Design of the glass pulse-tube cryocooler

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Abstract. With the purpose of generating the curiosity of the public, a pulse-tube cryocooler with regenerator, pulse-tube, inertance tube and reservoir made of glass has been designed constructed and operated. The dimensions of the glass regenerator have been determined using REGEN3.3 [1] from given parameters of the conductive porous medium inside of the regenerator and a 150K target cooling temperature at the cold head. The geometry of the glass pulse-tube and glass inertance tube has been fixed using an approximate design method [2], and the entire system parameters checked using SAGE [3]. The thickness of each glass component is based on a charge pressure of around 7 bar and a pressure ratio of about 1.35. The dimensions of the after-cooler are calculated using ISOHX [4] assuming a gas temperature of 300 K at the inlet of the regenerator.

1. Introduction

The goals of this glass pulse-tube cryocooler are to operate it as a teaching tool and to create curiosity in the first-time observers. The glass system enables the audience to observe the inside of the cryocooler while it is operating, and encourages subsequent questions from the audience. Frost forms on the outside of the cold head of the cryocooler since it is exposed directly to ambient conditions. However, the observers will not see any moving parts or fluid flow because the working fluid, helium gas, is transparent.

The design process of the glass pulse-tube cryocooler begins with the dimensions of the regenerator. Based on the given parameters of the screen mesh matrix and a target cold head temperature of 150 K, the dimensions of the regenerator are optimized using REGEN3.3 by adjusting the length, mass flow rate, pressure ratio and charge pressure. The design of the glass pulse-tube is based on the mass flow rate from the cold head of the regenerator and a consideration of avoiding turbulence at the walls. The geometry of the glass inertance tube has been determined from the properties at the warm end of the pulse-tube. A SAGE simulation based on the calculated parameters has been run in order to predict the performance of the entire system. Since the helium gas is compressed by the pressure wave generator, an aftercooler is required between the pressure wave generator and the regenerator. The geometry at the warm end of the regenerator is designed using the ISOHX code with a 300 K helium gas temperature at the inlet of the regenerator as a goal.
2. Design details
The design of the whole glass pulse-tube cryocooler begins from defining the geometry of the regenerator. The dimension of the pulse-tube is based on the properties of the helium gas at the outlet of the regenerator. The inertance tube and the reservoir are optimized by SAGE. An aftercooler is installed between the regenerator and the pressure-wave generator in order to cool down the compressed gas before entering the regenerator. The aftercooler design is limited by ISOHX simulation.

2.1. The dimension of the regenerator
The conductive porous media put inside the regenerator is made up of 150 mesh copper screens with an outer diameter of 19.05 mm, wire diameter of 66.0 μm and a wire spacing of 169.3 μm. The porosity ε of the screen is calculated by:

\[ 1 - \varepsilon = \frac{\pi}{4} \times \left( \frac{d}{s} \right) \]  

(1)

where \( d \) is the wire diameter and \( s \) is the wire spacing. The porosity of the screen mesh matrix is 0.6939.

The pressure-wave generator unit that this project used is a 2S132W TwinSTAR motor made by CFIC Inc. The operating frequency of this star motor is 60 Hz which is another of the given parameters for the regenerator design. The maximum operating pressure of the compressor is 31 bar. For the target design, the working pressure inside of the regenerator should be around 7 bar, a value that is within the safe operating limits of the glass components.

Figure 1. The 2S132 Pressure Wave Generator

Other parameters of the regenerator dimension are adjusted in order to optimize its performance. The parameters are iterated in a closed-loop manner using REGEN 3.3. The sequence of parameters being optimized is shown in the Figure 2. As a result of the optimization process with the target temperature of 150 K, the fixed inner diameter of 19.05 mm, an average pressure of 7 bar and a pressure ratio of 1.35, the optimized mass flow rate at the cold end is 1.697 g/sec and the length is 59.94 mm. For these conditions, REGEN 3.3 calculates an adjusted gross refrigeration power of 32.88 W.
2.2. The dimension of the pulse-tube

The helium gas flow at the cold end of the regenerator extends a certain distance into the pulse tube. This distance determines a swept volume of helium at the cold temperature, $V_c$ that is defined by equation (2) where $\omega$ is the angular frequency, $T_c$ is the cold end temperature and $m_c$ is the mass flow rate at the cold end. The pulse-tube volume should be sufficiently large to contain a slug of helium gas in the middle in order to prevent the extended cold volume $V_c$ from reaching the warm end. Therefore the total volume of the pulse tube should be around three to five times of the cold end volume [5]. Because the target temperature at the cold head is 150 K, which is relatively high, the volume of the pulse tube only needs to be about three times the volume of the cold end volume. The calculated pulse-tube volume is 16.6 cm$^3$.

$$V_c = \frac{2m_cRT_c}{\omega}$$

(2)

In order to avoid turbulence at the walls of the pulse-tube, the oscillatory helium fluid must maintain the Reynolds number of the fluid lower than the critical Reynolds number defined by Akhanvan, Kamm and Shapiro [6] for turbulent oscillatory Stokes flow in a circular pipe:

$$Re_{crit} = \frac{\rho u_{crit} \delta}{\mu} = 280$$

(3)

A minimum cross-sectional area requirement based on equation (4) is applied at cold end and the warm end of the pulse tube. The larger value of these two area limits defining the minimum cross-sectional area of the pulse-tube, and occurring at the cold end of the pulse tube is 94.57 mm$^2$. The resulting pulse-tube length is 175.5 mm and the inside diameter is 11.0 mm.

$$A_{minimum} = \frac{m_c \delta}{280 \mu}$$

(4)

However, rather than using this minimum cross-sectional area, and for ease of fabrication by the glass-blower the regenerator and the pulse-tube are made from one glass tube with the same inner diameter of 19.05 mm. A larger inside diameter for the pulse-tube maintains the flow further away from the possibility of the oscillating turbulence. With this choice for the pulse tube diameter, the resulting length, given by:

$$L_{pt} = \frac{V_{pt}}{\pi(19.05 \, mm)^2/4}$$

(5)
becomes is 58.4 mm.

A rib feature with a smaller diameter than the inner diameter of the stock tube separates the pulse-tube and the regenerator. The rib feature built into the glass tube while it is rotated at a high speed is produced by heating and turning down the glass with a sharp tool as shown in Figure 3. A very low-mesh piece of stainless screen inserted on the regenerator side of the rib inhibits the copper screen pack that makes up the regenerator from moving into the pulse tube portion of the glass tube.

2.3. Inertance tube and reservoir dimensions
The diameter and the length of the inertance tube have been determined using an optimization process in SAGE, resulting in an inner diameter of 3.4 mm and a length of 2.36 m. In order to have enough volume to store the gas during half of the cycle with no appreciable pressure oscillation, the reservoir is chosen as a 1 liter heavy duty flask from AceGlass.

2.4. Aftercooler dimensions
Because the helium gas is compressed by the pressure wave generator, and does not have the opportunity to directly exchange heat with the surroundings, its temperature will rise above the inlet, or ambient temperature. An aftercooler is therefore installed between the pressure wave generator and the regenerator, and the pressurized helium gas is cooled down as it flows through the aftercooler and before it enters the regenerator.

At the design operating conditions the gas exits the pressure wave generator at around 330 K, and should be cooled to 300 K. The after-cooler is comprised of a copper screen matrix packed inside a 12.7 mm diameter copper tube. A helical winding of 3.2 mm ID copper tubing is wrapped around the 12.7 mm tube and serves as a flow path for water that absorbs the heat from the warm helium gas flowing through the stack of copper screens. The 80 mesh copper screens have a wire diameter of 139.7 μm and a porosity of 0.6544. The software ISOHX is used to calculate the required length of the heat exchanger in order to limit the difference between the gas and ambient temperature at the outlet to less than 1% of the same temperature difference at the inlet of the heat exchanger. We find that the length of 50.3 mm easily satisfies the desired temperature difference at the heat exchanger outlet, and allows a convenient
wrap of 5 turns for the water-cooling tubing. Additionally, the corresponding ratio of the pressure change through the screen stack to the average pressure $\Delta P/P$ is less than 0.075 for the chosen geometry.

3. SAGE and test result
After fixing the dimensions of the various individual components, the performance of the assembled system was simulated for a final check using SAGE. The results predict a cooling power of 8.6 W at 150 K with the design average pressure and pressure ratio. The acoustic power at the warm end of the regenerator is estimated at 58 W. The predicted cooling power represents only 26.2% of the adjusted gross refrigeration power as calculated by REGEN3.3, but is expected to be more than sufficient to produce a frost effect on the outside of the location where the pulse tube and regenerator meet.

In its initial test, the system was charged with Helium at a pressure of 6.8 bar. Within one minute of turning on the compressor, frost was observed at the cold end of the pulse tube. The effect is shown in Figure 5 along with a view of the fully assembled glass pulse tube.

Figure 5. The left side of the picture shows the components of our glass pulse tube machine. The right side picture is a zoomed-in picture of our regenerator and the pulse-tube when the frost effects was shown. The frost effect can be observed at the end of the regenerator and at the head of the pulse tube.

4. Summary
The successful design and operation of a glass pulse tube refrigerator has been completed. Beginning with the geometric parameters of an existing set of copper screens for the regenerator, the specifications of an existing pressure wave generator, and a desired cooling power and temperature, the approximate design process was used to define the geometry of the
regenerator, pulse tube, inertance tube, reservoir, and after-cooler. Various software tools including REGEN3.3, ISOHX and SAGE were used in the process. The integrated performance of the entire system as simulated by SAGE suggests a potential cooling power of 8.6 W at 150 K, and an initial test of the fully assembled system produced a frost layer at the cold end of the pulse tube within one minute of turning on the pressure wave generator.

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