AIP Conference Proceedings

The effect of component junction tapering on miniature cryocooler performance

Cite as: AIP Conference Proceedings **1434**, 435 (2012); https://doi.org/10.1063/1.4706949
Published Online: 12 June 2012

Ted Conrad, Mihir G. Pathak, S. Mostafa Ghiaasiaan, and Carl Kirkconnell

View Online Export Citation

ARTICLES YOU MAY BE INTERESTED IN

OPTIMAL PULSE-TUBE DESIGN USING COMPUTATIONAL FLUID DYNAMICS
AIP Conference Proceedings **985**, 1445 (2008); https://doi.org/10.1063/1.2908505

Microcryocooler for tactical and space applications
AIP Conference Proceedings **1573**, 357 (2014); https://doi.org/10.1063/1.4860723

Miniature pulse tube cooler at 100HZ
AIP Conference Proceedings **1434**, 1033 (2012); https://doi.org/10.1063/1.4707022

© 2012 American Institute of Physics.

THE EFFECT OF COMPONENT JUNCTION TAPERING ON MINIATURE CRYOCOOLER PERFORMANCE

T.J. Conrad[1,2], M. Pathak[1], S.M. Ghiaasiaan[1], and C.S. Kirkconnell[3]

[1]Georgia Institute of Technology
Atlanta, GA, 30332, USA

[2]Raytheon SAS
El Segundo, CA, 90245, USA

[3]Iris Technology Corporation
Irvine, CA, 92614, USA

ABSTRACT

Due to their relatively smaller volume and available cooling power, miniature cryocoolers are likely to be more sensitive to hydrodynamic losses than their full scale counterparts. Abrupt changes in diameter between cryocooler components are a possible source of such losses as flow separation and recirculation may occur at these points. Underutilization of regions of the regenerator and heat exchanger porous matrices may also occur due to jetting of fluid into these components. Eliminating such abrupt diameter changes by tapering transitions between cryocooler components may therefore improve system performance.

The effects of various tapers applied at component interfaces on the performance of miniature pulse tube cryocoolers were investigated using system-level CFD models. A miniature scale pulse tube cryocooler design whose suitability for cryocooling under ideal conditions has been theoretically demonstrated was used as the basis for these models. Transitions between different combinations of open and porous regions were considered; tapers or chamfers were applied to these component junctions and the performance predictions for the resulting systems were compared to those for a model with sharp component transitions. Visualizations of the predicted flow patterns were also used to determine the effects of the applied tapers on the flow within the pulse tube.

KEYWORDS: Pulse Tube, Miniature, Computational Fluid Dynamics,

Advances in Cryogenic Engineering
AIP Conf. Proc. 1434, 435-442 (2012); doi: 10.1063/1.4706949
© 2012 American Institute of Physics 978-0-7354-1020-6/$0.00

INTRODUCTION

Miniature scale Pulse Tube Cryocoolers (PTCs) have been a subject of intense research interest for some time [1-4] and have recently begun to be practically demonstrated [5]. Such cryocoolers are attractive due to their minimal size and weight for space applications and portable devices. Due to their relatively smaller volume and available cooling power, however, miniature cryocoolers are likely to be more sensitive to hydrodynamic losses than their full scale counterparts. Abrupt changes in diameter between cryocooler components are a possible source of such losses as flow separation and recirculation may occur at these points. Underutilization of regions of the regenerator and heat exchanger porous matrices may also occur due to jetting of fluid into these components.

In this study the effects of reducing or eliminating such abrupt diameter changes by tapering or chamfering the transitions between the various PTC components have been investigated using CFD models of miniature PTCs. Because the flow patterns resulting from such changes in diameter are inherently complex and multidimensional, a multidimensional modeling approach such as CFD is desirable for simulating their effects on the performance of PTCs. Commercial CFD packages such as the Fluent package [6] used in this investigation have been shown to be capable of detailed solutions of models encompassing very complex geometries in two or three dimensions. Furthermore, recent successful simulations of cryocooler systems using CFD tools [1], [7], [8] have shown that such models can provide useful performance predictions for pulse tube refrigerators. In this investigation, these models have been used to quantitatively predict variations in performance for miniature PTCs incorporating various tapers between their components and to reveal some of the mechanisms believed to be responsible for these variations.

MODELING METHODOLOGY

To simulate the effects of tapering or chamfering the component junctions on the performance of miniaturized PTCs, Fluent models of these devices were constructed incorporating various tapers along with a base model having sharp component transitions. A basic schematic of these models is shown in FIGURE 1 with the chamfered junctions identified and a detail view of the chamfer geometry included. Detailed geometry and operating conditions for these miniature PTC models are given in TABLE 1 and the lengths, depths, and angles of the various investigated tapers, shown in FIGURE 1, are given in TABLE 2. The ratios b/c and b/r in this table are the taper depth nondimensionalized by the step change in radius and the radius of the component being tapered, respectively. As shown in TABLE 2, the effect of the taper depth was investigated using the 45° models and the effect of the taper angle was investigated with models having the maximum depths for each component junction. Much of the geometry for these miniature PTC models was loosely based on our previous work [1] but some additional preliminary analysis was performed using Sage, particularly the determination of a reasonable inertance line length. Significant geometry optimization in Fluent is difficult and computationally expensive; therefore, the parallel use of Sage can greatly expedite model development. It is important to note, however, that due to inherent differences between the two models the optimal inertance line lengths predicted by Sage are unlikely to be the best possible lengths for the CFD models.

The Fluent models were two dimensional axisymetric representations of the entire PTC, with ideal-gas helium specified as their working fluid. The compressor was modeled

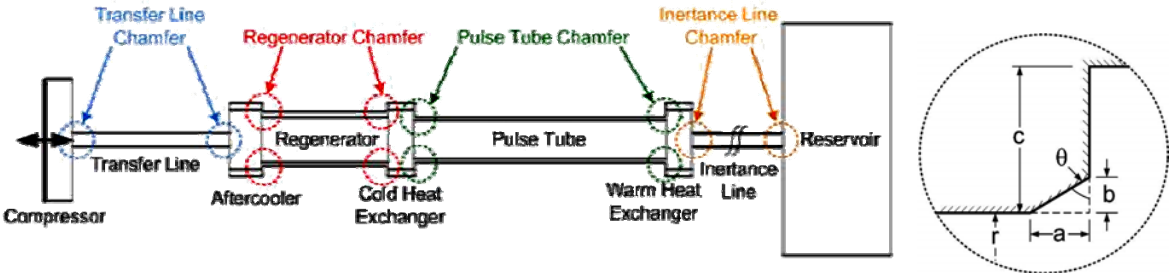

FIGURE 1. Schematic of PTR model with detail view of taper geometry.

with a moving wall and a dynamic meshing scheme which added and subtracted mesh layers as the wall moved. A user-defined sinusoidal displacement with a frequency of 200 Hz was applied to the moving compressor wall, shown with a double ended arrow in FIGURE 1, resulting in a pressure ratio at the transfer line inlet of approximately 1.25. In Fluent simulations 'PRESTO!' pressure discretization was used along with 'PISO' pressure-velocity coupling and second order upwind discretization of all other quantities; these settings were chosen to provide the best and fastest convergence of the models. Double precision, pressure-based steady and unsteady solvers were used with the physical velocity porous media flow formulation. Simulation results suggested that oscillatory turbulent flow might occur in the transfer and inertance lines; therefore, the standard k-omega turbulence model with low Reynolds number corrections was utilized. This turbulence model was chosen for its ability to handle transitionally turbulent flow and because it improved the convergence of the models. Residual convergence criteria were set at 10^{-9} for the energy equation and 10^{-8} for continuity, velocity, k, and omega. Grid spacing of 0.1 mm in the axial and radial directions was used from the compressor to the warm heat exchanger, while the inertance tube had its axial spacing increased to 0.25 mm and the reservoir was meshed with axial and radial spacing of 0.25 mm.

Materials were selected for the models based upon their suitability for the fabrication of miniature PTCs. For the regenerator filler, #635 stainless steel mesh was chosen and the aftercooler, warm and cold heat exchangers were all modeled as #325 phosphor-bronze mesh. These mesh fillers were selected for their small pore sizes and ability to be cut into discs small enough for the modeled PTCs. To model these materials, the Fluent porous media model requires viscous and inertial resistance coefficients related to the Darcy permeability and Forchheimer's inertial coefficient. These parameters have been published for stacked screens of #635 stainless steel and #325 phosphor bronze mesh at 63% and 67% porosity, respectively, and are shown in TABLE 3 [9].

The aftercooler, cold and warm heat exchanger walls were modeled as sterling silver with wall thicknesses of 0.4 mm and the regenerator and pulse tube walls were modeled as stainless steel with a thickness of 0.28 mm. Wall conduction in these components was incorporated into the CFD models by discretizing the solid regions and applying the appropriate material properties. The outer surfaces of the aftercooler and warm heat exchanger walls were modeled isothermally at 293 K. The outside of the cold heat exchanger wall was also modeled isothermally at the various cold temperatures required for the load curve plots. The outer surfaces of the regenerator and pulse tube walls were modeled as adiabatic. The reservoir, inertance line, and the transfer line between the compressor and aftercooler were all modeled with isothermal walls at 293 K. Modeling wall thicknesses for these components was not necessary because the isothermal boundary condition eliminates axial temperature gradients rendering axial heat conduction negligible in their walls.

TABLE 1. CFD model geometry and operating conditions.

Regenerator		Pulse Tube		Inertance Tube		Frequency	Operating
length (mm)	dia (mm)	length (mm)	dia (mm)	length (m)	dia (mm)	(Hz)	Pressure (MPa)
20	3	40	2.5	0.8208	1	200	4

Aftercooler		Cold Heat Exchanger		Warm Heat Exchanger		Reservoir	Approximate Total
length (mm)	dia (mm)	length (mm)	dia (mm)	length (mm)	dia (mm)	Volume (cm^3)	Volume (cm^3)
5	4	4	4	4	4	5	6.3

TABLE 2. Taper lengths and depths for various models.

Model	Chamfer Dimensions (mm)							
	Transfer Line				Regenerator			
	a (mm)	b (mm)	b/c	b/r	a (mm)	b (mm)	b/c	b/r
45° Taper C	0.1	0.1	0.067	0.2	0.25	0.25	0.5	0.167
45° Taper B	0.2	0.2	0.133	0.4	0.5	0.5	1	0.333
45° Taper A	0.5	0.5	0.333	1	0.5	0.5	1	0.333
60° Taper A	0.866	0.5	0.333	1	0.866	0.5	1	0.333
75° Taper A	1.866	0.5	0.333	1	1.866	0.5	1	0.333

Model	Pulse Tube				Inertance Line			
	a (mm)	b (mm)	b/c	b/r	a (mm)	b (mm)	b/c	b/r
45° Taper C	0.25	0.25	0.333	0.2	0.1	0.1	0.067	0.2
45° Taper B	0.5	0.5	0.667	0.4	0.2	0.2	0.133	0.4
45° Taper A	0.75	0.75	1	0.6	0.5	0.5	0.333	1
60° Taper A	1.3	0.75	1	0.6	0.866	0.5	0.333	1
75° Taper A	2.8	0.75	1	0.6	1.866	0.5	0.333	1

TABLE 3. Hydrodynamic parameters of modeled porous fillers.

Porous Media	Axial Direction		Radial Direction	
	Viscous Resistance $1/m^2$	Inertial Resistance 1/m	Viscous Resistance $1/m^2$	Inertial Resistance 1/m
# 325 Phosphor Bronze Mesh Screens	1.70E+10	50000	2.90E+10	50000
# 635 Stainless Steel Mesh Screens	9.50E+10	40000	1.11E+11	120000

The models were first initialized with an approximate temperature distribution by iterating with the steady solver, then they were iterated with the first-order implicit transient solver until they approached periodic steady state. A time step of 20 μs was used, corresponding to 250 time steps per period of the 200 Hz operating frequency. To judge convergence, selected output values from the models were monitored and cycle-averaged. These included pressures, velocities, mass flow rates, and enthalpy flow rates at the inlet of each component, wall heat fluxes, and the total system mass and energy. The cycle-averaging was performed using a moving window with a width of 250 time steps, equal to one period of the compressor's oscillation. Calculated errors in the overall cycle averaged energy and mass balances for the models were less than 3% and 0.3% of the input power and total fluid mass, respectively.

RESULTS

The effects of the investigated tapers on the predicted miniature PTC performance were quantified using the simulated net cooling and efficiency. The effect of the taper depth is shown in the predicted load curves and plots of COP as a percentage of the Carnot COP presented in FIGURE 2 for the 45° taper models. From these results it is apparent that the simulated performance increases significantly as the chamfer depth is increased. Across the range of simulated cold tip temperatures the 45° Taper A model, which has the largest taper depths, is predicted to produce 0.1 to 0.2 W of additional cooling and an increase in COP of approximately 2% of Carnot relative to the base model. Similarly, the effect of the taper angle on the predicted PTR performance is shown in the plots of FIGURE 3. Angles of 45°, 60°, and 75° were investigated using models having identical taper depths. The results indicate that although increasing the taper angle from 45° to 60° has little effect on the predicted performance, the further increase in angle to 75° leads to a significant additional gain in heat lift and COP.

The individual effects of the component junction tapers, investigated with the 45° chamfer models for a 180 K simulated cold tip temperature, are shown in FIGURE 4. From this figure it is apparent that the tapering applied to the pulse tube has the most significant effect on the predicted PTR net cooling; additionally, there is also a smaller improvement due to the tapering of the transfer line between the compressor and aftercooler. The

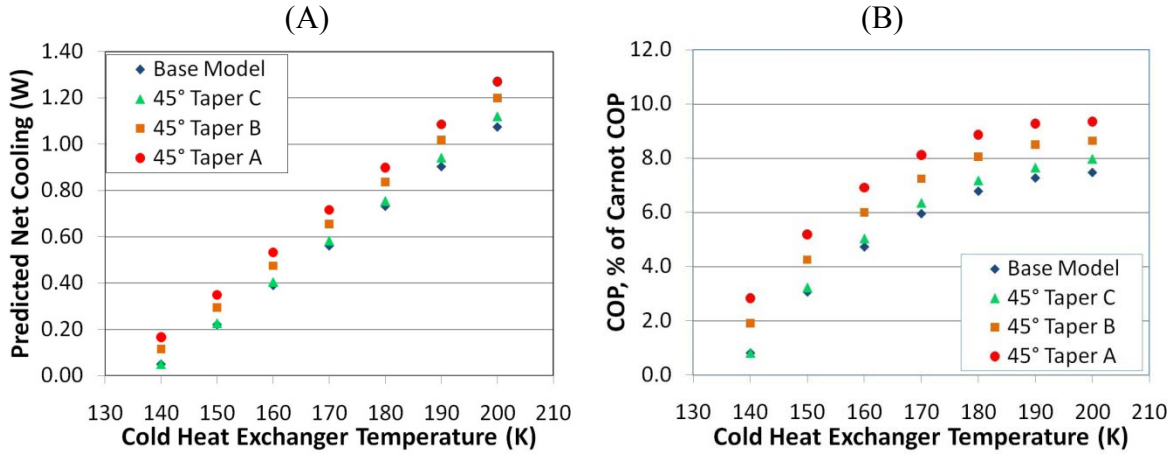

FIGURE 2. Predicted load curves and COPs for 45° taper models.

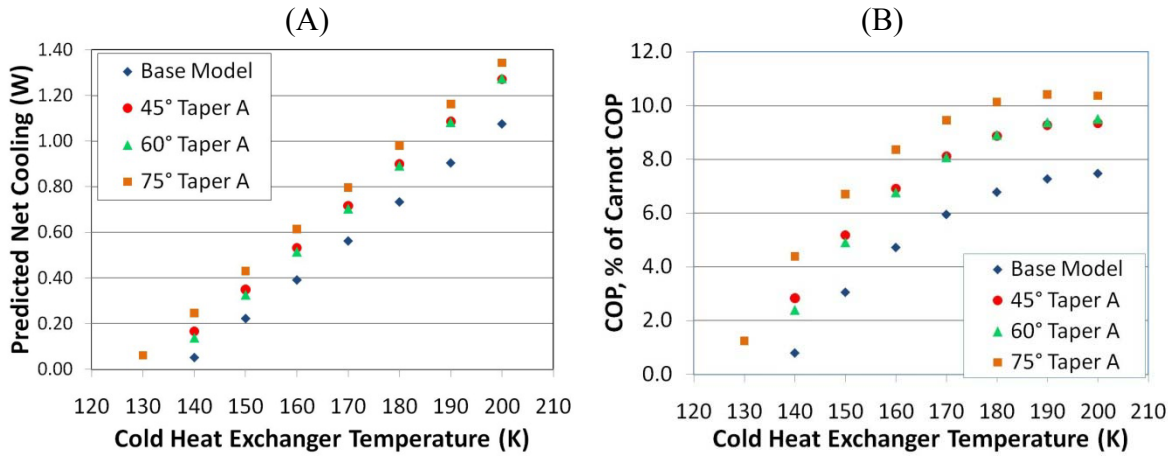

FIGURE 3. Predicted load curves and COPs for taper models with various angles.

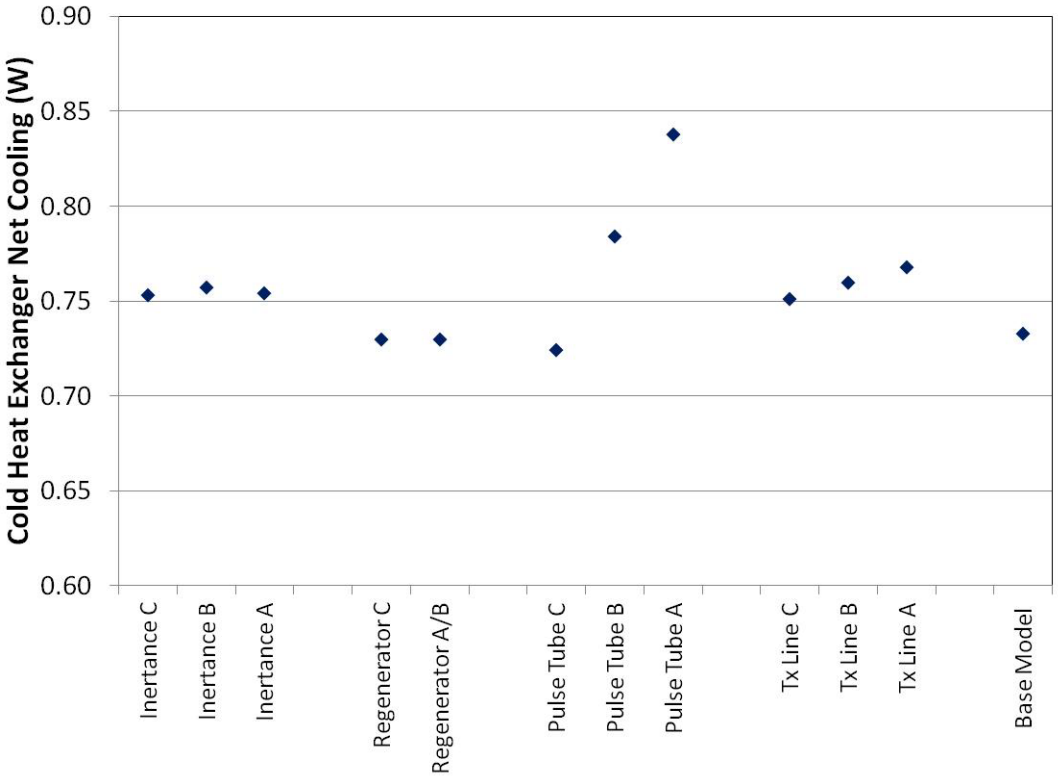

FIGURE 4. Predicted net cooling for 180 K cold tip temperature, 45° individually tapered junctions.

regenerator taper appears to provide little to no benefit and the presence of the inertance line taper results in a slight increase in predicted performance which is insensitive to the taper depth.

In order to reveal the mechanisms by which the tapers may be improving the predicted PTR performance, detailed representations of the simulated flow in the CFD models have been produced. Contour and vector plots are presented which reveal some of the effects of the tapers on simulated flow believed to be responsible for the increases observed in their predicted overall performance. The transfer line and aftercooler are examined first in FIGURE 5, which depicts instantaneous contours of velocity (A) and oscillatory pressure (B)for the base and 75° Taper A models at the point in their cycles corresponding to the maximum velocity at the aftercooler inlet.

From these figures it is apparent that although the maximum velocity in the transfer line is higher for the tapered model, the pressure drop across the transfer line is significantly lower. The reduction in oscillatory pressure depicted in FIGURE 5 B results in a decrease in the pressure ratio predicted at the compressor. This in turn results in lower calculated input powers for the tapered models which are partially responsible for the increases in the predicted COP shown in FIGURES 2 and 3. Additionally, FIGURE 4 A shows that the low velocity regions in the corners of the aftercooler of the base model have been significantly reduced in size or eliminated in the tapered model. Regions such as these where the flow is minimal are essentially dead volume: they do not contribute to the cooling produced by the PTR but still require work input for oscillatory compression of the gas that they contain.

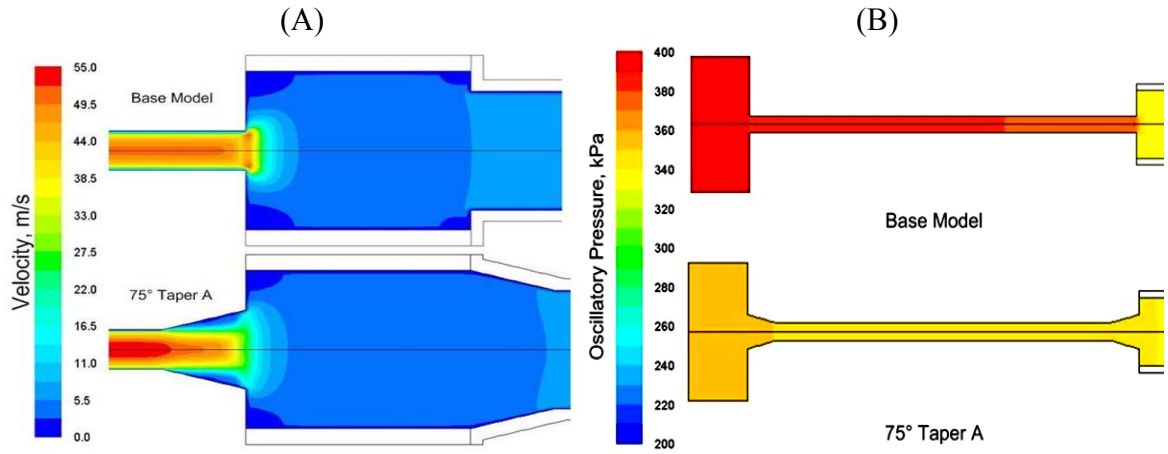

FIGURE 5. Contours of velocity (A) and oscillatory pressure (B) in the compressor, transfer line and aftercooler, 180 K cold tip temperature.

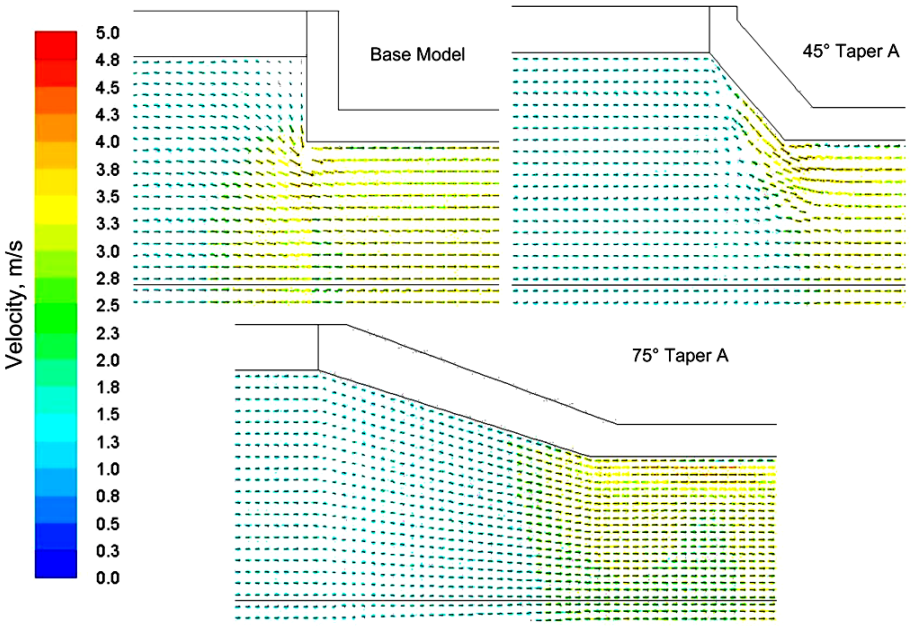

FIGURE 6. Instantaneous vector plots of velocity, junction of cold heat exchanger and pulse tube, 180 K cold tip temperature.

Because the tapering applied to the pulse tube was identified in FIGURE 4 to have the greatest effect on the overall model performance, instantaneous vector plots of simulated velocity have been created to illustrate the flow patterns at the junction of the pulse tube and cold heat exchanger; these are displayed in FIGURE 6. These plots depict the point in the oscillatory flow cycle when the average velocity magnitude at the pulse tube inlet is at its maximum value. It shows that the flow entering the pulse tube becomes more uniform both when the 45° taper is applied and again when its angle is increased to 75°. Significant non-uniformity is seen in the predicted flow for the base model due to the presence of the sharp corner. For the 45° taper model, the simulated flow at the pulse tube entrance is more uniform but it is still disturbed by the edge of the taper inside the pulse tube. The 75° taper model, however, exhibits a predicted flow pattern that is much more uniform throughout the entire transition. Similar patterns are seen a half cycle later when the flow reverses directions and also at the warm end of the pulse tube where it joins the warm heat exchanger. These more uniform predicted flow patterns in the pulse tube are believed to be

partially responsible for the increase in the simulated net cooling and COP reported for the tapered PTR models.

CONCLUSIONS

CFD models of miniaturized pulse tube cryocoolers were used to investigate the effects of eliminating sharp edged transitions between components of different diameter by tapering their junctions. The predicted net cooling and COP of the miniature PTC models were shown to increase as these tapers increased in depth and as their angles were increased from 45° to 75°. Tapering of the pulse tube had the most pronounced effect on the predicted performance and was shown to reduce non-uniformity of the simulated flow as it entered and exited that component. Tapering of the transfer line between the compressor and aftercooler was also shown to result in a decrease in the simulated pressure drop across its length, leading to a reduction in the inlet pressure ratio and input PV power. These results suggest that sharp edged transitions between PTC components should be avoided if possible, although for physical PTCs this may sometimes be difficult due to practical fabrication considerations. Although this investigation focused on miniature PTCs, the results are believed to be relevant to conventionally scaled devices as well.

REFERENCES

1. T. Conrad, E. Landrum, S. M. Ghiaasiaan, and C. S. Kirkconnell, "CFD Modeling of Meso-Scale and Micro-Scale Pulse Tube Refrigerators," *Cryocoolers*, vol. 15, pp. 241-249, 2008.
2. R. Peterson, "Size limits for regenerative heat engines," *Microscale Thermophysical Engineering*, vol. 2, pp. 121-131, 1998.
3. R. Radebaugh and A. O'Gallagher, "Regenerator operation at very high frequencies for microcryocoolers," *Adv. in Cryogenic Engineering*, vol. 51, pp. 1919-1928, 2006.
4. P. Nika, Y. Bailly, M. D. Labachelerie, J. Jeannot and J. Lalee, "Miniature Pulse Tube for the Cooling of Electronic Devices: Functioning Principles and Practical Modeling," *Microscale Thermophysical Engineering*, vol. 8, pp. 301-325, 2004.
5. I. Garaway, Z. H. Gan, P. E. Bradley, A. Veprik and R. Radebaugh, "Development of a Miniature 150 Hz Pulse Tube Cryocooler," *Cryocoolers*, vol. 15, pp. 105-113, 2008.
6. Fluent Inc., *Fluent 6.3 User's Guide*. 2006.
7. J. J. Cha, S. M. Ghiaasiaan, P. V. Desai, J. P. Harvey and C. S. Kirkconnell, "Multi-dimensional flow effects in pulse tube refrigerators," *Cryogenics*, vol. 46, no. 9, pp. 658–665, 2006.
8. R. Taylor, G. Nellis and S. Klein, "Optimal Pulse-Tube Design Using Computational Fluid Dynamics," *Adv. in Cryogenic Engineering*, vol. 53, pp. 1445-1453, 2008.
9. E. Landrum, T. Conrad, S. M. Ghiaasiaan and C. S. Kirkconnell, "Hydrodynamic parameters of mesh fillers relevant to miniature regenerative cryocoolers," *Cryogenics*, vol. 50, no. 6-7, pp. 373-380, 2010.