ANALYTICAL MODELING AND PERFORMANCE ANALYSIS OF A PULSE TUBE CRYOCOOLER

Kedam Naresh, Dmitry A. Uglanov, Blagin E.V., Panshin, Roman A.
Samara University, Samara, Naresh.kedam@gmail.com

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This work focused on the development of a comprehensive analytical model for a pulse tube cryocooler (PTC) with the intent to enhance the understanding of its operating principles and performance metrics. The study employs mathematical modeling techniques to simulate the thermodynamic cycle of the PTC [1, 2], capturing essential mechanisms such as the phase relationship, pulse pressure wave, and gas movement. Performance indicators, including cooling capacity, efficiency, and temperature distribution, are systematically analyzed against factors like operating frequency, charge pressure, and regenerator characteristics. The quest for reliable, cost-effective, and efficient cooling systems has steered research towards pulse tube cryocoolers (PTCs), given their unique advantages including fewer moving parts, lower vibration, and the ability to reach low temperatures. This research work is dedicated to the in-depth exploration of PTCs by developing an analytical model that captures their intricate operating principles and performance characteristics. The study starts by providing a brief overview of the principles of operation of PTCs, shedding light on the thermodynamic cycle, the role of the regenerator, and the movement of the working gas inside the system. The discussion then delves into the various factors that affect the performance of a PTC such as operating frequency, charge pressure, and regenerator characteristics. This paper presents a model that enables us to understand and predict the performance of a PTC under varying conditions. The regenerator within the pulse tube cryocooler (PTC) is a crucial component responsible for the heat transfer process. To accurately model the regenerator's operations, we utilized Regen 3.3 software. This computational tool allows us to simulate the fluid dynamics and heat transfer within regenerators by solving the conservation equations (1-4).

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

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

$$\frac{\partial \emptyset A E}{\partial t} + \frac{\partial (\emptyset A (E+p) v)}{\partial x} - \frac{\partial \left(\frac{\emptyset A k_g \partial T}{\partial x}\right)}{\partial x} - \emptyset A q(p, T, T_m, v) = 0 \quad (3)$$

$$\frac{\partial D}{\partial t} + \emptyset A q(p, T, T_m, v) - \frac{(1-\emptyset) A k_m \frac{\partial T_m}{\partial x}}{\partial x} = 0 \quad (4)$$

In this model, we made an assumption of sinusoidal mass flow at the ends of the regenerator. We categorized regenerator parameters into two sets: fixed parameters and study parameters. These parameters were selected based on a literature review focusing on PTCs with an 80 K cold end temperature. The regenerator length, phase angle, and mass flow rate intervals are adjusted according to the ideal ranges. An essential factor in this model is the gas flow area (Ag), calculated by multiplying the total cross-sectional area by porosity. Although the mass flow rate fluctuates during calculations, our primary focus lies in the mass-specific cross-sectional area or inverse mass flux (Ag/mc). The coefficient of performance (COP) depends on the ratio of Ag/mc. The cross-sectional area is held constant while adjusting mc to manipulate this ratio. Notably, we assume no heat loss through the regenerator matrix via its tube wall for the scope of these calculations. However, it's important to note that this model can be adapted to include such thermal loss for a more precise analysis if required. The design approach adopted here involves maintaining the fixed parameters, optimizing the values of regenerator length (L), inverse mass flux (Ag/mc), Phase angle (θc), calculating the COP for optimal performance, and determining the cooling power per cross-sectional flow area. The last step allows for scaling as per the required cooling power. The methodology concludes with the computation of the optimal regenerator design for a PTC. This step necessitates a phase shifting mechanism to deliver the optimal cold end phase angle and a suitable compressor to match the inverse mass flux at the cold end as calculated. This research examines the impact of key parameters-working fluid frequency (f), phase angle (c), inverse mass flux (Ag/mc), and regenerator length (L)-on the performance of a pulse tube cryocooler (PTC). we found the optimal values for these parameters and the coefficient of performance (COP). Our analysis resulted in a COP of 0.132, with the optimal values for L, f, c, and Ag/mc being 0.045 m, 40 Hz, -40 degrees, and 0.145 (m2-s/kg) respectively. These findings highlight the importance of a comprehensive parameter consideration for optimizing the power and efficiency of a PTC. Parametric studies provide insights into the impact of various design and operating parameters on the cryocooler's performance. The results contribute to the optimization of the regenerator design and the improvement of the overall efficiency of pulse tube cryocoolers.

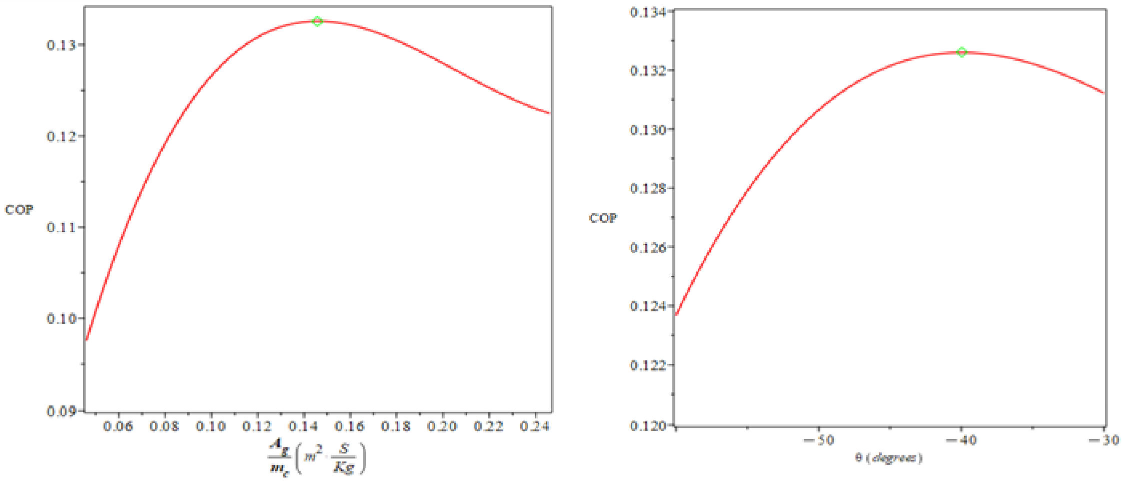

Fig. 1 a) COP vs Inverse mass flux (m^2-s/kg) b) COP vs Phase angle (degrees)

References

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Information about the authors:

Kedam Naresh: PhD Scholar, Assistant Lecturer, Research interests are heat transfer, cryocoolers.

Dmitry A. Uglanov: Associate Professor, Research interests are heat transfer, cryocoolers, cryogenics.

Blagin E.V: Senior Lecturer, Research interests are heat transfer, cryogenics.

Panshin, Roman A.: Assistant Lecturer. Research interests: cryogenics, heat transfer.