CFD Modeling of Meso-Scale and Micro-Scale Pulse Tube Refrigerators

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ABSTRACT

For miniature cryocoolers, CFD modeling is the best technique available to accurately represent phenomena which becomes important as the device scale is reduced. However, the increased detail provided by CFD models is paid for with greatly increased computational time, and thus performing extensive parametric studies with CFD may be prohibitively time consuming. This paper describes work in progress on system-level CFD modeling of miniature pulse tube refrigerators using Fluent, following a preliminary scaling study done with the Sage PTR modeling program. Using Fluent and Sage together in this manner allowed for fast initial model development using Sage, the results of which will then be authenticated and extended in Fluent.

Several different mesoscale and micro-scale models having respective total volumes of 3-4 cm^3 and approximately 1 cm^3, excluding the compressor, were constructed and optimized in Sage. These provided initial geometry and operating conditions to similarly scaled Fluent models. In order to produce meaningful results, the Fluent models also required accurate closure relations for their porous segments, which were made up of stacked 635 mesh stainless steel and 325 mesh phosphor-bronze screens. Therefore, experimentally measured hydrodynamic parameters for these porous fillers were incorporated into the Fluent models.

Thus constructed, the Fluent models were iterated towards their periodic steady-state solutions. To hasten their convergence, a technique of initializing the PTR models with an assumed cold temperature and linear temperature gradients in the regenerator and pulse tube was employed. The performance parameters associated with the CFD simulations as they approach steady-periodic conditions are presented here along with the predictions of the Sage cryocooler models. The results demonstrate the feasibility of miniature PTRs, particularly for staging applications.

INTRODUCTION

The design and performance of Pulse Tube Refrigerators (PTRs) have continually evolved since their invention[1] in response to new demands and applications. Recently, there has been a great deal of interest in miniaturizing PTRs in order to minimize their size and weight for space applications and portable devices. Miniature coolers might also be useful as final stages for applications where small cooling loads must be carried at temperatures lower than that required by the primary load. In such an application, a larger cryocooler might carry the primary load while miniature stages carry the smaller, colder ones, improving the overall efficiency of the cooling system.

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The extent to which PTRs may be miniaturized is still unclear, and it is believed that certain physical processes will limit the performance as the PTR size is reduced. It is likely that a minimum size threshold will be reached below which loss mechanisms become practically insurmountable. This size threshold may exist for the entire cooler, or it may be that limits on one or more crucial component will determine the size of the entire system. This paper describes work in progress that attempts to estimate this size threshold using an approach which combines Sage and CFD PTR models.

MODELING TECHNIQUE

Modeling and analysis of miniature PTRs must be done carefully because some of the phenomena affecting their performance are likely to differ from those that are dominant at larger scales. As a result, the applicability of currently existing analytical tools to the design of miniature PTRs is uncertain. Even the most advanced design tools[2,3] are typically one-dimensional and rely on constitutive and closure relations that are at best approximations for the complex and periodic flow conditions in PTRs. As PTRs are miniaturized, it is expected that multidimensional flow effects and detailed prediction of thermal-hydraulic flow phenomena, particularly in the regenerator, will become even more important, requiring models able to accurately represent these flow details.

Recent successful CFD simulations of cryocooler systems using Fluent[4] have shown that such models can provide useful performance predictions for pulse tube refrigerators. Fluent is a state of the art commercial CFD package capable of detailed solutions of models encompassing very complex geometries in two or three dimensions. It is capable of obtaining either steady state or transient solutions to problems involving a variety of flow phenomena, including flow in porous media. Fluent may also be expanded using user defined functions (UDFs) in order to add or modify closure relations and incorporate custom boundary conditions. Because CFD models such as Fluent solve the governing conservation equations throughout the model domain, they do not include some of the simplifying approximations and assumptions which are present in dedicated PTR models. As a consequence, there may be more confidence about their applicability to miniature systems. CFD models are also able to predict the complex flow details overlooked by one-dimensional models, likely improving their accuracy for miniature PTRs. For these reasons, CFD modeling is likely to be the most useful technique available for modeling miniature PTRs.

There are a few limitations, however, that come along with the advantages of CFD modeling. The models still need accurate closure relations and boundary conditions in order to produce meaningful results, particularly with regard to the hydrodynamic and thermal transport processes occurring in the porous segments of the PTR system. To address this need, experimental measurements of the hydrodynamic parameters of stacked 635 mesh stainless steel and 325 mesh phosphor-bronze screens, materials suitable for use as regenerator and heat exchanger fillers respectively, were performed and will be presented in a separate paper.[5]

Additionally, the increased detail provided by CFD models is paid for with greatly increased computational time, and thus performing extensive parametric studies with CFD may be prohibitively time consuming. However, previous efforts at modeling miniature PTRs in Fluent by directly scaling down existing models of larger cryocoolers resulted in drastically reduced performance[6] and thus, at the outset of this investigation, such parametric studies and optimizations were necessary to produce viable miniature PTR models. Such optimization would be time prohibitive with a CFD tool. For this reason, the Sage PTR modeling program was used to first provide an estimate of the feasible geometry and operating conditions for the miniature PTRs before modeling them in Fluent.

Sage is a widely used cryocooler model and design tool incorporating component level models which can be assembled to represent almost any Stirling or pulse tube cryocooler system. It is capable of very quickly solving for the steady-periodic performance of PTRs and performing multidimensional optimization of the many input variables to its component models. Sage does not solve for time-dependent behavior, however, and instead addresses the final steady-periodic operation. It is also one-dimensional, although it does include empirical corrections for some specific multidimensional effects. For larger scale systems, Sage has proven to be reliable and fairly accurate, particularly when its empirical corrections are based on directly relevant experimental results. Its direct applicability to miniature systems is unknown, however.

To take advantage of the complimentary strengths of Fluent and Sage in this work, the two were used in parallel to model the miniature PTRs. Time was saved in the initial model development by using Sage to perform the necessary scoping, parametric and optimization studies, and Fluent was used to further verify and extend the results of Sage.

SIMULATED SYSTEMS

In order to observe the effects of miniaturization on PTR performance, progressively smaller models of PTRs were constructed. Both standard inertance tube PTRs and novel reservoir-less[7] PTRs, shown schematically in Fig. 1, were investigated in this study. Models were built at the mesoscale and micro-scale, defined here as having total volumes of 3-4 cm^3 and approximately 1 cm^3, respectively, excluding the compressor. Mesoscale models had pulse tube and regenerator diameters of 2.5 mm and 4 mm, respectively, while for the micro-scale models these dimensions were 1 mm and 2 mm. Many of the remaining dimensions and operating conditions were determined through Sage modeling and are thus presented later with those results.

Materials were selected for the models based upon their suitability for the fabrication of miniature PTRs and their ability to address some of the challenges inherent to miniaturizing PTRs. Specifically, stainless steel 635 mesh and phosphor-bronze 325 mesh were selected as regenerator and heat exchanger fillers, respectively, for their small pore sizes and ability to be cut into discs small enough for the modeled PTRs. Sterling silver was chosen for the heat exchanger shells due to its high thermal conductivity and workability, and polyetheretherketone (PEEK) was selected for the pulse tube and regenerator shells for its low thermal conductivity and easy machinability. The low thermal conductivity of the PEEK is expected to significantly mitigate the problem of axial conduction resulting from the large temperature gradients which must exist in a miniature PTR.

SAGE MODELS

Sage modeling of the various PTRs was performed in order to provide initial geometry and operating conditions to Fluent. Previously, an attempt at directly down-scaling[6] of proven larger PTR models to the meso and micro-scales had resulted in CFD model predictions demonstrating poor performance. Based upon those results and the likelihood that the geometry and operating conditions for miniature PTRs would be different than for larger coolers, it was concluded that optimization of these parameters was needed to produce better performing miniature PTR models. This optimization was performed with Sage to take advantage of its fast solutions and multidimensional mapping and optimization capabilities.

The developed Sage models are based upon an existing, experimentally tested model of a relatively small PTR. Initially, this model was directly scaled down to produce base models at the meso and micro-scale. Parametric mappings and optimizations of select parameters were then performed in order to determine the geometry and operating conditions more suitable to miniature PTRs. Even with the multi-parameter optimization capabilities of Sage, only a limited number of

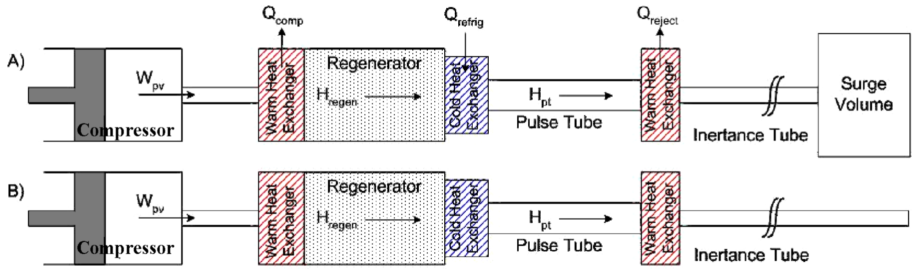

Figure 1. Schematics of modeled PTRs; (A) Inertance Tube PTR, (B) Reservoirless Inertance Tube PTR.

geometrical dimensions could be effectively optimized. Therefore, one or more dimensions of many PTR components were fixed after scaling and only the parameters expected to have the greatest effect on the system performance were optimized. Specifically, the dimensions of the cold and warm heat exchangers and transfer lines were held constant after the initial scaling, along with the pulse tube and regenerator diameters. The lengths of the pulse tube and regenerator were optimized, however, along with the inertance tube length and the reservoir volume, when present. The dimensions which were held constant were not necessarily fixed at the exact scaled values from the larger model, but rather were adjusted as necessary to ensure that they were feasible for more practical construction of a miniature device. The compressor proved to be more difficult to scale. If its volume and stroke were optimized, Sage tended to increase them until an unrealistic pressure ratio was reached. Instead, for consistency the compressor volume and piston stroke were adjusted to give a pressure ratio of 1.15 for all of the models. As experimental verification of these models may eventually be performed, this pressure ratio was chosen to approximate the highest pressure ratio currently available on our test bench at the frequencies of interest for the models.

The operating conditions optimized by Sage were the frequency and charge pressure. In both cases, however, Sage predicted that the performance would increase almost linearly as the parameter value increased. With all other variables are held constant, increasing the frequency or charge pressure results in a higher input power to the model. The Sage optimizer would not predict reasonable upper bounds for either parameter. Instead, values of these parameters were chosen and the remaining model geometry was optimized around them. The operating pressure was fixed at 3.55 MPa (515 psi), the maximum absolute pressure available in the current test facility. The frequency was set at 200 Hz for the mesoscale PTRs, also based on compressor restrictions, and 400 Hz for the micro-scale coolers.

With these operating conditions, fixed dimensions, and the pressure ratio determined, the optimized dimensions of the PTRs could be determined. For many of the PTR component dimensions, however, there was no distinct value resulting in maximal overall system performance. Often, the Sage–predicted performance asymptotically approached a maximum as component lengths increased beyond the reasonable dimensions of a miniature PTR. Thus, compromises had to be made between achieving maximum performance and limiting the overall system size. Figures 2 and 3 show the variation of the overall system performance with changes in pulse tube length and regenerator

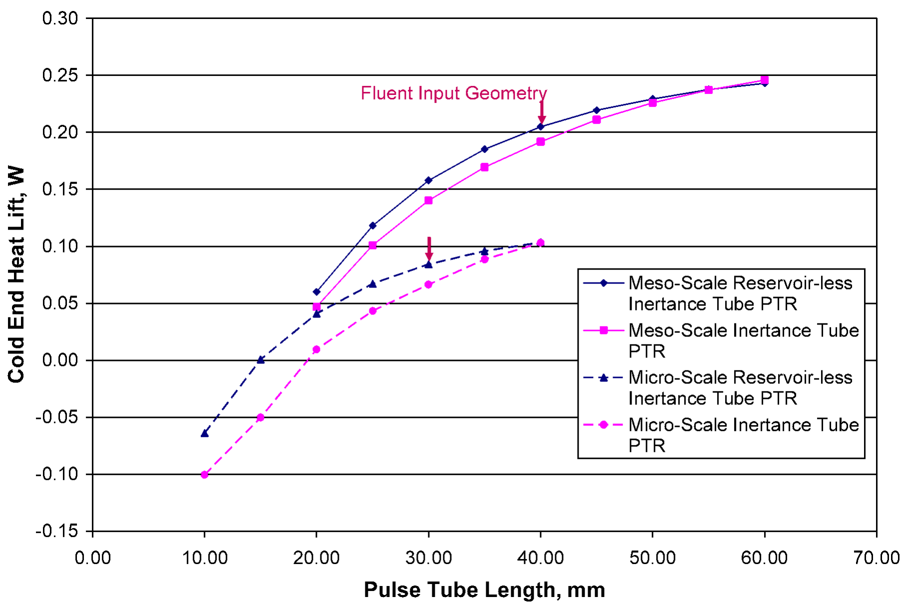

Figure 2. Map of PTR performance versus pulse tube length.

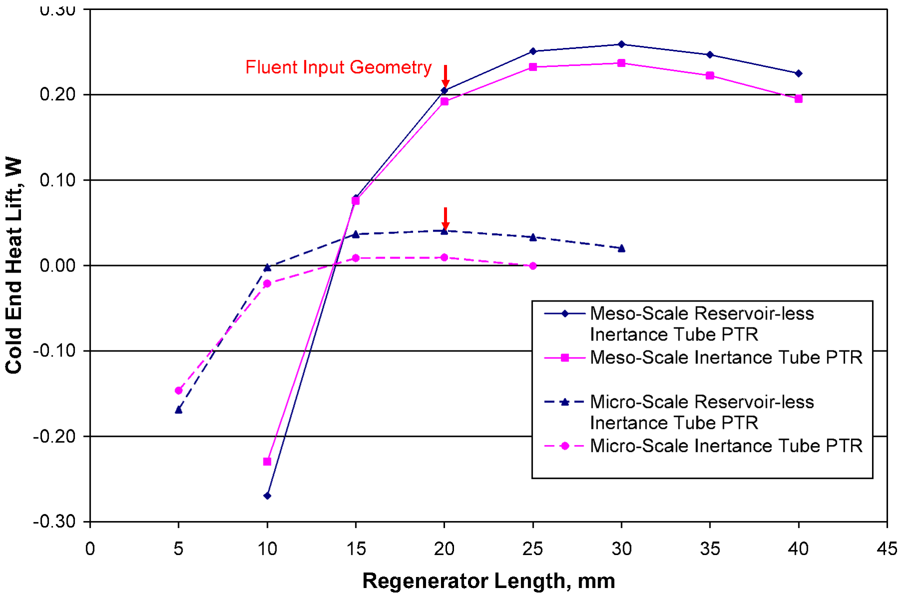

Figure 3. Map of PTR performance versus regenerator length.

length, respectively, and the chosen design points for the meso and micro-scale coolers are marked on each plot. For each point on these figures, the compressor stroke and inertance length were optimized to provide a pressure ratio of 1.15 and optimal phase shift. For the mesoscale models, the optimizations were performed with a cold tip temperature of 150 K while for the micro-scale models 170K was used.

Several different inertance line lengths can provide near-optimal phase shift and thus maximize performance. The absolute maximum system performance occurs with the shortest of these. It is important to start the Sage optimizer near this length so that it doesn't pick up one of the other, less optimal points by mistake. The variation in system performance due to changes in the inertance tube length is shown in Fig. 4 for all four models.

Fig. 5 shows load curves for the meso and micro-scale models with each point optimized to maintain a constant pressure ratio of 1.15. At the mesoscale, Sage predicts ultimate (no-load) cold temperatures of 102 K and 104 K for the standard inertance tube and reservoir-less inertance tube PTRs, respectively. At the micro-scale, these two cooler types were predicted to reach 145 K and 144 K. Based on these Sage modeling results, initial dimensions and operating conditions for mesoscale and micro-scale Fluent models were determined. These are given for the various models in

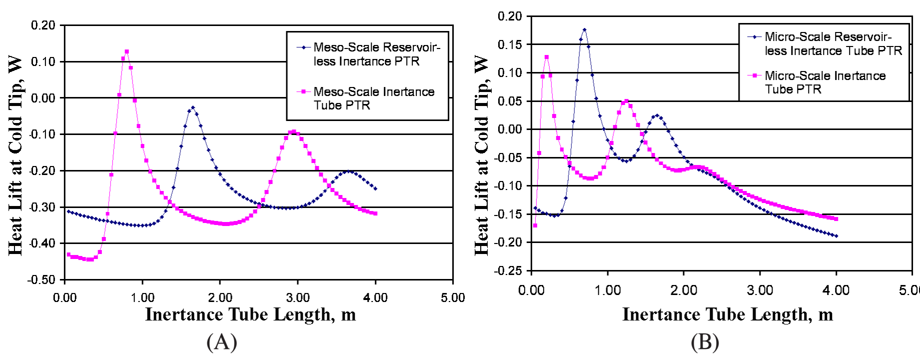

Figure 4. (A) Micro-scale and (B) Mesoscale PTR performance versus inertance tube length.

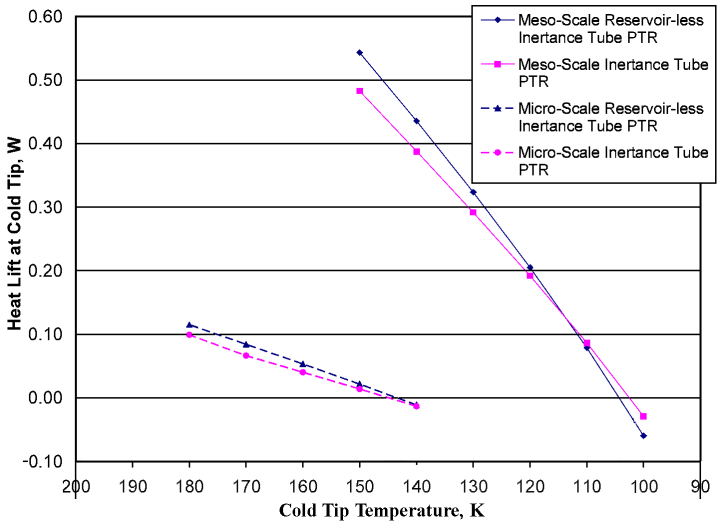

Figure 5. Load curves for micro-scale and mesoscale Sage PTR models.

Table 1. Practical considerations of device construction and available test facilities were also taken into account in their selection, as well as the desire to keep the system dimensions as small as possible.

CFD MODELS

In order to expedite their development, the Fluent system-level models developed in this study had their initial geometry and operating conditions based on the results of the Sage models described in the previous section. These Sage results were not expected to produce the best possible Fluent PTR model performance, but were instead intended to be a suitable starting point. Perhaps most significantly, the inertance line lengths determined by Sage are unlikely to be the exact values which will produce the best possible performance of the CFD models. Eventually, optimization of these values in Fluent will be necessary.

The Fluent models were two dimensional axi-symetric and included the entire cold head from the outlet of the compressor all the way to the reservoir or end of the inertance line, as applicable. Because they were two dimensional, the CFD models were able to incorporate 2D effects that can not be modeled in Sage, such as the tapering done to the inner and outer walls of the pulse tube. The inner diameter of the pulse tube was expanded from 2.5 mm in the center to 4 mm at either end, over a distance of 3 mm, in order to avoid the flow disruption caused by a step change in diameter. For all of the CFD models, second order upwind discretization, PISO pressure-velocity coupling, and a second order implicit unsteady solver were utilized and ideal helium was specified as the working

Table 1. Summary of Sage − optimized meso and micro-scale PTR dimensions

Model	regenerator		pulse tube		inertance tube		total
	length (mm)	dia (mm)	length (mm)	dia (mm)	length (m)	dia (mm)	volume (cc)
Meso-Scale Inertance Tube	20	4	40	2.5	0.8097	0.6	4.06
Meso-Scale Reservoir-less Inertance Tube	20	4	40	2.5	1.656	0.6	2.29
Micro-Scale Inertance Tube	20	2	30	1	0.2176	0.4	0.9834
Micro-Scale Reservoirless Inertance Tube	20	2	30	1	0.688	0.4	0.2425

Model	Warm Heat Exchanger 1		Cold Heat Exchanger		Warm Heat Exchanger 2		(SAGE) Cold
	length (mm)	dia (mm)	length (mm)	dia (mm)	length (m)	dia (mm)	Temp (K)
Meso-Scale Inertance Tube	10	4	4	4	5	4	102
Meso-Scale Reservoir-less Inertance Tube	10	4	4	4	5	4	104
Micro-Scale Inertance Tube	5	2	3	2	3	2	145
Micro-Scale Reservoirless Inertance Tube	5	2	3	2	3	2	144

fluid. Convergence criteria were set at 10E-7 for continuity and velocity and 10E-8 for energy. Time steps of 10 and 20 μs were used for the micro-scale and mesoscale cases, respectively, which operated at 200 and 400 Hz. For all of the cases, this resulted in 250 time steps per period of pressure oscillations.

To model the compressor, a user-defined oscillatory pressure boundary condition was applied at the compressor outlet. The user defined pressure was a simple cosine function with an amplitude of 0.25 MPa, resulting in a pressure ratio of 1.15 which was consistent with the Sage models. The models used the previously mentioned experimentally determined hydrodynamic parameters for stainless steel 635 mesh and phosphor-bronze 325 mesh in their regenerators and heat exchangers, respectively. Wall conduction was included by meshing the walls of the heat exchangers, regenerator, and pulse tube along with the fluid regions and applying the appropriate material properties. The wall thicknesses of the transfer lines, inertance tube, and reservoir volume were neglected, however, because their contribution to adverse heat conduction is small relative to that of the pulse tube and regenerator walls.

To reduce computational time, the Fluent models were started with assumed linear temperature distributions having cold temperatures as near as possible to their expected final steady state values. To set up the linear temperature distributions, models were first initialized at a constant temperature of 293 K. The warm heat exchanger exterior walls were prescribed their normal boundary conditions, a constant temperature of 293 K, while the cold heat exchanger exterior wall boundary condition was changed from adiabatic to a constant temperature, the assumed cold tip temperature. The model was then iterated using the steady state solver and conduction was allowed to set up linear temperature gradients in the pulse tube and regenerator. The cold heat exchanger exterior wall was then returned to an adiabatic boundary condition and the unsteady solver was selected to begin the simulations.

Fig. 6 shows cycle-averaged temperature histories for the cold heat exchangers of the mesoscale standard inertance tube PTR model started with an assumed cold temperature of 140 K and reservoir-less inertance tube PTR model started from 190 K. The standard PTR model has reached a temperature around 143 K while the reservoir-less PTR model appears to be converging towards a final temperature around 187 K. Both models have yet to converge to periodic steady state, a condition at which all cycle averaged variables (e.g. temperatures, enthalpy flows, etc.) will become invariant with time. While it appears that the standard inertance tube PTR is the higher-performing design, such conclusions cannot be drawn until optimization of the inertance line lengths responsible for phase shifting can be performed in Fluent.

Similarly to the mesoscale PTRs, micro-scale inertance tube and reservoir-less inertance tube PTR models were started with assumed cold temperatures of 170 K and 200 K, respectively. The cycle-averaged temperature histories of their cold heat exchangers are shown in Fig. 7. Like their

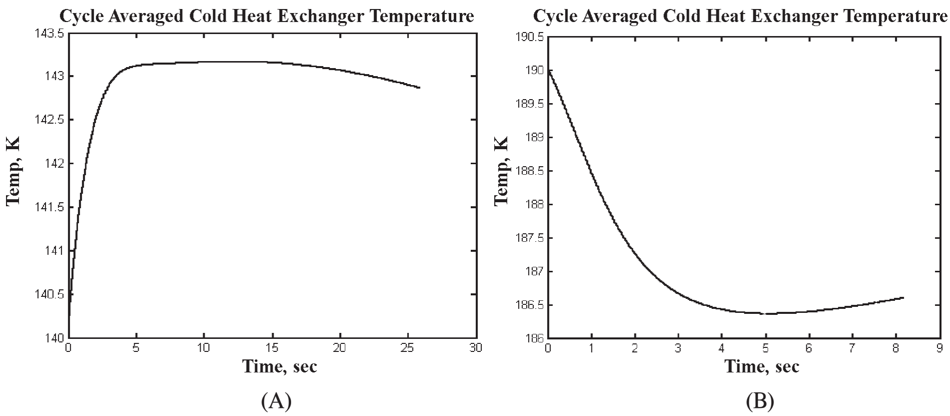

Figure 6. Cycle-averaged cold heat exchanger temperatures, mesoscale models; (A) ITPTR and (B) Reservoir-less ITPTR.

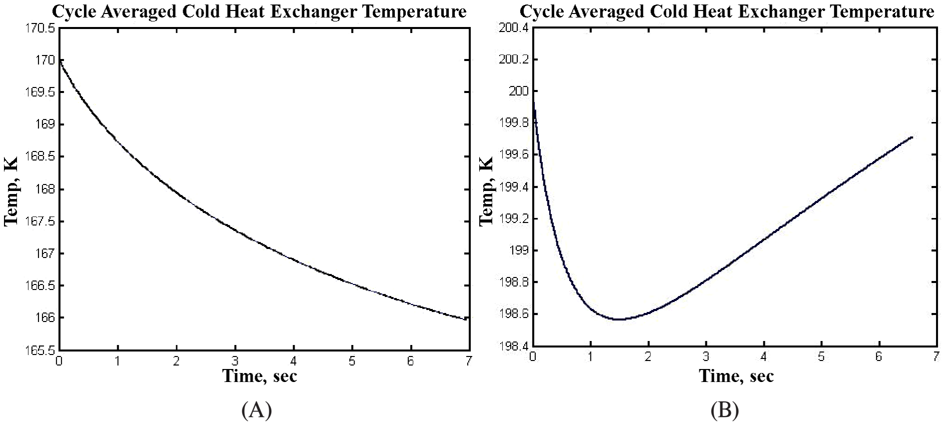

Figure 7. Cycle-averaged cold heat exchanger temperature histories, micro-scale models; (A) ITPTR and (B) Reservoir-less ITPTR.

mesoscale counterparts, these models have yet to reach periodic steady state. The micro-scale standard inertance tube model appears to be headed to an ultimate cold temperature below 166 K. The reservoir-less model, however, appears to have overshot its ultimate cold temperature and begun warming up; therefore, its likely final temperature cannot be determined at this time.

CONCLUSIONS

System-level models of mesoscale and micro-scale pulse tube refrigerators have been constructed using the Fluent CFD code following a scaling study done with the Sage PTR modeling program. These models had total volumes, excluding the compressor, of 3-4 cm^3 and approximately 1 cm^3, respectively. They incorporated experimentally determined closure relations for their regenerators and heat exchangers, which were constructed of stainless steel 635 mesh and phosphor bronze 325 mesh, respectively. While the CFD models results show that they are capable of cooling their cold ends 100 K or more below their warm end temperatures. Improved performance is expected once the periodic steady state models and their phase shift mechanisms can be optimized using CFD simulations.

The mesoscale standard and reservoir-less inertance tube PTRs models reached ultimate cold temperatures of approximately 143 K and 186 K, respectively. At the micro-scale, the standard PTR reached approximately 166 K while its reservoir-less counterpart's ultimate cold temperature was significantly higher. It is emphasized that these models need further optimization, particularly with respect to their inertance tube lengths, to reach their best possible performance. Nevertheless, it appears in comparison with CFD predictions the Sage models have predicted better performance parameters for the miniature coolers.

The CFD modeling of mesoscale and micro-scale PTRs, and optimization of their geometric dimensions and operating conditions are in progress, and are expected to further improve the performance of the models. Nevertheless, the current results demonstrate the feasibility of these miniature PTRs, particularly for staging applications where they would not need to maintain as large a temperature difference to be able to reach cryogenic temperatures.

ACKNOWLEDGEMENTS

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REFERENCES

1. Gifford, W.E., Longthworth, R.C., "Pulse-Tube Refrigeration," Trans. ASME, J. Eng. Ind. (series B), 86 (1964), pp. 264-268.

2. Gideon, D., *Sage: Pulse Tube Model Class Reference Guide*, Gideon Associates (1999).

3. Yu, Y.L., Wang, C., Zhou, Y., "Numerical Simulation and Experimental Verification of the Oscillating Flow in Pulse Tube Refrigerator," *Cryogenics*, Vol. 28 (1998), pp. 169-176.

4. Cha, J.S., Ghiaasiaan, S.M., Desai, P.V., Harvey, J.P., Kirkconnell, C.S., "Multi-Dimensional Effects in Pulse Tube Refrigerators," *Cryogenics*, Vol. 46 (2006), pp. 658-665.

5. Conrad, T.J., Landrum, E.C., Ghiaasiaan, S.M., Kirkconnell, C.S., Crittenden, T., Yorish, S., "Anisotropic Hydrodynamic Parameters of Regenerator Materials Suitable for Miniature Cryocoolers", *Cryocoolers 15*, ICC Press, Boulder, CO (2009), (this proceedings).

6. Cha, J.S., "Hydrodynamic Parameters of Micro Porous Media for Steady and Oscillatory Flow: Application to Cryocooler Regenerators," Doctoral Thesis, Georgia Institute of Technology, Atlanta, GA, 2007.

7. Garaway, I., Grossman, G., "A Study of High Frequency Miniature Reservoir-less Pulse Tube," *Adv. in Cryogenic Engineering*, Vol. 53, Amer. Institute of Physics, Melville, NY (2008), pp. 1547-1554.