H(p, v)$ is the coefficient of heat transfer

4. Regenerator Design Details

As per the literature survey, the state of art for regenerator filler matrix material used for the high-frequency regenerator is SS 635# wire mesh screen. In the present work, an investigation has been carried out to study the influence of filler material on the performance of the high-frequency MTPC. A numerical study was carried out for a regenerator matrix SS 635 # wire mesh screen and brass 500 # wire mesh screen. The regenerator geometries and other parameters were reported in table 1.

Table 1. Fixed regenerator for Investigation

Parameters	*Dimensions*	*Units*
Regenerator Tube Internal Diameter (D)	4	mm
Regenerator Length (L)	30	mm
Regenerator tube thickness	0.1	mm
Hot End Temperature (T_h)	300	K
Cold End Temperature (T_c)	80	K
Frequency (f)	100	Hz
Charge Pressure (P_c)	35	Bar
Cold end Pressure Ratio (Pr)	1.3	-
Cooling Capacity (Q_{net})	1	W

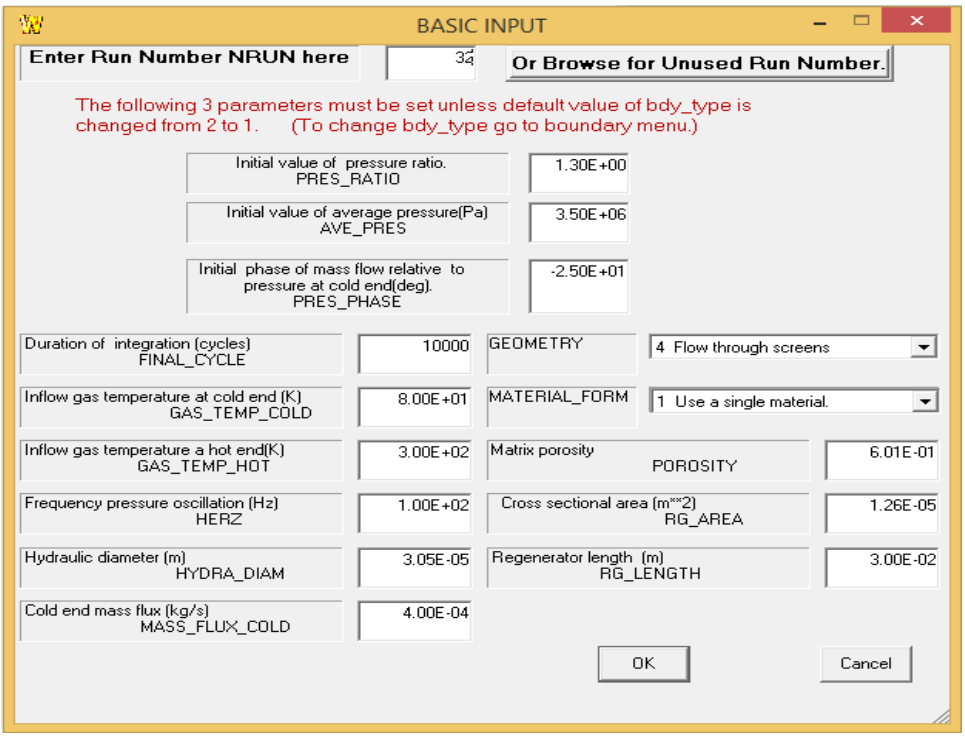
The REGEN 3.3 software tool was used for regenerator design with operating at a hot end and cold end temperatures of 300 K and 80 K @ 1W. He-4 gas is selected as a working fluid and both gas and matrix material properties were selected as a temperature-dependent property. All the simulated cases were assumed that the compressor impedance is agreed with the system.

A numerical model used for iterative optimization depends on the grid interval, time interval, number of iterations, and some initial guess values of parameters. The numerical model is initially simulated with spatial mesh points of 41, time steps per cycle of 81 and 1000, number of iterations. The same cases were then again simulated with an 81 mesh point and finer mesh 101 points. However, the variation found in the COP of the regenerator is less than 0.012 % for 81 mesh points with significant time reduction. Thus, all the cases were simulated with the 81 mesh points. The set of cases with various mass fluxes at the cold end are generated for fixed regenerator dimensions. Further, these cases were repeated for each phase angle at the cold end to predict the maximum COP. The time required for each numerical simulation case run in REGEN 3.3 for selected numerical parameters is approximately 4 to 5 hours on a personal computer i4 core.

5. Results and Discussion

The regenerator is modeled in REGEN 3.3 with two different regenerator matrix materials viz. SS wire mesh screen (SS 635 #) and Brass wire mesh screen (500 #) were investigated for the miniature very high-frequency regenerator. REGEN 3.3 models were simulated by varying mass flux at the cold end and phase angles. The maximum COP of the regenerator for both the matrix materials would occur with the matching of mass flux and phase angle. The hydraulic diameter of the SS 304 wire mesh screen and brass wire mesh screen is 30.58 µm and 39.28 µm with porosities of 0.6014 and 0.6422 respectively. Figure 2 and Figure 3 shows the screenshot of REGEN 3.3 software input parameters for SS 635 # and Brass 500 # wire mesh screen.

Figure 4 (a) and (b) show the REGEN 3.3 software plots for the average temperature of gas and matrix material over the longitudinal axis of the regenerator for SS 635# and Brass 500 # regenerator materials. It is observed that the average gas and matrix temperature varies linearly over the length of the regenerator. Figure 5 (a) and (b) demonstrates the REGEN plot of cold end pressure (P), the mass flux (MFX0) at the hot end, and the mass flux (MFX1) at the cold end against the time. There exists a phase difference between hot end mass flux and cold end mass flux in both the regenerator materials. The mass flux at the hot end is slightly more in the case of SS 635 # regenerator than Brass 500 #. The maximum mass flow at the hot end is 3.729 E-04 kg/s when mass flow at the cold end is 4.0 E-04 kg/s for SS 635 # and Brass 500 # maximum mass flow at the warm end is 3.654 E-04 when mass flow at the cold end is 4.0 E-04 kg/s. However; cold end mass flux for both the cases are the same.



Enter Run Number NRUN here: 34

The following 3 parameters must be set unless default value of bdy_type is changed from 2 to 1. (To change bdy_type go to boundary menu.)

Initial value of pressure ratio. PRES_RATIO: 1.30E+00

Initial value of average pressure(Pa) AVE_PRES: 3.50E+06

Initial phase of mass flow relative to pressure at cold end(deg). PRES_PHASE: -2.50E+01

Duration of integration (cycles) FINAL_CYCLE: 10000

GEOMETRY: 4 Flow through screens

Inflow gas temperature at cold end (K) GAS_TEMP_COLD: 8.00E+01

MATERIAL_FORM: 1 Use a single material.

Inflow gas temperature a hot end(K) GAS_TEMP_HOT: 3.00E+02

Matrix porosity POROSITY: 6.01E-01

Frequency pressure oscillation (Hz) HERZ: 1.00E+02

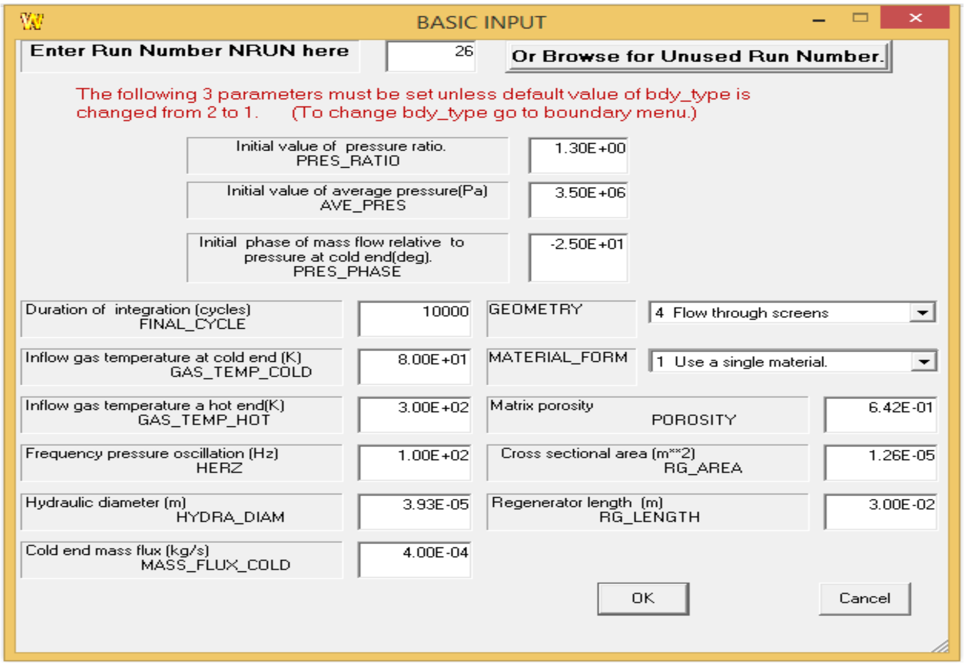
Cross sectional area (m**2) RG_AREA: 1.26E-05

Hydraulic diameter (m) HYDRA_DIAM: 3.05E-05

Regenerator length (m) RG_LENGTH: 3.00E-02

Cold end mass flux (kg/s) MASS_FLUX_COLD: 4.00E-04

Figure 2. Screenshot of REGEN 3.3 with input parameters for SS 635#



BASIC INPUT

Enter Run Number NRUN here: 26

Or Browse for Unused Run Number.

The following 3 parameters must be set unless default value of bdy_type is changed from 2 to 1. (To change bdy_type go to boundary menu.)

Initial value of pressure ratio. PRES_RATIO	1.30E+00
Initial value of average pressure(Pa) AVE_PRES	3.50E+06
Initial phase of mass flow relative to pressure at cold end(deg). PRES_PHASE	-2.50E+01
Duration of integration (cycles) FINAL_CYCLE	10000
GEOMETRY	4 Flow through screens
Inflow gas temperature at cold end (K) GAS_TEMP_COLD	8.00E+01
MATERIAL_FORM	1 Use a single material.
Inflow gas temperature a hot end(K) GAS_TEMP_HOT	3.00E+02
Matrix porosity POROSITY	6.42E-01
Frequency pressure oscillation (Hz) HERZ	1.00E+02
Cross sectional area (m**2) RG_AREA	1.26E-05
Hydraulic diameter (m) HYDRA_DIAM	3.93E-05
Regenerator length (m) RG_LENGTH	3.00E-02
Cold end mass flux (kg/s) MASS_FLUX_COLD	4.00E-04

Figure 3. Screenshot of REGEN 3.3 with input parameters for Brass 500#

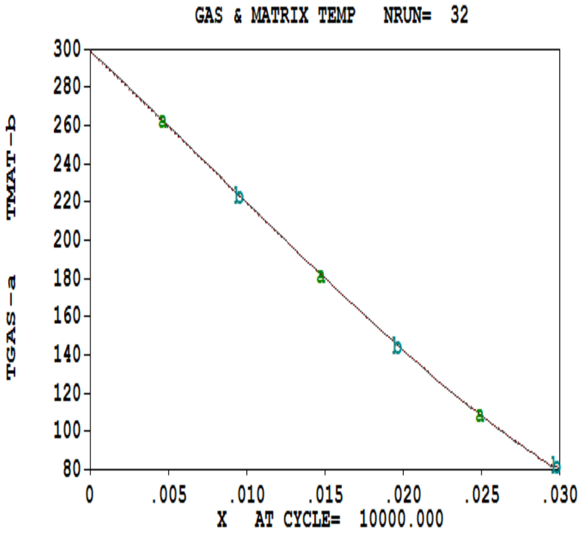


Figure 4.a. Average gas and matrix temperature over a length of the regenerator for SS 635 #

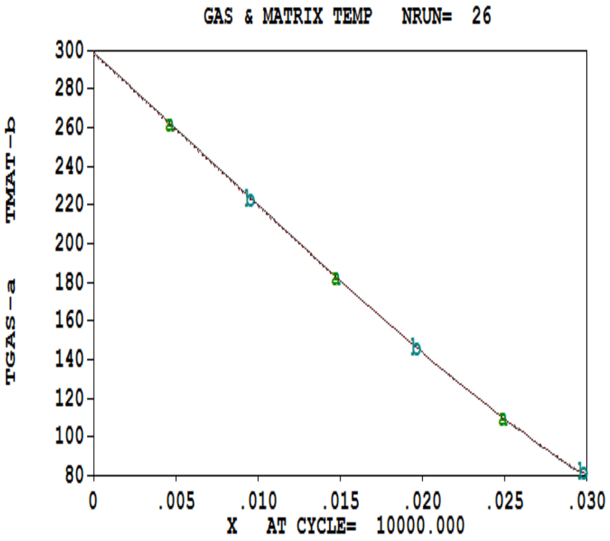


Figure 4.b. Average gas and matrix temperature over a length of the regenerator for Brass 500 #

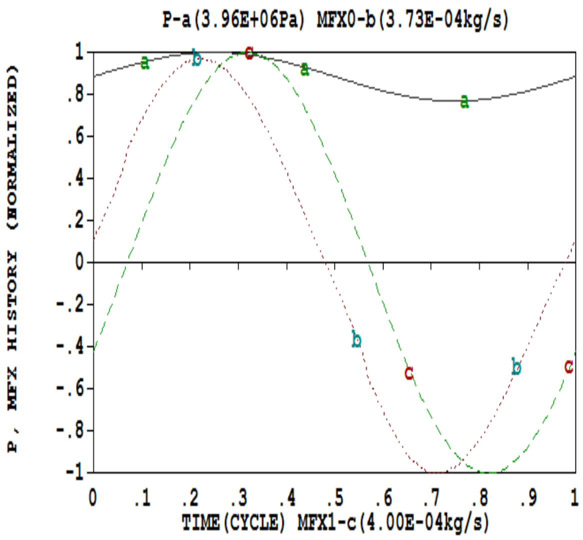


Figure 5.a. Variation of pressure, the mass flux at the cold end, the mass flux at the hot end over a cycle for SS 635 #

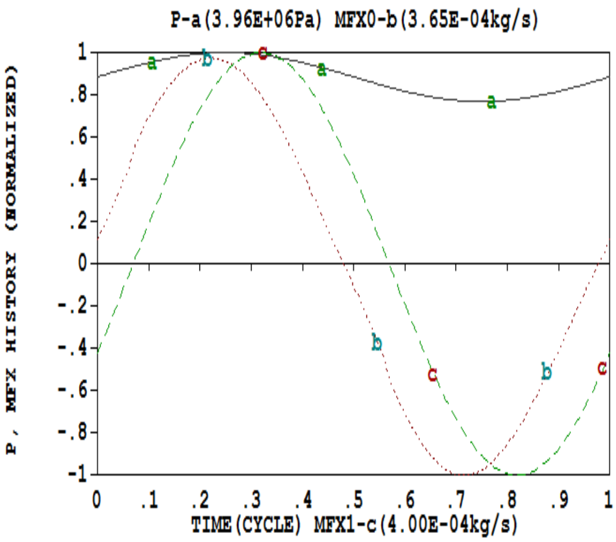


Figure 5.b. Variation of pressure, the mass flux at the cold end, the mass flux at the hot end over a cycle for Brass 500 #

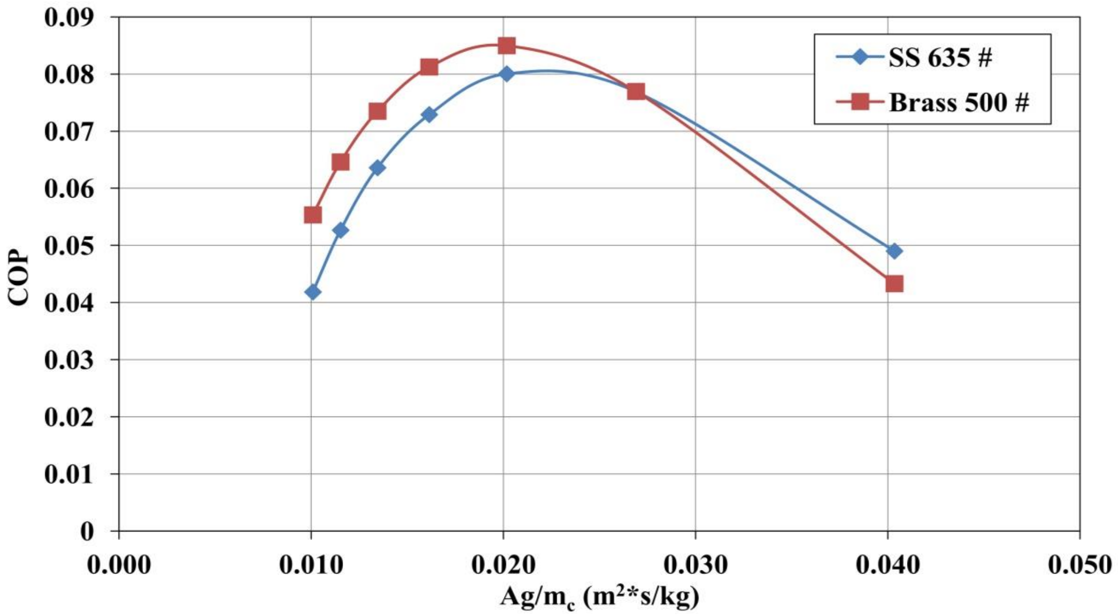


Figure 6. COP vs. inverse mass flux (Ag/mc)

Figure 6 shows the effect of inverse gas flux on the COP for the two regenerator matrix materials viz. SS 635 # wire mesh screen and Brass 500 # wire mesh screen operating at 100 Hz frequency and cooling load 80K@ 1W. Figure 6 shows that the coefficient of performance of Brass 500 # wire mesh screen is better than SS 635 # wire mesh screen. However; the maximum coefficient of performance for both cases are observed at the same inverse mass flux.

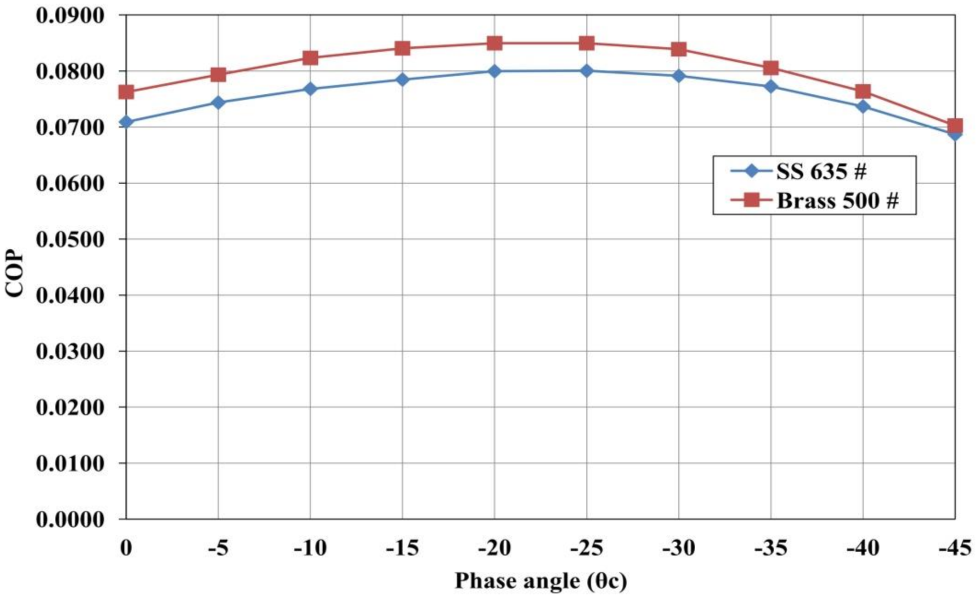


Figure 7. COP values as a function of cold end phase angle (θc)

The effect of phase angle on COP is depicted in figure 7 for the regenerator materials viz. SS 635 # and Brass 500 # wire mesh screen. It is observed from figure 7 that there is an optimal phase angle at which the system produces a maximum COP for both models. At -25° phase angle, the COP of the system are maximum for both the regenerator materials SS 635 # and Brass 500 # and it is also found that the phase angle increases, the COP also increases. The MPTC cryocooler using the brass wire mesh screen as a regenerator material compared to the SS wire mesh screen material exhibits higher COP at the stated conditions for all the phase angles.

6. Conclusion

In the present investigation, the numerical simulations have been performed to determine the optimal operating parameters for the high-frequency regenerator of the miniature pulse tube cryocooler using stainless steel (SS 635#) wire mesh screens and brass (Brass 500#) wire mesh screens. The REGEN 3.3 software tool was used for the analysis with cold end and hot end operating temperatures of 80K and 300 K respectively with a frequency of 100 Hz. The maximum COP value is observed at a phase angle of -25^0 for both the regenerator matrix materials. The COP for SS wire mesh screen and Brass wire mesh screen regenerator are 0.08004 and 0.085 respectively. For both the regenerator matrix materials, the maximum mass flux at the hot end increases with an increase in mass flux at the cold end. There is an optimal combination of the mass flux and phase angle at the cold end for maximizing the COP in designing an MPTC cryocooler. The regenerator model with matrix material (Brass 500 # mesh screen) produces a higher coefficient of performance than stainless steel (SS 635 #) matrix material. The obtained results in the present study will be helpful while designing an MPTC cryocooler operating at a very high operating frequency

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