Experimental studies on twin PTCs driven by dual piston head linear compressor

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Abstract.

An experimental study on pulse tube cryocooler is presented with a twin pulse tube configuration. The study is conducted with a dual piston head linear compressor design which is developed indigenously. The two identical pulse tube cryocoolers are operated by a single linear motor which generates 180° out of phase dual pressure waves. The advantages of the configuration being the reduction in fabrication cost and the increased cooling power. The compressor is driven at a frequency of 48 Hz using indigenously developed PWM based power supply. The CFD study of pulse tube cryocooler is discussed along with the experimental cool down results. A detailed experimental and FEM based studies on the fabrication procedure of heat exchangers is conducted to ensure better heat transfer in the same.

1. Introduction

A lot of advancements have gone into the field of pulse tube cryocoolers to increase its COP. One of the commonly researched arrangements is the single PTC. A single PTC uses two compressors in dual oppose configuration [1]. The present work focuses on connecting two single PTCs driven by a single compressor, by utilizing the back thrust of the compressor.

Design and study on phase angle variation due to frequency change for various components of single, twin and joint twin PTCs using Sage software are discussed elsewhere [2] for 20 bar Helium charging pressure. In this paper, development of Twin Pulse Tube Cooler (TPTC) that uses the same methodology for 34 bar charging pressure is discussed [2]. Developed TPTC was driven by indigenously developed dual piston heads linear compressor operated by single motor. The dual piston head compressor generates to pressure waves 180° out of phase, which in turn drives TPTC.

The Coefficient of Performance (COP) of PTC depends on proper phase shift between pressure amplitude and mass flow rate, pressure ratio and operating frequency [3]. The proposed design of TPTC doubles the cooling power at half the cost of linear motor which in turn enhances COP.

The dimensions of TPTC components were selected using 1-D Sage software for 34 bar charging pressure, 1.18 pressure ratio and 48 Hz of operating frequency. In later section, the computed TPTC dimensions from Sage software was validated by axis symmetry Computational Fluid Dynamics (CFD) studies using ANSYS FLUENT software. As two identical PTCs were
used in TPTC, therefore CFD analysis was carried out by modeling single PTC of TPTC in ANSYS to reduce the computational time.

TPTC uses six soldered Copper mesh stack heat exchangers. In general, unsoldered Copper mesh stacked heat exchangers are used. The experimental and transient heat transfer comparative studies between soldered and unsoldered heat exchangers were carried out and are discussed in this paper. Thereafter, assembly procedure of TPTC, its instrumentation and experimental no load cooldown curve are discussed.

2. Sage Simulation

Figure 1 shows components of TPTC. Initially, the developed compressor was tested for full stroke length of ± 3 mm at different charging pressures and frequencies to find the maximum pressure ratio with minimum power input. Based on compressor performance TPTC dimensions were computed using Sage software for 34 bar charging pressure, 1.18 pressure ratio at 48 Hz of operating frequency. Detailed Sage computational procedure was discussed elsewhere [2]. The optimized TPTC dimensions obtained from Sage simulation are listed in Table 1 for maximum cooling of 0.3 W at 80 K. As Sage works on 1-D modeling, therefore, it is must to validate its result using CFD tools as discussed in later section.

![Figure 1. Twin PTC Configuration](image)

3. CFD analysis of TPTC

The CFD simulation is more accurate when compared to Sage because it takes into consideration the multidimensional flow effects by using a 2-D model but at the expense of computational time. On other hand, Sage computes the dimensions very fast with moderate accuracy. Thus, it is advisable to validate the computed PTC dimensions by Sage using CFD analysis.

A Two-dimensional, axis-symmetric model of TPTC was developed for CFD analysis with the dimensions obtained from 1-D Sage simulation to evaluate its performance in commercial CFD package FLUENT of ANSYS software. As TPTC uses identical two pulse tubes, thus
Table 1. Sage TPTC dimensions for 0.3 W at 80K

| Parameters                  | Dimensions | Parameters          | Dimensions |
|-----------------------------|------------|---------------------|------------|
| Charging pressure (bar)     | 34         | Pulse tube length (mm) | 70         |
| Transfer line ID (mm)       | 4          | Hot heat exchanger ID (mm) | 6          |
| Transfer line length (mm)   | 400        | HHx length (mm)      | 6          |
| After cooler ID (mm)        | 8          | Inertance tube A ID (mm) | 1.2        |
| After cooler length (mm)    | 6          | Inertance tube A length (m) | 1          |
| Regenerator matrix OD (mm)  | 8          | Inertance tube B ID (mm) | 2.5        |
| Length regenerator (mm)     | 55         | Inertance tube B length (m) | 0.5        |
| Cold heat exchanger ID (mm) | 6          | Inertance tube C ID (mm) | 3          |
| CHx length (mm)             | 5          | Inertance tube C length (m) | 1.5        |
| Pulse tube ID (mm)          | 6          | Volume (CC)          | 80         |

only single pulse tube was modeled. Ideal Helium gas was used as a working fluid in model. Modeling of geometry and nodalization of various parts was done using ANSYS Workbench. The mesh metric was of orthogonal quality of 0.997. Model boundaries were defined after importing model into fluent solver. Boundary conditions for various components are tabulated in Table 2. Minimum temperature of 85 K was obtained on computation at cold heat exchanger.

Based on these results six heat exchangers of TPTC, two sets of regenerators, pulse tubes, inertance tubes and buffer volumes were fabricated and assembled as discussed in later sections.

Table 2. Parameters and boundary conditions for TPTC

| Component                  | Wall material | Boundary conditions | Mesh no. | Mesh material |
|----------------------------|---------------|---------------------|----------|--------------|
| Transfer line              | SS            | Isothermal (300 K)  | -        | -            |
| After cooler               | Copper        | Isothermal (300 K)  | 100      | Copper       |
| Regenerator                | SS            | Adiabatic           | 400      | SS           |
| Cold heat exchanger        | Copper        | Isothermal (300 K)  | 100      | Copper       |
| Pulse tube                 | SS            | Adiabatic           | -        | -            |
| Hot heat exchanger         | Copper        | Isothermal (300 K)  | 100      | Copper       |
| Inertance tube A           | Copper        | Isothermal (300 K)  | -        | -            |
| Inertance tube B           | Copper        | Isothermal (300 K)  | -        | -            |
| Inertance tube C           | Copper        | Isothermal (300 K)  | -        | -            |
| Buffer                     | SS            | Isothermal (300 K)  | -        | -            |

4. Heat exchanger fabrication and performance testing

In general heat exchangers for PTC are fabricated using stacked copper meshes. The purpose of heat exchanger is to exchange the heat of fluids. Therefore, in high frequency operating systems the time response of heat exchangers plays an important role. Considering this fact, Copper heat exchangers were fabricated for aftercooler, cold heat exchanger and hot heat exchanger using soldered stack of copper 100 meshes (100 holes per inch). Lead tin (Pb37Sn63) based soldering wire was used to solder the copper mesh stack.

It was important to check the performance of fabricated heat exchanger for response time, heat transfer rate and thermal conductivity. A comparative study was carried out on heat exchangers fabricated using soldered and unsoldered copper mesh stacks.

In first heat exchanger, stack of copper mesh was press fitted in the copper block. Whereas, in second heat exchanger, stack of soldered copper meshes was solder with the copper block.
Both the heat exchangers consist of 50 copper meshes of 100 mesh size of 18 mm diameter. Outer diameter of heat exchanger copper block was 36 mm. Manganin heater wire of 76 ohms was coiled on the outer periphery of each heat exchanger. Heat exchangers were mounted inside the multilayer insulated cryostat using the dip stick as shown in Figure 2.

**Figure 2.** Schematic of heat transfer experimental setup for heat exchanger.

Following procedure was followed for testing the response of unsoldered and soldered heat exchangers at 297 K and 65 K:

- Two RTDs were used in four wire configuration for temperature measurement. One RTD was mounted on the outer edge of solid copper of heat exchanger. Whereas, other RTD was mounted at the center of mesh. RTDs wire was connected to NI-DAQ system via feedthrough.
- Heat exchanger was mounted using the dip stick inside the cryostat.
- Top flange was sealed and vacuum was created in cryostat.
- Under high vacuum (adiabatic) condition, constant current pulse of 264 mA was supplied for 30 seconds to the heater coil to deliver 5.26 W of heat input at outer periphery of heat exchanger. The responses of both the RTDs were logged.
- Thereafter, cryostat was purged using helium gas to avoid ice formation during testing at low temperature.
- Helium gas balloon was connected to the LHe reservoir chamber and LN\(_2\) was filled in the outer LN\(_2\) jacket and LHe reservoir chamber. RTDs were allowed to attain stable minimum temperature.
- LN\(_2\) was allowed to evaporate and thereafter, high vacuum was created. Due to creation of vacuum, temperature in the cryostat would drop further.
- Under high vacuum (adiabatic) condition and stable minimum temperature a constant current pulse of 264 mA was supplied for 30 seconds to the heater coil to deliver 5.26 W of heat input at outer periphery of heat exchanger. The responses of both the RTDs were logged.

Figure 3 shows the temperature response for unsoldered and soldered heat exchanger at 297 K and 65 K respectively. It was observed that time response and heat transfer rate was better in the case of soldered heat exchanger under adiabatic conditions. Thus, faster time response of soldered heat exchanger is because of solder material filled between copper block and mesh edges which improves contact area. To understand the temperature variation a detailed heat transfer study is discussed in the next section.

![Figure 3](image)

**Figure 3.** Temperature response of unsoldered and soldered heat exchangers at a) 297 K b) 65 K.

5. Heat exchanger transient FEM analysis
The time response of unsoldered heat exchanger was lesser than that of soldered heat exchanger. This is caused due to irregularities in contact surface between mesh and solid copper. FEM simulation was carried out based on the experimental results to understand the surface irregularities. A quarter section of heat exchanger was consider for analysis as there exist two symmetric planes for the heat-exchanger as shown Figure 4. Contact irregularities are shown in unsoldered heat exchanger whereas, contact irregularities were filled with solder material in case of soldered heat exchanger. It was assumed to be one dimensional radial heat transfer and the model thickness was limited to the thickness (114.3 µm) of a single wire mesh. Contact imperfections were introduced in the analysis of unsoldered heat exchanger to match with the experimental results. Simulation of unsoldered heat exchanger was carried out with 24756 number of nodes and 2570 elements. Whereas, in case of simulation of soldered heat exchanger 41005 nodes were used with 16403 elements. The input heat flux was provided at the outer
surface of the copper block for 30 seconds in the transient thermal analysis of heat exchangers. Figure 5 shows the temperature gradient profile along the radial direction of heat exchanger. An approximate temperature difference of 0.1 K and 0.05 K were obtained in case of unsoldered and soldered heat exchanger respectively both at 300 K and 65 K.

Figure 4. Quarter section schematic of unsoldered and soldered heat exchanger.

Figure 5. FEM transient heat transfer analysis.

6. Pulse tube assembly
After analyzing the fabrication process of heat exchangers, six soldered heat exchangers were fabricated i.e. two sets of after cooler, cold heat exchanger and hot heat exchanger. The fabricated heat exchangers were joint with other pulse tube components in sequence to form TPTC. Vacuum tight joints could be accomplished by fabricating the flanges with smooth surface. Indium O-rings of 1.2 mm wire diameter were used for sealing the flanges. Lock washers were used to maintain constant pressure on the tightened flanges. Figure 6 shows assembly sequence of twin PTC.
7. Instrumentation
After assembly it is must to mount the sensors at proper locations to monitor performance and health of TPTC during operation. Thus, instrumentation design plays a very important role. Six PT100 RTDs (Resistance temperature detector) were used in three wire configuration and two in four wire configuration for each pulse tube. All RTDs were pre-calibrated against temperature sensor Cernox. Four wire RTDs were glued on cold heat exchangers. Whereas, three wire RTDs were glued on various components of TPTC as shown in Figure 7. Two pressure sensors one on each transfer line were mounted. Data from all the sensors were logged using Supervisory Control And Data Acquisition (SCADA) developed using National Instruments interfacing LabVIEW software. Figure 7 shows screenshot of front panel of SCADA system.

8. Cool down curve of TPTC
After mounting the sensors, the vacuum jacket was sealed and high vacuum of 10−5 Torr was created. Figure 8 shows the cooldown curve of TPTC. The dual piston head compressor was
operated at 48 Hz with Helium gas as a working fluid. The charging pressure of helium gas was 34 bar in TPTC and pressure ratio was 1.18 at the inlet of after cooler. The cold heat exchangers of TPTC attained minimum temperature of 92.4 K in two hours at no load condition. Thereafter, the temperature remained constant.

![Cooldown temperature curve for twin PTC operated at 48 Hz](image)

**Figure 8.** Experimental cool down curve of twin PTC.

9. Conclusions

Sage software was used to compute the dimensions of TPTC for 34 bar charging pressure, 1.18 pressure ratio and 48 Hz of operating frequency for 0.3 W of cooling power at 80 K. Based on 1-D Sage computed component dimension, a 2-D CFD analysis was carried out for single PTC for same operating conditions (34 bar charging pressure, 1.18 pressure ratio and 48 Hz operating frequency). Lowest temperature of 85 K was achieved in CFD simulation. The heat exchanger fabrication procedure with soldered stacked Copper meshes was developed successfully, which has fast response time when compared to press fitted unsoldered stacked Copper meshes. Transient heat transfer analysis for heat exchanger was carried out in accordance with experimental results to understand the contact irregularities when stacked meshes without solder are used. A SCADA based instrumentation was developed to record various sensor readings and monitor the health of the system. Lowest temperature of 85 K was achieved in CFD simulation. Fabrication and assembly procedure was developed to test PTC. The lowest no load temperatures experimentally achieved at the cold heat exchanger of TPTC was 92.4 K in two hours.

References

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