Stirlin*GUIDE* - GRAPHICAL USER INTERFACE FOR DESIGN AND EDUCATION OF STIRLING TYPE MACHINES

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The work presented in this paper aims to develop a user interface which can be used to investigate the performance of Stirling type machines. This interface provides a simulation of the cryocooler and computes the net refrigeration effect, total work input and Coefficient of Performance (COP) based on the design parameters given by the user. The program is developed based on the cyclic analysis for Stirling cryocooler and isothermal model for pulse tube cryocooler. The results in terms of various losses and variation in pressure, volume, mass flow rate, phase angle etc. can be obtained in graphical form. The gross refrigeration effect and net work input obtained can help the user to estimate first order performance of the cryocooler. Thus, StirlinGUIDE can be used to optimize the Stirling type machines. The program also incorporates a separate educational interface along with the design tool for the students of Cryogenic Engineering courses.

Key words: Graphical User Interface (GUI), Stirling Cryocooler, Stirling type Pulse Tube Cryocooler

INTRODUCTION

The computer programs available for Stirling type machines help to design and optimize Stirling cryocoolers. However, these softwares are only intended for the serious researcher and knowledgeable hobbyist to perform high-end research work. The young researchers are faced with conceptual challenges in understanding cryogenics and cryocoolers. This brings to the fore a need for a pedagogical tool which facilitates the undertanding of cryogenics and cryocoolers along with a design tool that could be used to approximate first order performance of cryocoolers and to carry out parametric studies.

In this paper, a new software, the Graphical User Interface for Design and Education of Stirling type machines (Stirlin*GUIDE*), is presented which can be used as an interactive tool to understand Stirling type machines. Stirlin*GUIDE* is a GUI built using MATLAB® and can be used to study a Stirling cryocooler and a Pulse Tube Refrigerator (PTR). The MATLAB code for the Stirling Cryocooler uses assumptions based on cyclic analysis as proposed by Atrey et al. [1]. The isothermal model suggested by Zhu and Chen [2] along with cyclic analysis has been utilized for devising the algorithm for PTR with an inertance tube. Along with cyclic analysis, the interface also provides a visualization of the specific cryocooler and a learning module for the user. The design model involved in writing the algorithm and the features of Stirlin*GUIDE* are discussed in detail further.

DESIGN MODEL

Stirlin*GUIDE* utilizes various design models [1, 2] for the simulation and analysis of Stirling type Cryocoolers. The dimensions and operating conditions are entered by the user and Stirlin*GUIDE* computes the cooling effect and power input with some basic assumptions.

Cyclic Analysis [1]

Certain assumptions taken into consideration for the analysis are listed below

- The gas behaves as a Perfect Gas.
- Piston and Displacer move sinusoidally.
- Whole system has a constant pressure.
- Cooler dead space temperature is mean of inlet and outlet temperatures.
- Compression process is adiabatic whereas expansion is isothermal.
- Regenerator mass flow rate is the logarithmic mean of that in the compression and expansion spaces.

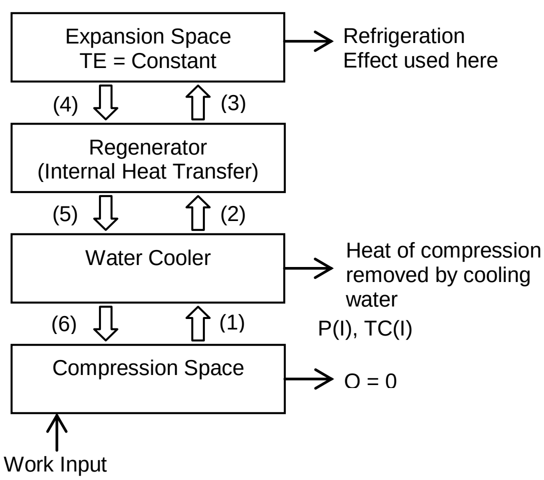

Figure 1. Cyclic analysis for Stirling cryocooler

The volume variations for the expansion and compression spaces on the basis of the input parameters and dimensions are first computed. Pressure at each interval is calculated which is then utilized to evaluate temperatures for the corresponding intervals with the assumption of adiabatic compression and using Newton-Raphson method as a mathematical tool. A correction factor is then obtained to correct the previous pressure values.

Ideal Power input and Ideal Refrigeration effect are then calculated by simple integration using trapezoidal rule. The procedure for cyclic analysis is shown by a model for a Stirling cryocooler in Figure 1.

Isothermal Model [2, 3]

The isothermal model proposed was for the investigation of orifice PTR. The isothermal model does not account for the losses in the pulse tube. A second order isothermal model is developed by Atrey et al. [3] that includes losses in an orifice PTR by using cyclic analysis. Similar methodology is used for an inertance tube PTR.

The simple isothermal model can be illustrated using the schematic of an inertance tube PTR as shown in Figure 2. The gas within the pulse tube can be split into three parts. Part III is the cold part that flows from regenerator and expands to give out work. Part I of the gas is the hot part which flows to the reservoir and absorbs work. Part II is the moving gas displacer in the middle part which replaces the solid piston in a split Stirling refrigerator. This part is always inside the pulse tube.

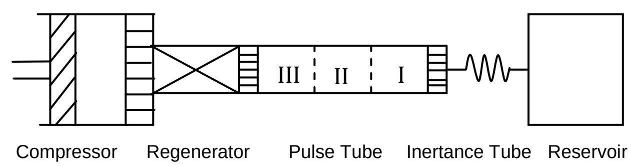

Figure 2. Schematic of inertance tube PTR

Some of the assumptions of the isothermal model are as follow

- The gas is an ideal gas and there is no gas leakage through the piston seal.
- There is no fluid resistance.
- Pressures at all points in the system remain the same at any instant.
- Gas in middle part of the pulse tube is adiabatic. Other parts are isothermal.

A pressure-volume cycle of 360° is divided into several small time intervals. Ideal gas law is applied and pressure for corresponding interval is obtained. Applying conservation of mass for sections I, II and III, all the volumes and temperatures are obtained. Using the values of temperatures and volumes, the ideal refrigeration effect and ideal power required are calculated. The ideal parameters are then modified considering the various identifiable losses.

Loss Analysis

Mass flow rates are different because of different regenerator, cooler and condenser dead spaces. Variation in mass fraction of gas inventory for each space is calculated for each interval.

The losses taken into consideration are:

- Regenerator Ineffectiveness Loss: It results in slightly higher temperature in the expansion space.
- Shuttle Heat Conduction: Displacer absorbs heat from the hot end and gives it out at the cold end.
- Temperature Swing Loss: Accounts for constant change in temperature of the regenerator matrix.
- P-V Loss: Due to pressure drop in the regenerator, cooler and evaporator. The pressure at the expansion space is lesser than that in the compression space.
- Pumping Loss: Continuous pressurization and depressurization of the cooler results in the gas (present in the gap between the expander and the wall) to flow in and out of this gap, thus, reducing the refrigeration.
- Losses due to conduction in solid members
- Additional power requirement due to pressure drop in the cooler, the regenerator and the condenser because of flow friction.

FEATURES OF Stirlin*GUIDE*

In Stirlin*GUIDE*, a GUI is used to display the simulations and calculations done in the algorithm. The GUI consists of two modules: (a) Educational (b) Design and they are described below.

Educational Module

It is a user friendly interface designed to help an individual to understand the fundamentals of cryogenics and various cryocoolers. The module explains the working mechanism of the Stirling cycle with the help of animation, describes the different types of cryocoolers and lists their advantages, disadvantages and applications. Several losses incurred in cryocoolers have also been explained both by text and animation. Figure 3 gives a glimpse of one of the losses.

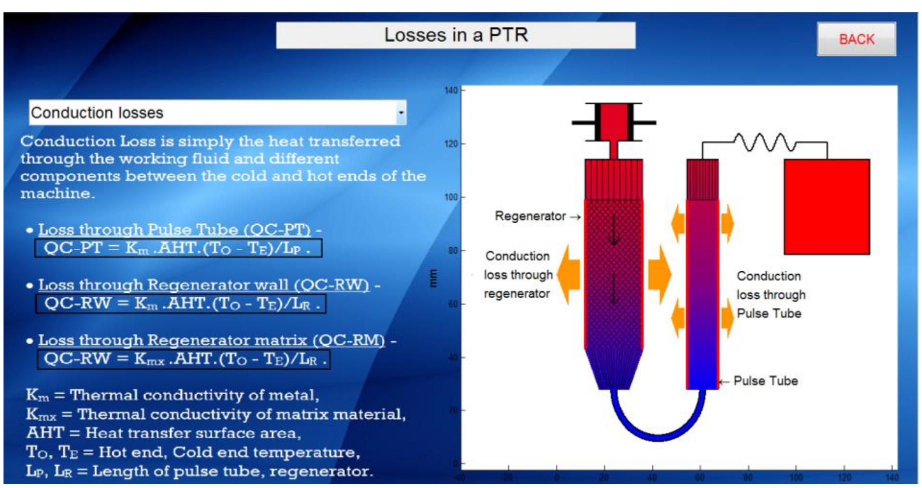

Figure 3. Conduction Losses occurring in a PTR as a part of the educational module

Design Module

Along with the educational tool, Stirlin*GUIDE* also has a design section. The Design section helps the user to simulate and compute results for a cryocooler.

The user can choose between the Stirling cryocooler and the PTR. For the Stirling machine, one can select the alpha (α), beta (β) or gamma (γ) configurations. The Inline and U type configurations can be used while designing a PTR with inertance tube.

The program first interrogates the user to acquire the necessary data input. These include the design parameters such as average pressure, temperature, phase angle etc. and the dimensions of regenerator, displacer, piston etc. Using that information, Stirlin*GUIDE* determines the performance of a cryocooler by calculating the parameters, for instance, the net refrigeration effect, total work input and COP. An animation of the cryocooler with the particular input dimensions also can be viewed alongside the results as evident in Figures 4 and 5.

The losses in the cryocooler are computed using the aforementioned analyses

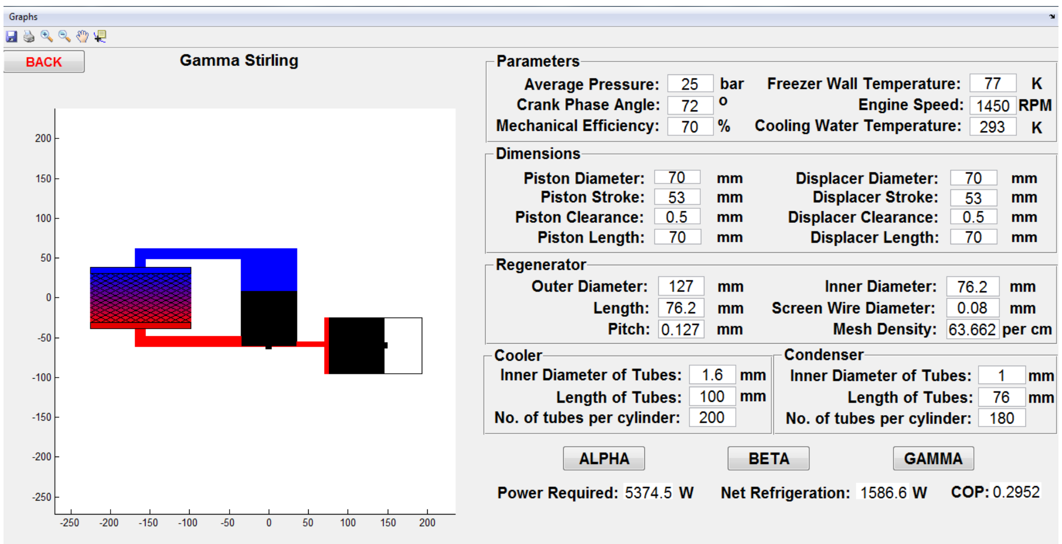

Figure 4. Model of a Gamma Stirling machine

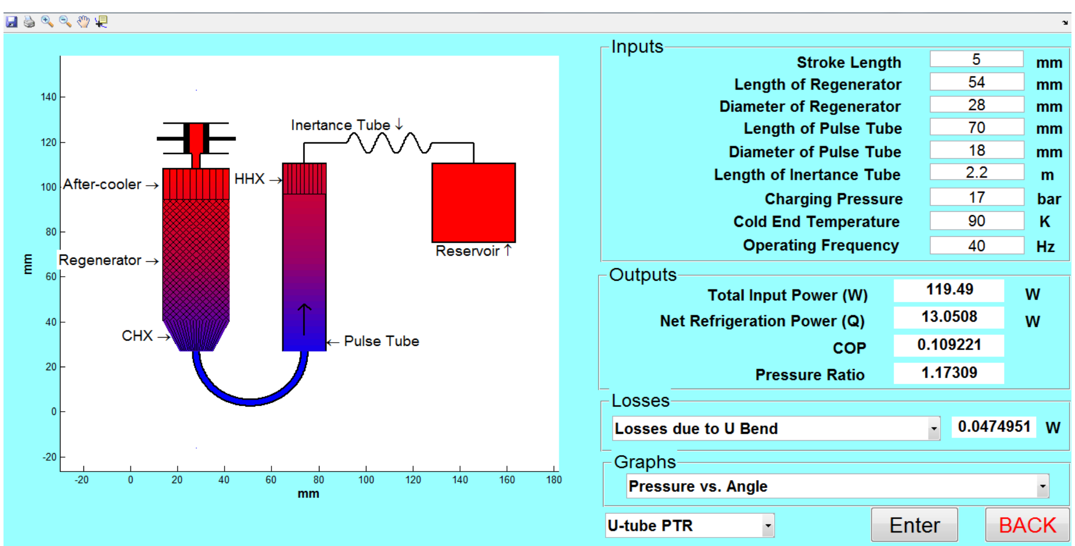

Figure 5. Simulation and Computations of a U-type PTR

and one can select from among various losses which can be viewed on the screen. There is also a feature wherein the losses are displayed in the form of a pie chart. The chart helps the user recognize the dominating loss and modify the design accordingly. The user may continue to vary the operation and design parameters and observe the outputs till the requirements are met.

The user can then advance to examine the graphical data. For a given cryocooler, the change in pressure, volume and mass flow rates with crank angle and variation of pressure with volume (P-V diagrams) at different locations in a cryocooler can be analyzed by the plotting tool which displays various graphs. In Stirling cryocoolers, gas flow distribution can be explained by graphs between mass fraction of gas in compression or expansion space and crank angle. Some graphical illustrations are displayed in Figures 6 and 7.

The variation of the output by altering the design and operating parameters can be studied through several graphs. For instance, we can assess the change in net refrigeration effect (Q) and net input power with the minimum temperature attained (T), dimensions of regenerator, etc. at different pressures. Such a case is visible in Figure 8.

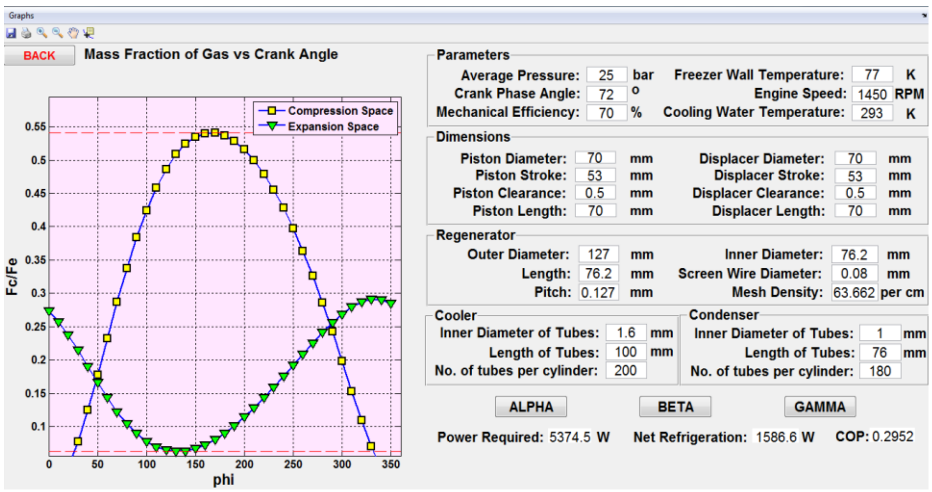

Figure 6. Mass Fraction of Gas in compression and expansion space vs. Crank angle in a Stirling cryocooler

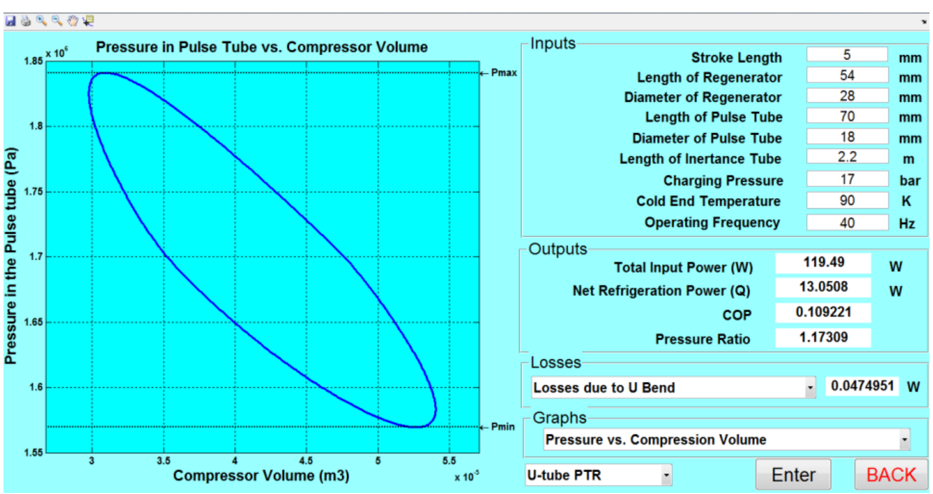

Figure 7. Pressure in Pulse Tube vs. Compressor Volume in a PTR

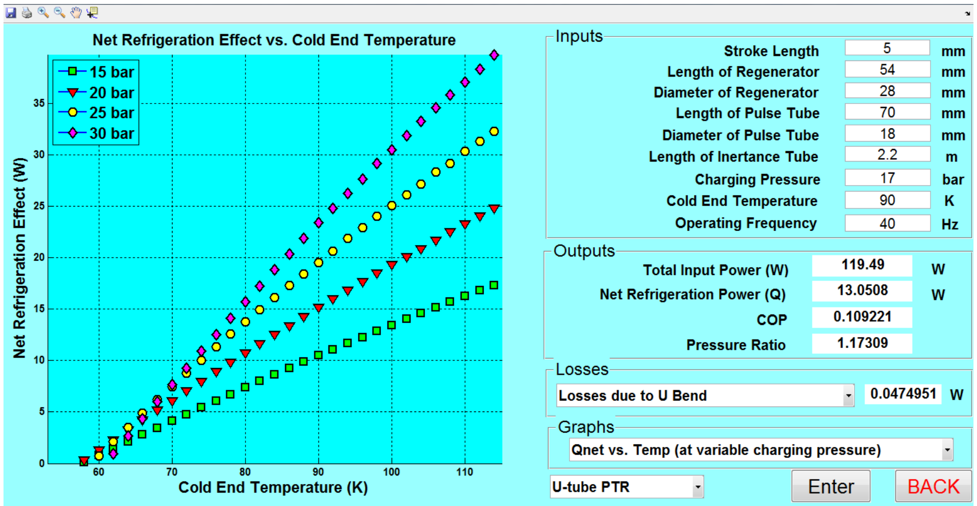

Figure 8. Q vs. T for Varying Pressures for a PTR

OPTIMIZATION

Besides being a design and an educational tool, Stirlin*GUIDE* can be used to inspect the performance characteristics of Stirling type machines. The gross refrigeration effect and gross work input obtained can help the user in finding an initial estimate for the fabrication of a cryocooler according to the target specifications. Further design modifications can be made to incorporate the geometric constraints. In this way, the user can utilize the results of Stirlin*GUIDE* to build an optimum Stirling machine.

CONCLUSION

Stirlin*GUIDE* provides a comprehensible platform for non-computer specialists to attain results for a particular cryocooler based on the required design and performance parameters. It also offers wide-ranging graphical illustrations which can assist in experimental courses in Cryogenic Engineering. A decent interpretation of the results can help in optimization of the cryocooler. Future work includes integrating the optimization tool into the software that would supplement the current interface.

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