A Hybrid Counterflow Pulse-Tube Refrigerator

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ABSTRACT

Counterflow pulse-tube refrigerators (CFPTR) are a special type of pulse-tube refrigerators (PTR). They use two identical PTRs which run in opposite phase. When one PTR is in the charging phase the other one is in the discharging phase. The gases of the two PTRs exchange heat by a counterflow heat exchanger. Thus CFPTRs have the possibility of avoiding expensive regenerator materials.

In order to provide a low starting temperature for the CFPTR a hybrid system is constructed which consists of two subsystems, one CFPTR and one conventional PTR. The latter is used to precool the CFPTR. The two subsystems work independently and have their own running parameters. The results of the first experiments of the hybrid system will be described in this paper. Our setup has great potential, and improvements will be made to optimize the performance both in cooling power and temperature range.

INTRODUCTION

The regenerator, which must have a high heat capacity, is one of the most important components of traditional pulse-tube refrigerators. Stainless steel or phosphor bronze is normally used in refrigerators working in the temperature range above 50 K. Lead is often used in refrigerators working at 10 K to 30 K. Rare-earth magnetic materials, which have a maximum in heat capacity below 15 K, are required if the refrigerator works below 4.2 K. In many cases the regenerator is large, heavy, expensive, and complicated [1]. The hybrid system provides a possibility to avoid rare-earth materials by employing a CFPTR working at low temperatures.

The CFPTR has two identical PTRs working in opposite phases. The regenerators are replaced by a counterflow heat exchanger. Figure 1 is a schematic representation of the hybrid system. It consists of a traditional PTR, which is the precooling stage (the first stage) and a CFPTR operating at low temperatures (the second stage). The two subsystems are thermally connected by a heat exchanger, the so-called precooling heat exchanger. There is an alternating flow in the counterflow heat exchanger of the CFPTR because the rotary valve is at the room temperature. The volume of the heat exchanger acts as a void volume which contributes to the losses. Furthermore, the heat exchanger partly works as a regenerator because there is an alternating temperature in the wall.

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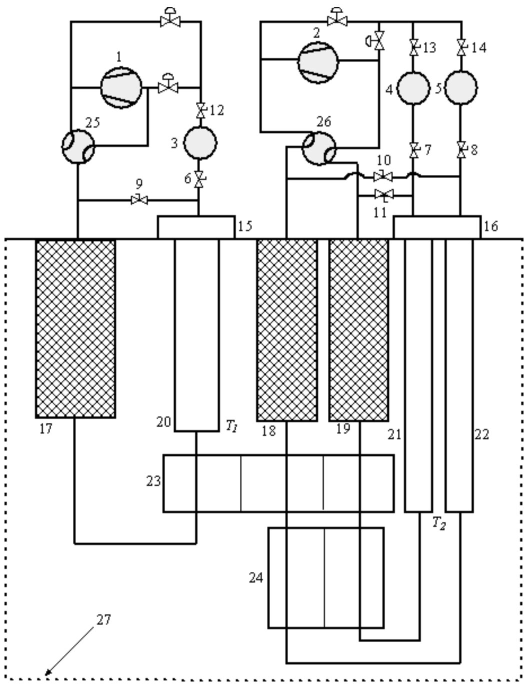


Figure 1. Schematic representation of the hybrid system.1-2 - compressors; 3-5 - buffers; 6-8 - first orifices; 9-11 - double-inlet valves; 12-14 - minor orifices; 15-16 - water coolers; 17-19 - regenerators; 20-22 - pulse tubes; 23 - precooling heat exchanger; 24 - counterflow heat exchanger; 25-26 - rotary valves; 27 – vacuum chamber. The lowest temperatures of the first and the second stages are indicated with T_1 and T_2 respectively.

EXPERIMENTAL SETUP

The hybrid system has two separate subsystems. Each subsystem has a 6 kW compressor and a 'no-contact' rotary valve [2] to generate the pressure wave. Each pulse tube has its own orifice, double-inlet valve, and minor orifice to optimize the performance. Table 1 gives the dimensions of the pulse tubes and the regenerators. Table 2 gives the compositions of the regenerators of the two stages. Two types of sintered stainless steels are used as second-stage regenerator materials. Material with a high porosity is used in the high-temperature parts while material with low porosity is used in the low-temperature parts.

Table 1. Dimensions of the pulse tubes and the regenerators.

	Stage	1	2
pulse tube	diameter (mm)	35	13
	length (mm)	220	400
	volume (cm^3)	212	53
regenerator	diameter (mm)	56.3	28
	length (mm)	221.5	221.5
	volume (cm^3)	551	136

Table 2. Composition of the regenerators of the hybrid system.

	material	Size	mass
1st stage	phosphor bronze screens	mesh # 200	1581 g
2nd stage	sintered stainless steel	porosity 51%	243 g
	sintered stainless steel	porosity 46%	268 g

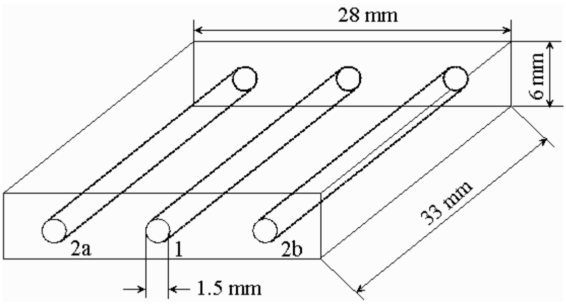


Figure 2. Schematic representation of a unit of the precooling heat exchanger.

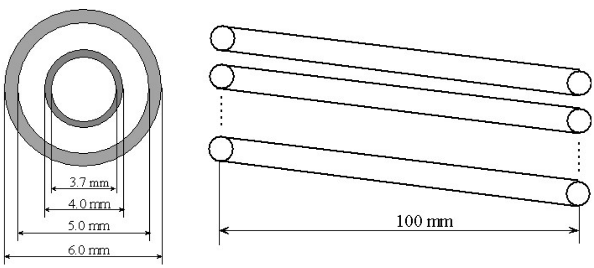


Figure 3. Schematic representation of the tube-in-tube heat exchanger.

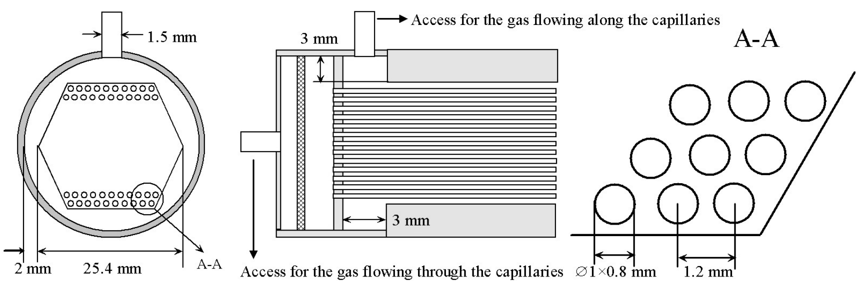


Figure 4. Schematic representation of the 331-capillary counterflow heat exchanger.

In order to create a low starting temperature for the CFPTR, the first stage extracts heat from the second stage by the precooling heat exchanger which consists of four identical units. Figure 2 shows the dimensions of a unit which is made of a copper block with three channels. The middle channel (indicated with 1) is for the gas of the first stage and the channels on the two sides (indicated with 2a and 2b) are for the gases of the CFPTR. In the experiments the four units are arranged in series or in parallel to compose different precooling heat exchangers.

Two counterflow heat exchangers are designed for the CFPTR. One is a coiled tube-in-tube heat exchanger as shown in Figure 3. It has a length of 2.0 m. The other one is the so-called 331-capillary counterflow heat exchanger which is 100 mm long. Figure 4 shows the schematic drawing. Two such heat exchangers have been made and can be arranged in series or in parallel.

The total entropy production (loss) in the counterflow heat exchanger is due to heat exchange between the gas flows, heat conduction in the gas and in the heat exchanger body in the axial direction, and due to the flow resistance. At temperatures far below 200 K the contribution of the heat conduction in the axial direction becomes significantly larger than the contributions of the flow resistance and the heat exchange [3]. The tube-in-tube heat exchanger is much longer and causes losses due to the heat conduction in the axial direction, whereas the 331-capillary heat exchanger has more heat exchanging surface.

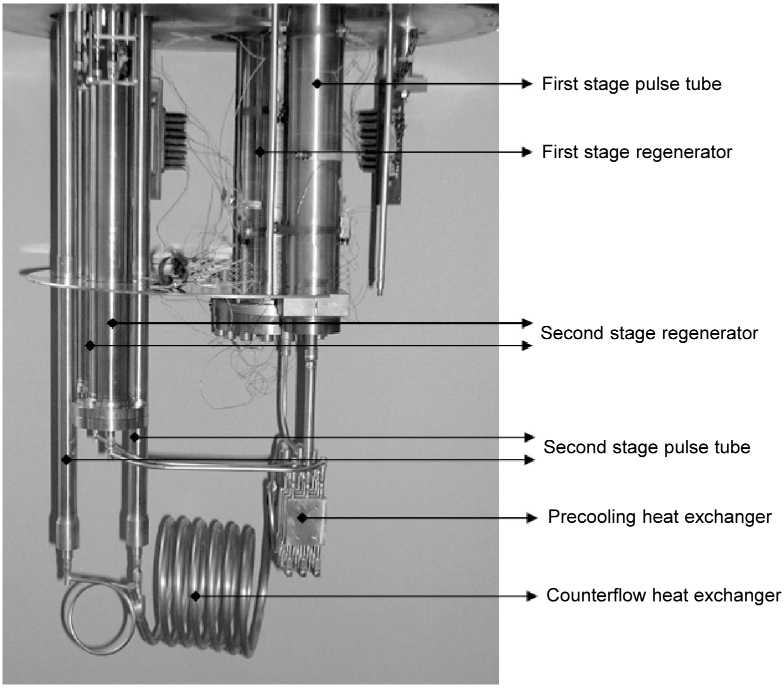


Figure 5. Picture of the setup with the tube-in-tube heat exchanger in place.

PRELIMINARY EXPERIMENTAL RESULTS

Figure 5 shows the setup with the tube-in-tube heat exchanger in place. The first and second stages are separately tested before running the hybrid system. A lowest temperature 38.5 K and 20 W cooling power at 44 K are obtained on the first stage. The second stage, without precooling by the first stage, reaches 114 K in the no-load situation.

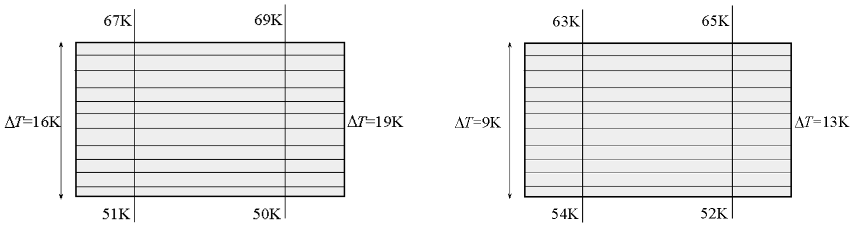
Three configurations of the precooling heat exchanger have been tested. Table 3 shows the lowest temperatures and pressure losses for the different configurations. The temperature T_1 is the temperature at the cold end of the first stage and T_2 is the temperature at the cold end of the second stage. The pressure drop due to the flow resistance of the regenerator and the precooling heat exchanger of the first stage is Δp_1; Δp_2 is the pressure loss caused by the regenerator, the precooling heat exchanger, and the inner tube of the tube-in-tube heat exchanger for the second stage. Comparing the lowest temperatures obtained on the separate stages and the hybrid system, T_1 goes up and T_2 goes down. It means that the first stage is precooling the second stage in the hybrid system. Comparing the results in Table 3, it can be seen that the pressure loss in the precooling heat exchanger has a great influence on the performance of the system. The smaller the pressure loss the lower the temperature. Figure 6a shows typical temperatures at the ends of the tube-in-tube heat exchanger. There is a temperature crossing along the heat exchanger. This cannot happen in a DC-flow heat exchanger.

Table 3. Lowest temperatures and pressure losses of the hybrid system with the tube-in-tube heat exchanger.

Label	Configuration of precooling heat exchanger	T_1 (K)	T_2 (K)	Δp_1 (bar)	Δp_2 (bar)
a	4 units in series	86.9	62.6	1.7	1.9
b	2 units in series	73.4	53.1	1.3	1.8
c	2 units in series in parallel	67.7	48.7	1.2	1.5

Table 4. Lowest temperatures of the hybrid system with 331-capillary heat exchanger.

Label	Configuration		T_1 (K)	T_2 (K)
	Precooling heat exchanger	Counterflow heat exchanger		
d	2 units in parallel	1 heat exchanger	55.1	51.6
e	2 units in parallel	2 heat exchangers in parallel	62.5	58.3
f	2 units in series in parallel	2 heat exchangers in series	77.9	62.1



(a) tube-in tube heat exchanger (b) 331-capillary heat exchanger

Figure 6. Typical temperatures at the ends of the counterflow heat exchanger.

The results in Table 4 are obtained on the hybrid system with the 331-capillary heat exchanger. The temperature profile of this system is given in Figure 6b. Comparing the two last cases labeled c and f it can be found that the hybrid system works better with the tube-in-tube heat exchanger. The 331-capillary is only 100 mm in length and generates more losses due to the heat conduction in axial direction than the tube-in-tube heat exchanger. Furthermore, the void volume of the 331-capillary heat exchanger is also much bigger than of the tube-in-tube heat exchanger. The void volume at the low temperature has great influence on the performance of the pulse tube refrigerator. It does not improve the performance of the CFPTR even though it has a much bigger heat-exchanging surface area than the tube-in-tube heat exchanger. The negative influence of the void volume is clearly seen by comparing the two cases d and e.

CONCLUSION

A hybrid counterflow pulse-tube refrigerator has been built to investigate the possibility of avoiding regenerators at low temperatures. Two types of the counterflow heat exchangers have been tested. The basic performance of the hybrid counterflow pulse tube has been investigated. The lowest temperature was 48.7 K. In the future improvements will be made to obtain better performance both in cooling power and temperature range.

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