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Numerical Simulation of Pulse-Tube Refrigerators

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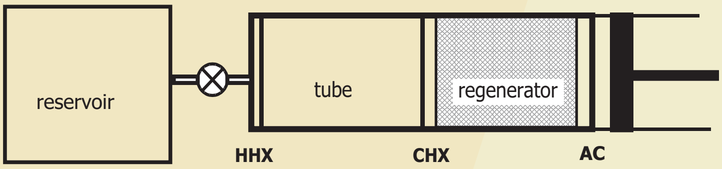
Introduction

Pulse-tube refrigerators are among the newest types of cryocoolers. Introduced in 1963, they typically reached temperatures of about 120K. By the end of the 1990's, temperatures below 2K had been reached. Due to their simplicity, low cost and reliability pulse-tube cryocoolers are beginning to replace the older types (Stirling, Gifford-McMahon and Joule-Thomson cryocoolers) in a wide variety of military, aerospace, medical and industrial applications.

Physical model



The pulse tube works by the cyclic compression and expansion of a gas, usually helium. Due to heat exchange between gas, regenerator, tube walls and the two heat exchangers, a temperature difference arises along the tube. The basic system consists of (from right to left):

Piston. Produces an oscillating pressure.

Aftercooler. (AC) Removes the heat of compression.

Regenerator. Absorbs heat from the gas on the compression part of the pressure cycle and returns heat to the gas on the expansion part.

Cold heat exchanger. (CHX) The coldest point of the system. Here heat is extracted from the object to be cooled.

Tube. If there is a suitable phase relationship between the pressure and the gas flow, heat is transported from the cold end to the hot end of the tube.

Hot heat exchanger. (HHX) Removes the heat carried through the tube.

Orifice and Reservoir. Work together to provide a suitable phase shift for effective cooling.

Objectives

To study the energy transfer from the cold to the hot end, and hence cooling power, we concentrate on the fluid dynamics in the tube section of the pulse-tube refrigerator.

Mathematical model

Mass, momentum and energy conservation and the equation of state describe the compressible gas flow in the tube. The unknowns are *density* $\rho(x,t)$, *velocity* $u(x,t)$, *temperature* $T(x,t)$ and *pressure* $p(x,t)$. Dimensional analysis reveals that the pressure is uniform in space and that the momentum equation can be neglected. The temperature in the tube is described by a convection dominated equation. The temperature equation is solved with a flux-limiter scheme for the convective part in an attempt to preserve the steep temperature gradients in the tube.

Numerical results

With this mathematical model the tube's steady-state thermodynamic behaviour under sinusoidal and step-function pressure variations can be studied.

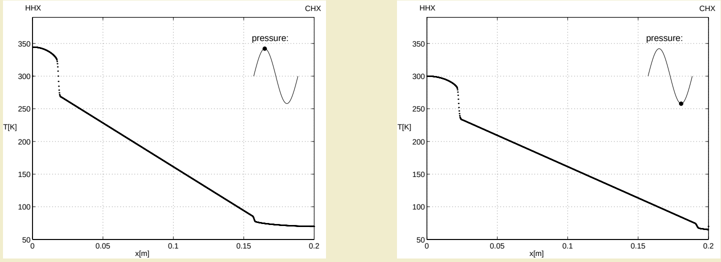


Figure 1: Temperature profiles at different moments of the pressure cycle. Sinusoidal pressure variation, boundary conditions $T_{hot} = 300K$, $T_{cold} = 70K$ and a linear temperature profile as initial condition.

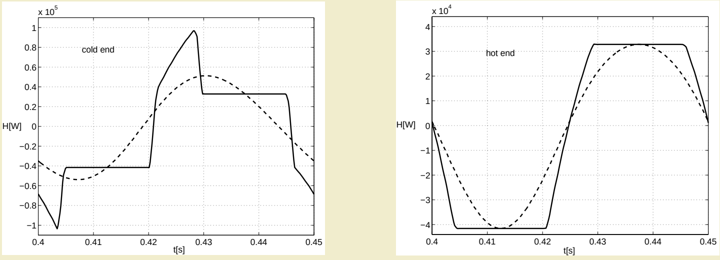


Figure 2: The energy flow (H) at the cold and hot ends for the sinusoidal (- -) and step-function (-) pressure variations.

Cooperation

This project is carried out in cooperation with

the Low Temperature Physics Group
Department of Applied Physics[1]

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