Design of High Frequency Pulse Tube Cryocooler for Onboard Space Applications

Srikanth Thota, Padmanabhan, Gurudath C S, Amrit A, Basavaraj S , Dinesh K

Department of Space, Govt of India, ISRO Satellite Centre, Bengaluru, India

srikant@isac.gov.in

Abstract. To meet the growing demands of on-board applications such as cooling meteorological payloads and the satellite operational constraints like power, lower mass, reduced size and redundancy; a Pulse Tube Cryocooler (PTC) is designed by arriving at an operating frequency of 100 Hz and Helium gas pressure of 35 bar based on insights obtained from combination of phasor diagram, pulse tube and regenerator geometries with overall system mass of ≤ 2.0 kg. High frequency operation would allow reducing the size and mass of pressure wave modulator for a given input power. High Frequency also helps in reducing the volume of regenerator for a given cooling power, which increases the power density and leads to faster cool down. A component level modelling of the regenerator for optimising length and diameter for maximum Coefficient of Performance (COP) is carried out using REGEN3.3. The overall system level modelling of PTC is carried out using 1-D software SAGE. The cold end mass flow rate of the optimised regenerator is taken as reference for the system modelling. The performance achieved in REGEN3.3 is 2.15 W of net heat lift against the performance of 1.02 W of net heat lift at 80 K in SAGE.

Nomenclature

A	heat transfer surface area of the matrix (m^2)
A_g	gas cross-sectional area (m^2)
A_m	matrix cross-sectional area (m^2)
A_w	wetted area (m^2)
c_p	specific heat of gas flowing through the regenerator (J/kg K)
c_m	specific heat of matrix (J/kg K)
D_h	hydraulic diameter (µm)
D_{pt}	internal diameter of the pulse tube (mm)
D_{pul}	outer diameter of the pulse tube (mm)
D_{it}	diameter of inertance tube (mm)
D_{reg}	internal diameter of the regenerator (mm)
D_{rt}	outer diameter of the regenerator (mm)
E_g	energy of gas (J)
E_s	energy through matrix (J)
k_s	thermal conductivity of solid matrix (W/m K)
k_g	thermal conductivity of gas (W/m K)
k_e	effective thermal conductivity (W/m K)
L_{pt}	length of the pulse tube (mm)
L_{reg}	length of the regenerator (mm)
L_{it}	length of the inertance tube (mm)
P_1	minimum pressure (bar)
P_0	helium gas charge pressure (bar)
s	stroke - amplitude (mm)
T_c	cold end temperature, K
T_w	warm end temperature, K
t_{pt}	wall thickness of the pulse tube (mm)
t_{reg}	wall thickness of the regenerator (mm)
$W_{pv,c}$	cold end PV work (W)
δ_t	penetration depth (mm)
ρ_g	density of the gas (kg/m^3)
ρ_s	density of the solid (kg/m^3)
σ_{max}	maximum tensile strength of the material including FOS (MPa)
$V_{c,pt}$	pulse tube cold end volume (mm^3)
$V_{swept,c}$	cold end swept volume (mm^3)
V_{pt}	volume of pulse tube (mm^3)
Q_s	refrigeration power, SAGE (W)
Q_r	refrigeration power, REGEN (W)
T_g	temperature of the gas, K
ϕ	porosity of regenerator
ϕ_c	angle b/w pressure and cold mass flow rate of the regenerator (deg)

IOP Conf. Series: Materials Science and Engineering **171** (2017) 012081 doi:10.1088/1757-899X/171/1/012081

m	mass flow rate of gas through the regenerator (kg/s)	ϕ_h	angle b/w pressure and hot mass flow rate of the regenerator (deg)
m_c	mass flow at the cold end of regenerator (kg/s)	$\phi_{pt,h}$	angle between the pressure and mass flow rate at hot end of the pulse tube (deg)
m_h	mass flow at the hot end of regenerator (kg/s)		
$m_{pt,c}$	mass flow at the cold end of pulse tube (kg/s)	θ	angle between the imaginary axis and motor force (deg)
$m_{pt,h}$	mass flow at the hot end of pulse tube (kg/s)		
P_r	pressure ratio	φ	angle between the dynamic pressure and real axis (stroke) (deg)
P_{max}	maximum pressure in the pulse tube (bar)		

1. Introduction

A Pulse Tube Cryocooler (PTC) is a mechanical vibration free device which operates on the principle of Stirling cycle. There are various types of PTCs like; basic, orifice, double inlet and inertance and various configurations like; inline, co-axial and U tube. The expander consists of regenerator, U tube and pulse tube. The Stirling-type pulse tube is characterized by the direct coupling of the cold head to the compressor. The schematic of the PTC is shown in Figure 1.

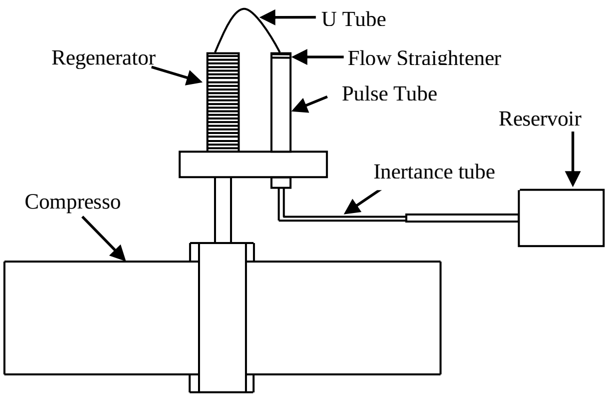


Figure 1. Schematic of Pulse Tube Cryocooler

PTC to meet a specification of 1W at 80K has been developed at ISRO Satellite Centre (ISAC) for cooling Focal Plane assemblies (FPA) of IR detectors. The PTC developed is of the Stirling type having U – Tube configuration with a mass of $\approx$ 3 kg. 1-D model called SAGE has been used to design the technology development model. The system that is discussed in this report is referred to as miniature pulse tube refrigerators and produce cooling power of 1.0 W at 80 K. A regenerative cycle operates with a relatively small cyclic pressure wave oscillating around a large mean fill pressure. For applications such as cooling the IR detectors, non-dissipating superconducting circuits and to meet the spacecraft constraints like redundancy, the cryocooler should be further miniaturized. It has been considered as the most promising mini type cryocooler in the future, and has been playing more and more important roles in 80 K temperature space applications and information industries. The objective of this study is to design high frequency pulse tube cryocooler by combining REGEN and SAGE models.

2. Regenerator

Regenerator is the important component of PTC. In a regenerator, an oscillatory flow of helium gas passes though the porous medium or matrix. The fluid is alternatively heated and cooled as the flow direction is reversed. Energy is first transferred from the hot stream into the matrix. When the cold fluid flows through the matrix during the next part of the cycle, the energy is transferred from the solid material to the cold stream as shown in the Figure 2. The main function of the regenerator is to transmit exergy of the compressor to the cold end of the expander.

<u>Goal of the regenerator:</u>

To store energy during the period of flow of the hot stream and deliver this energy back to the cold stream when it flows through the regenerator.

<u>Desirable characteristics of the regenerator:</u>

High heat capacity, low axial conductivity, high permeability, low pressure drop and high heat transfer coefficient between gas and solid.

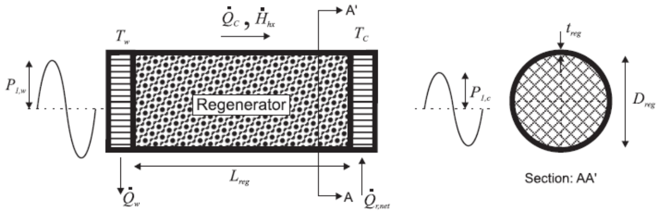


Figure 2. Schematic of Regenerator

2.1 The conservation equations for flow through a regenerator (porous media)
Conservation of mass

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho v)}{\partial x}=0 \quad (1)$$

Equation of momentum

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

where $f(\rho,T,v)$ represents the friction term
In addition to the friction term, the conservation equations must be extended to account for the thermal capacity of the matrix and the heat transfer between the matrix and the gas. This leads to the following conservation of energy equation for the regenerator.

$$\frac{\partial}{\partial t}\left(\phi\rho_g E_g+(1-\phi)\rho_s E_s\right)+\vec{\nabla}\bullet\left(\vec{v}\left(\rho_g E_g+p\right)\right)=\vec{\nabla}\bullet\left[k_e\vec{\nabla}T_g+\left(\tau\bullet\vec{v}\right)\right] \quad (3)$$

$$k_e=\phi k_g+(1-\phi)k_s \quad (4)$$

3. Parameter Selection
Based on the literature survey and the end use application, the parameters of high frequency pulse tube cryocooler are selected. Thermal penetration depth vs frequency and temperature is shown in Figure 3 and Figure 4.

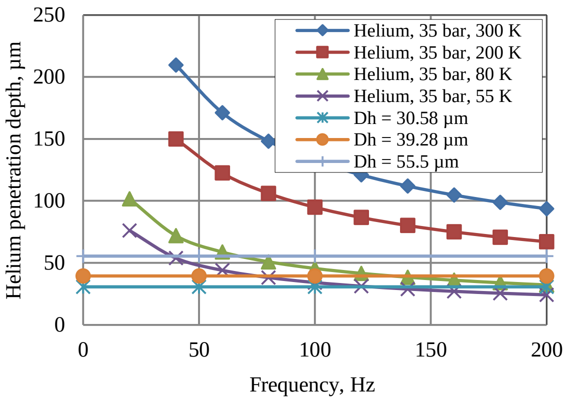


Figure 3.thermal penetration depth vs frequency

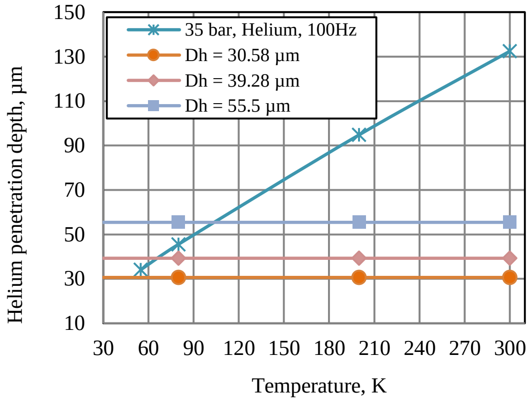
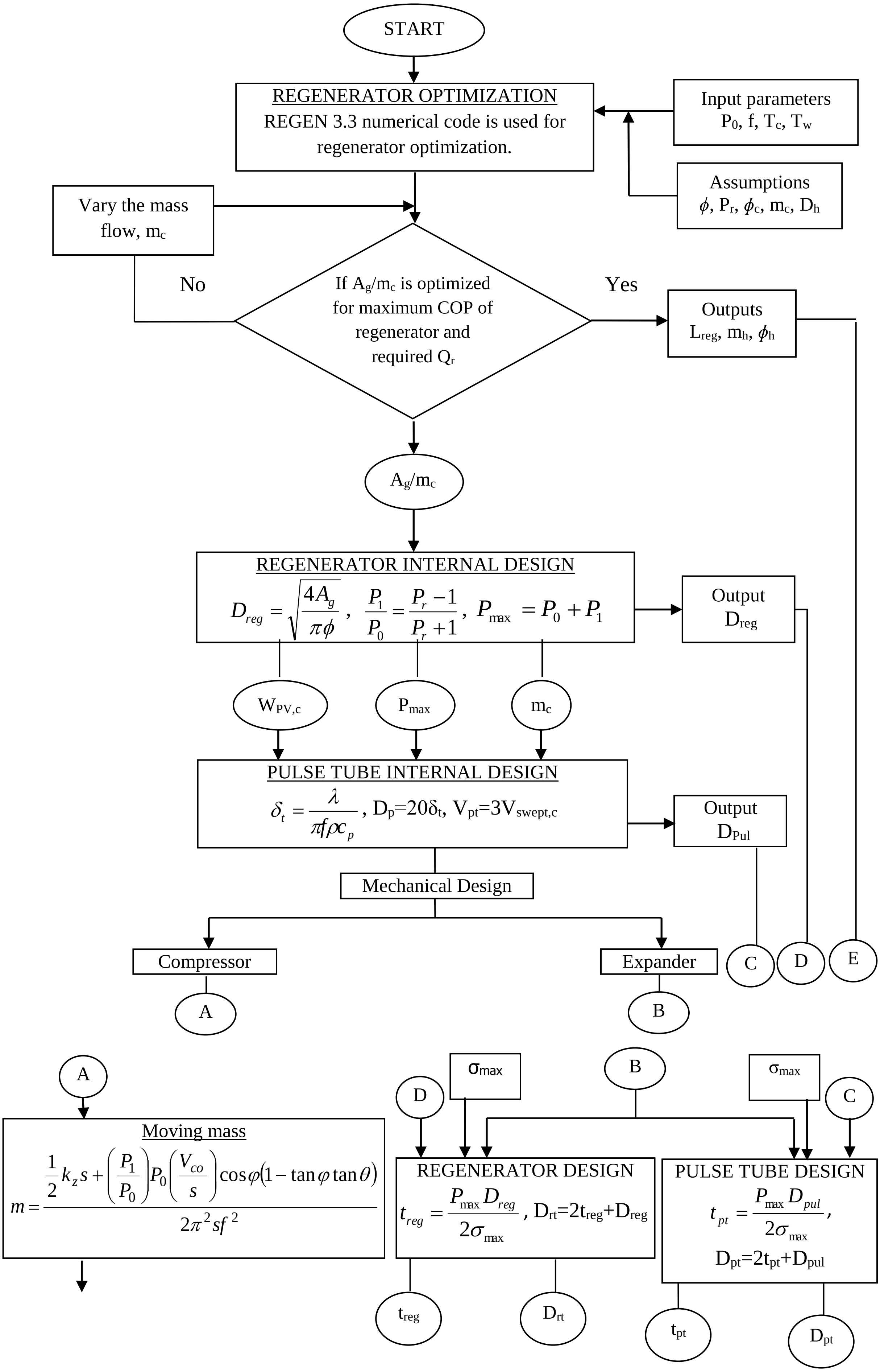


Figure 4. thermal penetration depth vs temperature

In the Figure 3, the 55 K line touches and crosses the 635 grade SS mesh at around 150 Hz and above. At 100 Hz frequency, 55 K line satisfies the condition that hydraulic diameter should be less than the thermal penetration depth of helium in the case of #635 grade mesh line (Hydraulic diameter = 30.58 µm). It means using 635 grade mesh beyond the operating frequencies of around 150 Hz is not advisable. The same is applicable in case of Figure 4. In order to lift load at lower temperature we need to go for higher grade mesh. The operating frequency in this study is limited to 100 Hz. The above parameters are considered for achieving the cooling load of 1.0 W @ 80 K.

4. Design Approach of High Frequency Pulse Tube Cryocooler



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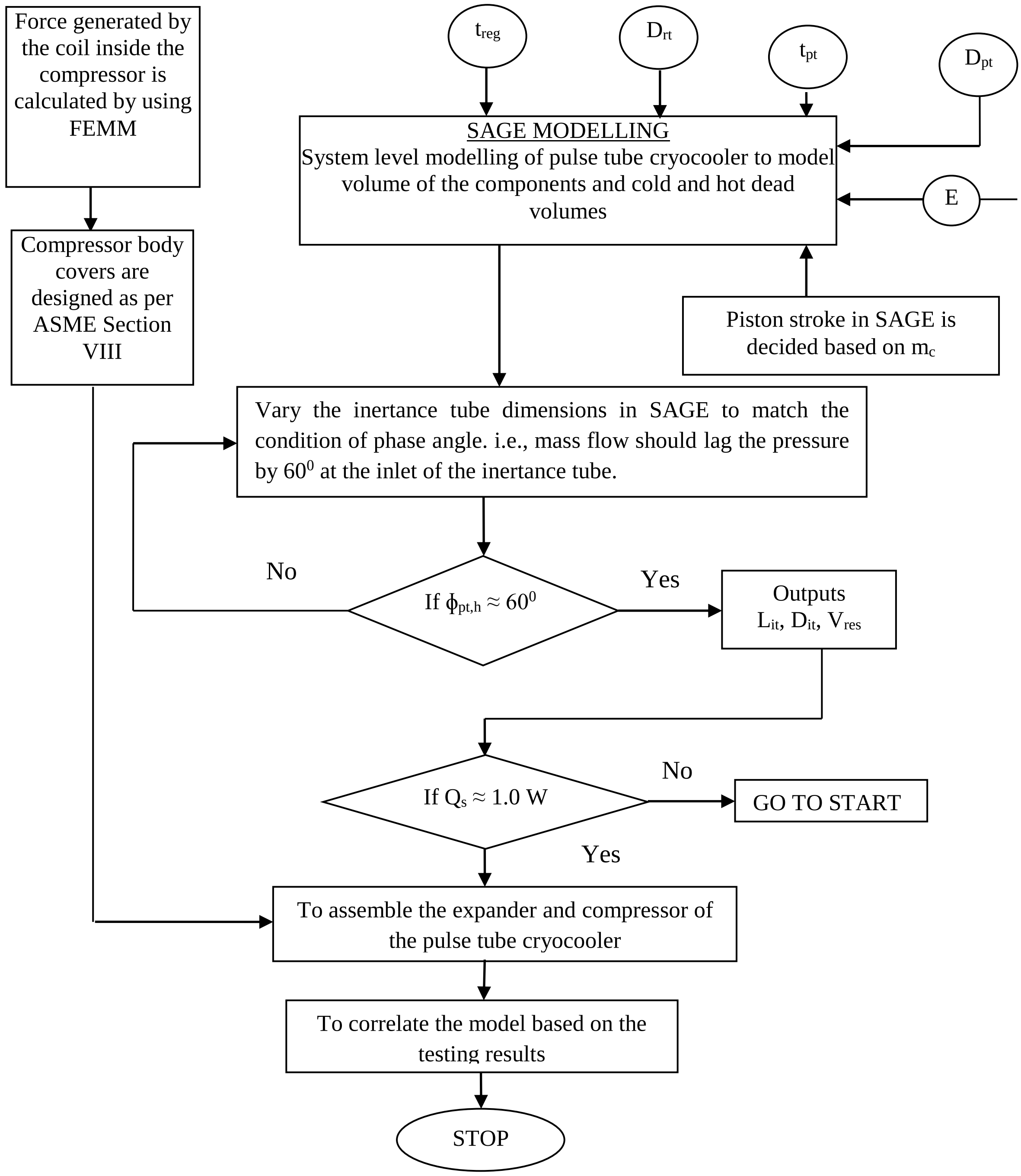

Figure 5. Design approach of high frequency PTC

5. Regenerator Analysis

The regenerator design code developed by NIST in its most recent version, REGEN 3.3, provides a powerful tool for the user to investigate the influence of geometry, material selection, frequency, temperature, pressure ratio, and the phase between flow and pressure on regenerator performance. This tool is used for an iterative optimization to perform a regenerator able to produce 1W at 80K. The program is computationally intensive to run, particularly for low temperature modelling. A large number of iterations, 10,000 increments for full output (cycles), time steps per cycle, 80 and spatial mesh points, 21 are considered in this analysis. These numerical parameters cause REGEN to require approximately 75 minutes to simulate a single condition when run on a typical personal computer. In order to guarantee accurate results, a large number of iterations, large time steps per cycle and a large number of spatial mesh points are to be considered. The time required to simulate such a condition with 10,000 iterations, 250 time steps per cycle and 200 spatial mesh points is 24 to 36 hours when run on a typical personal computer.

Table 1 Fixed Parameters, considered in the process of optimization

Pressure, P_o (MPa)	Warm end Temperature, T_w (K)	Cooling Capacity, Q_{net} (W)	Cold end Temperature , T_c (K)	Frequency, f (Hz)	Dynamic Pressure, P_d (kPa)	Pressure ratio, P_r
3.5	300	1	80	100	456	1.3

Table 2 Parameters of commonly used Stainless Steel Screens

Mesh	Wire dia/µm	Hydraulic dia/ µm	Porosity
#325	35.6	63.98	0.6422
#400	25.4	55.44	0.6858
#500	25.4	39.28	0.6073
#635	20.3	30.58	0.6014

In REGEN model the numerical approximation is a discretization of the differential equations for conservation of mass, momentum and energy in the gas and regenerator matrix. The resulting non-linear system of equations for the temperature, pressure and mass flux at all the mesh points simultaneously is solved by a Newton iteration. REGEN 3.3 provide convenient graphs to characterize regenerator performance and thereby determine its geometry. Here the COP is influenced by many variables and the maximum value of COP is most strongly influenced by T_c. The optimization process through the use of REGEN also reveals that the oscillation frequency and end temperatures determine an optimum length of the regenerator. Here, in this process of optimization #635 grade SS mesh, wire diameter of 20.3 µm, hydraulic diameter of 30.58 µm and porosity of 0.6014 is considered.

6. Results

As shown in Figure 6 and figure 7 , for a fixed choice of the parameters listed in Table 1, a maximum COP can be identified as a function of mass flux through the regenerator and length of the regenerator. For example, with the conditions chosen in Table 1, REGEN3.3 finds that the COP is maximized for a regenerator length, *L* of 35 mm, diameter, D of 7 mm and an inverse mass flux (A_g/m_c) of 0.0577 m^2s/kg respectively. The frequency and pressure ration used is 100 Hz and 1.3. The maximum *COP* at these optmimum regenerator length and inverse mass flux at converged results of REGEN after 10,000 iterations is 0.1044 and the maximum net refrigeration power is 2.156 W. The results are tabulated in Table 3. Desig parameters obtained from SAGE and REGEN3.3 are tabulated in Table 4. Figure 6 shows COP vs A_g/m_c plot. From this plot we can observe that as the length of the regenerator increases, the COP also increases and starts coming down after some length. The optimum case from figure 6 is which gives maximum COP. But, as per the figure 7, the cooling power increases with increase in the length of the regenerator. Therfore, the final length of the regenerator is selected based on both the plots for maximum COP and maximum cooling power. The dimensions of regenerator and pulse tube shown in Figure 6 and Figure 7 are in mm.

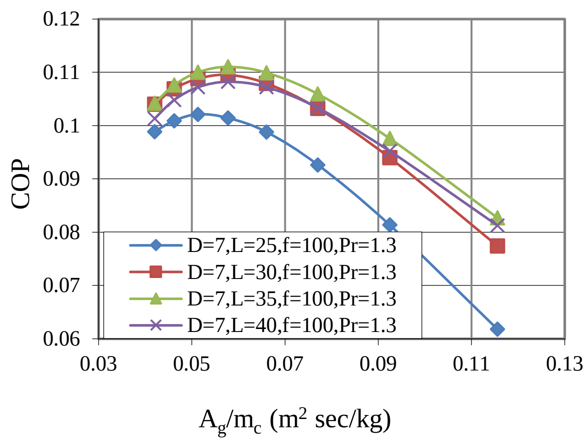

Figure 6. COP Vs A_g/m_c

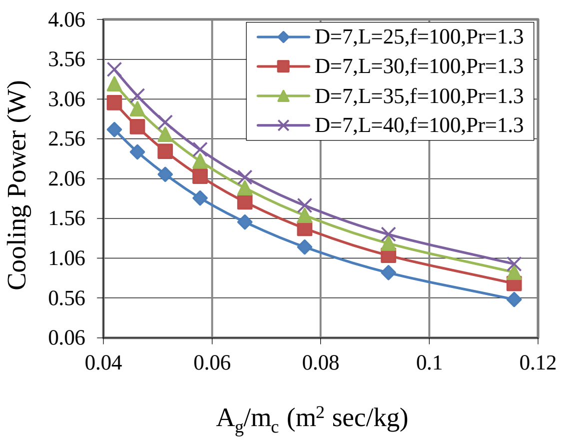

Figure 7. Cooling Power Vs A_g/m_c

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Table 3 Regenerator results for 100Hz frequency

Frequency 100 Hz, Length 35 mm, Diameter=7mm, Phase angle -30^0						
Porosity	Diameter (m)	Mass Flow(kg/sec)	Ag/m_c (m^2 s/kg)	COP	Cooling Power(W)	REGEN Iteration
0.601	0.007	0.0004	0.05779	0.1044	2.156	10000

Table 4 Design parameters obtained

Sl No		REGEN	SAGE
Input Parameters			
1.	Charge pressure, bar	35	35
2.	Frequency, Hz	100	100
3.	SS Mesh, Grade	635	635
4.	Regenerator wall thickness, mm	0.125	0.125
5.	Pulse tube wall thickness, mm	-	0.125
6.	Regenerator and Pulse Tube material	Titanium	Titanium
7.	Working gas	Helium	Helium
8.	Hot end temperature, K	300	300
9.	Cold end temperature, K	80	80
Outputs			
1.	Diameter of regenerator, mm	7.00	7.00
2.	Length of regenerator, mm	35	35
3.	Mass flow at cold end, g/s	0.4	0.55
4.	Mass flow at hot end, g/s	0.42	0.62
5.	Cold end Phase b/w m and P, deg	-30	-18.20
6.	Pressure ratio at the cold end	1.3	1.09
7.	PV power, W	20.66	23.83
8.	Tip heat load @ 80K, W	2.15	1.02
9.	No load temperature, K	-	53.20
10.	COP	0.104	0.050
Pulse Tube			
		Thumb Rule	SAGE, Optimized
1.	Diameter, mm	3.00	5.00
2.	Length, mm	35	35

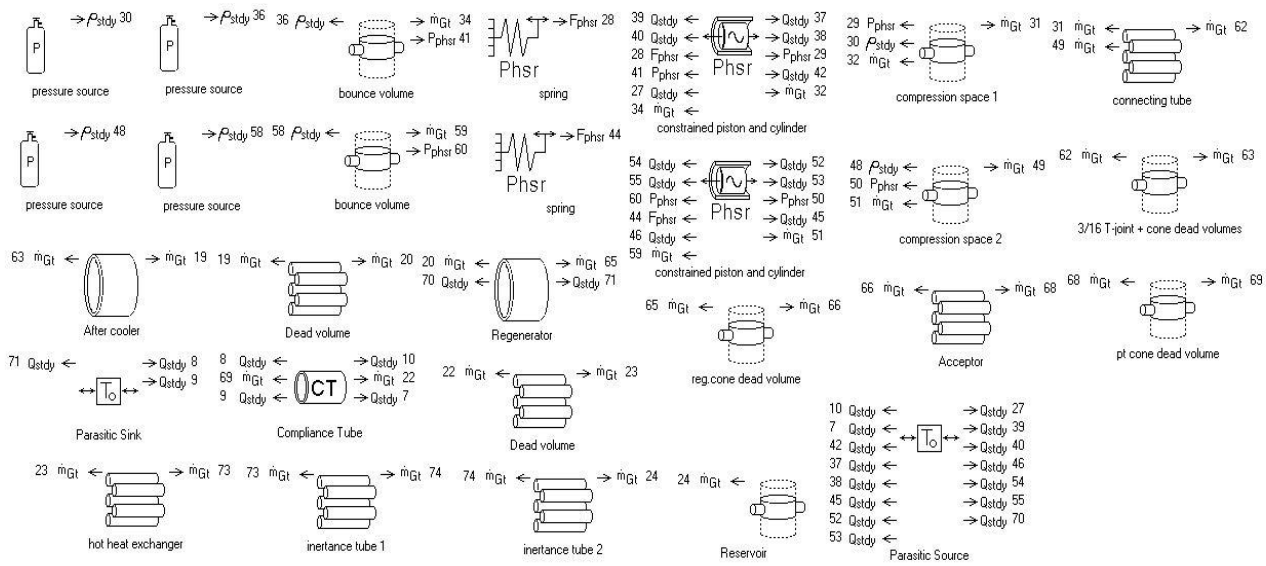

Figure 8. Modeling of PTC components using SAGE

Table 5 Dimensions of compound inertance tube.

Sl No	Description	SAGE results
1.	Inertance tube 1, mm	ϕ1.12 x 660 or ϕ1.12 x 650
2.	Inertance tube 2, mm	ϕ1.76 x 1360 or ϕ2.35 x 1780
3.	PV power, W	23.76
4.	Phase angle at inlet of inertance 1, deg	52.73
5.	Phase angle at inlet of inertance 2, deg	65.66
6.	Reservoir, CC	50

All the components with dead volumes are optimized in the SAGE model such that the design requirement of 1.0 W @ 80 K is achieved. The input value of stroke of the piston in the SAGE model is decided based on the optimised cold end mass flow rate (m_c) obtained from REGEN. As per REGEN the mass flow rate at the cold end of the regenerator is 0.4 g/sec. The stroke of the piston in SAGE is varied such that it delivers 0.4 g/sec of mass flow at the cold end of the regenerator. But as we know SAGE is a system level model, the mass required at the cold end of the regenerator to achieve 1.0 W cooling at 80 K is 0.56 g/sec and is achieved iteratively. The higher mass flow requirement in SAGE is because of the presence of dead volumes. The dead volumes include; interconnecting tube (which connects the compressor and expander), after cooler, hot end heat exchangers, acceptor (U-tube), cold end volumes, pulse tube, cone (nozzle) and compound inertance tube. These dead volumes are modelled to meet all the conditions of the phase angle criteria [4].

7. Conclusion

A parametric study on high frequency pulse tube cryocooler is carried out and selected an operating frequency of 100 Hz, charge pressure of 35 bar and a pressure ratio of 1.3. The cold and hot end temperatures of cold head considered to achieve a cooling load of 1.0 W are 80 K and 300 K. The performance of high frequency pulse tube cryocooler achieved using system level simulation tool SAGE and component level code REGEN 3.3 is 1.02 W and 2.15 W of cooling load at 80 K temperature with 23.8 W of PV power. This has to be validated experimentally. For this, it is planned to fabricate and demonstrate the high frequency pulse tube cryocooler.

Acknowledgement

Authors would like to thank Mr Lancy Vas, Junior Engineer for his suggestions on practical issues. Authors would also like to thank Shri Rajendran P, Head, Thermal Testing Division and Shri Barve S G, Head, Thermal Systems Group for their encouragement throughout the work.

References

1. Radebaugh R., O’Gallagher A. 2006, “Regenerator Operation At Very High Frequencies For Microcryocoolers”, *Advances in Cryogenic Engineering* **51B** 1919
2. Vanapalli S., Lewis M., Gan Z. H., and Radebaugh R. 2007 “120 Hz pulse tube cryocooler for fast cooldown to 50 K”, *Appl. Phys. Letters* **90(7)** 072504
3. Garaway I., Gan Z. H., Bradley P., Veprik A., and Radebaugh R. 2009, “Development of a miniature 150Hz pulse tube cryocooler”, *Cryocoolers **15*** 105
4. M. Pfotenhauer, Z. H. Gan, and R. Radebaugh. 2008 “Approximate Design Method for Single Stage Pulse Tube Refrigerators” AIP Conf. Proc. **985,** 1437
5. Radebaugh R. 2000 “Pulse Tube Cryocoolers for Cooling Infrared Sensors”, *SPIE, The International Society for Optical, Engineering, Infrared Technology and Applications XXVI* Vol. **4130** 363
6. John Gary, Abbie O’Gallagher, Ray Radebaugh, Yonghua Huang and Eric Marquardt. 2008 “REGEN3.3 User Manual” *National Institute of Standards and Technology (NIST), Boulder, CO 80303*
7. David Gedeon, “SAGE User’s Manual” *Gedeon Associates*