

Performance Characteristic of a Two-Stage Pulse Tube Refrigerator in Coaxial Configuration

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ABSTRACT

Based on our extensive experience with the development of single-stage pulse tube refrigerators in a coaxial configuration we have designed a new type of two-stage pulse tube refrigerator. Our experimental results concerning the intermediate thermal contact between the pulse tube and the regenerator have allowed us to combine the two-stage arrangement with the coaxial design. We arranged two needle valves at the hot end of each pulse tube to create a valve-controlled active type of phase shifting. The second stage regenerator matrix is composed of our latest self-made lead-coated screen material. To make this material, stainless steel screens with an initial wire diameter of $36\text{ }\mu\text{m}$ (158 mesh) were electroplated to a resulting wire diameter between $105\text{ }\mu\text{m}$ and $125\text{ }\mu\text{m}$. Hence, this wide range of lead coated wire diameters at constant mesh number made it possible to achieve an inhomogeneous regenerator with porosities from 0.43 to 0.37 into the second stage. The resulting refrigerator reached a no load temperature of 6.5 K and provides a cooling capacity of 2 W at 9.5 K; this is limited by the 6.2 kW electrical input power of our Leybold RW 6000 compressor. The design parameters and the influencing variables to optimize the cooling performance are discussed.

INTRODUCTION

The concept of a two-stage pulse tube refrigerator (PTR) in an entire coaxial configuration will be presented within this paper. The well-known two-stage coaxial design of the Gifford-McMahon refrigerators is combined with the concept of the PTR and its non-existing moving parts within the coldfinger. Hence, the advantages of the coaxial configuration are unified with the low vibration levels of the cold tip and the long economic life-time. This new type of a two-stage PTR enlarges the area of application of research prototypes or commercially available PTRs of the U-tube design [1-5].

As a pilot study we researched the intermediate thermal contact of a single stage pulse tube refrigerator. The direction and the quantity of transferred heat between the pulse tube and the regenerator significantly influences the cooling performance [6]. The temperature distribution, together with the volume and the arrangement of the first stage regenerator, has to be considered to combine the two-stage arrangement with a coaxial design. Special design parameters of the coldfinger can be found in condensed form in [7].

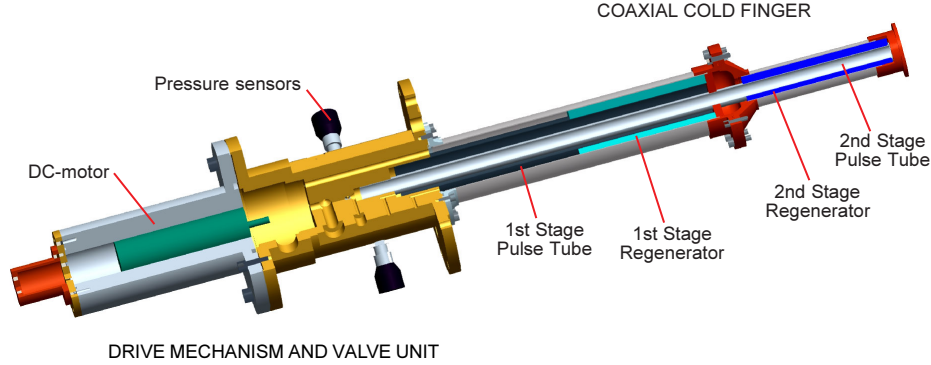


Figure 1. Layout of the two-stage PTR. The pulse tubes are located inside the respective regenerators. Additionally, the 2nd stage pulse tube is placed at the centreline of the 1st stage pulse tube. Therefore, a ring-shaped space for the 1st stage pulse tube occurs.

EXPERIMENTAL SET-UP

We arrange two needle valves at the hot end of each pulse tube to create the valve controlled active type of phase shifting. It is equivalent to the four valve technology of single stage PTRs [8]. All four needle valves are controlled by the rotary valve which is integrated in the valve unit together with the accessory equipment for pressure measurement.

The second-stage regenerator is composed of our self-made electroplated lead screen material [9]. The wide range of lead coated wire diameters at constant mesh number makes it possible to integrate an inhomogeneous regenerator with stepwise varied porosities from 0.43 to 0.37, see Table 1 and Fig. 2 [10].

Table 1. Parameters of the lead coated screens used in the 2nd stage regenerator [7].

	Sample 1 original screen material	Sample 2 towards the warm end of regenerator II	Sample 3 towards the cold tip of regenerator II
Stainless steel wire diameter (μm)	36	36	36
Mesh distance (μm)	125	55	45
Lead coated wire diameter (μm)	-	105	120
Porosity	0.82	0.43	0.37

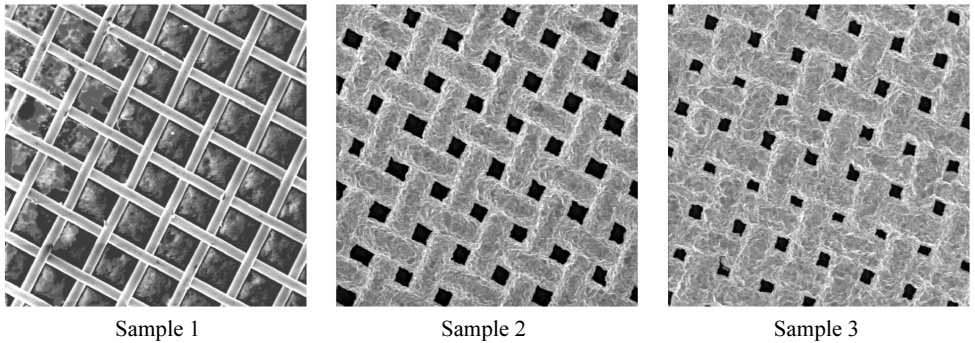


Figure 2. Electron microscope pictures of the lead coated screens that are integrated in the inhomogeneous matrix of the 2nd stage regenerator.

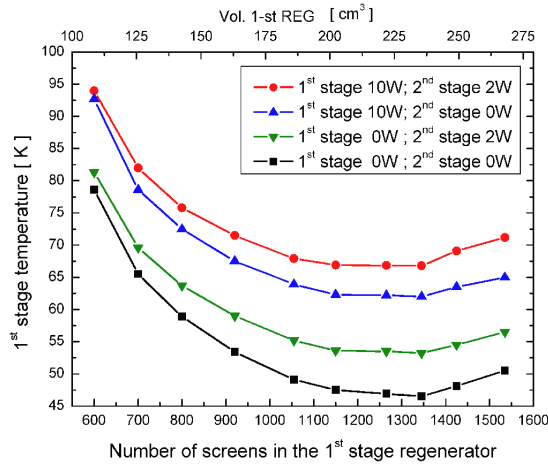


Figure 3. Variation of the first-stage temperature with number of screens in regenerator. The optimum value is around 1300 screens depending on the quantity of heat input at both stages.

The 1st stage regenerator is filled up with a random stack of commercially available stainless steel screens with 200 mesh. The temperature of the 1st stage is dependent on the length of its regenerator. Caused by the strong thermal coupling between the stages, the temperature distribution of the 2nd stage is influenced, too. The intermediate thermal contact between the pulse tubes causes an additional effect on the precooled 2nd stage. Therefore, we analyzed the cooling performance of the two-stage PTR by varying the 1st stage regenerator.

EXPERIMENTAL RESULTS

Figure 3 and Fig. 4 show the dependency of cold tip temperatures at the 1st and 2nd stage regarding the length (tantamount to the volume) of the 1st stage regenerator. The temperature distribution inside the pulse tube interacts with the temperature profile inside the regenerator. Additionally, the pressure drop of the entire regenerator matrix increases by elongating the regenerator.

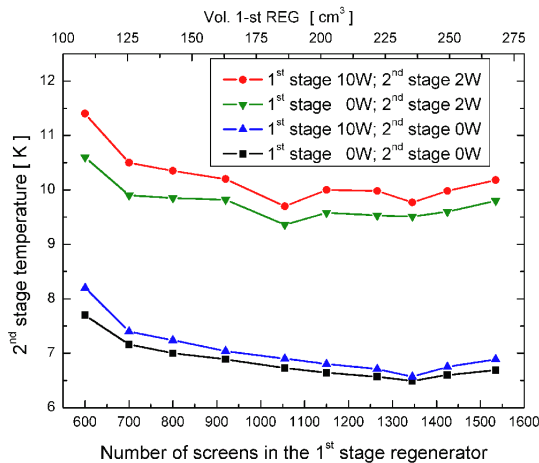


Figure 4. Variation of the 2nd-stage temperature with number of screens in regenerator. The influence on the 2nd-stage cold tip temperature is caused by the thermal coupling between the two stages.

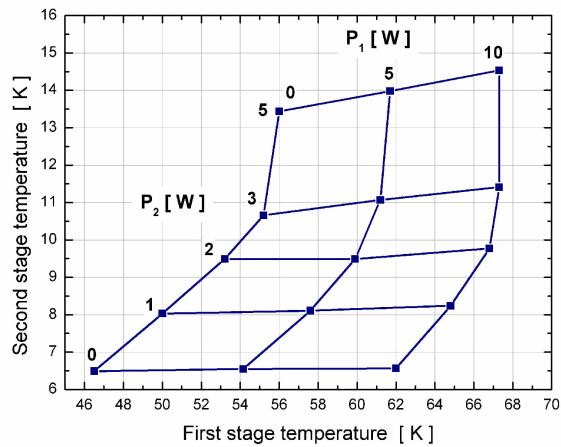


Figure 5. Cooling performance of the two-stage PTR. The parameters P_1 and P_2 are the heat inputs at the respective stages. The 2nd stage regenerator is filled up with an inhomogeneous stack of lead coated screens, without rare earth compounds. Compressor unit Leybold RW 6000, filling pressure 1.6 MPa.

The optimum regenerator fill is observed to be around 1300 screens depending on the amount of heat input. For instance, the optimum number of screens is greater at the 2nd stage with a heat input at both stages than it is in the no-load case. Fig. 5 shows the performance characteristic of the two-stage PTR with a chosen number of 1340 screens inside the 1st stage regenerator. This set-up is optimized for lowest no-load temperatures at both stages. A heat input of 10 W at the 1st stage causes a temperature increase of less than 0.15 K at the 2nd stage cold tip. Caused by periodic pressure oscillations inside the refrigerator and the high thermal conductivity of the cold tip, temperature oscillations are detected at the 2nd stage cold tip as shown in Fig. 6. The amplitude of oscillation is seen to be less than 0.22 K. The averaged value is what is indicated as the cold tip temperature.

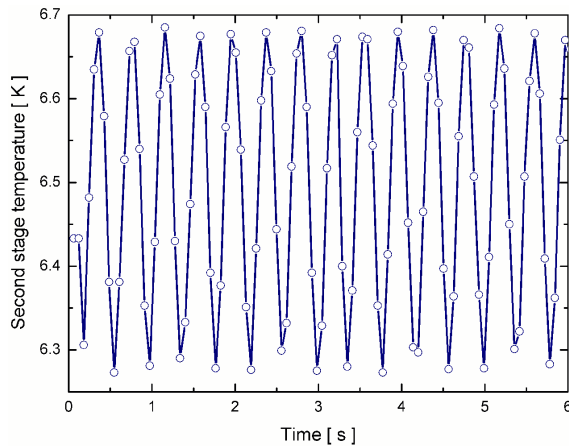


Figure 6. Temperature oscillations at the 2nd stage cold tip. The pressure ratio inside the coldfinger is 2.0 MPa/1.1 MPa. The operating frequency is 2.3 Hz.

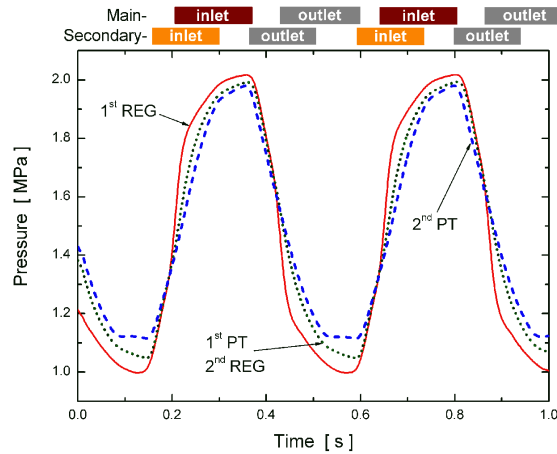


Figure 7. Pressure oscillations inside the coldfinger. (PT: pulse tube, REG: regenerator). The bars above the diagram indicate the span of time while the respective valves are open.

The rotary valve, in combination with the auxiliary valves at the PT warm end, generates the pressure waves inside the coldfinger. Fig. 7 shows the periodic change of the pressure at the main inlet - named 1st REG. The pressure in the 1st stage pulse tube - named 1st PT - is equivalent to the entrance pressure of the 2nd stage regenerator - named 2nd REG. The pressure drops across the regenerator stacks can be extracted, see Fig. 8. It has to be mentioned that the 1st and 2nd stage are in phase regarding the valve timing procedure. Only a time shift of about 10 ms is detected between the 1st and 2nd stage PT. The origin is assumed in the imbalance of the rotary valve. The areas of interest are the small peaks in the slope of the pressure drops, highlighted in Fig. 8. A higher pressure drop in the 2nd stage regenerator than in the 1st stage one indicates a short time counterflow in the 1st stage PT (the main inlet is closed) [11]. This generates internal losses and could be a reason for the relatively high temperature at the 1st stage cold tip, compare Fig. 5. The temperature distribution along the coldfinger, plotted in Fig. 9, points up the imbalance effect on the 1st stage. In spite of the relatively high temperature of the 1st stage cold tip the temperature of the 2nd stage regenerator is not influenced towards the cold end.

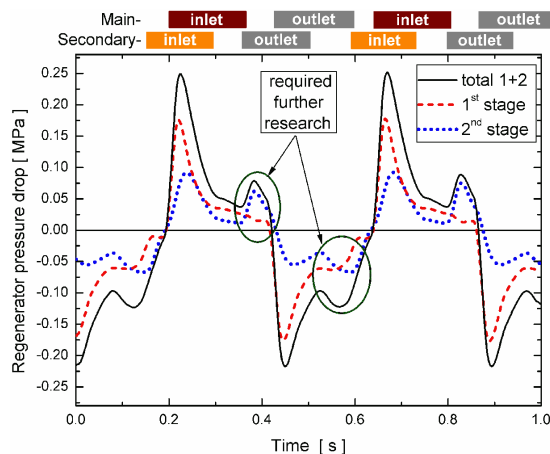


Figure 8. Pressure difference across the regenerators. The highlighted regions suggest a need for further research regarding the internal loss mechanisms in combination with the valve timing.

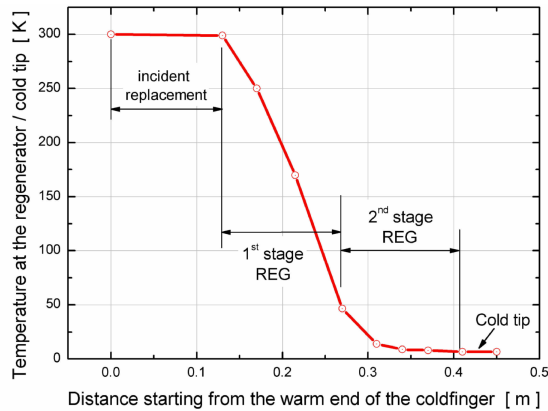


Figure 9. Temperature distribution at the outside of the two-stage coldfinger.

CONCLUSIONS

We demonstrated the coaxial concept of a two-stage PTR, successfully. The intermediate thermal contact between the pulse tubes and the respective regenerators are utilized in the coldfinger arrangement. The best cooling performance was determined by integrating 1340 screens in the 1st stage regenerator. The PTR achieved a no load temperature of 6.5 K and provided a cooling capacity of 2 W @ 9.5 K. Further studies concerning the internal losses in combination with the valve timing procedure are necessary.

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