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Thermodynamic analysis of reverse Brayton cycle based cryocoolers for cooling HTS cables

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Abstract. Cryocoolers based on reverse Brayton cycle (RBC) and its derivatives are considered for High Temperature Superconducting (HTS) cables. In this work, thermodynamic analysis has been performed for the configurations based on reverse Brayton cycle for different heat loads from HTS cables that have been reported in open literature. The derived RBCs have expanders in series and parallel arrangements to reduce the exergy destruction in the components of the thermodynamic cycle thereby enhancing the thermodynamic efficiency. Investigation has been done on the optimized cycles using helium as working fluid. The irreversibilities due to entropy generation in each component of every cycle is examined to find the opportunities for further improvements. The performance of the most suitable configuration of RBC for each load case is compared with that of the existing cryocoolers. The results of the analysis may be useful for finding out the suitable thermodynamic configuration of RBCs along with the component sizes for different load scenarios generating from HTS cables.

1. Introduction

High temperature superconductors (HTS) at 30 K and 93 K were discovered in 1986 and 1987 [1], [2]. After this discovery, many small and large scale projects were established to test the viability of these HTS in power sector by countries like USA, Denmark, South Korea and Japan [3–5]. The YBCO or BSSCO based HTS power cable are used for these projects to test practical viability with different load conditions and temperature levels. Some of the projects on the HTS cable are presented in the table 1 which are considered for the present study. The existing cooling technology for these HTS is also given.

Table 1. HTS power cable projects and the cooling technology

Case	*Project*	*Cooling capacity*	*Cooling Technology*	
#1	Albany Project	6 kW at 71.5 K	Hybrid system with Stirling and thermosyphon technology	[6]
#2	Danish HTS cable Project	1.11 kW at 78 K	Stirling cryocooler with LN_2 Backup	[3], [7]
#3	ORNL HTS cable	1.16 kW at 80 K	Open system with direct LN_2 cooling	[4]
#4	Yokohoma Power cable project	2.1 kW at 69 K	RBC Cryocooler	[8]
#5	Korean HTS cable project	10 kW at 70 K	RBC cryocooler	[9]

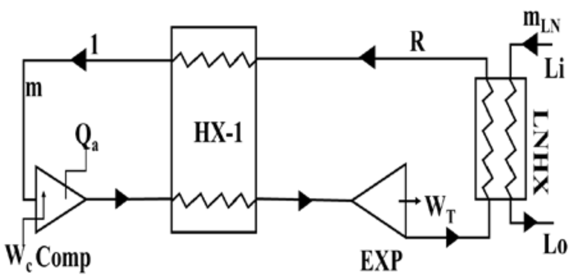
The Albany and Danish HTS power cable projects used two Stirling cryocooler for cooling of the cable. The Carnot efficiency of the Stirling cryocoolers is 24 – 25% based on the current Stirling technology of the same capacity [10]. However, the cooling system for Danish power cable did not meet the desired reliability and maintainability as many faults were observed while in operation [7]. Therefore, a cryocooler based on RBC that is more reliable and requires lower maintenance had been used for the Yokohama and Icheon, Korean project with Carnot efficiency of 16% and 26%, respectively. The industries like Taiyo Nippon Sanso Corporation, Japan and Air Liquide, France had developed the RBC cryocooler based on the neon and helium gas as working fluid for these power cable projects [9], [11]. Dhillon et al. had optimized and suggested the modification in the RBC cryocooler for HTS cable and also reported the capability of the cryocooler for heat loads at a fixed temperature of 65 K to meet the cryogenic road map of 30% Carnot efficiency [12]–[14].

In this paper, the basic RBC along with its three derivatives have been studied for their performance when subjected to the heat loads at different temperature ranges for five cases as given in table 1. The best suitable modifications based on the thermodynamic as well as design constraints are presented and suggested in the article.

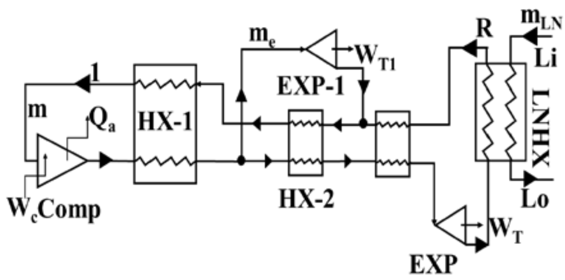
2. Basic and modified RBC Cryocooler

The analysis of cryogenic refrigeration system is carried out on four different configurations of the RBC cryocooler. The modifications in the basic RBC cryocooler are accomplished using two stage turboexpander in the cycle by arranging them in the series and parallel. The arrangements of turboexpanders has improved the performance of the cycles used in different applications such as Collins helium liquefier and RBC for LNG liquefactions [15], [16]. The parallel expanders in the RBC with 30% Carnot efficiency have been reported by Dhillon and Ghosh [14].

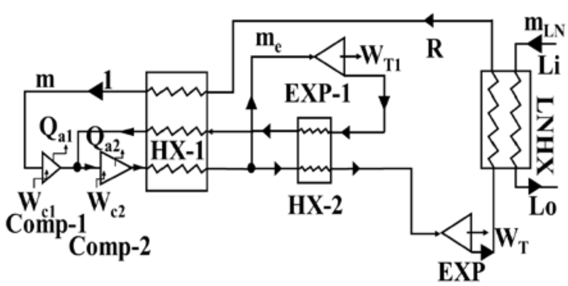
The four cycles considered for the present work are basic (Basic), parallel expansion with same pressure ratio (PE), parallel expansion with different pressure ratio (PED) and series expansion (SE) RBC as shown in figure 1.



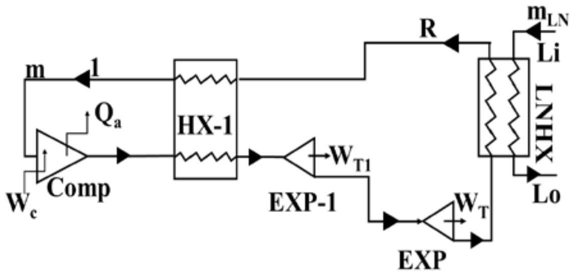
a – Basic



b – PES



c – PED



d – SE

Figure 1. Different configurations of RBC and its derivatives

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3. Modelling

3.1. Simulation Environment

The analysis of the optimized basic and modified RBC cryocooler is carried out for aforementioned heat load cases in table 1 using Aspen HYSYS V8.6®. The analysis is carried out using the following assumptions:

- The polytropic efficiency of the compressor is 60%.
- The adiabatic efficiency of the turboexpanders is 70%.
- The pressure drops in the heat exchangers and aftercooler are 5 kPa and 20 kPa, respectively.
- Minimum approaches in the heat exchangers are 0.5 - 1% of the highest temperature.
- The optimized pressure and pressure ratio are given in table 2 for each configurations.

Table 2. Optimized process parameters for RBC and its derivatives

Configuration	*Inlet pressure (bar)*	*Pressure ratio*
Basic RBC	10	1.9
PES RBC	25	1.7
PED RBC	14	1.8
SE RBC	10	1.9

3.2. Performance parameters

The analysis has been carried out using the exergy tool based on the second law of thermodynamics [12]. The exergy efficiency (η_{ex}) is calculated to compare and selection of the cycle for different as given in equation (1).

$$\eta_{ex} = \left(1 - \frac{\sum \dot{E}_D}{W_{COMP}}\right) \times 100 \quad (1)$$

Where, $\dot{E}_D$ is the exergy destruction in the component and W_{comp} is the work input to the compressor. Figure of Merit (FOM) is defined as the ratio of COP_{actual} to the COP_{ideal} of an RBC cryocooler [14].

3.3. Components design

While exergy efficiency is the performance indicator, the equipment specifications are the design constraints that decide the feasibility of the thermodynamic cycle for practical implementations. To estimate the specifications, preliminary design of the turboexpander and heat exchangers for all configurations has been carried out. A radial inward-flow turboexpander has been considered for the design based on the methodology suggested by Ghosh [17]. Brazed aluminum plate fin heat exchangers with serrated fins has been considered for the heat exchangers in all the RBC configurations. The heat exchangers are designed using the Aspen Exchanger Design and Rating®.

4. Results and discussions

The basic and modified RBC cryocoolers have been investigated from thermodynamic and design point of view for five different cooling loads conditions at different temperature.

4.1. Performance analysis

The modifications in basic RBC improves the performance of the cycle by reducing the exergy destruction in the components. The FOM and exergy efficiency for each case have been shown in figure2. It is observed from the figure that the modified RBC cryocoolers perform better than the basic RBC cryocooler. It is found that the exergy destruction in the components of PED RBC cryocooler is increased except that in the compressor due to two stage compression as given in table 3. In the case of other two modifications of the RBC cryocooler, the exergy destruction is reduced in all components compared to the basic RBC. The PED has performed considerably better than all other configurations for case 2 and 3 due to significant reduction of exergy destruction in the compressor. The improvement in the exergy efficiency is about 8% than the basic RBC and 3 to 4% more than the PES RBC cryocoolers. The PES and PED have similar performance for case 1 and have 8% higher exergy efficiency than the basic RBC. However, the PES RBC cryocoolers have better performance than others for case 4 and 5. The exergy efficiency of the PES RBC for these cases is increased by more than 9% compared to the basic cycle. It is found that the PES have better performance below 70 K while PED RBC cryocoolers have better performance above 70 K. The PED RBC cryocooler have a significant better performance than all other configurations of the RBC for the refrigeration temperature of 80 K. It is also found that the mass flow rates through secondary turboexpander for case 2 and 3 are 3.5 and 3.6 g/s, respectively. Such low mass flow rate turboexpander can have small diameter with very high rotational speed. Therefore, the specifications of turboexpanders have to be considered for selection of the best configuration for given cases in table 1.

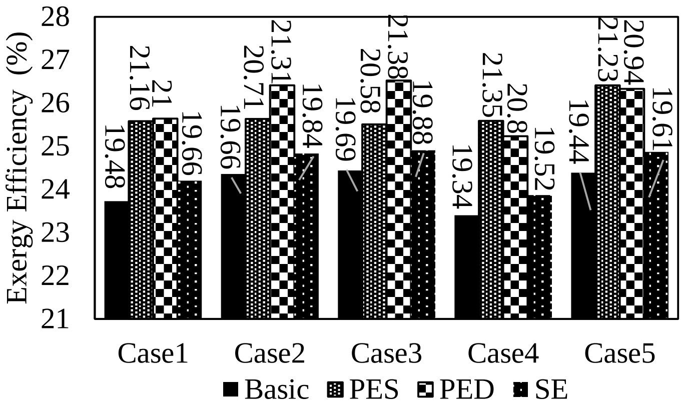

Figure 2. Performance of RBC for different case scenarios. (data labels are FOM of each configurations)

Table 3. Exergy destruction per watt of refrigeration (W/W) in components for case 1.

	Basic	PES	PED	SE
Comp	10.1	9.1	8.6	10.1
HX	1.37	1.34	**1.61**	1.25
EXP	2.80	2.68	**2.87**	2.75
Load HX	0.27	0.22	**0.24**	0.29

4.2. Turboexpanders

As it is discussed earlier that the turboexpander speed and size are some of the specifications that dictates the selection of a particular cycle configurations, the preliminary design of the turboexpanders for all configurations of the RBC cryocooler have been carried out in the present work. The turboexpander diameter and speed are presented in the table 4 and 5 for all cases. It is observed from table 4 that the size of the secondary turboexpander (TE-2) of PES and PED have sizes about 5 mm for case 2, case 3 and case 4 which are considerably small. The turboexpander with a speed of 1,000,000 rpm can be designed using the present state of art of the bearing technology. However, the cost of the turboexpander will also increase significantly high [18]. The small size of turboexpanders have very high speed above than 600,000 rpm as shown in table 5. Therefore, the large diameter turboexpanders with speed of 250,000 – 350,000 rpm of the SE RBC cryocoolers for the case 2 and case 3 are more reliable compared to other turboexpander for other configurations of the RBC cryocooler [18].

Table 4. Wheel diameter (mm) of turboexpanders for the basic and modified RBC cryocooler

Case	Basic	PES		PED		SE	
	TE-1	*TE-1*	*TE-2*	*TE-1*	*TE-2*	*TE-1*	*TE-2*
1	31.5	19.5	12.5	27.1	27.1	37.5	32.9
2	13.0	8.2	**5.2**	10.4	10.89	15.6	13.6
3	13.2	8.4	**5.2**	10.5	**4.7**	15.7	13.8

4	18.4	11.7	7.6	16.1	**4.8**	22.6	19.8
5	40.9	25.3	16.2	29.6	14.8	48.7	42.6

Table 5. Speed of turboexpanders (rpm) for the basic and modified RBC cryocooler

Case	***Basic***	***PES***		***PED***		***SE***	
	TE-1	*TE-1*	*TE-2*	*TE-1*	*TE-2*	*TE-1*	*TE-2*
1	177970	262894	478948	204445	372856	103767	123930
2	448838	**650729**	**1166000**	554453	**897924**	260616	311308
3	446430	**648722**	**1152000**	554488	**896042**	260928	311426
4	314514	430620	**794899**	338197	579225	168857	202751
5	136027	201583	368712	185509	272589	79375	94942

4.3. Heat exchangers

While turboexpander is the most sensitive component of the RBC cryocooler which decides the reliability of the cryocooler. The size and weight of cryocooler is mainly governed by HX. In case of size and cost of the heat exchangers are also constraints for the cryocooler, then the design of the heat exchanger has to be considered. Therefore, the design of the main heat exchangers (include HX1, HX2 and HX3 in case of PES and PED) and the load heat exchanger has been carried out to realize the size of the cryocooler. The area required for heat transfer in the main heat exchanger and load heat exchanger of all configurations of the RBC cryocooler is presented in the table 6. It is observed that the modification in the RBC cryocooler do not have significant impact on the heat transfer area of the load heat exchanger. However, the arrangement of the turboexpander in parallel with same pressure ratio have significant impact on the size of the main heat exchanger. The heat transfer area of the main heat exchanger for case 1, 4 and 5 is increased by 45 – 55% compared to basic cycle. It is found that the reduction in the refrigeration temperature increases the change in the heat transfer area of the main heat exchanger of PES compared to that of the basic RBC as given in table 6.

Table 6. Heat transfer area (m^2) of the heat exchangers and percentage change from basic RBC

Case	**Main heat exchanger**			Area **(% Change)**		**Load Heat exchanger**		
	Basic	*PES*	*PED*	*SE*	*Basic*	*PES*	*PED*	*SE*
1	35.68	51.68 **(+45)**	41.13 **(+15)**	35.30 **(-1.1)**	4.10	4.31 **(+5)**	4.48 **(+9)**	4.08 **(-0)**
2	6.74	8.42 **(+25)**	6.68 **(-1)**	6.75 **(+0.1)**	0.56	0.58 **(+3)**	0.54 **(-4)**	0.61 **(+8)**
3	6.79	7.70 **(+13)**	7.06 **(+4)**	6.74 **(-0.7)**	0.66	0.66 **(-0)**	0.65 **(-1)**	0.66 **(-0)**
4	14.27	22.20 **(+55)**	17.25 **(+21)**	14.83 **(+4)**	1.29	1.24 **(-4)**	1.35 **(+4)**	1.29 **(-0)**
5	61.25	89.44 **(+46)**	67.10 **(+10)**	61.57 **(+0.5)**	4.23	4.48 **(+6)**	4.28 **(+1)**	4.23 **(-0)**

5. Conclusions

The analysis of four configurations of the RBC have been carried for five different cases of HTS cable with different cooling load conditions.

The PED RBC cryocooler have better performance above 70 K. However, The SE RBC cryocooler is suggested for cooling capacity < 2 kW for a refrigeration temperature above 70 K due to very high speed turboexpanders required for PED RBC cryocooler. The PES RBC cryocooler performs well below 70 K. It is also need to consider the increment in the size of the main heat exchanger for the PES RBC cryocooler when there is a size constraint for the cryocooler. The data obtained from this work will be helpful in choosing appropriate cycle configuration for the different heat loads in cooling HTS cables considering the technological limitations arising from the component specifications.

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